Research Article

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Developing large-scale international ecological networks based on least-cost path analysis – a case study of Altai mountains

https://doi.org/10.1515/geo-2020-0173
received March 24, 2020; accepted June 15, 2020

Abstract: Habitat fragmentation and loss of landscape connectivity have resulted in the degradation of natural ecosystem services. Identifying international transboundary ecological network is an integrated approach to maintain regional ecological sustainability. In this study, taking Altai Mountains as a case study area, we suggested a set of procedures to construct an ecological network. First, we identified ecological patches by evaluating the values of the protected area. Second, we generated resistance surfaces based on the land cover characteristics. Third, we integrated habitat patches and resistance surfaces to identify potential corridors using the least-cost path analysis. The ecological network we introduced consists of 22 patches, 65 potential ecological corridors, and 5 stepping-stones. Furthermore, 26 ecological fragmentation points were marked. We proposed to carry out efficient and effective international cooperation between China, Russia, Kazakhstan, and Mongolia. In addition, the installation of road-crossing structures should be taken into consideration to minimize the negative impacts of the road-related disturbances.

Keywords: patch-corridor-node framework, landscape connectivity, large-scale planning, ecological security pattern

1 Introduction

Connectivity, the degree to which the landscape facilitates or impedes movement between resources or habitats [1], is a key aspect of the conservation of species and communities in land management [2]. High connectivity promotes species communication and colonization [3], maintains genetic diversity [4], improves species' ability to respond to disturbances and climate change [5], and supports the overall viability of species in heterogeneous landscapes [6]. Therefore, increasing landscape connectivity has been identified as a fundamental strategy for mitigating impacts of climate change on biodiversity [5]. The identification and protection of ecological corridors, which allow the movement of flagship or focal species between two or more habitat areas [7], has become an important tool for maintaining landscape connectivity [8]. In response to global concerns about habitat fragmentation, climate change, and loss of landscape connectivity, the establishment of large-scale international ecological networks has accelerated over the past few years, and research studies aimed at improving connectivity by developing ecological networks have become central to conservation science and practice [7,9,10].

The concept of ecological networks was proposed by Forbes in 1887 in the field of biology. Normally, it referred to the various interactions between species, such as competition, symbiosis, and predation [11]. Then it was introduced into landscape ecology, meaning the spatial organization of habitats [12]. Although the definition of ecological network in landscape ecology is still changing and improving, it normally has the following characteristics: (a) maintaining ecological processes [13]; (b) protecting internal habitats from external disturbances and increasing species habitats [14]; (c) enhancing landscape connectivity and reducing the degree of landscape fragmentation [15]; (d) connecting scattered animal habitats, providing channels for animal migration, increasing species gene exchange, and preventing population segregation [16]; and (e) addressing the threat posed by the global climate change [17].

An Ecological Network is usually composed of three elements: ecological patch (or ecological source, ecological

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core area), ecological corridor, and ecological node (or stepping-stone). Ecological Patch is the core area with the richest biodiversity, where species can live their entire life cycle within. It serves as a reservoir, from which the species disperse. Ecological Corridor is described as a narrow pathway that enables the dispersal and migration of flora and fauna [18]. Stepping-stones are small habitat areas that can serve as stopovers when traveling through the unfavorable matrix between two patches in the network [60]. All these three elements together create possible areas in which species can migrate and, therefore, some species can be capable of maintaining the protection to some extent [19].

To propose ecological networks, one normally used methodology is the least-cost path (LCP) analysis, which can be implemented in most Geographic Information Systems (GIS) [20]. LCP analysis is one of the best methods for achieving the optimal establishment of paths between landscape elements [21] and allows decision makers to determine the ideal way to connect two segmentations in the cost surface. This modeling tool, derived from the graph theory that is based on the fact wildlife movement, is affected by the characteristics of landscapes, including the land cover, roads, and slope [22,23], and is being increasingly applied to land and species management projects and research [24,25]. LCP has been used in conjunction with GIS to interconnect ecosystems primarily designed to maintain the sustainability of protected areas in several studies [26–34].

Altai Mountains are listed on the “Global-200” as one of the most biologically distinguished ecoregions [35]. This complex mountain system extends approximately 2,000 km in a southeast–northwest direction from the Gobi (Desert) to the West Siberian Plain, through China, Mongolia, Russia, and Kazakhstan [36]. The average height of the system is 2,500 m and the highest point reaches 4,507 m (Belukha Mountain). The presence of isolated mountain valleys helps to preserve many relict and endemic species of flora and fauna [37]. The Russian part of the Altai Mountains was inscribed in the World Heritage List as The Golden Mountains of Altai in 1998, and China’s part as China Altay was included in the tentative list in 2010. Areas in Mongolia and Kazakhstan are included under their own natural protection systems. Multilateral four-nation talks have been held many times with the intention to include Altai Mountains as a transboundary World Heritage property. One of the biggest challenges is how to form an effective protection and management system to preserve the biodiversity and ecological sustainability that are divided in different countries.

This study proposed a possible ecological network to strengthen the links among Altai transboundary natural reserves. The methodological perspective helps us to identify new potentially protected areas, with aims to form more representative, interconnected, and effective ecological networks for this region. This research brings forward valuable information that can be used for further decision making.

2 Methods

2.1 Study area

The study area covers six administrative regions belonging to four countries: The Altay Area of the Xinjiang Uygur Autonomous Region of China, the Altai Republic and the Altai Krai of the Russian Federation, the East Kazakhstan State of Kazakhstan, and the Bayan-Ölgii Province and Khovd Province of Mongolia, with a total area of 7,80,000 km^2 (Figure 1). The region represents the most complete sequence of altitudinal vegetation zones in central Siberia, from steppe, forest-steppe, mixed forest, subalpine vegetation to alpine vegetation. The area is also an important habitat for endangered animal species such as the snow leopard. This region is also the origin and biodiversity center for various rare flora and fauna of north and central Asia, and the most representative and well-preserved region of the Siberian ecosystem.

2.2 Data

For our spatial analyses, we used open available land cover data (from USGS – Global Land Cover Characterization, GLCC, https://earthexplorer.usgs.gov/), Natural World Heritage Sites data (UNESCO World Heritage Center, http://whc.unesco.org/), nature reserves data (IUCN and UNEP-WCMC, available at https://www.protectedplanet.net/), as well as DEM data (United States Geological Survey, USGS). Land cover types were classified into seven major categories: forests, grassland, cultivated land, permanent snow and ice, water bodies and wetland, artificial surfaces, and barren lands. All data were used in raster format with 1,000 m spatial resolution as this resolution is fine enough for a large-scale research and can significantly speed up the software’s running speed.

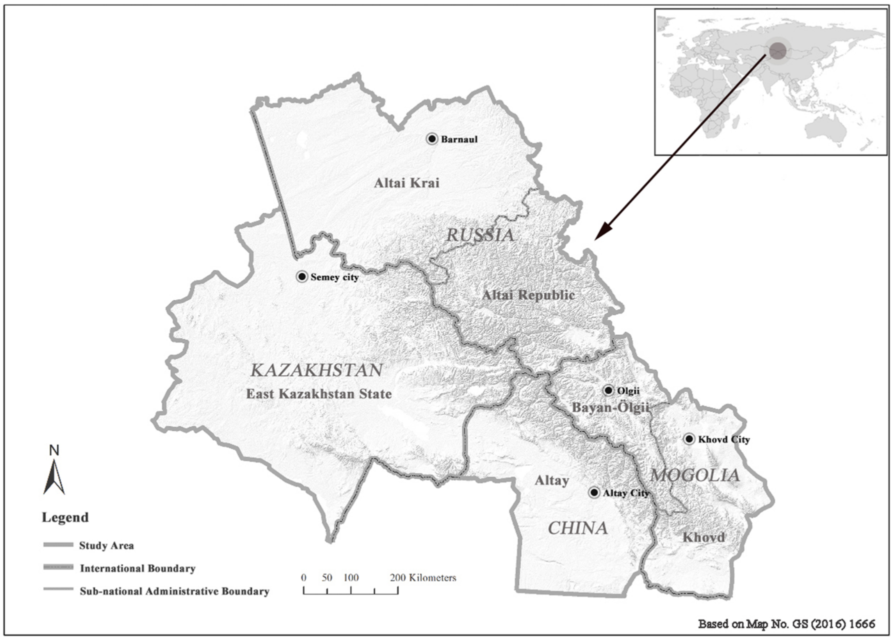

Figure 1: Geographical location of the study area at the intersection part of China, Russia, Mongolia, and Kazakhstan of Eurasia.

2.3 Methods

2.3.1 Ecological patches

Since ecological patches are core areas with the highest biodiversity, our research identified ecological patches as designated protected areas at the global level and national level, as these areas are often of ecological and biological importance and are the best representation of biodiversity in a given region. Through an in-depth investigation and research on this area, 22 Ecological Patches were selected (Figure 2), including the UNESCO World Heritage Sites, Ramsar wetland, and national nature reserves of the four countries. Since different countries have different natural reserve systems, there is no direct comparability of the importance level; therefore in this research, they are given the same weight in the calculation.

2.3.2 Least-cost path analysis

To propose the most suitable path for ECs, a LCP analysis is used to determine the path with the least resistance between two points (from one ecological patch to another). The LCP analysis calculates the minimum cumulative resistance (MCR) to produce the best route for ECs. The Formula of MCR is as given below [38,39]:

$$\mathrm{MCR} = f_{\min} \sum_{j=n}^{i=m} (D_{ij} \times R_i)$$

where MCR is the minimum cumulative resistance, f is a function of the positive correlation that reflects the relation of the least resistance for any point in space to the distance from any point to any source and the characteristics of the landscape base surface; min denotes the minimum value of cumulative resistance produced in different processes of landscape unit i transforming into a different source unit j; D_{ij} is the spatial distance between landscape unit i and source unit j; and R_i denotes the resistance coefficient that exists in transition from landscape unit i to source unit j.

2.3.3 Cost surface generation

As wildlife species are affected differently by land cover characteristics, including impervious surface and natural green surfaces [40–42], this study considered three types of factors related to the cost: ecological factors, topographical factors, and human activity factors (Table 1).

Ecological factors are the decisive factors that affect the movements of wildlife. Resistance values of ecological factors are usually determined based on the difficulty of migration of the local species. Since our research does not target specific species, the resistance

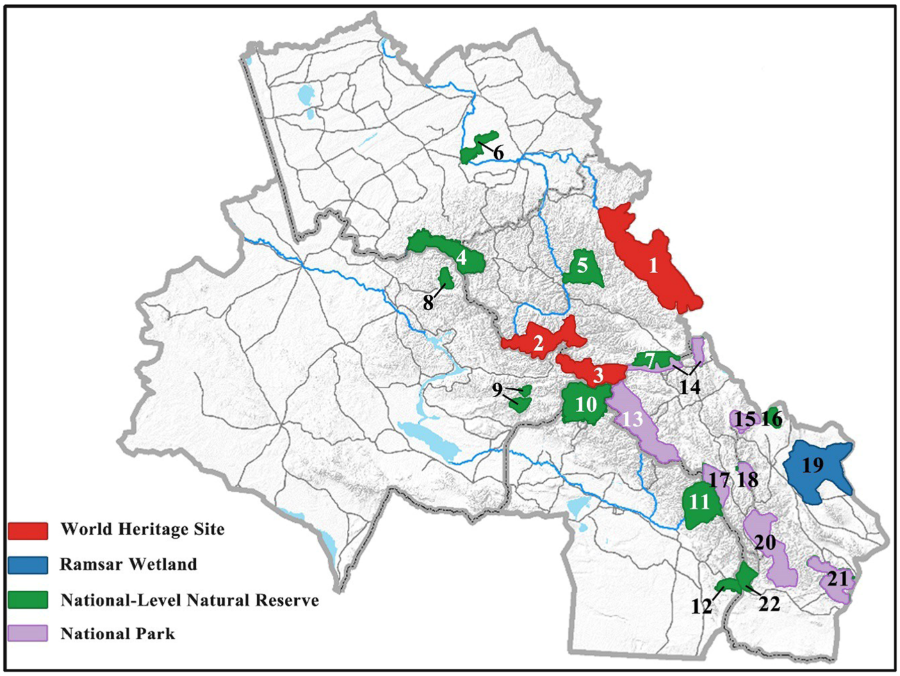

Figure 2: Selected ecological patches. 1–7 are located in Russian Federation, 1, 2, and 3 are three component parts of the Golden Mountains of the Altai World Heritage Site, namely Altaisky Zapovednik of Teletskoye Lake, Katunsky Zapovednik around Belukha Mountain, and Ukok Quiet Zone. 4: Kosh-Agachskiy; 5: Sumul'tinskiy Khrebet; 6: Bol'Sherechenskiy; 7: Tigireksky. 8 and 9 are located in Kazakhstan, namely Zapadno-Altayskiy and Markakol'skiy. 10–12 are situated in China, 10: Kanas Nature Reserve, 11: Liangheyuan Nature Reserve, and 12: Burgen Beaver National Nature Reserve. 13–22 are located in Mongolia. 13: Altai Tavan range; 14: Siilkhemiin Nuruu National Park; 15: Tsambagarav Uul National Park; 16: Altan Khukhii Uul Nature Reserve; 17: Chigertein Golin Ai Sav National Park; 18: Khukh Serkhiin Nuruu National Park; 19: Har Us Nuur Ramsar Wetland; 20: Munkhkhairkhan uul-Uenchiin Khavtsal National Park; 21: Myangan-Ugalzat National Park; 22: Bulgan Gol-Ikh Ongog National Park.

value is determined according to the ecological service values of different land types based on previous research studies [43,44] and adjusted by expert assessments. Areas with a high ecological service value normally allow less energy loss as species pass through them, and thus are given smaller resistance values.

Topographical factors can identify ecological corridors more accurately, while similar landscapes under different topographical settings may have different functional significance. The distribution of ecological corridors is significantly correlated with ridges and valleys, that is, most species occurred more frequently in valleys than on ridges [45]. Besides, elevation and slope are the most commonly used indicators. As suggested by Jenness et al. [46], we selected slope, ridge, and valley as topographical factors. Resistance values are given based on previous research studies [21,47,48].

Human activity factors are mainly construction features such as villages, cities, roads, and highways. These factors reflect the degree of influence from human activities on the protection of natural reserves' ecological functions. Resistance values of human activity factors were represented as density values [21] and distance to constructions [47].

2.3.4 Ecological connectivity analysis

Ecological connectivity is the relationship between landscape elements in their spatial structures. To construct an ecological network considering the highest connectivity possible, continuity index including the structural continuity index and the functional continuity index are commonly used [49]. The evaluation indices used in this study are shown in Table 2. Following Gao et al. [50], this study used the hierarchical clustering module in SPSS 21.0 to divide each class into three further classes to determine the importance of ecological patches and corridors. Classification matrix can be seen below (Table 3) – when both indices ranked as "very important," or one index is "very important" while the other is "important," this ecological patch or corridor is considered as a "primary patch." When both indices

Table 1: Resistance values to generate cost surface

Factors	Indicators		Resistance value
Ecology factors	Forests		5
	Grassland		30
	Water bodies and wetland		70
	Cultivated land		90
	Permanent snow and ice		100
	Barren lands		100
Topographical factors	Slope	<5°	5
		6°–15°	10
		16°–55°	20
		26°–35°	40
		16°–45°	80
		>45°	100
	Ridges		50
	Valleys		0
Human activity factors	Highway	<Eight lanes	80
		>Eight lanes	100
	Density of road	0–1 km/km^2	5
		1–2 km/km^2	10
		2–4 km/km^2	25
		4–6 km/km^2	35
		>6 km/km^2	50
	Villages (low- to medium intensity of land use)		80
	Cites (high intensity of land use)		100
	Distance to constructions	0–1,000 m	100
		1,000–3,000 m	70
		3,000–5,000 m	50
		5,000–7,000 m	30
		>7,000 m	5

were ranked as "ordinary," the patch or corridor was considered to be a "tertiary patch." In all other cases, patches or corridor were considered to be a "secondary patch."

Table 2: Ecological connectivity indices

Index	Definition
Integral Index of Continuity (IIC) $IIC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \cdot a_j}{1+nl_{ij}}}{A_L^2}$	Based on the binary connections model in which two points are directly linked if the distance between them is less than a given value [36]. n is the total number of habitat patches; a_i and a_j are the area of habitat patch i and that of habitat patch j; nl_{ij} is the number of connections between patches i and j; A_L is the total regional area
Probability of Continuity (PC) $PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \cdot a_j \cdot P_{ij}^{*}}{A_L^2}$	A probabilistic connections model without being influenced by adjacent patches or elements in the analyzed datasets [52]. n is the total number of habitat patches; P_{ij}^{*} is the probability of directional migration between habitat patch i and habitat patch j; $0 < PC < 1$
Importance index (I_{remove}) $d_{IIC} \frac{IIC - IIC_{remove}}{IIC} \times 100\%$ $d_{PC} = \frac{PC - PC_{remove}}{PC} \times 100\%$	The relative ranking of patches by their contribution to overall connectivity, namely the change in landscape connectivity of the whole area when this point is broken (or removed), is most useful in evaluating patch significance [53]. IIC (PC) is the continuity index; IIC_{remove} (PC_{remove}) is the index after removing one habitat patch. Each iteration removes one habitat patch. Greater d_{IIC} (d_{PC}) indicates that a particular habitat patch is of higher importance in the network

Table 3: Classification matrix of ecological patches and corridors

IIC			
PC	**Very important**	**Important**	**Ordinary**
Very important	Primary	Primary	Secondary
Important	Primary	Secondary	Secondary
Ordinary	Secondary	Secondary	Tertiary

3 Results

3.1 Spatial patterns

Spatial patterns and cost surface of the study area are shown in Figure 3. Several commonly used landscape indices that reflect the spatial structural characteristics of the landscape were calculated with Fragstats 4.2 (Table 4).

Based on the analysis of landscape indices, our research shows that grassland accounts for 51.91% of the area and is the dominant landscape type. Barren land is the second largest type, accounting for 23.34% of the area, mainly distributed in the south and southeast of the study area. Barren land of this area is composed of deserts and Gobi, such as the Gulban Tungu desert in China and the Great Gobi Desert in Mongolia. Forests are mainly Taiga forest in the northern part of the study area in Russia, extending southwest along the border between China and Mongolia. The patch area of artificial surface accounts for the smallest part (accounting for only 0.083%). LPI also shows the same conclusion that grassland is the dominant landscape type with the biggest continuous area. Glaciers in the study area show a tendency of fragmentation with the highest PD and the lowest MPS.

3.2 Ecological network

Based on the LCP analysis, this study proposes 65 potential ecological corridors (ECs) to connect 22 Ecological Patches in the Altai Mountains (Figure 4). The landscape pattern of potential ECs is shown in Table 5. Total area of the ECs is 8,88,391 ha, accounting for 1.12% of the total area of the study area. Grassland is the main landscape type constituting the potential EC, accounting for 54% of the ecological corridor area, followed by forest, accounting for 24.1%. Forests and grasslands play an important role in species migration and building ecological networks in protected areas.

In general, ecological network of the study area is separated into two isolated clusters: The Northern Cluster and the Southern Cluster. The Northern Cluster is formed on the border of Russia, China, and Kazakhstan, and the Southern Cluster is located between China and Mongolia. The internal connections inside each cluster are strong; however, the external links between the two clusters are relatively weak. Barren lands block the exchange of species in these two clusters, resulting in a biological isolation. To address this issue, approximately 100 km green way of shrub and grassland is suggested to be built between Kosh-Agachskiy and Cambagarav mountain nature reserve, as well as another 40 km green way between the Altai Tavan range and Chigertein Golin Ai Sav.

Seven patches and 12 corridors were classified as primary ecological units with a significant ecological connectivity function. Patches with a large area, such as three component parts of the Golden Mountains of Altai, and Kanas Nature Reserve, provide a continuous protection for wildlife. Large patches have the advantage that their species are less prone to extinction, as they provide more stable habitat conditions and could support larger population sizes and higher migration rates [51]. Previous research has shown the positive influence of patch size on the conservation of biodiversity in species of mammals [52], insects [53], birds [54], and reptiles [55].

Except for patches and corridors, five stepping-stones were noted in the study area. The stepping-stone theory is derived from the Island Biogeography theory [51]. Ecologists and planners highlight the role of stepping-stones in supporting biodiversity and species movement [54,56,57]. This study spotted stepping-stones by searching contiguous areas with a low-cost value where important corridors cross over. All of the five stepping-stones were located in Russia. This result gives local authorities suggestions on the delimitation of priority future protected area.

Cross-border ECs widely exist among countries in the study area. Eighteen cross-border ECs were identified, including corridors between Tigireksky (Russia) and Zapadno-Altayskiy (Kazakhstan), Katunsky Zapovednik (Russia), Ukok Quiet Zone (Russia) and Markakol'skiy (Kazakhstan), Ukok Quiet Zone (Russia) and Kanas Nature Reserve (China), Kanas Nature Reserve (China) and Markakol'skiy (Kazakhstan), Kanas Nature Reserve (China) and Altai Tavan range (Mongolia), Liangheyuan Nature Reserve (China) and Chigertein Golin Ai Sav (Mongolia); Burgen Beaver National Nature Reserve (China) and Bulgan Gol-Ikh Ongog (Mongolia); and

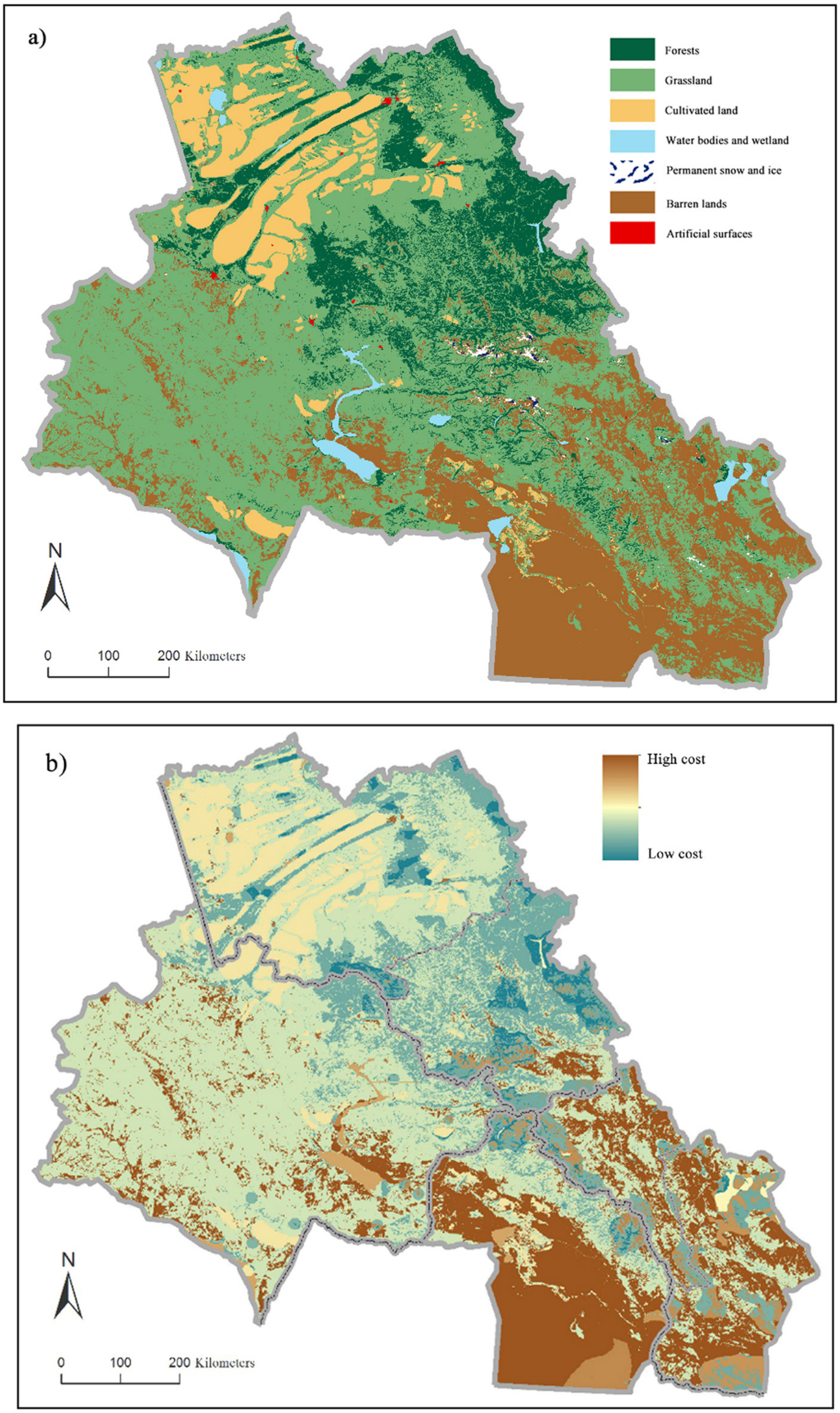

Figure 3: (a) Landscape patterns and (b) cost surface of the study area.

Ukok Quiet Zone (Russia) and Altai Tavan range (Mongolia). Important habitat patches around international borders are fragmented due to the existence of border fences, and the degree of ecological connectivity is drastically reduced, destroying the connectivity and stability of the ecosystem. One good example to address this problem is the Transboundary Ramsar Sites (TRS) Project by RAMSAR [58]. Thirteen TRS have been

Table 4: Landscape indices for each land cover type[a]

Landscape	CA (ha)	PLAND (%)	LPI (%)	NP	PD (/100 ha)	MPS (ha)
Forests	1,03,75,444	13.139	4.180	35,055	0.044	295.97
Grassland	4,09,87,596	51.905	42.290	48,753	0.062	840.71
Cultivated land	65,10,888	8.245	1.139	9,871	0.013	659.59
Water bodies and wetland	11,15,024	1.412	0.535	2,043	0.003	545.77
Permanent snow and ice	14,74,356	1.867	0.044	2,05,815	0.261	7.164
Barren lands	1,84,37,556	23.349	15.438	55,259	0.070	333.65
Artificial surfaces	65,520	0.083	0.016	533	0.001	122.92

[a] CA refers to the class area, PLAND is the percent of landscape, and these two indices can reflect the composition and proportion of each landscape type; LPI refers to the largest patch index and shows the dominance of landscapes. NP is the number of patches, PD is the patch density, and MPS is the mean patch size. NP, PD, and MPS show the degrees of landscape fragmentation.

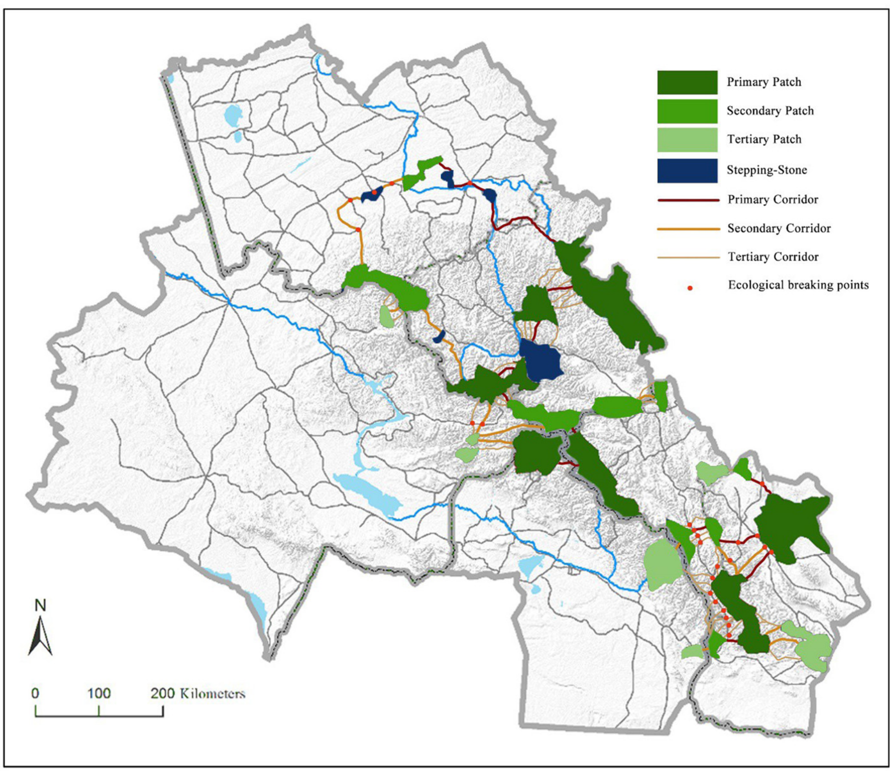

Figure 4: Potential ECs based on the LCP analysis.

Table 5: Landscape pattern of the potential ECs in the study area

Landscape	Total area (ha)	Proportion (%)	Corridor area (ha)	Proportion (%)
Forests	1,03,75,444	13.14	2,14,100	24.10
Grassland	4,09,87,596	51.91	4,75,820	53.56
Cultivated land	65,10,888	8.25	360	0.04
Water bodies and wetland	11,15,024	1.41	3,000	0.34
Permanent snow and ice	14,74,356	1.87	16,730	1.88
Barren lands	1,84,37,556	23.35	1,78,380	20.08
Artificial surfaces	65,520	0.08	50	0.01
Total	7,89,66,384	100.00	8,88,391	100.00

established to deduce ecological fragmentation, one in Africa – the Niumi-Saloum Complex in Gambia and Senegal – and the remainder in Europe. Another effective precedent is The Caspian Coastal Assessment Plan [59]. A convention concerning the protection and restoration of the Caspian Sea was signed by Russia, Azerbaijan, and Iran in Tehran in 2003, committed to connecting the broken ecosystems in different parts of the Caspian Sea. Subsequently, initiated by the Critical Ecosystem Partnership Fund (CEPF), District Biodiversity Hotspot projects have been carried out and 10 large-scale ecological corridors have been delimited. Hence, this study suggested all four counties of the study area to step forward on an international cooperation by first signing conventions on the protection of their common home – the Altai Mountains, and explore actively the potentially suitable areas for wildlife migration to ensure that barriers to migration are eliminated to the greatest possible extent.

ECs, which pass through roads and highways, marked 26 ecological breaking points. Roads have many aspects of negative effects on the ecological system. Road-related disturbances filter animal activity in habitats on both sides of the road, and in the long-term time frame, may lead to populations decrease or disappearance of animal populations from habitats that have been isolated and segregated by roads [60]. In addition, roads are a source of mortality for wildlife, especially for some large, rare species that are regularly brought into contact with busy roads, road-kills can have a significant effect on the conservation status [44]. Most of the breaking points (18) are located in Mongolia, especially along the Bulgan-Deluun Road that connects Takshiken trade port with China to two major cities, Khovd City and Ölgii City, in the west of Mongolia. While promoting economic exchanges, this road obstructs wildlife migration and biomass interflow between Liangheyuan Nature Reserve in China and Munkhkhairkhan Uul-Uenchiin Khavtsal Protected Area in Mongolia. Few ecological breaking points occur in Altai Krai of Russia and East Kazakhstan Province of Kazakhstan. Wildlife conservation must receive full consideration in the planning, construction, and ongoing management of road systems. Managers of the road system should take further investigations and implement practical measures to reduce the negative effects of roads on natural environment and to minimize the mortality of wildlife related to transportation facilities. The installation of road-crossing structures, such as road underpasses or the overhead bridges, is a valid way to handle these issues for wildlife.

4 Discussion

Ecological networks are ecological spaces where the actual ecosystems of a region are objectively interrelated. The purpose of an ecological network analysis is to promote the energy and information flow by taking certain measures to increase the structural and functional connections between fragmented and isolated habitats in a certain area, and thus to maintain the stability of a regional ecosystem [61]. This study adopted LCP to propose international large-scale ecological corridors for the Altai Transboundary Area that covers the different national territories but with similar eco-environmental settings.

Some research studies have proposed the ecological network based on the habitat suitability evaluation of flag or focal species, such as Amur Tiger (Panthera Tigris Altaica) [62], mink and warblers [63], while our study aims to optimize regional ecological security pattern and not subjected to a particular species. Therefore, resistance factors in this study selected factors that will affect the ecological security pattern under normal circumstances such as land types, topography, and human disturbance. Follow-up studies in this area could focus on flagship species, such as snow leopard, to build species conservation network.

In the model of LCP, the assignment of resistance value is the premise of the rationality of the result. However, the assignment of resistance value often depends on the expert experience, which is normally subjective to some extent, and does not always match the actual situation. Although the absolute value of this method is yet to be discussed, it can objectively reflect the comprehensive resistance of heterogeneous landscapes to species movements. Moreover, the resistance value is the relative resistance in the process of species movement, not the absolute value. Under the condition of assigning the correct resistance value to the relative concept, it can meet the requirements of the LCP model.

The ecological corridor determined by the LCP method has no width. The main reason is that the width of the biological corridor should be determined by multiple factors such as the protected object, vegetation type and status, corridor function, surrounding land use status, terrain, climate change, and so on. For different areas or even the same area in different times, the widths of the corridors are different. With detailed experimental research and data, the reasonable width of the corridor can be determined.

In conclusion, this study proposed a transboundary ecological network consisting of 22 ecological patches, 65 potential ecological corridors, and 5 stepping-stones. Among the ecological corridors, 18 were cross-border ECs; thus, an efficient and valid international cooperation between the four countries should be carried out. The stepping-stones give a suggestion to the priority of future nature reserves' location selection. In addition, 26 ecological breaking points have been marked. The installation of road-crossing structures should be taken into consideration to minimize the negative impacts from road-related disturbances.

Acknowledgment: The research was supported by the Western China Young Scholars Project, Chinese Academy of Sciences (2016-QNXZ-B-18).

Author contributions: Data curation, Wang Cuirong and Liu Huaxian; Funding acquisition, Wang Cuirong; Methodology, Liu Huaxian; Visualization, Wang Cuirong; Writing – original draft, Wang Cuirong; Writing – review and editing, Wang Cuirong and Liu Huaxian.

References

[1] Taylor PD, Fahrig L, Henein K, Merriam G. Connectivity is a vital element of landscape structure. Oikos. 1993;68(3):571–3.
[2] Abrahms B, Sawyer SC, Jordan NR, Mcnutt JW, Wilson AM, Brashares JS. Does wildlife resource selection accurately inform corridor conservation? J Appl Ecol. 2017;54(2):412–22.
[3] Hanski I, Gilpin ME. Metapopulation dynamics: brief history and conceptual domain. Biol J Linn Soc Lond. 1991;1991:3–16.
[4] Hendrick PW. Genetics of populations. Boston: Jones and Bartlett Publishers; 2005.
[5] Heller NE, Zavaleta ES. Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biol Conserv. 2009;142(1):14–32.
[6] Vasudev D, Fletcher RJ, Goswami VR, Krishnadas M. From dispersal constraints to landscape connectivity: lessons from species distribution modeling. Ecography. 2015;38(10):967–78.
[7] Beier P, Majka DR, Spencer W. Forks in the road: choices in procedures for designing wildland linkages. Conserv Biol. 2008;22(4):836–51.
[8] Gilbert-Norton L, Wilson RR, Stevens J, Beard KH. A meta-analytic review of corridor effectiveness. Conserv Biol. 2010;24(3):660–8.
[9] Beier P, Spencer W, Baldwin RF, Mcrae BH. Toward best practices for developing regional connectivity maps. Conserv Biol. 2011;25(5):879–92.
[10] Rudnick DA, Ryan SJ, Beier P, Cushman SA, Dieffenbach F, Epps CW, et al. The role of landscape connectivity in planning and implementing conservation and restoration priorities. Issues Ecol. 2012;16(1):1–20.
[11] Nature. Ecological networks 2020. https://www.nature.com/subjects/ecological-networks.
[12] Opdam P, Steingröver EG, Van Rooij S. Ecological networks: a spatial concept for multi-actor planning of sustainable landscapes. Landsc Urban Plan. 2006;75(3–4):322–32.
[13] Naiman RJ, Decamps H, Pollock M. The role of Riparian corridors in maintaining regional biodiversity. Ecol Appl. 1993;3(2):209.
[14] Vergnes A, Viol IL, Clergeau P. Green corridors in urban landscapes affect the arthropod communities of domestic gardens. Biol Conserv. 2012;145(1):171–8.
[15] Soule ME. Land use planning and wildlife maintenance: guidelines for conserving wildlife in an urban landscape. J Am Plann Assoc. 1991;57(3):313–23.
[16] Ahern J. Greenways as a planning strategy. Landsc Urban Plan. 1995;33(1):131–55.
[17] Beier P, Brost BM. Use of land facets to plan for climate change: conserving the arenas, not the actors. Conserv Biol. 2010;24(3):701–10.
[18] Beier P, Noss RF. Do habitat corridors provide connectivity? Conserv Biol. 1998;12(6):1241–52.
[19] Liang J, He X, Zeng G, Zhong M, Gao X, Li X, et al. Integrating priority areas and ecological corridors into national network for conservation planning in China. Sci Total Environ. 2018;2018:22–9.
[20] Driezen K, Adriaensen F, Rondinini C, Doncaster CP, Matthysen E. Evaluating least-cost model predictionswith empirical dispersal data: a case-study using radiotracking data of hedgehogs (Erinaceus europaeus). Ecol Modell. 2007;209(2–4):314–22.
[21] Lee JA, Chon J, Ahn C. Planning landscape corridors in ecological infrastructure using least-cost path methods based on the value of ecosystem services. Sustainability. 2014;6(11):7564–585.
[22] Beier P, Penrod KL, Luke C, Spencer WD, Cabanero C. South coast missing linkages: restoring connectivity to wildlands in the largest metropolitan area in the United States. In: Crooks KR, Sanjayan MA, editors. Connectivity and Conservation. Cambridge: Cambridge University Press; 2006. pp. 1–23.
[23] Singleton PH, Gaines WL, Lehmkuhl JF. Landscape permeability for large carnivores in Washington: a geographic information system weighted-distance and least-cost corridor assessment. Washington, DC: USDA Forest Service Pacific Northwest Research Station; 2002.
[24] Adriaensen F, Chardon JP, De Blust G, Swinnen E, Villalba S, Gulinck H, et al. The application of 'least-cost' modelling as a functional landscape model. Landsc Urban Plan. 2003;64(4):233–47.
[25] Effat HA, Hassan OA. Designing and evaluation of three alternatives highway routes using the analytical hierarchy process and the least-cost path analysis, application in Sinai Peninsula. Egypt Egypt J Remote Sens Space Sci. 2013;16(2):141–51.
[26] Belote RT, Dietz MS, Mcrae BH, Theobald DM, Mcclure ML, Irwin GH, et al. Identifying corridors among large protected areas in the United States. PLoS One. 2016;11(4):e0154223.
[27] Benz RA, Boyce MS, Thurfjell H, Paton D, Musiani M, Dormann CF, et al. Dispersal ecology informs design of large-scale wildlife corridors. PLoS One. 2016;11(9):e0162989.

[28] Casterline M, Fegraus E, Fujioka E. Wildlife corridor design and implementation in Southern Ventura County. California: Donald Bren School of Environment; 2003.
[29] Chetkiewicz CLB, Boyce MS. Use of resource selection functions to identify conservation corridors. J Appl Ecol. 2009;46(5):1036–47.
[30] Cohen Y, Amit-Cohen I, Cohen A, Shoshani M. Least cost path for green corridors delineation in metropolitan margins: the distance weighting effects. J Spat Sci. 2009;54(1):63–78.
[31] Joshi PK, Yadav K, Sinha V. Assessing impact of forest landscape dynamics on migratory corridors: a case study of two protected areas in Himalayan foothills. Biodivers Conserv. 2011;20(14):3393–411.
[32] Karlson M, Karlsson C, Mörtberg U, Olofsson B, Balfors B. Design and evaluation of railway corridors based on spatial ecological and geological criteria. Transp Res D Transp Environ. 2016;46:207–28.
[33] Larue MA, Nielsen CK. Modelling potential dispersal corridors for cougars in midwestern North America using least-cost path methods. Ecol Modell. 2008;212(3–4):372–81.
[34] Pascual-Hortal L, Saura S. Comparison and development of new graph-based landscape connectivity indices: towards the priorization of habitat patches and corridors for conservation. Landsc Ecol. 2006;21(7):959–67.
[35] Olson DM, Dinerstein E. The Global 200: priority ecoregions for global conservation. Ann Missouri Bot Garden. 2002;89(2):199–224.
[36] Urban DL, Keitt TH. Landscape connectivity: a graph-theoretic perspective. Ecology. 2001;82(5):1205–18.
[37] Dirin D, Mądry C. Transformation Processes in Traditional Nature Management Systems in the Altai Mountain Region. 17th International Multidisciplinary Scientific GeoConference, Bulgaria; 2017
[38] Yu K. Landscape ecological security patterns in biological conservation. Acta Ecol Sin. 1999;19(1):8–15.
[39] Liu H. Suitability analysis of heritage corridor in rapidly urbanizing region: a case study of Taizhou City. Geogr Res. 2005;24(1):69–76.
[40] Hoffmeister TS, Vet LE, Biere A, Holsinger K, Filser J. Ecological and evolutionary consequences of biological invasion and habitat fragmentation. Ecosystems. 2005;8(6):657–67.
[41] Teng M, Wu C, Zhou Z, Lord E, Zheng Z. Multipurpose greenway planning for changing cities: a framework integrating priorities and a least-cost path model. Landsc Urban Plan. 2011;103(1):1–14.
[42] Vos CC, Verboom J, Opdam PFM, Braak CJFT. Toward ecologically scaled landscape indices. Am Nat. 2001;157(1):24–51.
[43] Li J. Research of the nature reserve zonation based on the least-cost distance model. J Nat Resour. 2006;21(2):217–24 (in Chinese with English abstract).
[44] Li P, Chen D, Fan J. Research of ecological occupiability based on least-cost distance model – a case study on Xijiang river economic belt in Guangxi. J Nat Resour. 2011;26(2):227–36 (in Chinese with English abstract).
[45] Christen D, Matlack GR. The habitat and conduit functions of roads in the spread of three invasive plant species. Biol Invas. 2009;11(2):453–65.
[46] Jenness J, Brost B, Beier P. Land facet corridor designer; 2011. Retrieved from http://www.corridordesign.org/ in 2020-3-10.
[47] Chen XP, Chen WB. Construction and evaluation of ecological network in Poyang Lake Eco-economic Zone, China. Chinese J Appl Ecol. 2016;27(5):1611–18 (in Chinese with English abstract).
[48] Zeller KA, Mcgarigal K, Whiteley AR. Estimating landscape resistance to movement: a review. Landsc Ecol. 2012;27(6):777–97.
[49] Gonzalez JR, Barrio GD, Duguy B. Assessing functional landscape connectivity for disturbance propagation on regional scales – a cost-surface model approach applied to surface fire spread. Ecol Modell. 2008;211(1):121–41.
[50] Gao Y, Ma L, Liu J, Zhuang Z, Huang Q, Li M. Constructing ecological networks based on habitat quality assessment: a case study of Changzhou, China. Sci Rep. 2017;7(1):1–11.
[51] MacArthur RH, Wilson EO. The theory of island biogeography. Princeton: Princeton University Press, 2001.
[52] Lawrence A, O'Connor KE, Haroutounian V, Swei A. Patterns of diversity along a habitat size gradient in a biodiversity hotspot. Ecosphere. 2018;9(4):1–14.
[53] Rösch V, Tscharntke T, Scherber C, Batáry P. Biodiversity conservation across taxa and landscapes requires many small as well as single large habitat fragments. Oecologia. 2015;179(1):209–22.
[54] Maldonado-Coelho M, Marini MA. Mixed-species bird flocks from Brazilian Atlantic forest: the effects of forest fragmentation and seasonality on their size, richness and stability. Biol Conserv. 2004;116(1):19–26.
[55] Almeida-Gomes M, Rocha CFD. Diversity and distribution of lizards in fragmented atlantic forest landscape in Southeastern Brazil. J Herpetol. 2014;48(3):423–9.
[56] Herrera LP, Sabatino MC, Jaimes FR, Saura S. Landscape connectivity and the role of small habitat patches as stepping stones: an assessment of the grassland biome in South America. Biodivers Conserv. 2017;26(14):3465–79.
[57] Riordan P, Cushman SA, Mallon D, Shi K, Hughes J. Predicting global population connectivity and targeting conservation action for snow leopard across its range. Ecography. 2016;39(5):419–26.
[58] Bowman M, Goodwin PDE. Research Handbook on Biodiversity and Law. Massachusetts, Cheltenham & Northampton; 2016.
[59] Aliyev M. Success story: Caspian, 2018. https://www.unenvironment.org/news-and-stories/speech/success-story-caspian.
[60] Riley SPD, Pollinger JP, Sauvajot RM, York EC, Bromley C, Fuller TK, et al. FAST-TRACK: a southern California freeway is a physical and social barrier to gene flow in carnivores. Mol Ecol. 2006;15(7):1733–41.
[61] Qiang FU, Chaolin GU. Evaluation of the structural elements of Qingdao ecological network based on the CL-PIOP method. Acta Ecol Sin. 2017;37(5):1729–39. (in Chinese with English abstract).
[62] Qu Y, Luan X. Core habitat identification and gap analysis for Amur tiger based on least-cost distance model. Chinese J Ecol. 2010;2010(9):190–8 (in Chinese with English abstract).
[63] Bunn AG, Urban DL, Keitt TH. Landscape connectivity: a conservation application of graph theory. J Environ Manage. 2000;59(4):265–78.