Resistance-based connectivity model to construct corridors of Przewalski's gazelle in fragmented landscape

Jingjie Zhang[1], Feng Jiang[1], Zhenyuan Cai[1], Yunchuan Dai[2], Daoxin Liu[1], Pengfei Song[1], Yuansheng Hou[3], Hongmei Gao[1], and Tongzuo Zhang[1]

[1]Northwest Institute of Plateau Biology Chinese Academy of Sciences
[2]Chinese Academy of Forestry
[3]Affiliation not available

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Abstract

Habitat connectivity is indispensable for the survival of species that occupy a small habitat area and have isolated habitat patches from each other. At present, the development of human economy not only squeezes the living space of wild animals, but also strongly interferes and hinders the migration of species. Therefore, we need to enhance the habitat connectivity of species in broken habitats, which would facilitate the proliferation of species, enhance gene exchange between populations and improve the ability of species to respond to environmental changes. Przewalski's gazelle, as one of the world's most endangered ungulate mammals, has historically experienced a significant reduction in population and severe habitat shrinkage. At present, even though the population of this species has recovered to a certain extent, humans Infrastructure severely hindered the gene flow between several patches of this species. Therefore, we used habitat suitability index model combined with Przewalski's gazelle movement characteristics to establish 11 habitat patches, and used the least cost path and circuit theory based on resistance model to jointly simulate the landscape network pattern of this species. In addition, we also analyzed and selected important patches and key migration paths as important references for establishing corridors. Overall, our research aims to provide habitat networks and maintain landscape connectivity to achieve the fundamental goal of protecting and revitalizing Przewalski's gazelle populations.

1 Introduction

Habitat fragmentation is considered to be one of the most important threats to biodiversity and also seriously affects the continued survival of species (Kareiva 1987, Kruess and Tscharntke 1994, Collinge 1996). The transformation of the landscape by humans has caused the landscape to become scattered, and the habitat of the species has been divided into smaller, more isolated fragments. For a long time, the habitat loss of species and the increase of isolation would change the structure and function of the remaining debris (Taylor et al. 1993, Lindenmayer and Fischer 2013). Habitat fragmentation often hinder the spread and movement of individuals, reduces gene exchange between groups, increase the risk of extinction due to inbreeding, and limits the ability of species to cope with long-term environmental changes (Frankham 2005, Haddad and Tewksbury 2005, Heller and Zavaleta 2009, Lindenmayer and Fischer 2013). Therefore, enhancing habitat connectivity between populations or constructing ecological corridors can reduce the negative impact of habitat fragmentation, and provide more opportunities for the continued survival of small populations (Brown and Kodric-Brown 1977, Dixon 2007).

Przewalski's gazelle (*Procapra przewalskii*) is one of the world's most endangered large ungulate. It was once widely distributed in northwestern China. However, after a excessive illegal hunting and habitat loss, a series of human impacts, the habitat range shrank to the area around Qinghai Lake, and the population has declined significantly. Historically, when the population size of this species was the lowest, it was less than 300 in1994(Jiang et al. 1996, Li et al. 2008). Fortunately, Przewalski's gazelle has received the attention and protection of the Chinese government since 1990s, and the population has gradually increased (Wei et al. 1998, Jiang et al. 2003). According to the survey statistics of the Qinghai Lake Administration, the total number of Przewalski's gazelle as of 2019 was about 2,700. Nevertheless, the increasing human activities and infrastructure development have severely restricted the individual movement of Przewalski's gazelle among several independent populations around Qinghai Lake, which is very detrimental for the Przewalski's gazelle with low genetic diversity to maintain long-term viability of the population (Yu et al. 2017).

Currently, the establishment of ecological networks to enhance habitat connectivity has become one of the important strategies for protecting wildlife in fragmented habitats (Opdam 2002, Bruinderink et al. 2003, Baguette et al. 2013). Various methods and software have been developed to build ecological networks (Sahraoui et al. 2017). For example, many researchers used graph theory for landscape ecological assessment and planning and the construction of ecological corridors (Zetterberg et al. 2010, Pittiglio et al. 2014). At present, graph theory is regarded as a powerful and effective tool for landscape connection modeling, because it can not only simplify the landscape pattern into a functionally interconnected network, but also can perform complex analysis of landscape connectivity (Urban and Keitt 2001, Jordán et al. 2003, Pascual-Hortal and Saura 2006, Treml et al. 2008).

The commonly used graph theory methods include resistance-based connectivity models, such as least-cost paths (LCP) and circuit theory. These methods can analyze the movement costs between patches, which are conducive to identify possible routes for species spread and movement paths between habitat patches (Adriaensen et al. 2003, McRae et al. 2008). LCP was proposed by Knaapen (Knaapen et al. 1992), and has been widely cited in the fields of species diffusion and landscape pattern analysis (Knaapen et al. 1992, Adriaensen et al. 2003). The connectivity model is usually used to determine possible corridors or decentralized paths. It usually identifies a path with the lowest cumulative cost. Circuit theory can intuitively convert the potential of landscapes and animals to move into electric current, voltage, and resistance, thereby connecting landscape composition and pattern with functional connection. These concepts are directly related to random walking motion theory. In general, methods based on circuit theory allow multiple movement paths to be identified (McRae et al. 2008). Some studies believe that the actual observed species migration data can provide accurate connectivity estimates (Meegan and Maehr 2002, Osipova et al. 2019). However, this method is too labor-intensive and is suitable for species whose mobility rate is high enough to collect valid data within a reasonable time (Calabrese and Fagan 2004).

Our research used both methods of LCP and circuit theory to evaluate the habitat connectivity of Przewalski's gazelle. Our goals are: (1) to simulate the possible migration paths of Przewalski gazelle between isolated patches; (2) to assess the importance of all habitat patches and potential migration corridors for the connectivity of the entire Przewalski's gazelle habitat (3) to provide protection reference for the rejuvenation of Przewalski's gazelle population.

2 Materials and methods

2.1 Study area

The study area is located in the surrounding area (35.1-38.2°N, 97.4-102.6°E) of Qinghai Lake in Qinghai Province, China, which spans four autonomous prefectures in Qinghai Province (Fig. 1). The area is located between the Qaidam Basin in the west of Qinghai Province and the Huangshui Valley in the east, the source of several rivers in the south and the Qilian Mountains in the north. It is surrounded by closed mountain inland basins surrounded by high mountains. The altitude ranges between 2,100-5,300m. The area has a plateau continental climate with strong sunshine and short frost-free season. The average annual temperature in this area is -3.4–1.7degC, and the annual precipitation is 300-400mm. Due to its abundant water resources, the area is rich in wildlife and plants, and is one of the regions with the richest biodiversity on the Tibetan Plateau.

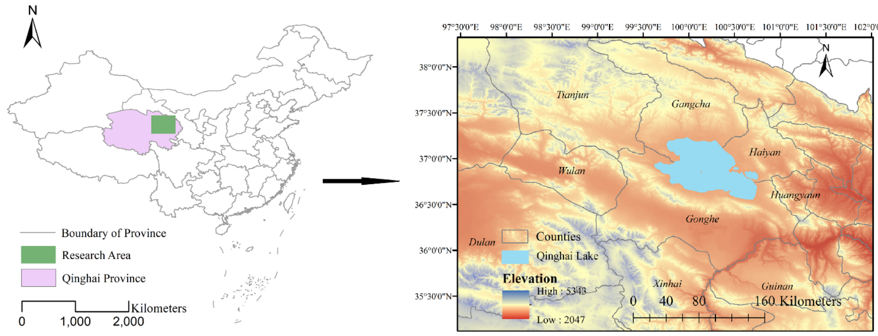

Fig. 1 The study area of Przewalski's gazelle

2.2 Data sources and processing

A total of two sets of data were used in this study, one of which was the 133 distribution sites of Przewalski's gazelle, and this set of data is all from the field survey in 2017-2019. Another set of data is environmental factors. We chose eight types of environmental variables that are closely related to the distribution of Przewalski's gazelle, including terrain variables (elevation, slope, and aspect), biological variables (land cover), and human interference variables (railroad, highway, residential points and point of Interest (POI) related to human activities). The elevation with 30m resolution used in this study was derived from the ASTER GDEM V2 digital elevation model (DEM;*http://www.gscloud.cn/*). The slope and aspect data were converted from the elevation data by ArcGIS 10.2. The land use data (2015) included many detailed land-use types, the major types of which were referring to forest, cropland, wetland, bare land, grassland, shrubland, water, residential area and snow/ice. The data comes from FROM-GLC version2 (2015_v1) (*http://data.ess.tsinghua.edu.cn/fromglc2015_v1.html*). The road data (2018) and the settlement points (2017) were obtained from the 1:250000 scale basic database of the National Basic Geographic Information Center (*http://www.ngcc.cn/ngcc/*), the road data including railways, highways, national highways, provincial roads and county roads. The 2019 POI were obtained through the extraction of Chinese maps.

In order to avoid the overlapping of information between environmental variables, we used SPSS22 to analyze the correlation of the eight environmental variables and remove the environmental variables with high correlation (p[?]0.8) (Zhang et al. 2019).

2.3 Determination of habitat patches

We imported the distribution points and environmental variables of the Przewalski's gazelle into ArcGIS. The attribute values of points were extracted from environmental variables. According to the characteristic frequency distribution, single environmental variables were divided into four suitability intervals of high, medium, poor, and unsuitable (Jiang et al. 2019). In addition, we used the entropy weight method (EWM) to perform weight analysis on the environmental variables (Zhang et al. 2014, Han et al. 2015), and used the habitat suitable index (HSI) model to calculate the habitat suitability of the species. We divided the results of the HSI model into four levels (high, medium, poor, and unsuitable) at equal intervals, and finally used high- and medium-quality habitats as the distribution area of species. Considering that Przewalski's gazelle is a species with a very low mobility rate, according to the literature, we superimpose the 3km buffer zone (Leslie Jr et al. 2010) of the species' distribution point and the distribution area calculated by the HSI model, and used the final area as the habitat patches of the Przewalski's gazelle.

2.4 Connectivity modeling

2.4.1 Resistance surface construction

Constructing landscape network called resistance surface is a key part of establishing a connectivity model. Generally, the resistance value of the habitat represents the degree of obstacles to wildlife activities. The higher the resistance value, the less chance of wildlife passing through the area (Poor et al. 2012). In this study, we adopted the expert empirical method, and assigned resistance values to different environmental variables through field visits and consultation with local experts who conducted long-term dynamic monitoring of Przewalski's gazelle. Land use type is an important factor that affects the distribution of wildlife (Anzures-Dadda and Manson 2007). Terrain factors such as altitude, slope, and aspect can limit the activities of ungulate species. In addition, the environment in which Przewalski's gazelle lives is strongly disturbed by humans, so the impact of intensive infrastructure is also taken into consideration. In this study, we assigned different environmental resistance values to each environmental factor. The resistance values ranged from 1 to 100, and were identified as 6 levels (Table 1). Finally, we superimposed the eight resistance environment layers after the classification according to the weights and obtained the final resistance layer (Fig. S1).

2.4.2 Connectivity assessment modeling

The LCPs represent the lowest cumulative cost of species loss from source (origin) to sink (destination). In our study, the habitat patches of Przewalskii gazelle were the source and sink of the network, and the constructed resistance surface was the landscape surface of species migration, and the lowest cost path between each two patches can be obtained by combining ArcGIS.

$$\text{MCR} = f min \sum_{j=n}^{i=m} D_{\text{ij}} \times R_i$$

MCR represents the minimum cumulative resistance. f is a monotonic increasing function, which indicates the positive correlation between the minimum cumulative resistance and the ecological process. D_{ij} represents the distance from source j to landscape unit i . R_i represents the resistance coefficient of landscape unit i to species movement.

The circuit theory is based on the random walk theory, which regards the landscape layer as the conductive surface and the habitat patch as the node. Among them, the patch resistance to promote species migration was lower, while that to hinder species migration was higher (McRae and Beier 2007, Peng et al. 2018). Therefore, high currents indicate a high probability of species migration (McRae et al. 2013), and vice versa. We used Julia of circuitscape 5.0 (which greatly improves performance) to calculate the pairwise connections between nodes.

2.5 Analysis of the importance of potential migration corridors

The intensity of interaction between habitat patches can reflect the importance of potential migration corridors in the network. Based on the gravity model (Linehan et al. 1995, Kong et al. 2010), quantitative assessment and identification of important ecological corridors can be achieved. $G_{\text{ij}} = \frac{N_i N_j}{D_{\text{ij}}^2} = \frac{\left[\frac{1}{P_i} \times ln(S_i)\right]\left[\frac{1}{P_j} \times ln(S_j)\right]}{\left(\frac{L_{\text{ij}}}{L_{\text{max}}}\right)^2} = \frac{L_{\text{max}}^2 ln(S_i S_j)}{L_{\text{ij}}^2 P_i P_j}$

G_{ij} represents the interaction force between patches i and j , N_i and N_j represent the weight values of the two patches, D_{ij} represents the normalized value of the potential corridor resistance between patches i and j , and $\mathrm{P_i}$ represents the resistance value of patch i, S_i represents the area of patch i , L_{ij} is the cumulative resistance value of the corridor between patches i and j , and L_{max} represents the maximum cumulative resistance value of all corridors.

2.6 Connectivity indices of the habitat patches

In graph-based connectivity analysis, habitat patches were used as modeling nodes. The importance analysis of patches is to identify habitats that are critical to maintaining landscape connectivity. In this study, we used the software Conefor 2.6 (Saura and Tornéa 2009) to calculate connectivity integral index ($dIIC$) and patch importance value (dPC), and these indicators were used to quantify the relative importance of habitat patches for overall network connectivity.

$IIC= \frac{\sum_{i-1}^{n}\sum_{j-1}^{n}\left[\frac{(a_i a_j)}{(1+nl_{ij})}\right]}{A_L^2}$ (1)

$dIIC_k\ (\%) = 100\ \times\frac{IIC-\mathrm{IIC}_{remove,k}}{\mathrm{IIC}}$ (2)

$PC\ =\frac{\sum_{i=1}^{n}\sum_{j=1}^{n}a_i\times a_j\times p_{\mathrm{ij}}^{*}}{A_L^2}$ (3)

$dPC_k\ = 100\ \times\frac{PC-\mathrm{PC}_{remove,k}}{\mathrm{PC}}$ (4)

In the above formula, n represents the total number of patches in the landscape, a_i and $a_j$represent the areas of patches i and j ,nl_{ij} represents the number of connections between patches i and j , and A_L represents the area of the entire landscape; *IIC* is the connectivity index value of a certain landscape and *IICremove,k* represents the overall index value of the remaining patches after removing a single patch;*PC* indicates the possible connectivity index of a patch in the study landscape, dPC_k indicates the importance of the patch and *PCremove* indicates the possible connectivity index after removing the plaque. We used Confer 2.6 software to calculate*IIC* , $dIIC_k$, *PC* anddPC_k .

3 Results

3.1 Habitat patches of Przewalski's gazelle

According to the correlation analysis between variables, we found that the correlations of the eight variables were all less than 0.8. Therefore, we take all variables into consideration. In addition, according to the EWM analysis results, the human disturbance factor seems to be the most important among the all variables, the railway had the largest weight, accounted for about 42%, followed by the highway, accounted for about 15% (Table S1).

According to the calculation results of the HSI model, combined with the buffer area of Przewalski's gazelle distribution points, we have divided 11 habitat patches. These 11 habitat patches were located in four counties around Qinghai Lake. Among them, the three populations of Shengge and Kuaierma township are distributed in Tianjun County, the two habitat patches of Wayu and Ketu and Yuzhe township are distributed in Gonghe County, and the habitat patches of Shadao and Hudong township are located in Haiyan County, the largest population of the Ganzihe-Haergai population is located at the junction of Haiyan County and Gangcha County. Among the 11 patches of the Przewalski's gazelle, the patches of Ganzihe-Haergai was the largest, with an area of about 433km^2, and the smallest distribution area of the Bird Island area was about 13km^2 (Fig. 2).

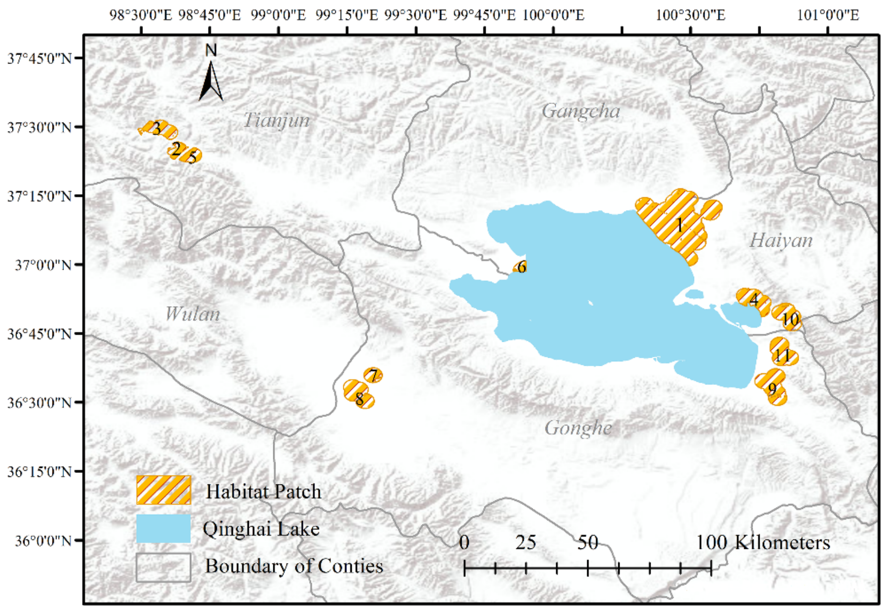

Fig. 2 Identification of eleven habitat patches of Przewalski's gazelle around Qinghai Lake. 1 represents the Ganzihe-Haergai, 2 and 5 represent the two distribution areas of Kuaierma, 3 is the shengge, 4 is the Shadao, 6 represents the Bird Island, 7 and 8 represent the Wayu, 9 is the Yuanzhe, 10 is the Hudong and 11 is the Ketu.

3.2 Least-cost pathway model

The LCP model simulated the lowest cost migration path of Przewalski's gazelle among the 11 habitat patches. A total of 55 migration pathways were formed between the two habitat patches (Table 2, Fig. 3a). Among them, the migration cost between patch 3 and 9 was the highest, and the migration cost between patch 2 and 5 was the lowest. In fact, too many migration paths can provide more migration options for species. However, the 55 migration corridors simulated by the LCP model had corridors redundancy, so we used the gravity model to screen the important migration corridors in the network, and the results showed that the forces between several patches with relatively short geographic distances were relatively strong. For example, the interaction force between patch 1, 4, 9, 10 and 11, patch 2, 3 and 5, and patch 7 and 8 were relatively strong, proving that the corridors between these patches were of great significance for species migration and population diffusion. We chose corridors with Gij value greater than 0.5. The results showed that the interaction force between several patches on the east side of Qinghai Lake was higher than the force between several patches on the west, and the interaction force between the patches on the east and west sides of Qinghai Lake was too small to be used as important corridors (Table S2). However, considering that all species between platches need to communicate with each other, we chose patches 1 and 6, patches 2 and 6, and patches 2 and 7 while considering migration costs and inter- forces of patches. The migration path between patches 7 and 11 serves as a bridge connecting patches between east and west habitats.

In addition, the patch importance analysis showed that the Ganzihe-Haergai patch is the most important patch among all Przewalski's gazelle distribution, because the area of the patch was not only the largest among all the patches, but also the connectivity between the patch and others was the strongest (Table S2).

Since the road has the largest weight among all environmental variables, we believe that this variable was the most important influence factor. We analyzed the intersection of the LCP and the roads, and found that the road distribution was very dense, and many migration paths need to cross the obstacles of the roads. Among them, there were 5 intersections of railway and LCP, and 29 intersections of highway and LCP (Fig. 3b).

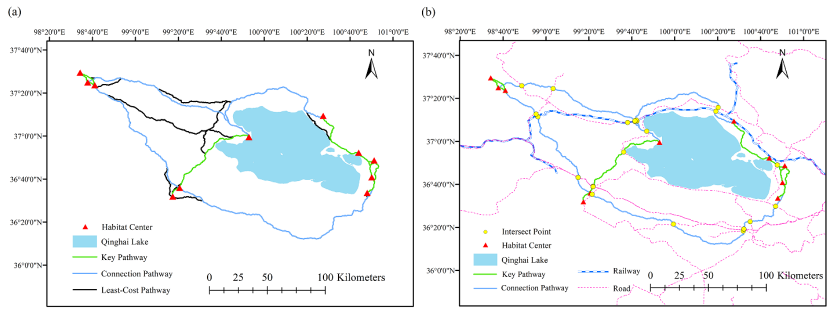

Fig. 3 The lowest cost path among 11 patches simulated by the LCP model. Figure (a) shows a total of 55 paths. The green path represents the important path calculated by the gravity model with a value greater than 0.5, and the blue path represents the connection migration path supplemented to form a complete landscape network. In Figure (b), the yellow intersections represent the intersections of the critical paths and supplementary connection paths between roads and railways.

3.3 Circuit theory model

According to the resistance distance calculated by the circuit theory and the interaction force between the patches analyzed by the gravity model, it can be seen that the resistance distance of the three groups with close geographical distance, patches 1,4,9,10 and 11, patches 7 and 8, patches 2,3 and 5, was very small, and the interaction force between the patches was also very strong, which was consistent with the conclusion of the LCP model. In addition, the resistance distance between patches 2, 3 and 5 and patches 7 and 8 and the resistance distance between patch 7 and 8 and patch 9 were smaller, which can achieve several geographic Interconnections between distant patches (Table 3). However, the resistance distance between the patch 6 of Bird Island and each other patch is relatively large, which means that it is more difficult for individuals of the patch to migrate to other patches. But also considering that all patches need to maintain connectivity, we believed that patch 6 and patches 1 and 8 were suitable for establishing a connectivity corridor.

Similarly, some high-current areas simulated by circuit theoretical model had strong conflicts with roads (Fig. 4). In particular, the road facilities between several plaques that are far apart from each other are relatively dense, so if long-distance population communication is required, not only long-distance movement is required, but also obstacles to roads are overcome.

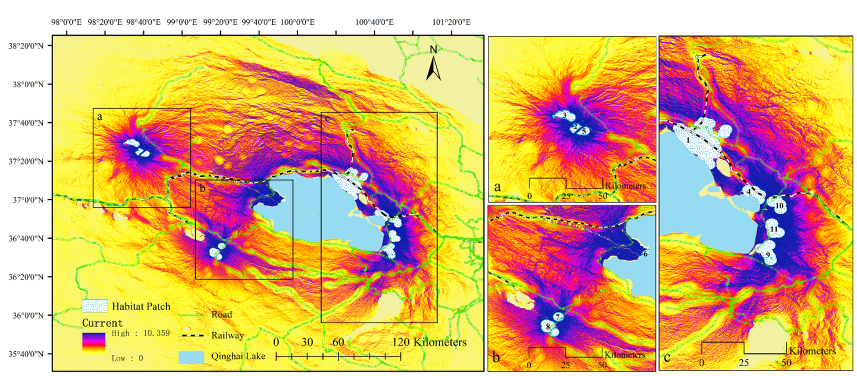

Fig. 4 Current graph based on circuit theory model. The more the purplish red region, the higher the current value. In Figure a, the connectivity between patches 2, 3, and 5 is strong; In Figure b, the connectivity

between patches 7 and 8 is strong; In Figure c, the connectivity between patches 1, 4, 9, 10 and 11 is very strong.

4 Discussion

At present, the survival of the Przewalski's gazelle in China still faces many challenges. Although the population of this species has increased year by year from 2000s due to the importance and protection of the species in recent decades, the researches of genetic structure of the Przewalski's gazelle based on mitochondrial and microsatellite methods published in 2003, 2011 and 2017 showed that the genetic diversity of this species was very low (Lei et al. 2003, Yang and Jiang 2011, Yu et al. 2017), and there was no trend of increasing with the increase of the number. In comparison, the genetic diversity of Tibetan antelopes (*Pantholops hodgsonii*) in China has improved significantly in 10 years of restoration (Du et al. 2016). And each independent population presented a strong systematic geographic structure. We believed that assessing the connectivity between various patches and establishing appropriate migration corridors could provide premises and opportunities for species to move and communicate smoothly, even if we cannot guarantee that species will migrate according to the route we set up.

We used eight environmental variables for the habitat assessment and connectivity analysis of the Przewalski's gazelle, which were the land cover factor, terrain factor and human disturbance factor. We didn't take into account the commonly used climate variables in our study, because these variables are generally more suitable for the study of a wider range of species (Gillespie et al. 2008, Elith and Leathwick 2009). Based on long-term monitoring and observation of the Przewalski's gazelle, we believed that these environmental variables were important factors that determine the distribution of the species. According to the weight analysis of the entropy weight method, the results showed that environmental variables related to human disturbance were the most important type of factors affecting the distribution of the Przewalski's gazelle. Among them, the influence of railway on the Przewalski's gazelle was particularly prominent, followed by highway. The impact of road facilities on wildlife has always been a concern of conservation biologists. As early as 1970, wildlife scientists began to publish studies on the impact of roads on wildlife (Mech et al. 1988, Bhattacharya et al. 2003). Roads are considered to be extremely strong obstacles to wildlife. In addition to the fact that it will cause the loss of species habitat and hinder the migration of species, it has also been pointed out by many studies that will directly cause wildlife to be killed by vehicles when crossing the road (Trombulak and Frissell 2000, Ramp et al. 2006, Neumann et al. 2012).

According to the 2017 genetic diversity study of the Przewalski's gazelle, this species formed a strong separation between the populations on the east and west sides of Qinghai Lake, which seems to confirm the poor connectivity between the patches on the east and west sides of Qinghai Lake. Studies have also shown that the Qinghai-Tibet Railway crossing the Ganzi River-Harge region may interrupt the gene flow of antelopes on both sides of the railway, which in turn causes genetic differences in populations on both sides of the railway (Yu et al. 2017). This means that the obstruction effect of the railway is very strong, and if the migration path is not increased, this negative effect would likely continue forever. Although currently there was no evidence that the highway caused significant segregation between antelope populations, studies have shown that highways do cause Przewalski's day and night activities to change (Li et al. 2009), and in 2019 there are reports that five Przewalski's gazelle were killed on the highway in the Ganzi River-Haergai region (Li and Wang, 2020). Therefore, dense roads do have a negative impact on the survival of Przewalski's gazelle, and these adverse effects are likely to deteriorate with the development of the region's overall economy. Our research results also showed that even if we can plan migration corridors for species, the densely distributed roads and potential corridors would produce a large number of inevitable junctions, which meant that species must cross the road to carry out inter-population communicate with. As far as the current situation is concerned, the highway is almost free of fences, so crossing the highway is relatively easy, but dense traffic is a big hidden danger. Although there are culverts under the Qinghai-Tibet Railway, they may not be used by ungulates due to the narrow tunnels (Singer and Doherty 1985, Rodriguez et al. 1996).

We used both LCP and the circuit theory model to simulate the potential corridors of Przewalski's gazelle.

The LCP model provided the only and least expensive migration path between each patch. This method can obtain a large number of migration paths, but some of the migration corridors were considered redundant, so it is necessary to provide information on the importance of patches and the importance of corridors in order to prioritize the paths, thereby eliminating redundant corridors and retaining key corridors in the entire landscape network (Mui et al. 2017). Based on the LCP model, we selected 17 best corridors, and based on the circuit theory model, we selected 25 highly connected paths. In addition, the disadvantage of the LCP model is that the lowest cost path simulated may not be the exact path used by the species (Walker and Craighead 1997), but if the species follow the LCP path, they may encounter smaller obstacles in migration, spend less travel time and increase survival because of the possibility of obtaining optimized food (Larkin et al. 2004, Penrod et al. 2006). Compared with the LCP model, the circuit theory model produces a non-linear path. This model can provide more migration options based on the assumption of random walk of animals, so it is more in line with the behavioral characteristics of organisms (Dickson et al. 2019). However, this method cannot limit the length and width of the corridor. Overall, the complementarity of the two methods can provide a better reference for corridor construction (Howey 2011, Mateo-Sánchez et al. 2015). In addition, we conducted an analysis of the importance of the species' habitat patches and simulated migration paths, and found that the Ganzihe-Haergai, located at the junction of Gangcha County and Haiyan County, was the most suitable area for survival of the Przewalski's gazelle. The results of the gravity model showed that this patch was an important node to build a complete landscape network. Field survey also found that the Przewalski's gazelle in this area accounted for more than 40% of the total. However, this hotspot area was seriously affected by highways and railways. Therefore, the construction of anti-road corridors inside the patch should be regarded as important strategy to protect the species. At the same time, several patches located on the northwest side of Qinghai Lake were relatively small and have a long geographic distance. In particular, the obstacles (roads) between several patches were relatively strong, which may increase the difficulty of building a migration corridor.

Regarding the current habitat connectivity of the Przewalski's gazelle, we first recommend establishing a migration corridor for this species as soon as possible, especially several connection hotspots and important migration corridors selected in the habitat patch network should be given priority. For the conflict area between the migration corridor and the most influential transportation facilities, especially the intersection of the railway and the migration path, a migration corridor such as an overpass should be established or the number of railway culverts and the width and height of the railway culvert should be increased. Secondly, since human activities squeeze the living space of the Przewalski's gazelle, it is necessary to expand the habitat area occupied by the Przewalski's gazelle. Human activities mainly include the construction of infrastructure, and livestock grazing. The large number of livestock took up a lot of living space, and competed with the Przewalski's gazelle for grassland resources (Li et al. 2012). Therefore, it is recommended to reduce the grazing in the areas where the Przewalski's gazelle lives to ensure their food requirements. Finally, the wire fence in the habitat of the Przewalski's gazelle is also a big hidden danger for this species (Hu et al. 2010, You et al. 2013). Due to the large number of wire fences and the wide range, we cannot include this influencing factor into the analysis. However, in our field investigation in recent years, we found several Przewalski's gazelles hanging dead on the wire fence as these species attempt to cross the fence. At present, we cannot ask the local residents to remove the wire fence because this involves the residents' pasture management and economic issues, so we plan to conduct field investigations and drone tracking technology to carry out the corridor before the construction of the Przewalski's gazelle migration corridor. The direct monitoring of this can not only check the possible deviations of our simulated corridor during the actual construction process, but also focus on the proposal to remove part of the small-scale wire fence to avoid unnecessary losses caused by blindly removing the fence. In general, these protection tasks have become challenging due to economic conflicts and manpower consumption. However, at present, the government and people are paying more and more attention to the protection of species, especially the protection of endangered species. Therefore, we hope to promote the communication between the species population through the construction of corridors, and then achieve the goal of rejuvenation.

5 Conclusions

Przewalski's gazelle is one of the world's most endangered large ungulate mammals. After experiencing a population bottleneck period, the population has been continuously restored by the efforts of the government and protectors for nearly two decades. However, the genetic diversity of this species has always been relatively low, which is likely to have a strong relationship with the strong human interference in the living environment. Therefore, we used LCP and circuit theory models to simulate the migration path between several independent patches, in which the hot spots of the species and the key migration corridors should be taken as the objects of key protection and planning. In addition, food competition and fence barriers between Przewalski's gazelle and domestic animals should also be fully considered by the protectors. We hope that the future corridor construction will provide convenience and possibility for the exchange of Przewalski's gazelle in several areas.

Data Availability

We used open-access data from the ASTER GDEM V2 digital elevation model (DEM; http://www.gscloud.cn/), and FROM-GLC version2 (2015_v1) (http://data.ess.tsinghua.edu.cn/fromglc2015_v1.html) and the National Basic Geographic Information Center (http://www.ngcc.cn/ngcc/).

Conflict of Interest

None declared.

Author Contributions

Tongzuo Zhang led conceptualization, project administration, resources and supervision. Jingjie Zhang collected data, performed the structure of manuscript and lead to write original draft. Feng Jiang contributed to learn methodology, modeling and manuscript editing. Zhenyuan Cai contributed to methodology and participated in data analysis. Yunchuan Dai and Pengfei Song contributed to software learning and Yunchuan Dai also participated in data analysis. Daoxin Liu and Yuansheng Hou collected original data. Hongmei Gao provided logistical support. All coauthors participated in the scientific discussions and commented on the manuscript.

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Table 1 Assignment values of resistance

Landuse	Value	Elevation	value	Aspect	Value	Slope	Value	railway	Value	highway	Value
Other	40	<3000	100	0-45	60	0-10	1	<50	100	<50	80
Orchard	40	3000-3100	40	45-90	40	10-15	20	50-200	60	50-200	60
bare farmland	40	3100-3200	40	90-135	20	15-20	40	200-500	40	200-1000	40
Broadleaf, leaf-on	40	3200-3300	1	135-225	1	>20	60	500-2000	20	1000-3000	20
Broadleaf, leaf-off	40	3300-3400	20	225-270	20			>2000	1	>3000	1
Needleleaf, leaf-on	40	3400-3500	40	270-315	40						
Needleleaf, leaf-off	40	3500-3600	80	315-360	60						
Mixed leaf, leaf-on	40	3600-3800	60								
Natural grassland	20	>3800	100								
Grassland, leaf-off	1										
Shrubland, leaf-on	40										
Shrubland, leaf-off	40										
Marshland	60										
Mudflat	60										
Marshland, leaf-off	60										
Water	100										
Herbaceous tundra	100										
Impervious surface	100										

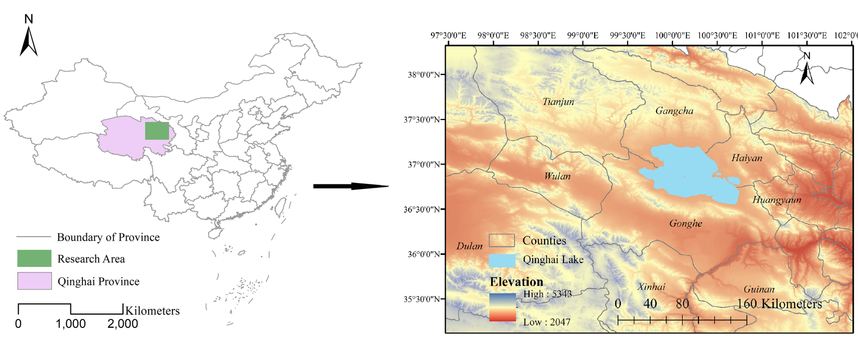
Landuse	Value	Elevation	value	Aspect	Value	Slope	Value	railway	Value	highway	Value
Bareland	20										
Snow	100										
Ice	100										

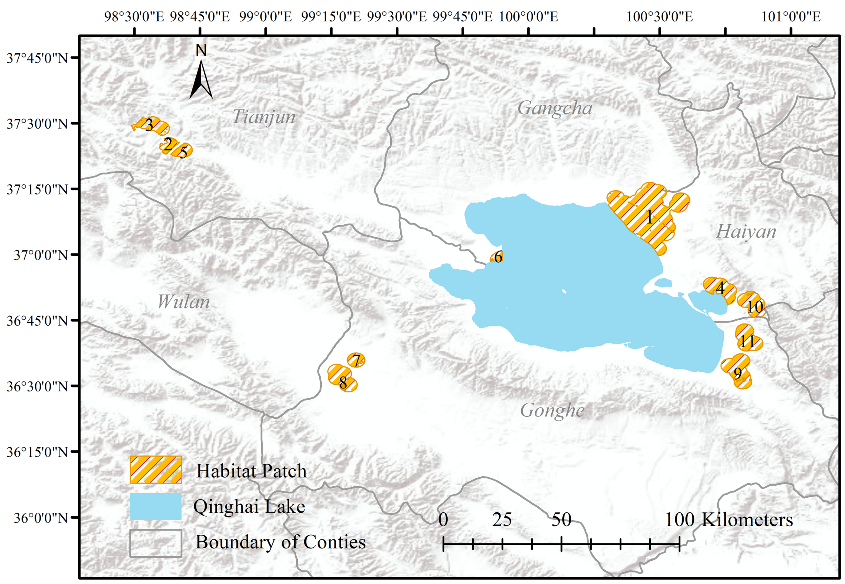
Table 2 Cost and Gij value between habitat patches under LCP model

Pathcost\G_{ij}	1	2	3	4	5	6	7	8	9	10	11
1	-	0.14	0.12	0.84	0.09	0.18	0.1	0.08	0.46	0.44	0.62
2	6.76	-	57.85	0.09	81.47	0.28	0.24	0.21	0.13	0.07	0.13
3	6.99	0.5	-	0.08	16.4	0.25	0.2	0.17	0.11	0.06	0.12
4	1.54	7.8	8.03	-	0.06	0.1	0.06	0.05	1.54	3.62	2.95
5	6.59	0.35	0.75	7.64	-	0.19	0.17	0.15	0.08	0.05	0.09
6	4.99	6.26	6.49	6.04	6.03	-	0.54	0.42	0.14	0.08	0.15
7	6.11	6.36	6.77	7.16	6.03	3.54	-	15.12	0.16	0.06	0.14
8	6.62	6.71	7.12	7.66	6.38	4.04	0.62	-	0.14	0.05	0.12
9	2.94	9.21	9.44	1.5	9.04	7.44	6.36	6.72	-	3.35	32.98
10	2.12	8.38	8.61	0.68	8.22	6.62	7.31	7.67	1.01	-	9.97
11	2.5	8.76	8.99	1.06	8.6	7	6.75	7.12	0.45	0.57	-

Table 3 Cost distance and G_{ij} value between habitat patches under circuit theory model

Cost Distance\G_{ij}	1	2	3	4	5	6	7	8	9	10	11
1	-	0.45	0.46	0.77	0.28	0.06	0.32	0.33	0.54	0.44	0.59
2	4.18	-	50.58	0.24	56.46	0.15	0.87	0.99	0.53	0.25	0.48
3	3.95	0.60	-	0.24	7.94	0.15	0.92	1.03	0.54	0.25	0.49
4	1.81	5.24	5.01	-	0.15	0.04	0.18	0.20	0.67	4.38	1.05
5	4.18	0.47	1.21	5.24	-	0.09	0.55	0.62	0.33	0.16	0.30
6	9.42	9.65	9.44	10.57	9.62	-	0.11	0.11	0.09	0.04	0.08
7	3.88	3.70	3.50	4.67	3.70	8.96	-	30.90	0.48	0.20	0.41
8	3.68	3.47	3.27	4.46	3.47	8.85	0.48	-	0.53	0.22	0.45
9	3.06	5.02	4.79	2.56	5.02	10.42	4.11	3.88	-	1.72	21.77
10	2.36	5.10	4.87	0.69	5.10	10.46	4.41	4.19	1.58	-	8.15
11	2.86	5.14	4.91	1.99	5.14	10.52	4.32	4.09	0.62	0.71	-

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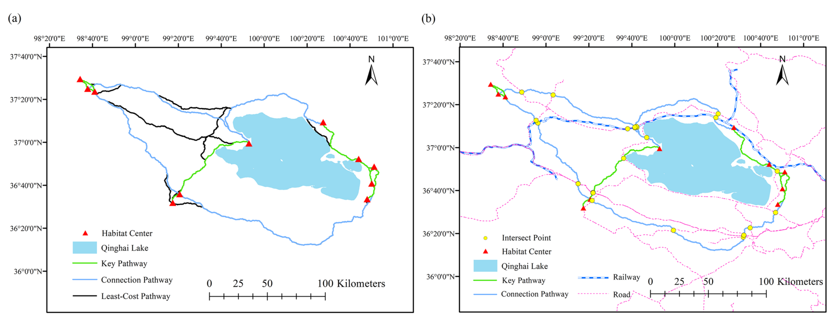
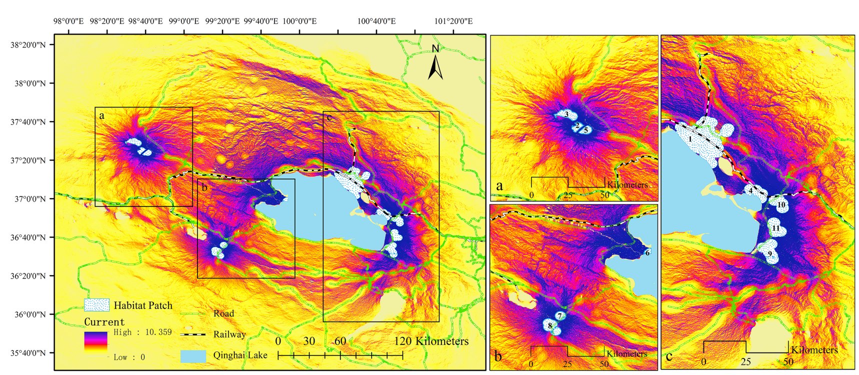

(a)
(b)
Habitat Center
Qinghai Lake
Key Pathway
Connection Pathway
Least-Cost Pathway
Intersect Point
Railway
Road
0 25 50 100 Kilometers


Habitat Patch
Current
High : 10.359
Low : 0
Road
Railway
Qinghai Lake
0 30 60 120 Kilometers
a
b
c
Kilometers