Influence of land use changes on landscape connectivity for North China leopard (*Panthera pardus japonensis*)

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April 28, 2022

Abstract

Aim: North China leopard (*Panthera pardus japonensis*), is the most widespread subspecies of leopard and one of the rare and endangered species in China. It is currently confined to several isolated reserves, and little is known about its habitat network connectivity with land use changes. We proposed an approach for the evaluation of the impacts of land use changes on landscape connectivity for North China leopard. Location: The Great Taihang Region, in the north of China, covers the entire territory of Shanxi province, as well as some districts and counties in Beijing, Hebei and Henan provinces. Methods: We analysed multiple background layers affecting North China leopard movement patterns, including environmental and anthropogenic factors, and generated a landscape resistance surface. Then we used Circuit theory-based connectivity models to delineate pathways suitable for species movement, and evaluate the connectivity status of core areas and the impacts of land use changes on landscape connectivity. Results: We identified 33 least cos distance paths in 1990 and 34 paths in 2020, and four key barrier areas. The landscape connectivity has not been greatly improved with the land use changes, especially with the increase of forest land from 26.61 to 34.85%. Nevertheless, there is a decreasing trend on connectivity in some key movement barrier areas. Improving landscape connectivity at a broad spatial scale is as important as protecting the habitats (natural reserves) where the species lived. Main conclusions: Our study can serve as an example of how to explore the relationships between land use changes and landscape connectivity for species at broad spatial scales with limited movement patterns data. This information is proved to be critical for enhancing landscape connectivity for conservation concern of North China leopard and planning of natural reserves network.

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Main conclusions: Our study can serve as an example of how to explore the relationships between land use changes and landscape connectivity for species at broad spatial scales with limited movement patterns data. This information is proved to be critical for enhancing landscape connectivity for conservation concern of North China leopard and planning of natural reserves network.

Key words

at broad spatial scales, circuit theory, land use changes, landscape connectivity, North China leopard, Protected areas

1 Introduction

Land use changes caused by human activities have led to the habitat loss and fragmentation at local, regional, landscape and global scales, which can hinder the migration and dispersal of species at gene, individual, population levels, further alter the structure and configuration of the landscape, and have become an important factor threatening biodiversity (*Kruess and Tscharntke, 1994* ;*Ewers and Didham, 2006* ;*Fischer and Lindenmayer, 2007*). Compounding the effects of habitat loss and fragmentation are key drivers of global biodiversity loss (*Fahrig, 2003*). Loss of natural habitats reduce the proportion of patches large enough to sustain a population over time, and make species highly dependent on connections between habitat patches (*Baguette et al., 2013* ; *Sahraoui et al., 2017*).

Landscape connectivity is the degree to which the landscape facilitates or impedes movement among resource patches (*Taylor et al., 1993* ;*Tischendorf and Fahring, 2000*). Connectivity determines the effective and availability habitat area within a territory for a given species (*Saura and Pascual-Hortal, 2007*). High Connectivity can facilitate the capacity movement to satisfy ecological requirements and reduce population isolation (*Minor and Urban, 2008*). An animal's ability to utilize a resource patch is determined not only by the distance between patches, but also by the biophysical nature of the routes between two patches and the biology and behavior of the organism (*Henein and Merriam, 1990*). Some routes facilitate or allow unimpeded movement among patches; others impede to varying degrees the amount, or success, of movement. Improving landscape connectivity can promote species migration, dispersal, foraging, reproduction and survival, and reduce the risk of extinction. Hence landscape connectivity will obviously vary according to both organism properties and landscape features. Maintaining and improving landscape connectivity is today considered a key part of efforts to protect biodiversity (*Taylor et al., 1993*).

Preserving and restoring connectivity has become a major conservation priority on biodiversity conservation. Conservation practitioners have long recognized ecological connectivity as a global priority for preserving biodiversity and ecosystem function. Understanding broad-scale ecological processes that depend on connectivity, and making effective conservation planning decisions, requires quantifying how connectivity is affected by landscape features. Connectivity among populations and habitats is important for a wide range of ecological processes. The assessment of landscape functional connectivity needs to comprehensively consider the spatial distribution of habitat patches, species movement characteristics, and landscape context. But field observations are extremely labor intensive and fail to provide a complete understanding of functional connections at a large scale, and it is often difficult to assess landscape functional connectivity because of data limitations (*Sahraoui et al., 2017* ;*Petsas et al., 2020*).

A graph-theoretic approach employs fast algorithms and compact data structures that are easily adapted to landscape-level focal species analysis. Graphs is built using GIS coverages to define habitat patches and determine the functional distance between the patches with least-cost path models. In landscape graphs, a graph is a set of nodes and links such that each link connects two nodes. Nodes represent sites of suitable habitat patches of a given species while links symbolize the potential ability of a species to directly disperse between two nodes. This method has been shown to be a powerful way of performing complex analysis of potential functional connectivity at relatively large scales (*Bunn et al., 2000* ;*Urban and Keitt, 2001* ;*Jordán et al., 2003* ;*Pascual-Hortal and Saura, 2006* ,*2008*). The advantage of a graph-theoretic approach is that it has relatively modest data requirements and improved from the initial results. Graph-theoretic approaches provide a new research idea for powerful leverage on ecological processes concerned with connectivity as defined by dispersal. Graph theory-based models and least-cost path models have gained increasing attention and are widely applied in connectivity modeling, conservation planning, and monitoring of land use changes and their environmental impacts (*Minor and Lookingbill, 2010* ; *Theobald et al., 2011* ; *Piquer-Rodriguez et al., 2012* ; *Rubio et al., 2012* ;*Devi et al., 2013* ;*Wang et al., 2016* ;*Sahraoui et al., 2017* ;*Liu et al., 2020* ;*Machado et al., 2020*).

The circuit theory modeling is an alternative approach to model gene flow and the dispersal or movement routes of organisms,and widely applied for assessing ecological functional connectivity across heterogeneous landscapes. This theory does not require new ways of representing landscape data; rather, it takes advantage of graph-theoretic data structures, and can be applied in graph-theoretic or raster GIS frameworks (*McRae et al., 2008*). Circuits are defined as networks of nodes connected by resistors (electrical components that conduct current) and are used to represent and analyze graphs. In circuit theory-based models, landscape is transformed into a cost map (called resistance surface), effective resistance, indicating landscape's resistance to current flow between two nodes separated by a network of resistors, and is calculated through multiple pathways. Comparing to least-cost path models that measured along a single optimal pathway or corridor with the lowest cost, circuit theory integrates multiple possible pathways in a landscape into distance calculations and offers a measure of isolation assuming a random walk. The multipath results obtained from the circuit theory-based connectivity models make it more realistic and objective in practical application. By predicting net movement probabilities through nodes, a new landscape raster is created (called current map), where every cell is assigned a value that reflects the probability of an animal traveling from one node to another. Current density can be used to identify landscape corridors or "pinch points," high current through a node indicates that removing it will have a high impact on connectivity (*McRae and Beier, 2007* ; *McRae et al., 2008*). Circuit theory has already been shown to be useful for predicting movement patterns and probabilities of successful dispersal moving across complex landscapes, generating measures of connectivity or isolation of habitat patches, or protected areas, and to identifying important connective elements for conservation planning and designing robust reserve network (*Epps et al., 2011* ; *Howey, 2011* ;*Walpole et al., 2012* ;*Koen et al., 2014* ;*Pelletier et al., 2014* ;*McClure et al., 2016* ;*Dickson et al., 2019* ;*An et al., 2021* ;*Hyseni et al., 2021* ;*Leskova et al., 2022*).

The North China leopard (*Panthera pardus japonensis* , commonly referred to as *Panthera pardus fontanierii* in the Chinese literature), is the most widespread subspecies of leopard and one of the rare and endangered species in China. Recent camera-trap surveys and other evidence revealed the presence of the North China leopard in Shanxi, Shaanxi, northern Hebei, Ningxia, and northern Henan. Most populations in these provinces are small, and occur in several isolated protected areas (*Consolee et al., 2020*). More and more attention has been paid to the protection of North China leopard. In Tieqiaoshan Provincial Nature Reserve, Shanxi Province, studies indicated that the North China leopard is in serious conflict with the locals, causing them personal economic losses due to lack of prey (*Consolee et al., 2020* ; *Vitekere et al., 2020*). The North China leopard density was 4.23 individuals/100 km^2, the population density increased with the distribution of wild boars (*Vulpes vulpe* s), and decreased with the distribution of roe deer (*Capreolus capreolus*) (*Zhu et al., 2021*). Habitat environmental factors and anthropogenic interference also significantly affected the population density and spatial distribution of the North China leopard. Previous studies were mostly based on literature, expert and villager interviews, and camera-trap surveys to determine the current status and distribution of North China leopard, and most studies were conducted within protected areas. But there are few studies on the impact of land use changes on the ecological network connectivity of North China leopard at a large scale.

The Great Taihang Region is the dominant distribution area of North China leopard and contains the most densely distributed population of North China leopard in China (*Laguardia et al., 2017* ;*Cao et al., 2020*). Due to the Human-Leopard conflict, North China leopard is mainly distributed in several isolated protected areas. In the past 30 years, with the implementation of a series of forestry projects, such as National Natural Forest Protection Program, Three-North Forest Shelterbelt Program and Grain for Green Project, great changes have taken place in the study area. Yet there is little insight concerning on the impacts of land use changes on the habitat ecological network connectivity of North China leopard. The present study, therefore, was an attempt to clarify the influences of land use changes on landscape connectivity for North China leopard. The main objectives of this study were: (1) to detect the land use changes in the Great Taihang Region from 1990 to 2020, (2) to clarify the influences of land use changes on landscape connectivity for North China leopard, and to answer the following research question, (3) how are the changes of the key barrier areas that affect the habitat ecological network connectivity of North China leopard? The purpose of this study was to explore the key barrier areas affecting the migration of North China leopard, and to provide the basis for this unique and rare wildlife species conservation planning in China.

2 Methods

21. Study area

The study area (214,100 km^2) is the Great Taihang Region (34deg 34' ˜ 40deg 47' N, 110deg 14' ˜ 116deg 34' E),located in the north of China and covers the entire territory of Shanxi province, as well as some districts and counties in Beijing, Hebei and Henan provinces, accounting for about 2.2% of China's terrestrial area (Fig. 1). In the study area, cropland covers 37% of this area, forest 35%, and Grassland 21%. There are various geomorphic types, including mountains, hills, platforms and plains. The eastern part is a massive mountain formed by the Taihang Mountain, and the western part is the Loess Plateau with Lvliang Mountain as the trunk (Fig. 2). The altitude ranges between 24 m to 3091 m. The climate in this region is temperate continental monsoon climate and the four seasons is distinct, with mean annual temperature between 8 and 13degC, and average annual precipitation between 400 and 1000 mm. Rainfall is concentrated from July to September. Deciduous broad-leaved forest is the most widely distributed plant community in the study area. Deciduous broad-leaved forest and secondary deciduous shrub are mainly distributed in the South, while temperate shrub and semi-arid grassland located in the northern part. The study area is mainly mountainous area, and the diversity of geographical environment leads to a good variety of flora and fauna.

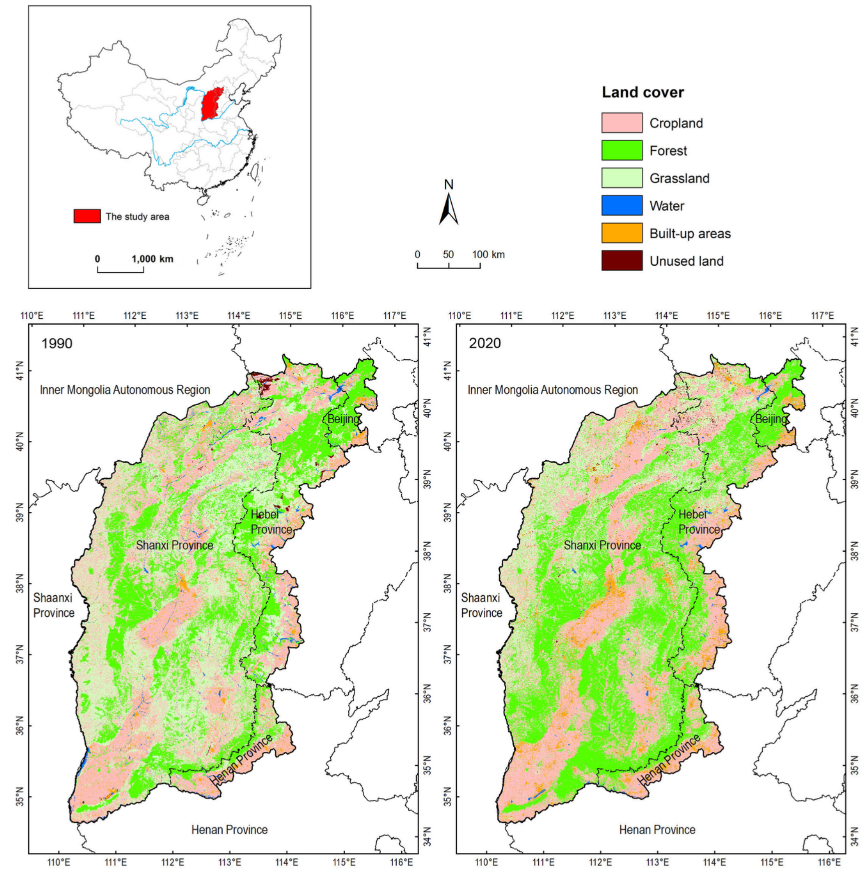

Fig. 1 Location of the study area and land cover in 1990 and 2020.

The government has established 11 national nature reserves and 54 provincial nature reserves in this area to protect biodiversity resources. North China leopard is considered the top predator in their range, as a result of large home ranges, Human-Leopard conflict has now reached a new level of intensity. North China leopards often attack livestock grazing in and around forest areas, where livestock keeping overlaps with the leopard range. At present, North China leopards are mainly distributed in several isolated protected areas supported by camera trap surveys and other evidence (Fig. 2) (*Laguardia et al., 2017* ;*Consolee et al., 2020*).

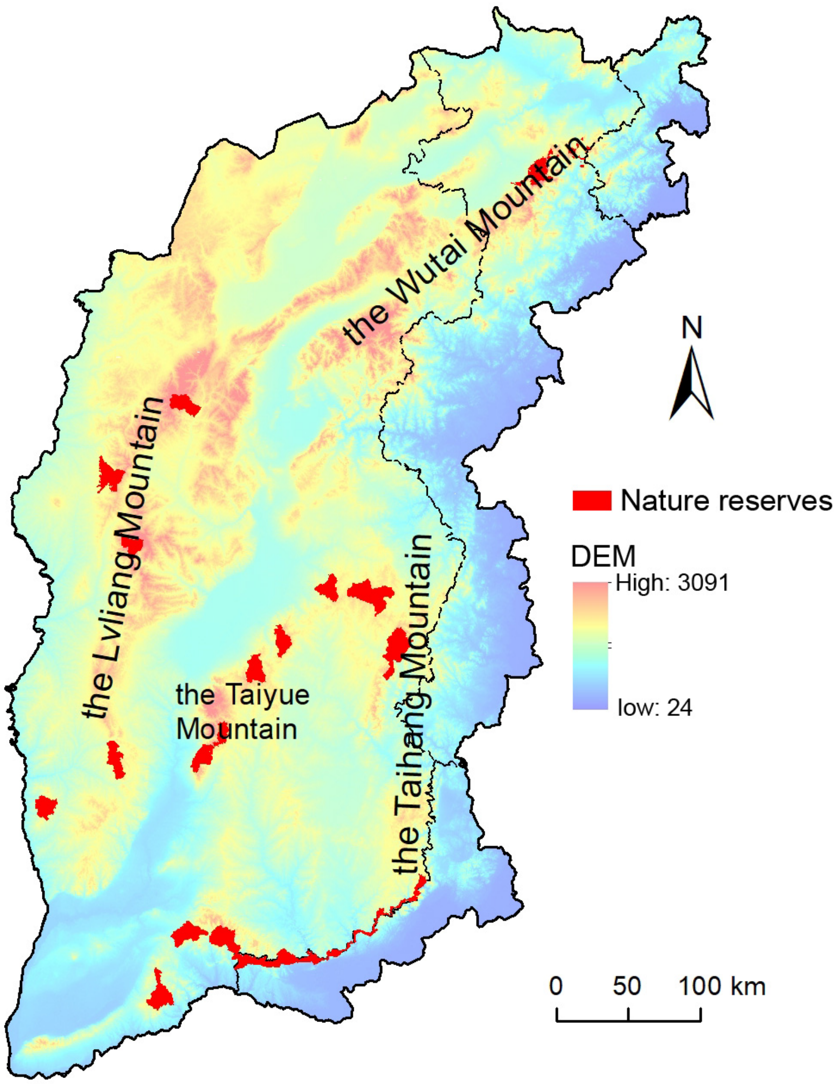

Fig. 2 Digital elevation model and nature reserves where the North China leopards are mainly distributed.

2.2 Focal species

The study focuses on North China leopard, a top carnivore and flagship species in the study area, which is facing severe challenges due to human activities and habitat fragmentation. To the best of our knowledge, it has not been carried out the study on the movement ecology of North China leopard using GPS wildlife tracking, therefore, there are few North China leopard movement data on the field migration and dispersal capacity available at present. But in several protected areas, wildlife surveys have been conducted by using infrared trigger camera capture technology. Based on the official information that the protected areas inhabited by North China leopard, provided by the nature reserves, published literature by peers and camera trap records, we think it is reasonable to select the natural reserves inhabited by North China leopard as source patches (core areas), and it is also the best available data on the distribution of North China leopard. Totally, we identified 18 nature reserves (Fig. 2) and used as core areas to analyze landscape connectivity. Data on nature reserves are downloaded from the National Earth System Science Data Center (http://www.geodata.cn). At the same time, we also consulted experts from the Chinese Felid Conservation Alliance, personnel and residents in the reserves, who are familiar with the current status of the North China leopard population in this region, so as to improve the reliability of the information collected.

2.3 Circuit theory-based connectivity models

Circuitscape uses circuit theory to model connectivity in heterogeneous landscapes. Its most common applications include modeling movement and gene flow of plants and animals, as well as identifying areas important for connectivity conservation. We used Circuitscape software (v4.0, www.circuitscape.org) and cost distance functions to assess landscape functional connectivity (*McClure et al., 2016*). First, we built several background layers, which affected species movement and were transferred into raster maps of 1 km^2 resolution. Next, these raster maps were converted into a resistance surface based on their values and corresponding weight, reflecting its opposition to species movement. Landscapes are represented as conductive surfaces, with low resistances assigned to landscape features types that are most permeable to movement, and high resistances assigned to movement barriers. The landscape raster cells represent the circuit nodes, and neighboring nodes are connected by resistors. The focal nodes are defined as the cells within the boundaries of core areas. For each pair of core areas, one core area is assumed to be the source node (i.e. the starting point), while the other is considered as the exit node (i.e. the ending point). The starting point node will arbitrarily be connected to a 1 Amp current source, while the ending point will be connected to ground (the exit of the circuit). Current will flow across the resistance surface from the source to the ground. Effective resistances will be calculated iteratively between all pairs of focal nodes. We ran models using the pairwise method and eight neighboring cells. A cumulative current density map was produced, with values at each cell representing the amount of current flowing through the node. Higher current density indicates areas through which dispersers have a high likelihood (or necessity) of passing. High current through a node or branch indicates that removing or converting it will have a high impact on connectivity (*McRae et al., 2008*).

2.4 Background layers

Considering the movement characteristics of North China leopard through landscape, we used a total of nine layers to define landscape properties (Fig. S1). The selection of layers is based on the relevant literature, the availability of spatial datasets and the opinions of relevant experts (*Cao et al., 2020* ;*Petsas et al., 2020* ;*Zhu et al., 2021*).

The first five layers was built upon land use types, namely agricultural areas, forest areas, grassland areas, water bodies and artificial surfaces. In each layer, the percentage cover of land use type within every 1 km range was calculated to form a background layer, and different resistance values were assigned according to the percentage cover of land use type in the later stage. For each background layer, if there was no presence of the respective land use type, the assigned value was zero. If a land use type was full coverage, the assigned value was 1.

The elevation and slope data were selected in the background layers to represent topographic features. Data of land use, elevation, and slope were obtained from the National Earth System Science Data Center (http://www.geodata.cn), with the spatial resolution of 30m.

As for the impact of linear transportation infrastructure, we developed a background layer by combining information from expressways, national highways, provincial highways and railways, which were known for posing barriers for the movement of North China leopard. The spatial distribution of linear traffic infrastructure datasets was derived from Earth Data Sciences and Sharing Research laboratory, Institute of Geographic Sciences and Natural Resources Research, CAS. Each cell was assigned a value, representing the shortest distance from the cell's center to any linear transportation feature, and the spatial resolution was 30 m.

The last layer represented human population density (http://www.geodata.cn), with a spatial resolution of 1 km.

2.5 Resistance surfaces

We extracted information from the nine background layers and produced resistance surfaces. We used 1 km grid to mask the study area, and every single grid (1 km) of the nine background layers was assigned a resistance value ranging from 1 (minimum movement resistance) to 100 (maximum movement resistance) representing the opposition of the selected layers to North China leopard movement according to expert opinions (Table S1). Each background layer was asked to assign a weight to define the final resistance surface, with weight values ranging from 0 (the layer has no impact on movement decision) to 10 (the layer is very important for movement decision). Then, we transformed the background layers to resistance layers according to the resistance values, and its corresponding weight. Therefore, the final two resistance surface layers (in 1990 and 2020) were created, indicating the impacts of all background layers on North China leopard movement (Fig. S2).

2.6 Species dispersal distance

We estimated the dispersal capacity of North China leopard according to the allometric growth equations (*Santini et al., 2013*), with body weight and home range as inputs data. Information about North China leopard' body weight was extracted from the literature (Online Resources). The adult male body weight of North China leopard is about 60-75 kg, and the adult female is about 40-55 kg. Data on home range were from panTHERIA (*Jones et al., 2009*). The maximum dispersal distance of North China leopard is calculated as$d$ $=13.11\times BS^{\ 0.34}\times HR^{\ 0.27}$,$BS$ is body weight (kg), HR is home range (km^2), and dispersal distance d is in km.

2.7 Quantifying connectivity properties

We identified the least-cost paths using Linkage Mapper v. 2.0.0. (*McRae and Kavanagh, 2011*), a GIS toolbox developed for connectivity analysis based on cost-weighted distance surface. We used the core area (protected area) polygons and resistance raster to perform cost-weighted distance calculations from each protected area. As each cost-weighted distance surface is created, Linkage Pathways also extracts minimum cost-weighted distances between source and target core area pairs. Once the linkage zones have been mapped using Linkage Mapper, the Centrality tools from the Linkage Mapper toolbox were used to calculate current flow centrality across the networks. Current flow centrality is a measure of how important a link or core area is for keeping the overall network connected.

To identify the barrier areas and priority areas of connectivity restoration,we used the Barrier Mapper tool from Linkage Mapper. Barrier Mapper detects important barriers that affect the quality and/or location of the corridors using a circular search window. Results give expected reduction in least-cost distance per unit distance restored assuming pixels in the window are changed to a resistance of 1.0. Greater reductions in cost-weighted distance (i.e. increase in connectivity) indicate areas of greater restoration potential (*McRae, 2012*). We applied a single moving window radius (110 km) to search. This range accounts for the maximum dispersal capacity of North China leopard. For each pixel we calculated the sum of connectivity improvement scores taken across all core area pairs, highlighting areas that impede movement between multiple pairs of conservancies.

3 Results

3.1 Land use change status

Table 1 sets out the descriptive statistics of land use type areas and changes from 1990 to 2020. The dominant land use types in the study area are cropland, forest land and grassland, with the areas of 79346.29 km^2, 74836.64 km^2 and 45670.23 km^2 in 2020, accounting for 36.95, 34.85 and 21.27 percentage of the study area, respectively. The area of forest land increased from 57142.74 km^2 to 74836.64 km^2 at a rate of 655.33 km^{2}year^{-1}, with the percentage increasing from 26.61 to 34.85%. The area of grassland decreased from 69226.26 km^2 to 45670.23 km^2 at a rate of 872.45 km^2 year^{-1}, with the percentage decreasing from 32.23 to 21.27%. Under the influence of human activities, the expansion of built-up areas was evident with the percentage increasing from 3.07 to 5.87%, and the area increasing from 6596.23 km^2 to 12605.26 km^2 at a rate of 222.56 km^2 year^{-1}.

Table 1 Descriptive statistics of land use type areas and changes from 1990 to 2020

Types of land use	Area in 1990 (km^2)	Area in 2020 (km^2)	Proportion in 1990	Proportion in 2020	Proportion change from 1990 to 2020
Cropland	78170.3	79346.29	36.40%	36.95%	0.55%
Forest land	57142.74	74836.64	26.61%	34.85%	8.24%
Grassland	69226.26	45670.23	32.23%	21.27%	-10.97%
Water	2830.98	1188.85	1.32%	0.55%	-0.76%
Built-up areas	6596.23	12605.26	3.07%	5.87%	2.80%
Unused land	789.80	1109.04	0.37%	0.52%	0.15%
Total	214756.31	214756.31	100.00%	100.00%	

3.2 Spatial distribution of the cumulative current map and least-cost paths

Fig. 3 shows the cumulative current map, least-cost paths and current flow centrality results for North China leopard. Two main corridors were identified by the cumulative current map. The larger corridor is recognized in the middle of the southern part of the study area, spanning the Taiyue Mountain and some part of the Taihang Mountain, including 12 nature reserves. Another large corridor is detected in the western part of the study area, mainly crossing along the Lvliang Mountains and including 6 nature reserves. 33 minimum cost distance paths were determined in 1990, of which 17 were less than 110 km. Nevertheless, there were 34 minimum cost distance paths in 2020, with 18 paths less than 110 km. In 1990, the least-cos paths with higher centrality were among the nature reserve of 3-2-17-18, 13-14 and 5-7-8-10-12-11-9, while in 2020 were among the nature reserve of 3-2-17-18, 13-14, 5-7-8-10 and 11-9.

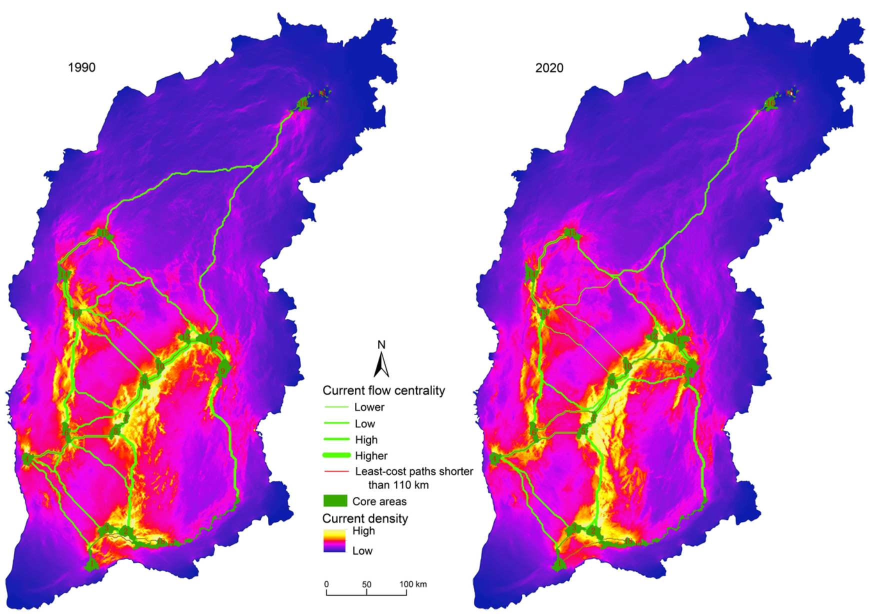

Fig.3 Cumulative current map, least-cost paths and current flow centrality results for North China leopard. Core areas are the 18 nature reserves used to model landscape connectivity

3.3 Change of key barriers

The Barrier Mapper analysis identified four key barrier areas (A, B, C and D) for restoring connectivity for North China leopard across the landscape (Fig. 4). As a result of land use changes, the migration path across the barrier area A in 1990 was not detected in 2020. Within the barrier area B and D, the important barriers to migration corridors identified by Barrier Mapper indicated a further increasing trend. Within the barrier area C, barriers to migration corridors tended to slow down. In contrast, in the area E, new connectivity corridors appeared, which were more conducive to improve the connectivity between core areas and promote species migration.

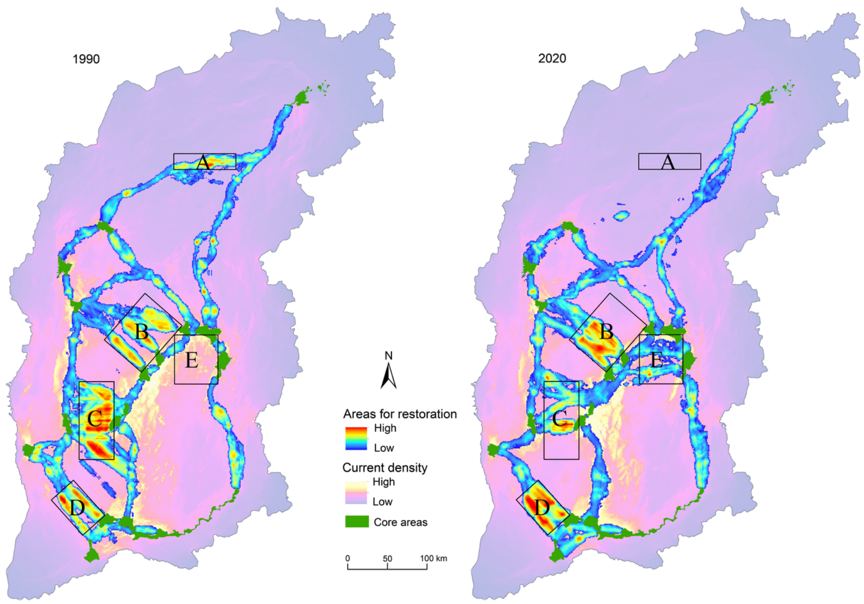

Fig.4 Key barrier areas marked with A, B, C, and D, with the greatest values of connectivity restoration potential. In the area E, new connectivity corridors appeared.

4 Discussion

Assessing landscape connectivity could be a complex task because species have different biological features and migration capabilities, and the ways they perceive the landscape are also differentiated (*Petsas et al., 2020*). We used circuit theory-based approach to model the impacts of land use changes on landscape connectivity for North China leopard, and to determine the priority restoration areas. The results achieved in our work showed that land use changes and human activities have most important impacts on landscape connectivity, especially the changes of the migration corridors and key barrier areas. In order to protect North China leopard, we should not only protect the habitats where the species lived, but also improve landscape connectivity at a broad spatial scale.

Circuitscape borrows algorithms from electronic circuit theory to predict patterns of movement, gene flow, and genetic differentiation among plant and animal populations in heterogeneous landscapes. Circuit theory complements least-cost path approach because it considers effects of all possible pathways across landscape simultaneously, and could identify multiple alternative paths among all patches,so Electric circuit theory is becoming very popular for connectivity analysis (*McRae et al., 2008*). In this study, we aggregated information from expert opinions and various factors that potentially affect the migration of North China leopard, in an effort to provide the migration corridors and key barrier areas. This could be used as a systematic approach for conservation planning of North China leopard.

When applying the circuit theory-based connectivity model to analyze the functional connectivity, it is necessary to determine the landscape resistance surface, by the means of using sets of resistance values. The movement patterns of species is affected by several factors, including landscape properties and individual variability, so it is difficult to accurately obtain the landscape resistance surface when species migrate between habitat patches(*Sahraoui et al., 2017* ; *Petsas et al., 2020*). Especially for the North China leopard, in addition to the infrared trigger camera research in several nature reserves, there is almost no large-scale radio continuous tracking research. In this study, to somehow overcome limitations, we evaluated the main factors affecting the migration of North China leopard by aggregating information from literature collation and expert opinion. Expert knowledge could not replace the information obtained from actual movement and species behavioral responses, but we do recognize that their contributions could be valuable, especially in the absence of species characteristics data at broad spatial scales. .

We determined 18 nature reserves (Fig. 2, 1. Taikuanhe, 2. Lishan, 3. Sushui River source, 4. Renzushan, 5. Huoshan, 6. Wulushan, 7. Lingkongshan, 8. Chaoshan, 9. Mengxinnao, 10. Sixiannao, 11. Tieqiaoshan, 12. Bafuling, 13. Pangquangou, 14. Heichashan, 15. Luyashan, 16. Xiaowutaishan, 17. Taihangshan, and 18. Manghe River Nature Reserve), the main activity regions of North China leopard, according to the investigation and consultation with relevant personnel. Finally, taking 18 nature reserves as core areas, we analyzed the landscape connectivity. It is considered that it is more in line with the actual situation to take these nature reserves where North China leopard is mainly distributed as the habitat patches (*Cao et al., 2020*).

Landscape connectivity modeling based on circuit theory needs to define a distance to characterize the movement capacity of species. Each species was characterized by its dispersal distance, which is different according to their physiological and behavioral attributes and difficult to obtain accurate data. In the study, we first extracted information on body weight and home range of North China leopard. Then based on the allometric growth equation, the maximum dispersal capacity were estimated according to body weight and home range, about 110 kilometers. The accuracy of the data needs to be further verified by field experiments. There are still more corridors longer than 110 kilometers, beyond the maximum migration capacity of species.

From 1990 to 2020, land use changes in the study area are characterized by the proportion of forest land increased by 8.24%, the grassland decreased by 10.97% and the built-up areas increased by 2.80%. Although forest land dominates the landscape type of habitats and activities of North China leopard, with the land use changes, especially the significant increase of forest land, the landscape connectivity has not been greatly improved. On the contrary, there is a decreasing trend in some key movement barrier areas.

In barrier area A (Fig. 5A, Fig. S3, Table S2), grassland and cropland are the main land use types. From 1990 to 2020, forest land increased 110.40 km^2, with the percentage by 7.02%. But grassland decreased 234.71 km^2 (by 14.93 percentage), and the area of cropland increased 108.76 km^2 (by 6.92 percentage). As the result of land use changes, the migration path crossing the barrier area A is not detected in 2020. In barrier area B and D (Fig. 5B and 5D, Fig. S3, Table S2), the land use type is characterized by cropland. In 2020, the proportion of cropland was 76.46% and 55.28%, respectively, and the forest land was 6.5% and 13.75%, respectively. The proportion of forest land and grassland is low. From 1990 to 2000, the area of built-up areas has increased significantly. Within the barrier area B and D, the important barriers to migration corridors detected by Barrier Mapper indicate a further increasing trend. In barrier area C (Fig. 5C, Fig. S3, Table S2), the proportion of cropland increased by 23.94%, and the built-up areas increased by 158.64%, but the forest land increased by 259.48%, and the proportion reached to 27.11% in 2020. Within the barrier area C, barriers to migration corridors tend to slow down. Area E (Fig. 5E, Fig. S3, Table S2) is dominated by forest land and grassland. In 2020, the proportion of forest land and grassland was 51.12% and 25.48%, respectively. Comparing with 1990, the proportion changed by 60.04% and -51.55%, respectively. The new migration corridors appeared in 2020, which were more conducive to improve the connectivity between core areas and promote species migration.

The results of our analysis further reveal that conservation efforts of North China leopard should not only be limited to the protected areas, which traditionally tend to be higher altitudes and isolated sites. We also need to consider the landscape connectivity on a larger scale. Otherwise, it may render the conservation network less effective and make the distribution of species more isolated.

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Fig.5 Land use changes within key barrier areas marked with A, B, C, D, and area E where connectivity effectively improved

5 Conclusion

In this paper, we used a circuit theory-based approach to explore the relationships between land use changes and landscape connectivity for North China leopard. Circuit theory have already been proven to be useful for conservation planning and landscape management. Our study provides an effective approach for assessing the impacts of land use changes on landscape connectivity for North China leopard at broad spatial scales, specifically, when information on species movement patterns is scarce. Therefore, the results could guide conservation actions and contribute in government decision-making, so as to enhance landscape connectivity for conservation concern of North China leopard and planning of natural reserves network.

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Data Accessibility Statement

The data that supports the findings of this study are available in the supplementary material of this article.