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An Integrated Approach to Constructing Ecological Security Pattern in an Urbanization and Agricultural Intensification Area in Northeast China

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Abstract: Ecological security pattern (ESP) can bridge the paradox between ecological conservation and socioeconomic development. Although various methods have been applied to establish ESP successfully, improving its scientificity and reliability for regional sustainability are still great challenges. Taking Harbin administrative region as the study area, this paper integrated the merits of the function-oriented method (assessing the importance of ecological services using the InVEST model) and the structure-oriented method (extracting the connectivity of landscapes based on the MSPA model) to improve the identification of ecological sources more scientifically. Night light data were used to modify the natural resistance surface to reveal the real natural and human disturbance for ES loss during species migration and ecological flows. Then, the ESP was established by combining the ecological nodes after extracting and grading the ecological corridors. The results showed that the individual ES performed with a high spatial heterogeneity and was highly correlated with land use patterns. The extremely important and slightly important were the dominant level types in the study area, and the proportion of extremely important declined greatly from 44.78% in 1980 to 30.14% in 2020. Core was the main landscape type with a proportion of 57.13% and mainly distributed in the Lesser Khingan Mountains and Zhangguangcai Mountains. More than 700 ecological corridors were extracted according to the MCR model and the important ecological corridors were selected based on the gravity model, with 86 ecological nodes obtained from the intersection points of ecological corridors. An ESP of "two zones, two barriers, one axis and one belt" was proposed, and relevant protection measures were put out for the sustainable development in the study area. The findings indicated that imposing ESP could form a stable secure frame for social economic development and ecological protection, avoiding irrational land use modes and excessive dispersion of landscapes. This study could provide valuable references for land use planning and the formulation of related ecological protection policies and regional sustainable development strategies.

Keywords: ecological service importance; landscape connectivity; function-oriented method; structure-oriented method; ecological resistance surface; MCR model; ESP; Harbin

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1. Introduction

Since the 20th century, the advancement of the modern economy and society has drastically increased the conflicts between human beings and ecosystems [1,2]. The high intensity of land use development, especially rapid urbanization and agricultural intensification, has put tremendous pressure on ecosystems and caused a series of ecological problems, including biodiversity loss [3], soil desertification and salinization [4], soil erosion, water resource scarcity [5], the 'three wastes' pollution [6] and so on, seriously threatening the sustainable development of social and ecological systems [7,8]. With the widespread concerns regarding the harmony between humanity and nature, it is quite necessary to construct a scientific and robust ecological security pattern (ESP) in advance for spatial planners to

avoid or mitigate the potential negative ecological impacts of land use conversions and to provide a spatial solution for regional ecological security issues [9–11].

Constructing ESP is an effective measure to improve the connectivity of fragmented landscapes and to carry out ecological protection and restoration of territorial space [12,13]. It is of great significance to maintain the normal ecosystem functions and to ensure regional biodiversity and ecological security [14]. The concept of ESP originated in Europe in the 1970s aiming at biodiversity conservation [15,16], and, in the 1990s, it began to emphasize the restoration of degraded ecosystems [17]. Research on ESP in China started at the end of the 20th century. Yu et al. [18] proposed the significance of ESP: specific indestructible landscape configurations and some ecological key elements, which have useful supporting effects on ecological processes. Since then, interdisciplinary research has continued to rise, and ESP has gradually shifted to coordinate natural ecosystems and social economics [19]. The contents involve the interaction between landscape patterns, ecological processes and disturbance factors, the identification of biodiversity conservation area and strategies for regional sustainable development, and the methods are constantly evolving from simple GIS spatial analysis to complex model simulation [19–21]. Although various methods have been applied to establish ESP successfully, improving the scientificity and reliability of ESP for regional sustainability are still great challenges. Currently, the ESP construction is still being improved, and the "Ecological Source-Ecological Corridor" framework is quite effective and has been widely used [10,22,23]. The paradigm for regional ESP construction and some necessary improvements are summarized in the following steps.

(1) Ecological source identification. The ecological sources are important habitat patches that play a decisive role in regional ecological processes and functions [24,25]. They are the sources of species diffusion and maintenance [26]. Ecological source identification could be achieved by functional or structural approaches. As for the function-oriented method, most early studies directly selected natural reserves, scenic areas or large habitats for focal species spots as the ecological sources, which ignored the effects of internal heterogeneity of landscapes and the external potential threats, such as soil erosion, pollution, human disturbance and so on, on ecological functions [27–29]. Other research identifies ecological sources by constructing evaluation systems from the perspectives of ecosystem service importance, ecological risk or vulnerability, or other related evaluation methods [23,30,31], which fail to exhibit the spatial connectivity of ecological patches, causing uncertainty in the spatial identification of protection priorities [32,33]. By contrast, the structure-oriented method, like the morphological spatial pattern analysis (MSPA) approach, emphasizes the inherent rationality of spatial patterns of ecological elements by analyzing their structural connectivity [34]. This method identifies areas playing an important role in landscape connectivity as the ecological sources from the pixel level, but it considers the spatial interactions between ecological sources with the surrounding environments less [35]. In this context, combining the merits of the two methods above in a complementary manner, called the integration-oriented method, could make the identification of ecological sources more scientific in terms of its capacity for upholding low habitat fragmentation, high landscape complexity and maximum ecological services.

(2) Ecological corridor construction. Ecological corridors transfer material, energy and information flows and provide an indispensable channel for species migration [36,37]. The premise of an accurate ecological corridor extraction is the resistance surface construction, a pattern representing the obstacles in the spatial migration of ecological processes [8]. The ecological resistance coefficient is typically determined by land cover types that are assigned directly based on expert scoring [38]. This method is not scientific enough due to its subjectivity, ignoring the spatial heterogeneity among the same land cover type and the interaction between land use and ecological processes [39]. Therefore, research in recent years has attempted to correct the ecological resistance surface with new indices, including topography, traffic, impervious surface index (ISA), nighttime light (NTL) data and human disturbance [40–42], which reflect the spatial variation of ecological resistance more accurately. Therefore, the weight of factors should be scientifically quantified. In

addition, determining the priority protection order of ecological corridors to improve the practicability of ESP for decision-makers to enact reasonable ecological protection and restoration measures needs some more exploration.

Located in the center of Northeast Asia, Harbin City is an important hub of the Eurasian land bridge and "air corridor". With a sound industrial base, strong agricultural development and excellent ecological environment, Harbin will serve as an important fulcrum for the revitalization and development of Northeast China and a main engine for the high-quality development of Heilongjiang Province. However, the very rapid urbanization and agricultural intensification makes the habitats there suffer disorder disturbance and the conflict between the social economy and ecological environment is escalating, threatening the regional sustainable development. Therefore, it is urgent to construct an ESP to frame the regional development pattern. The main objectives of this paper are to: (1) construct the ESP more scientifically and reliably based on the improved ecological source identification and ecological corridor extraction and (2) propose practical ecological protection and restoration policies and regional sustainable development strategies.

2. Materials and Methodology

2.1. Study Area and Data Source

Harbin City, located in the northeast of the Northeast Plain and the south of Heilongjiang Province, is the capital of Heilongjiang Province and the center of Northeast Asia. The geographical coordinates are 125°42′~130°10′ E, 44°04′~46°40′ N (Figure 1). The topography in the southeast is hills adjacent to branch of the Zhangguangcai Ridge, and in the north are the Lesser Hinggan Mountains. The Songhua River runs through the middle area, forming a vast plain (Songnen Plain). The rivers there crisscross and the water resource is rich. The annual precipitation is about 500~700 mm and mainly concentrated in June to September. The vast black soil resources make it very suitable for farming. A number of national or provincial nature reserves have been built up in Harbin during the past two decades for its excellent natural ecological conditions and important strategic position, making it an important water conservation and biodiversity protection spot for Heilongjiang Province and the whole of Northeast China. However, the rapid urbanization and intensive agriculture severely increase the disturbance to the habitats, encroaching on the ecological matrix, fragmenting ecological corridors, weakening ecological processes and functions and threatening the regional sustainable development. Therefore, it is urgent for Harbin to construct an ESP to promote the harmony between human society and natural ecosystems.

The data used in this study are summarized in Table 1. (1) Land use was used to calculate the relevant ecosystem functions and ecological resistance coefficient, and to identify the core area based on MSPA. According to the land use classification of CAS (Chinese Academy of Sciences), land uses were reclassified forest, grass, waters, construction land and other land use types. (2) The mean annual precipitation was obtained through inverse distance weight interpolation in ArcGIS based on 16 meteorological stations' data around Harbin, and it was used to calculate the water yield and the rainfall erosivity factor R, and to modify the carbon pool. (3) Soil type was used to calculate the water yield and the soil erosion factor K. (4) DEM was used to extract the slope and to construct the resistance surface. (5) NDVI was used to calculate the vegetation coverage and the crop management factor C, and to construct the resistance surface. (6) Rivers were used to construct the resistance surface. (7) Night light data were synthesized on the basis of the monthly NPP-VIIRS night light data provided by NASA/NOAA, and were used to modify the resistance surface.

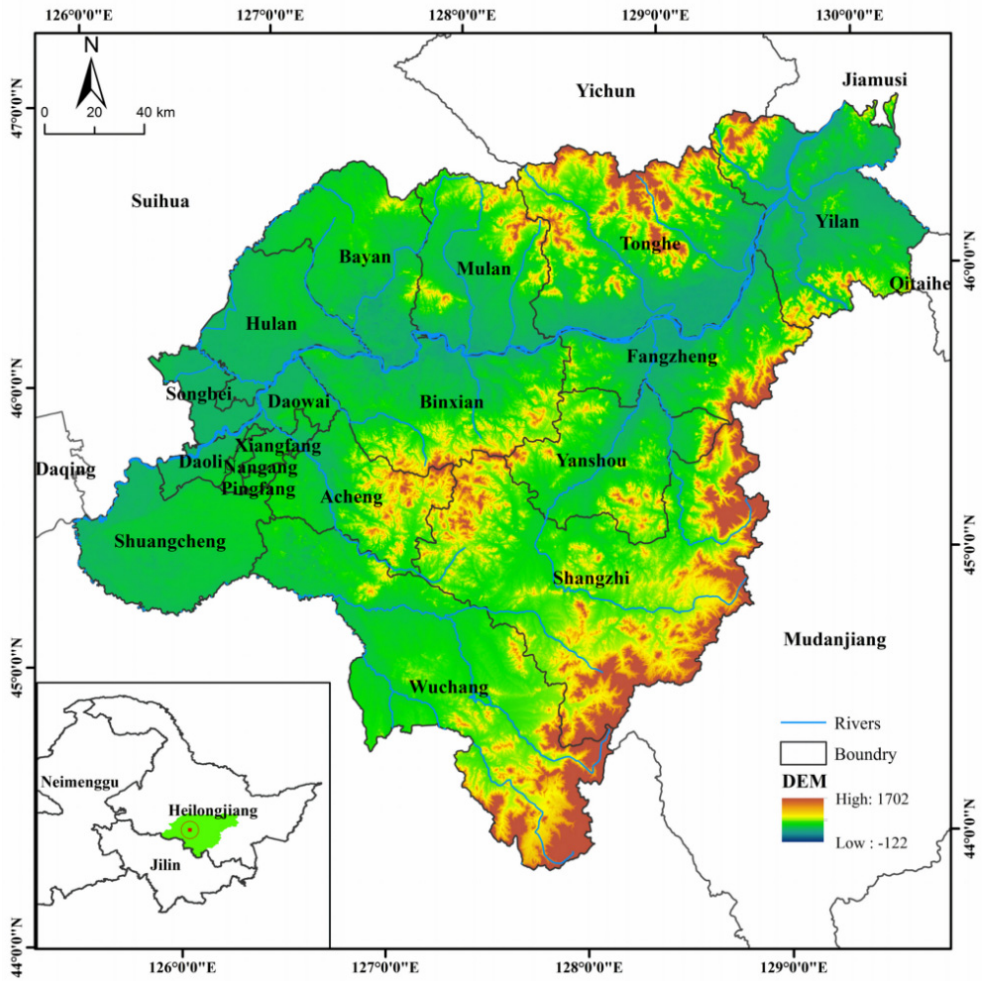

Figure 1. Location of the study area.

Table 1. Data sources and description.

Data	Source	Year	Description
Land use	Resource and Environmental Science Data Centre of the Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 6 September 2022)	1980, 2000, 2020	Raster (30 m)
Precipitation	China Meteorological Data Network (http://data.cma.cn/, accessed on 18 September 2022)	1980, 2000, 2020	Raster (30 m)
Soil	Harmonized World Soil Database (HWSD) at a scale of 1:1000000	-	Raster (1000 m)
DEM	Geospatial Data Cloud platform (http://www.gscloud.cn/, accessed on 6 September 2022)	-	Raster (30 m)
NDVI	Google Earth Engine	1980, 2000, 2020	Raster (30 m)
Water	National Geomatics Center of China (www.ngcc.cn, accessed on 6 September 2022)	-	Shapefile
Night light data	NOAA (https://www.ngdc.noaa.gov/, accessed on 10 October 2022)	2020	Raster (1000 m)

2.2. Methodologies

The methodological framework can be divided into three steps (Figure 2). (1) Identification of ecological sources. Firstly, the function-oriented method was conducted. Water conservation, carbon sequestration, biodiversity conservation and soil conservation were considered through the InVEST model and the RUSLE equation to evaluate the importance

of ecosystem services (ESs). The spatiotemporal evolution of individual ES and integrated ESs were analyzed to reflect the environment status. Secondly, the structure-oriented approach was adopted. The core patches were extracted using MSPA by Guidos software according to land use types, and the landscape connectivity of core patches were evaluated using Conefor software. Then, the important patches were obtained. The ecological sources were identified by overlying the two results of the function-oriented method and structure-oriented method in ArcGIS. (2) Construction of resistance surface. Five natural factors, including elevation, slope, vegetation coverage, land use type and distance from rivers, were selected to determine the natural ecological resistance, and the synthetic resistance surface was obtained by modifying the coefficient using night light data. The ecological corridors were extracted using the MCR model and graded using the gravity model. (3) Construction of ESP. The final ESP of Harbin was constructed jointly with the results of ecological sources and ecological corridors, and some future ecological protection and restoration policies and regional sustainable development strategies were proposed.

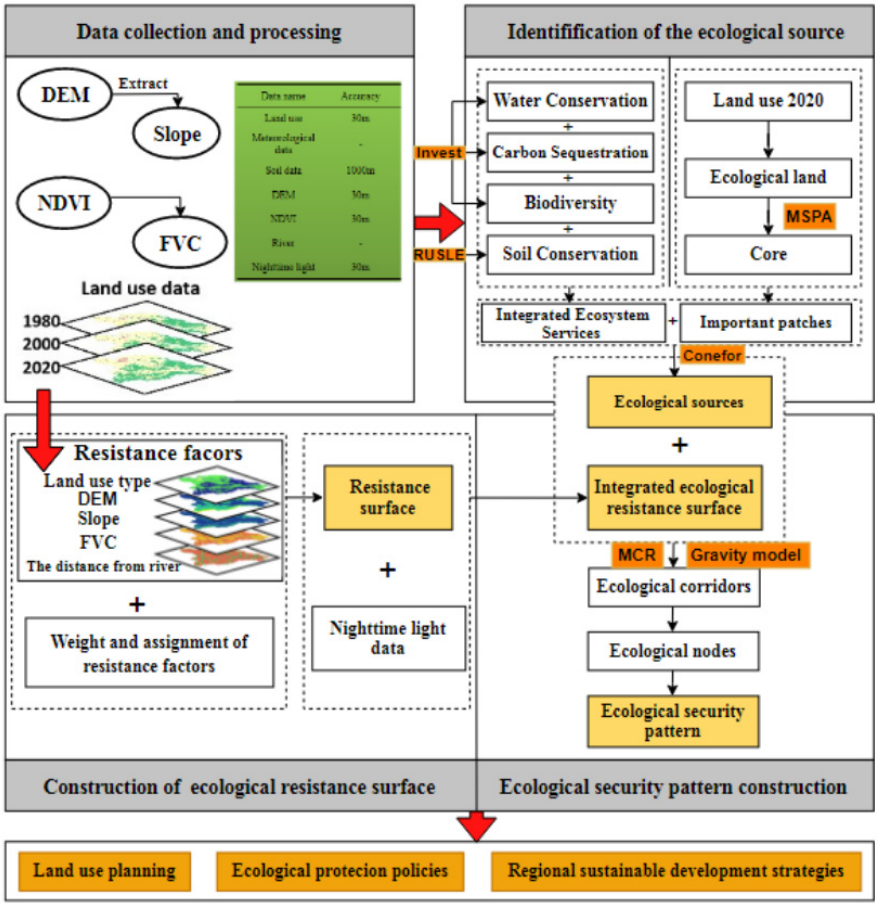

Figure 2. The research framework.

2.2.1. Identification of Ecological Sources

The ecological sources are the key ecological patches that ensure high quality of ecological process and function, supply sustainable ecosystem services and maintain ecological integrity and landscape connectivity [23]. How to identify patches with high ecological significance differentiating from the surroundings scientifically is the key in this process. Therefore, ecological sources in this study were identified by considering the integrated value of critical ecosystem services and importance of ecological patches in landscape connectivity.

(1) The importance of ecosystem service by function-oriented method

Urbanization, agricultural intensification and ecological protection were the three main forces for land use conversion. According to the ecological function regionalization of Heilongjiang Province, there are water conservation ecological function zones in the upper reaches of the Lalin River, soil conservation ecological function zones in the lower reaches of the Ant River and biodiversity conservation ecological function zones in the southern foothills of the Lesser Khingan Mountains. With the process of urbanization and agricultural production squeezing ecological space, excessive logging in water conservation areas and the encroaching of large-scale of wetlands aggravate soil erosion and biodiversity decline, making Harbin face the double pressure of economic development and ecological protection. In addition, carbon storage capacity is an important indicator of ecosystem service function. It is crucial for climate change mitigation and plays an important role in coordinating economic development and ecological conservation [43]. Therefore, water yield, carbon sequestration, biodiversity (characterized by habitat quality) [44] and soil conservation were calculated using the InVEST model and RUSLE equation to measure the status of the ecological environment. The calculation formulas and parameters are encapsulated in Appendix A Table A1. The comprehensive level of ecological importance was achieved by overlapping the normalized four ES maps through an equally weighted assignment process in ArcGIS. The ecological importance value was divided into four grades: extremely important, moderately important, slightly important and non-important through the natural breakpoint method. The formula was as follows:

$$ES = 0.25 \times Wc + 0.25 \times Bc + 0.25 \times Sc + 0.25 \times Cs \quad (1)$$

where *ES* represents the comprehensive ecological importance value, *Wc* refers to the water yield function, *Bc* is the biodiversity conservation function, *Sc* is the soil conservation function, and *Cs* refers to the carbon sequestration function.

(2) The connectivity of landscape by structure-oriented method

MSPA is a method to measure, segment and identify the spatial pattern of raster images based on the mathematical morphology algorithm to mine the geometry and connectivity of ecological spaces [45]. It provides a new method for landscape analysis from the perspective of structural connectivity and has been widely used in ecological source identification [46,47]. In this paper, forest, grass and water bodies were set as the foreground with a value of 2, and other land types were set as background data with a value of 1. Based on the Guidos Toolbox software, we applied the eight-neighborhood method to conduct MSPA analysis on land use raster data (30 m resolution) and finally obtained seven non-overlapping foreground elements: core, islet, perforation, edge, loop, bridge and branch [45], which are described in Appendix B Table A2. Among them, the core is the most important landscape type consisting of large forests, wetlands and other nature reserves. It has a stable morphology and is most conducive to the energy circulation and biodiversity conservation, maintaining the connectivity between different habitat patches [47].

Landscape connectivity is an index to measure the spatial continuity of various landscape corridors or matrices and the smoothness of species migration, diffusion or a certain ecological process in landscapes [48]. It is the link between landscape pattern and ecological process [49]. The possible connectivity index (PC) and plaque importance index (dPC) were selected to evaluate the landscape connectivity using Conefor 2.6 software. The calculation formula was as follows:

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \times a_j \times a_{ij}^{*}}{A^2} \quad (2)$$

$$dPC = 100\% \times (PC - PC_{\text{remove}})/PC \quad (3)$$

where n is the total number of patches. a_i and a_j are the area of patch *the* and j, A is the total landscape area, a^*_{ij} is the maximum probability of connectivity between patches i and j and PC_{remove} is the connectivity probability of the whole landscape after removing a

certain patch. In this paper, the connection distance was set to 1500 m and the connection probability was set to 0.5.

(3) Identification of ecological sources by integration-oriented method

The highly important and highly connected landscape patches were extracted and defined as the final ecological sources through a spatial overlapping process. Here, a threshold of 1 km^2 was set to exclude the small and scattered patches which were chosen as breakpoints.

2.2.2. Extraction of Ecological Corridors

Ecological corridors are belt landscape elements of different scales. They can connect the relatively isolated and dispersed ecological units and are the key carriers for the flow of matter and energy between ecological sources [50]. The establishment of ecological corridors is an important measure to solve the landscape fragmentation and many environmental problems caused by intensive human activities [51]. The MCR model illuminates possible trends in species migration and simulates different ecological flows. It can minimize the associated costs by coupling with landform, natural environment, human activities and other factors, and has been widely used for its advantages of operability and practicability [41,52].

(1) Construction of ecological resistance surface

Ecological resistance represents the resistance degree to the migration and communication of species and is determined by natural and human disturbance. The higher the ecological resistance, the more ES loss in dispersal and flow processes [1]. Common resistance factors usually include land-use types, topography (elevation and slope), vegetation (NDVI), distance factors (water, roads, residential areas) and other natural factors. In this paper, we used night light data to modify the natural resistance surface to make the synthetic resistance surface more scientific. The value assignments and weights of resistance factors are encapsulated in Table 2 [21]. The correcting formula was as follows:

$$R' = \frac{TLI_i}{TLI_a} \times R \quad (4)$$

where R' is the ecological resistance coefficient modified by the night light index, $TLIi$ is the night light coefficient of grid I, $TLIa$ is the average night light coefficient of land type a and R is the basic resistance coefficient of the grid.

Table 2. Value assignments and weights of resistance factors.

Resistance Factor	Resistance Value					Weights
	10	30	50	70	90	
Land-use type	Forest or grass land	Water body	Cultivated land	Bare land	Construction land	0.48
DEM(m)	<200	200–500	500–800	800–1100	>1500	0.18
Slope/°	0–15	15–30	30–45	45–60	>60	0.20
Forest cover rate	>80%	60–80%	40–60%	20–40%	<20%	0.08
Distance to river(m)	<1000	1000–2000	2000–3000	3000–4000	>4000	0.08

(2) Extraction of ecological corridors

The MCR model was used here to generate the potential ecological corridors. Based on ecological sources and synthetic ecological resistance surface, the Cost Distance and Cost Path tools in ArcGIS were used to calculate the minimum path between sources. The minimum cost distance is the cumulative cost of each pixel allocated to the nearest source pixel in the grid [53]. Superfluous paths were eliminated to obtain the final potential ecological corridors. The gravity model was then used to judge the relative importance

of ecological corridor by its intensity, thus the corridors were graded. The formulas were as follows:

$$MCR = f_{\min} \sum_{j=n}^{i=m} \left(D_{ij} \times R_i \right) \quad (5)$$

where MCR is the minimum cumulative resistance value, D_{ij} is the distance from source j to landscape I, R_i is the resistance factor of landscape I and f_{min} represents a positive correlation function reflecting MCR, D_{ij} and R_i.

$$G_{ab} = \frac{N_a N_b}{D_{ab}^2} = \frac{\left[\frac{1}{P_a} \times \ln S_a\right]\left[\frac{1}{P_b} \times \ln S_b\right]}{\left(\frac{L_{ab}}{L_{max}}\right)^2} = \frac{L_{max}^2 \ln S_a \ln S_b}{L_{ab}^2 P_a P_b} \quad (6)$$

where G_{ab} is the strength of the interaction between patch a and patch b, P_a and P_b are the average resistance values of patch a and patch b, respectively, S_a and S_b are the areas of patch a and patch b, respectively, L_{ab} is the cumulative resistance value of the corridor and L_{max} is the maximum cumulative resistance value of all corridors in the study area.

Ecological nodes refer to ecological sections in ecological corridors that play an important role in ecological processes, which can realize the transformation from structural linkage to functional connectivity between patches [18]. They are crucial in maintaining the stability of the ecological security pattern. In this paper, the intersections of ecological corridors were identified as ecological nodes.

3. Results

3.1. Identification of Ecological Sources

3.1.1. Functional Ecological Source Identification

The spatiotemporal variation of individual ecological services was significant (Figure 3). In general, water conservation and carbon sequestration were mainly of high value, while soil conservation was mainly of low value. Biodiversity conservation was mainly of high value in 1980 but of middle value in 2020; it changed the most.

(1) Water Conservation (Wc)

The spatial distribution of Wc in 1980, 2000 and 2020 was consistent. The high value was concentrated in mountains in the eastern part of the study area, where there was mainly forest with a sparse population, while the low value was distributed in the western part, where there was mainly residential construction land and highly intensive cultivated land. The value in Wuchang County and Shangzhi County declined clearly, but it increased in Yilan County. During the period of 1980–2020, the average grid water yield volume increased significantly, from 493.78 mm to 735.99 mm.

(2) Soil Conservation (Sc)

The soil conservation capacity was closely related to topography; the higher the elevation, the better the soil conservation capacity. The forest and grass in mountains could usually conserve soil well for their high vegetation coverage. The low value was concentrated in the plain region, where construction land and cultivated land occupied most of the area. The distribution pattern of soil conservation in 1980, 2000 and 2020 was nearly the same, and it improved constantly during the past 40 years, especially in mountainous and hilly areas. The total amount of soil conservation increased from 2.17×10^9 t in 1980 to 7.37×10^9 t in 2020.

(3) Carbon Sequestration (Cs)

The distribution pattern of Cs was similar to that of Wc. The average grid carbon sequestration was stable, but the total carbon sequestration slightly decreased from 7.10×10^8 t in 1980 to 6.89×10^8 t in 2020.

(4) Biodiversity Conservation (Bc)

The distribution pattern of Bc was similar to that of Wc and Cs. Mountains with high vegetation coverage were the location with high capacity of Bc. However, the region with

high value was constantly shrinking, especially in the center part of the study area. The average value declined from 0.692 in 1980 to 0.628 in 2020.

(5) the ecological importance of comprehensive ES

The spatiotemporal distribution of the comprehensive ES highly resembled that of Bc (Figure 4). Extremely important and slightly important were the dominant level types in the study area. The importance of comprehensive ES declined clearly during the past 40 years, especially in the middle region in the south of the Songhua River and the outskirts of Harbin City. The proportion of extremely important declined seriously, from 44.78% in 1980 to 30.14% in 2020 (Figure 5), while the other three levels all increased, with an increment of 7.61% (generally important), 5.53% (slightly important) and 1.5% (non-important), respectively. The total area suitable for potential ecological sources was 16219.65 km^2 after merging the densely distributed patches with their adjacent areas and eliminating the scattered fragments.

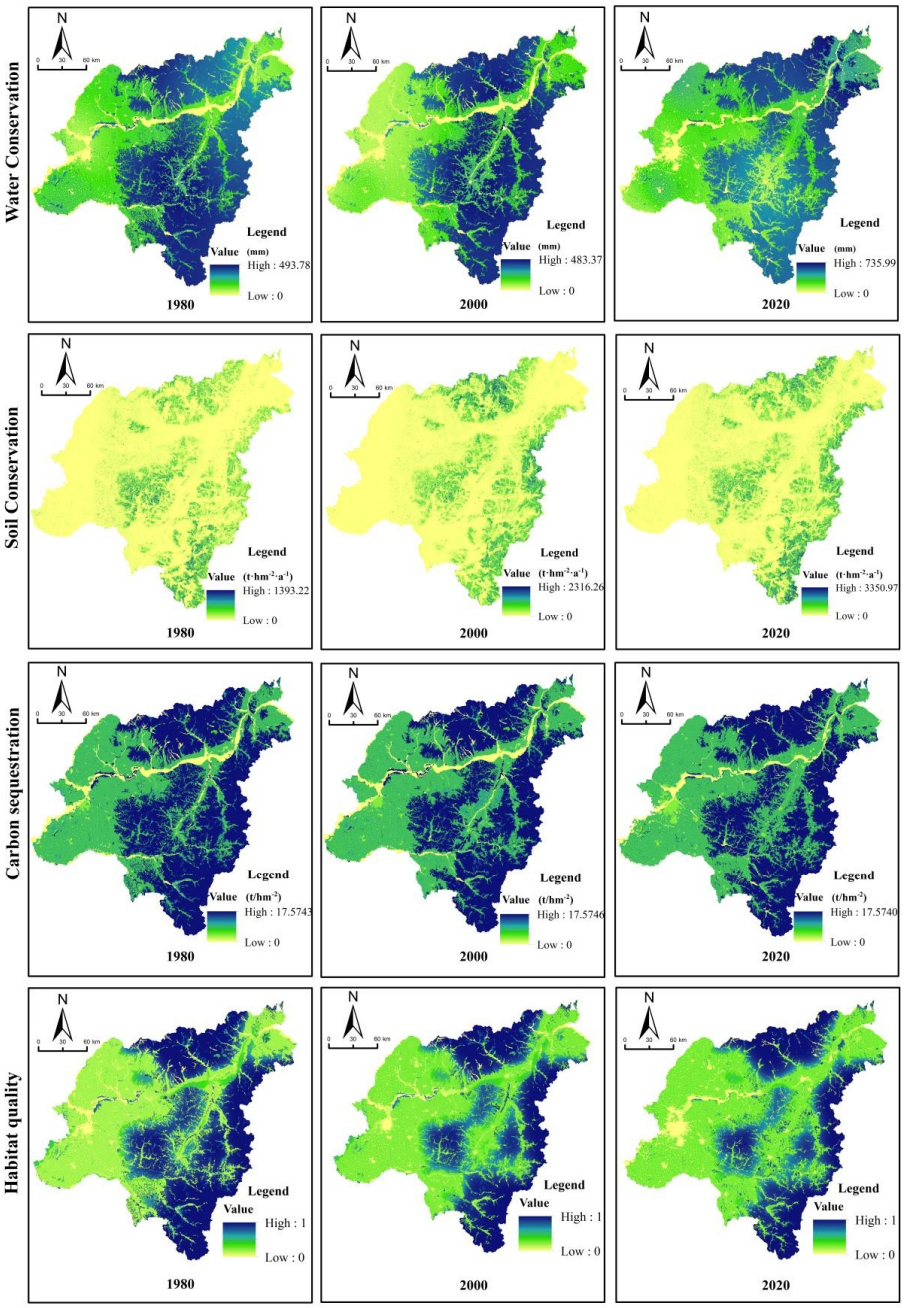

Figure 3. Spatiotemporal variation of individual ecological service from 1980 to 2020.

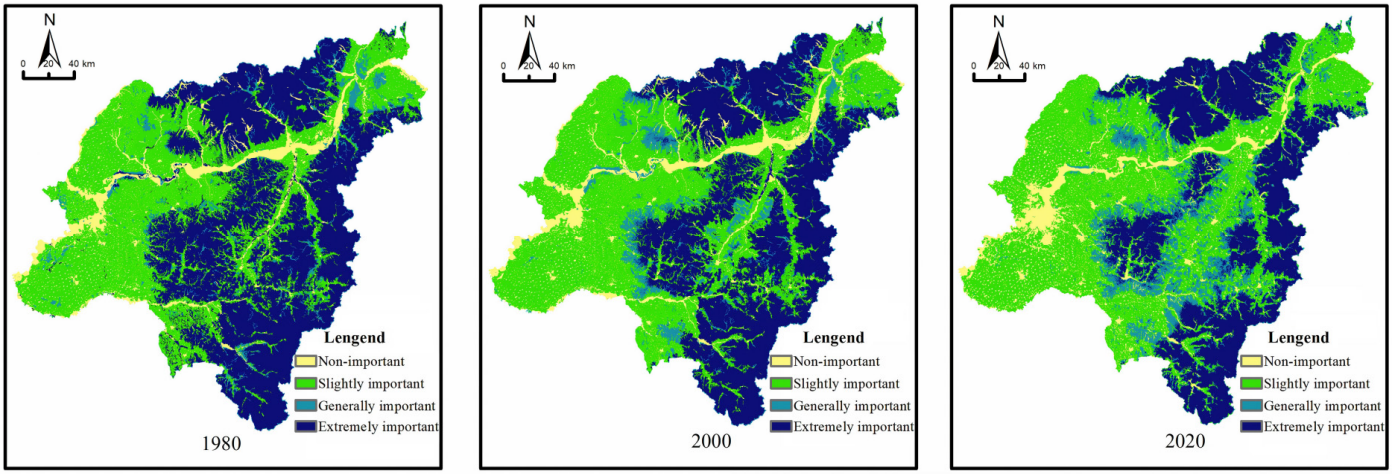

Figure 4. The ecological importance of comprehensive ES from 1980 to 2020.

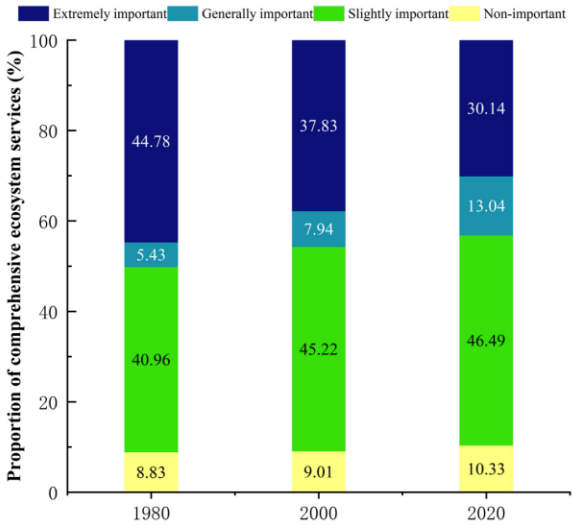

Figure 5. Proportion of ecological importance level from 1980 to 2020.

3.1.2. Structural Ecological Sources Identification

(1) The composition of plaque

The seven landscape types identified through MSPA are mostly concentrated in forest landscapes and a few in water bodies (core and bridge), with very little in grass (Figure 6). The area proportion order from large to small was core (57.13%) > edge (21.99%) > branch (9.24%) > bridge (4.11%) > islet (3.88%) > perforation (2.34%) > loop (1.31%). The core patches were mainly concentrated in mountainous and hilly areas. The edge and perforation patches could effectively maintain the stability of the core zone and were distributed at the outskirts of core patches. The islet areas usually acted as "stepping stones" to provide temporary habitat for migrating species, and they were small isolated and fragmented forest landscapes in the study area. The loop patches, as a kind of shortcut for energy flow within patches, accounted for a quite small proportion. The bridge patches played the role of a connecting corridor in species migration and energy flow, and the scattered bridges had low connectivity. The branch served to connect the foreground and background and its area was 2287.40 km^2.

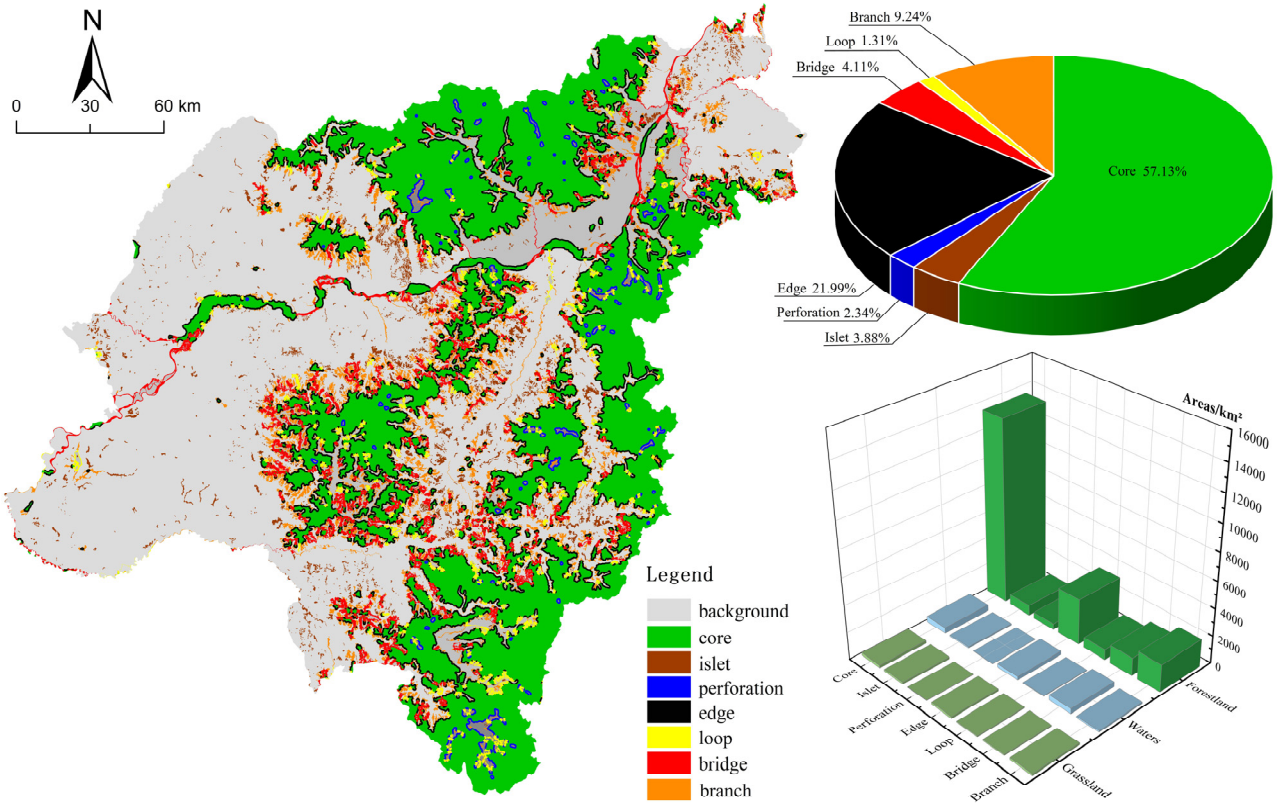

Figure 6. The identification results based on MSPA.

(2) The importance of core patches

The greater the dPC value of the patch, the more stable the ecosystem and the more important the landscape connectivity (Table 3). Patch 40 was the most important core with a maximum dPC of 66.97 and an area of 6216.95 km^2. It was located in the north of the Zhangguangcai Mountain, including the Hufeng Nature Reserve and Jiaxinzi Nature Reserve. Patch 9, located in the southern part of the Lesser Khingan Mountains, was the second most important core with a dPC of 29.89 and area of 4130.15 km^2. The Danqinghe Nature Reserve, Yangdali Waterfowl Nature Reserve and other suitable habitat areas were distributed in this patch. The dPC of patch 26 was 16.44 and its area was 938.97 km^2. It was located in the south of Daqingshan and contained the Songfeng Mountain Nature Reserve and Shanhe Forest Frog Nature Reserve. The patches with dPC values of 1–15 were adjacent to the biggest three patches above, which played an important role in maintaining regional landscape function, while the patches with dPC values of less than 1 contributed little to landscape connectivity and were scattered throughout the study area.

Table 3. The connectivity of core patches.

Node	dPC	Node	dPC	Node	dPC	Node	dPC	Node	dPC
40	66.97	2	1.34	10	0.32	27	0.03	44	0.02
9	29.89	16	1.08	21	0.30	17	0.03	13	0.01
26	16.44	14	1.05	34	0.27	12	0.03	42	0.01
37	14.57	28	0.92	19	0.23	3	0.03	50	0.01
30	11.25	23	0.63	7	0.20	48	0.02	29	0.01
1	10.04	15	0.52	31	0.14	32	0.02	49	0.01
35	7.17	24	0.38	22	0.10	41	0.02	36	0.01
5	6.21	25	0.35	11	0.04	45	0.02	47	0.01
39	1.79	18	0.34	33	0.04	4	0.02	43	0.01
38	1.63	20	0.34	6	0.03	46	0.02	8	0.01

3.1.3. Comprehensive Ecological Source Identification

Overlapping the function-oriented result and the structure-oriented result could obtain the final ecological sources. Here, we selected the intersection of extremely important regions of comprehensive ES and core patches with an area > 30 km^2 and dPC > 1 as important ecological sources, and the rest as general ecological sources (Figure 7). Forest determined the distribution pattern of the final ecological sources. Important ecological sources were mostly distributed in the mountainous and hilly areas in the north and southeast of the study area, with a few in the middle in Shangzhi County, and the general ecological sources were scattered randomly. The connectivity of final ecological sources in the north and southeast was high, but it was low in the middle.

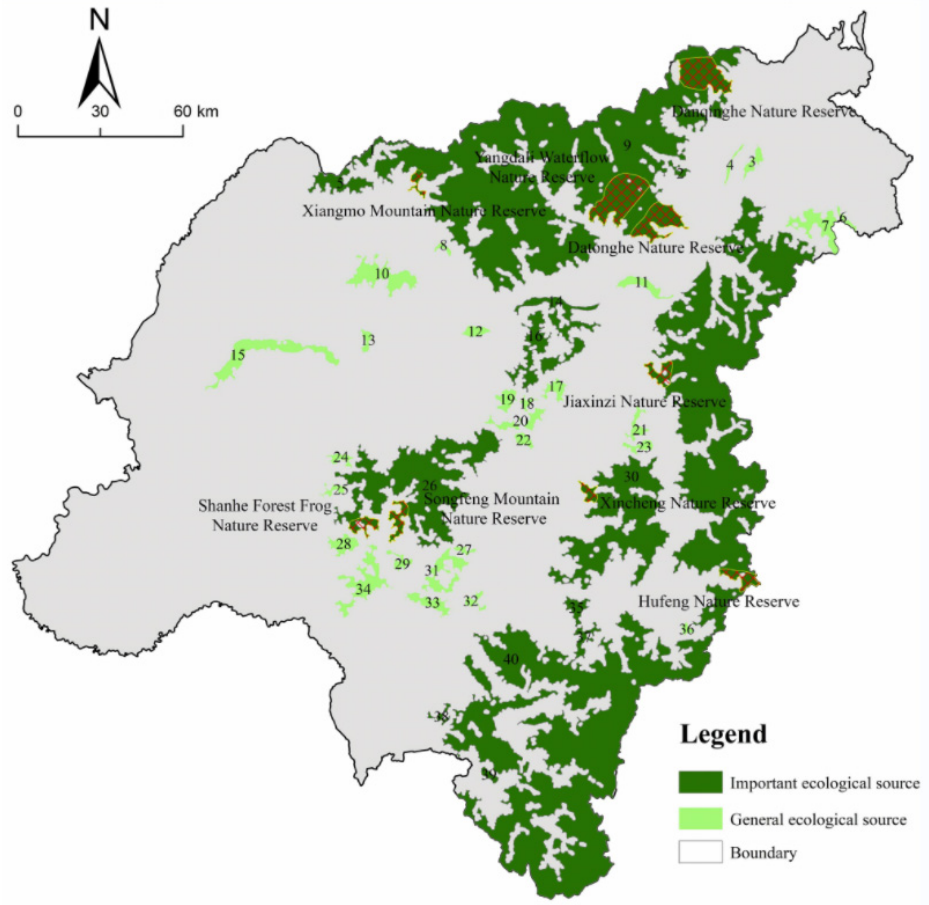

Figure 7. The ecological sources in Harbin.

3.2. Extraction of Ecological Corridors

3.2.1. The Ecological Resistance Surface

We obtained the synthetic resistance surface according to formula (4) based on the value and weight of natural factors in Table 2. The resistance of land use was just opposite to that of DEM (Figure 8). The resistance of slope and vegetation coverage were mainly of low value, while the distance from rivers was mainly of high value. After the modification of night light data, the value of the synthetic resistance surface changed from 8.98 to 74.72. The high resistance value was mainly distributed in plain regions in the west and the two sides of the Songhua River. The frequency of medium resistance was the highest, distributed in the north, middle and southeast of Harbin. The low resistance value was concentrated in the Songhua River (Figure 9).

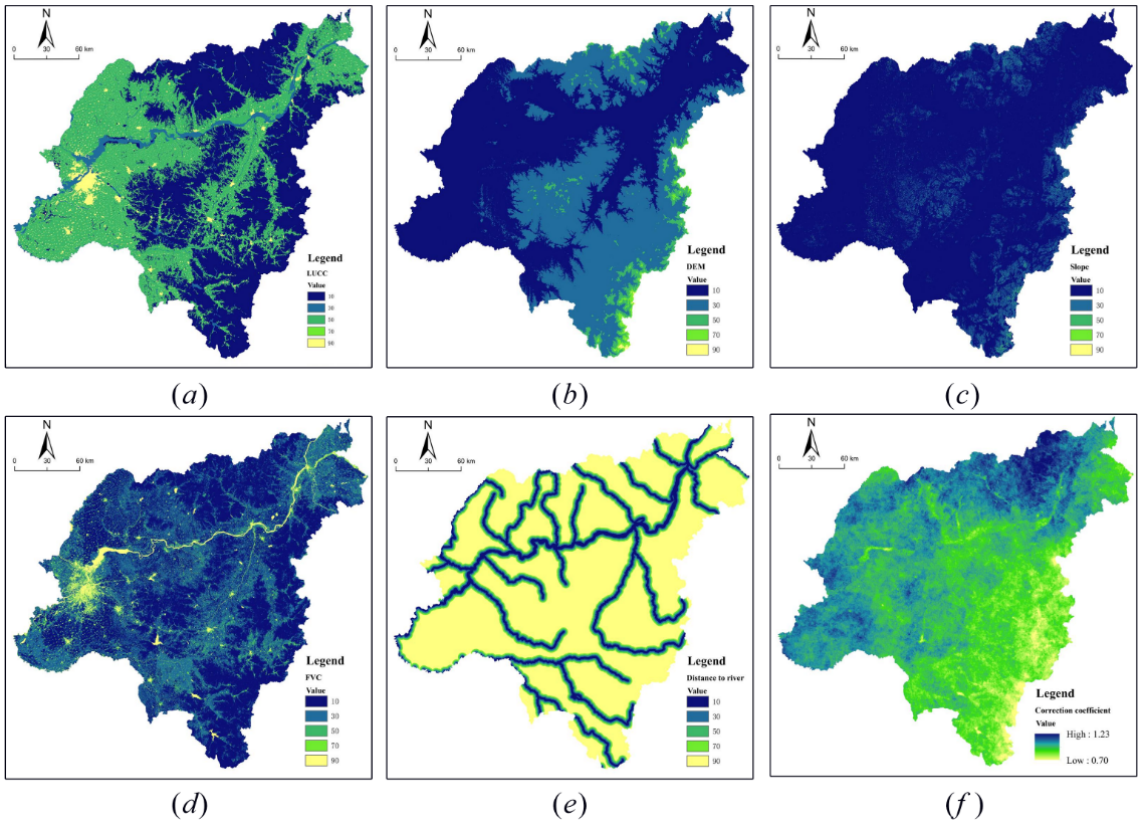

Figure 8. Factor of natural resistance surface(Note: (**a**) Land-use type. (**b**) DEM. (**c**) Slope. (**d**) Forest coverage. (**e**) Distance from river. (**f**) Correction factor of nighttime light).

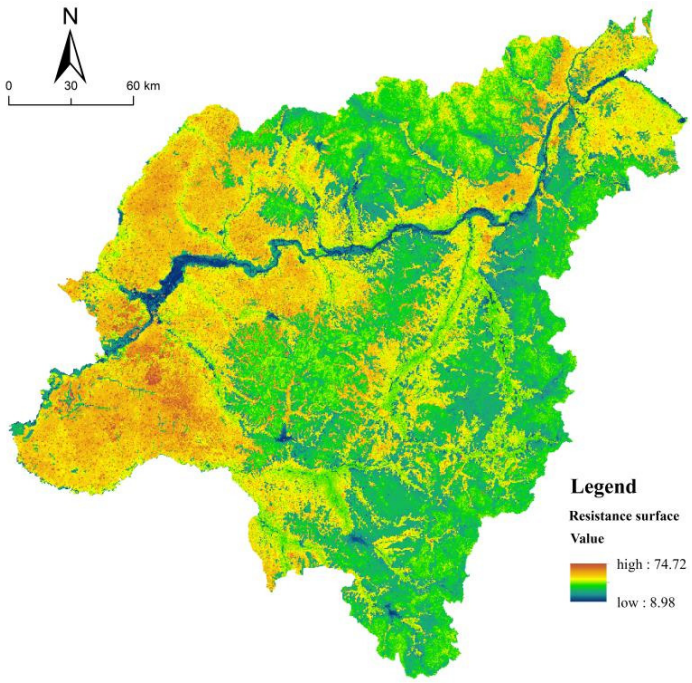

Figure 9. The synthetic resistance surface.

3.2.2. The Synthetic Resistance Surface

More than 700 ecological corridors were extracted according to the MCR model, and the important ecological corridors were selected based on the gravity model (Figure 10).

The ecological corridors in the study area were distributed in a network, and the important ecological corridors were mainly concentrated in the middle, as the material and energy link from east to west and south to north. Ecological corridors in the northeast and southwest were sparse. The intersection points of ecological corridors were taken as ecological nodes, and 86 ecological nodes were extracted based on the environment situation of the study area.

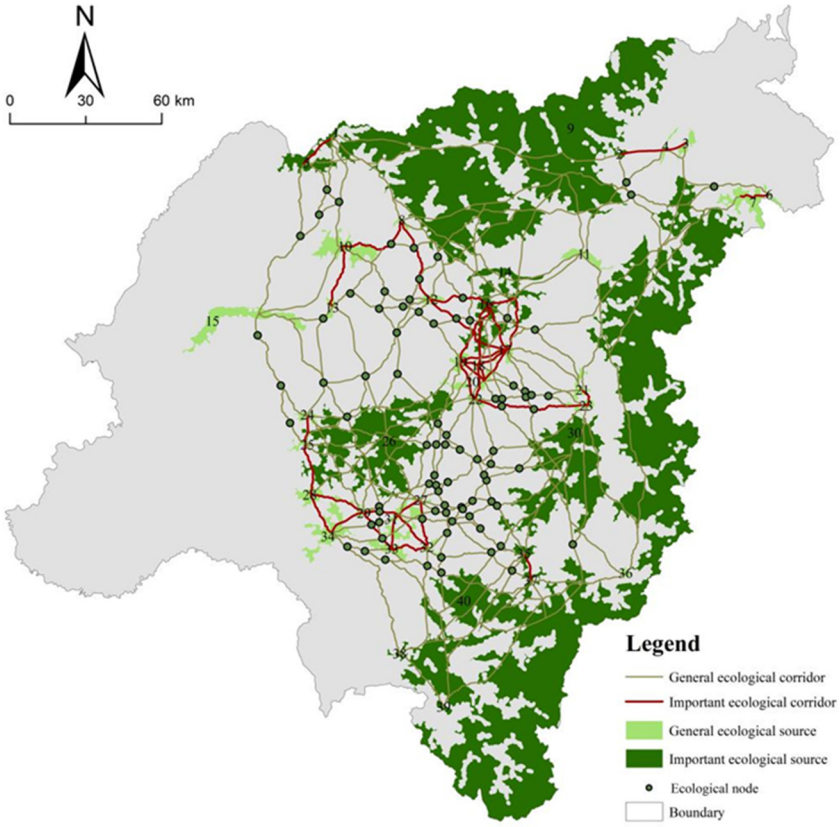

Figure 10. The ecological network of Harbin.

3.3. Construction of ESP

Comprehensively considering the research results above and the actual situation of the study area, this paper designed an ecological security pattern of "two zones, two barriers, one axis and one belt" that may be practicable for Harbin (Figure 11). Firstly, the two zones: the key ecological control zone in the west and the important ecological conservation zone in the center. The former included Harbin City and the intensive agriculture area around it. The ecological sources and corridors there were sparse, with little connectivity with other sources. The habitat quality was low but the ecological resistance was high. The latter was the opposite of the former. The ecological sources and corridors there were densely distributed with low resistance value, and the habitat quality was superior and suitable for species to thrive. Secondly, the two barriers: the Lesser Khingan Mountains ecological barrier in the north and the Zhangguangcai Mountain ecological barrier in the southeast. Forest was the dominant landscape in the two barriers with high vegetation coverage. The elevation there was higher, and the disturbance of human activities was sparse, making them important habitat patches for maintaining and protecting the environmental situation. Thirdly, the Songhua River ecological axis. Plentiful and high-quality wetland and water resources made the Songhua River an important ecological axis to maintain biodiversity and to transfer ecological flows. Finally, the southwest ecological corridor belt. It was necessary to construct a new ecological corridor to improve the sparse ecological network and the whole habitat quality in this region.

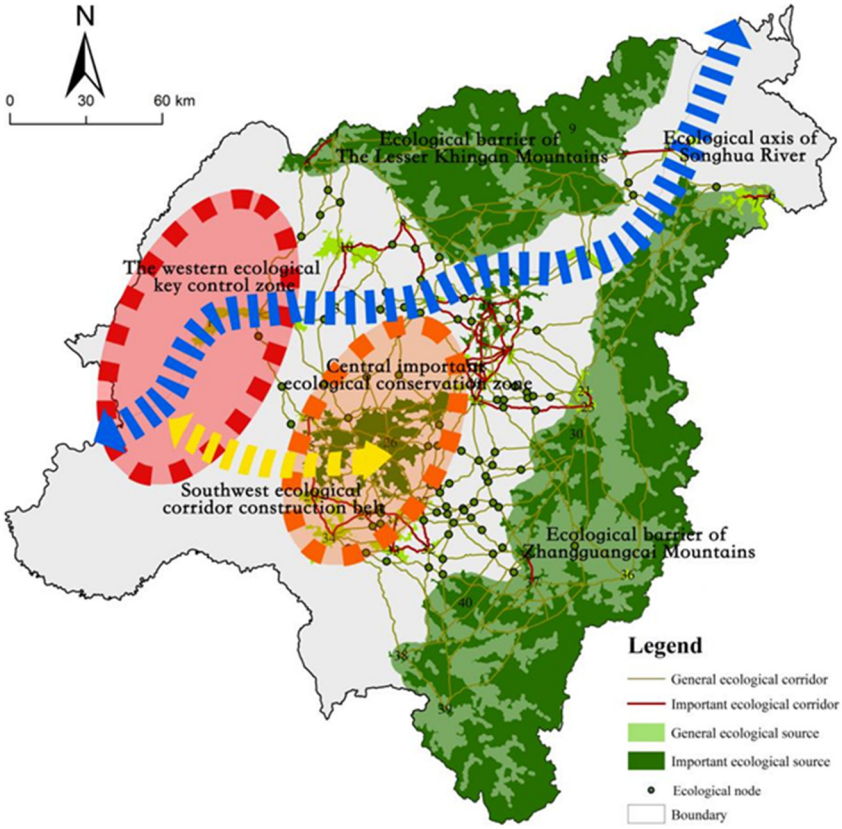

Figure 11. The ESP of Harbin.

4. Discussions

4.1. Response of ESP to Land Use Change

Both the individual ecological service and ecological resistance surface showed relatively strong spatial heterogeneity in the study area, which meant the ESP was closely associated with land use change [54]. The value of Wc and Sc showed an increasing trend, while the Cs and Bc showed a descending trend (Figure 3). Forest had a good performance for water and soil conservation, and the canopies could trap precipitation and prevent soil erosion, thus maintaining ecosystem stability [55]. The fragmentation pattern of forest in the Lesser Khingan Mountains region on the north bank of the Songhua River and in the Zhangguangcai Mountain region in the southeast of the study area was continuously recovered (Figure 12), improving the capacity for water conservation and soil conservation significantly, while the forest in the middle region was shrinking and fragmenting. The amount and configuration of habitats are independent, but tightly linked landscape characteristics and habitat configuration can be vital to species when habitat amount is low [56]. Therefore, the fragmentation of forest in Shangzhi County, the extension of paddy field encroaching on the wetland along the Songhua River in Fangzheng County and Tonghe County, the expansion of urbanization of Harbin City and the intensification of cultivated land in the west region were all responsible for the loss of critical ESs, such as Cs and Bc (Figures 3 and 4). The resistance surface was high in construction land and cultivated land but low in forest and water bodies. The rapid expansion of urbanization and intensification of cultivated land caused landscape fragmentation and habitat isolation [11,57], exacerbating barriers to species migration and flow transfer. On the whole, core patches with good connectivity were mainly concentrated in the eastern, northern, central and southern regions (Figure 10). Habitat patches in these areas were more suitable for the migration of biological species and the flow of material and energy. However, the ecological patches in the western part of the study area were sparse, so it would be necessary to build an ecological corridor in the future to establish a bridge of material and energy exchange

between the east and the west, so as to ensure the overall connectivity and to maintain the good development of ecosystem service functions in the study area. Therefore, assessing the importance of ESs and the spatial connectivity of patches were both necessary for ESP construction, improving its scientificity and reliability for regional sustainability.

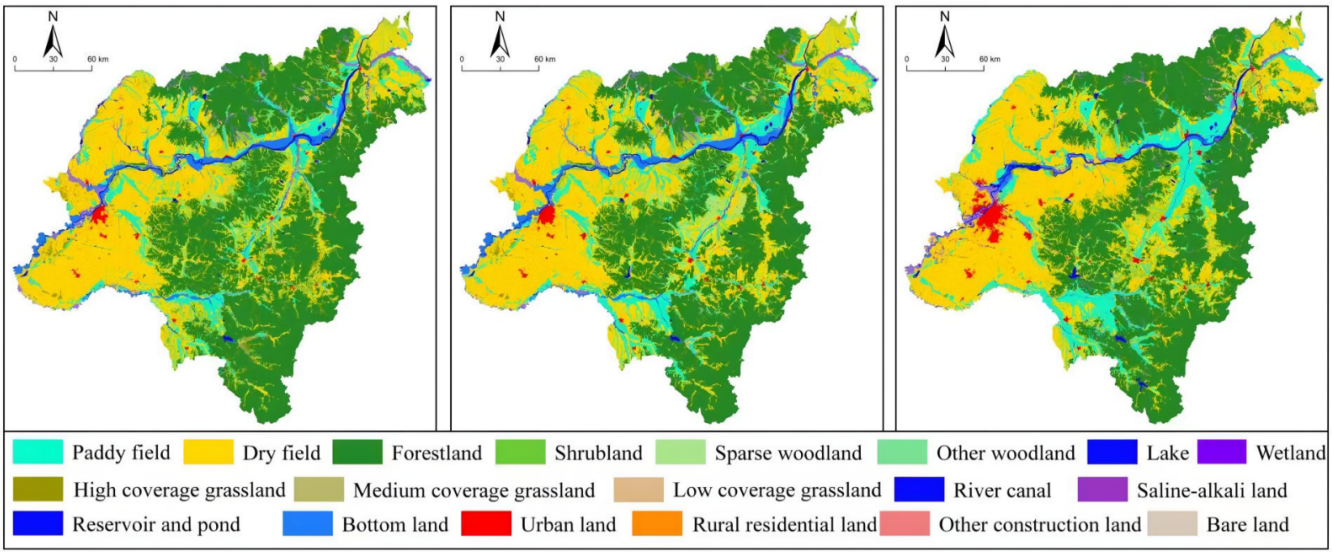

Figure 12. The LULC of Harbin.

4.2. Rationality of Established ESP

Most early studies have constructed ESP based on different criteria, using different methods with different focuses, but they rarely evaluate the effectiveness or rationality of the constructed ESP [8]. In this study, we used the integration-oriented method to avoid the defects of a single method. It comprehensively considered the ES situation and the landscape connectivity, reducing the influence of human subjectivity and landscape fragmentation between ecological sources. Some research showed the same opinions [15,58]. Nearly all the natural reserves were included in the ecological sources, effectively validating the accuracy and feasibility of our method, and this validation was proven in reference [59]. Spatially disconnected landscape components with small area usually provide greatly limited ecosystem services and are not conducive to the flow of material and energy [60]. In this study, we chose the intersection of extremely important regions of comprehensive ES and core patches with an area > 30 km^2 and dPC > 1 as the important ecological sources. The conclusion is the same as the reference [60]. When constructing ecological resistance surface, this paper fully considered the influence of human activities on species migration and ecological process, and used night light data to correct the basic natural resistance surface to make the final ecological resistance surface more scientific, as was proven in reference [61]. The MCR model used in this paper can fully reflect the interaction between landscape pattern and ecological process [21,58]. Identifying important ecological corridors using the gravity model and eliminating miscellaneous corridors can effectively reduce the maintenance cost of ecological corridors. Ecological nodes were the "stepping stone" of species transmission and could promote the circulation of ecological flow and improve the survival rate of migrating organisms [62]. A total of 86 ecological nodes were extracted by comprehensively considering the ecological corridors and the environmental situation of the study area. They were dense in the middle and sparse near the core patches, being the "stepping stone" of species transmission and of great significance for the stability of the ecological environment and the protection of biodiversity. The conclusion was the same as that of reference [62]. In summary, the ESP we constructed could maintain the stability of ecosystems with the smallest ecological lands to better coordinate the conflicts between socioeconomic development and nature conservation in the study area.

4.3. Policy Implication

Based on ecological source identification and ecological corridor construction, this paper proposed a "two zones, two barriers, one axis and one belt" landscape optimization scheme to achieve a "win–win" situation that supported both human activities and ecosystem services. The ESP provided decision-makers of relevant government departments with the idea of protecting key ecological patches in the region first, and then rationally using the remaining parts to configure the production space, living space and ecological space [8]. The western ecological key control zone was the region with the lowest ecological function. With the rapid urbanization and agricultural intensification, the interference of human activities was severe, and the linkage resistance of large ecological patches increased [63]. Therefore, the southwest ecological corridor belt was designed there to enhance the connectivity of the ecological green space in the region to the central important ecological conservation zone and other small ecological patches surrounding it. Protecting and constructing ecological green space inside the city and agricultural protection forest were the basic measures for the sustainability in this region. In addition, strictly controlling urban sprawl, tapping the potential of stock construction land, promoting the green transformation and development of agriculture and reducing agricultural non-point source pollution were important strategies for the sustainable development there. The central important ecological conservation zone was the area suffering degeneration by the shrinkage and fragmentation of forests. The expansion of paddy fields and residential land was the main reason for the decline of habitat quality in this region. Therefore, ecological corridors and ecological nodes were relatively intensive there to assist material and energy flow from east to west and south to north. Protecting the scattered small ecological nodes and the linear ecological corridors was the top priority measure in this region, supplemented by rationally controlling the expansion of paddy field and restoring fragmented forests. The Lesser Khingan Mountains ecological barrier in the north and the Zhangguangcai Mountain ecological barrier in the southeast were the two barriers. They were the core ecological sources with high ESs and had a high concentration of many nature reserves or national parks. Therefore, strengthening ecological protection and eliminating the negative effects of eco-tourism were the main protection measures there. Some ecological functions of the Songhua River ecological axis were weakening, such as the water-yielding capacity and biodiversity conservation (Figure 3). Lots of wetlands had been transformed into paddy fields in the downstream area, and the water quality would deteriorate by non-point source pollution with urbanization and agricultural intensification in the upstream area, both of which would negatively affect the ESs of the Songhua River. Controlling the water quality pollution and protecting the precious wetland resources were the radical measures for the Songhua River ecological axis. In a word, strengthening territorial space planning and rational land use control, optimizing production, living and ecological spaces, and strengthening legal supervision would be very helpful to promote the coordinated development of the social economy and ecological environment.

4.4. Limitations and Outlook

The construction of ESP is a complex systematic project and the variation of relevant elements during the construction would change the final spatial pattern. Although we developed an integration-oriented method for identifying the ecological sources to overcome the drawbacks of a single approach, here we just selected four main ESs to judge the ecological situation of the study area, ignoring the effects of other ESs on ecological importance. It was necessary to set the distance threshold for different species when calculating the landscape connectivity. There were different distance thresholds, overall connectivity, and connectivity probabilities between patches [64]. Limited by data access, this paper did not consider the life characteristics of species in the study area, but set the diffusion distance threshold as 1500 m uniformly, resulting in some uncertainty in the structure-oriented method. Ecological corridor width affected the performance of ecological functions, and conservation objectives, species behaviors and human activities should be integrated to

make the corridor construction more scientific. In addition, regional ESP was a continuous and dynamic process, and the relevant elements would change with the socioeconomic development and ecological situation. Moreover, ecological processes were not restricted by the boundaries of administrative regions. Therefore, scenario analysis of LUCC was quite essential to explore the long-term effectiveness of the ESP and it should be considered in future studies.

5. Conclusions

Based on the identification of ecological sources using the integration-oriented method and the construction of ecological corridors using the MCR model and the gravity model, this paper proposed an ESP of "two zones, two barriers, one axis and one belt", which was more scientific to overcome the drawbacks of a single approach to ESP construction. Nearly all the natural reserves were included in the ecological sources, effectively validating the accuracy and feasibility of our method. A total of 86 ecological nodes were extracted scientifically for maintaining the stability of the ecological environment and the protection of biodiversity to guarantee the reliability and practicality of the ESP. Urbanization and agricultural intensification exacerbated ecological disturbance, making the Songnen Plain in Harbin the most vulnerable region, with a high resistance coefficient and low ES importance. It was essential to protect and build ecological green Spaces and enhance their connectivity to each other and to the small ecological patches around them. In addition, promoting the green transformation and development of agriculture and improving the efficiency of urban construction land was more critical there. Forest resources were quite essential in the study area for maintaining the ecosystem functions and landscape connectivity. They were the ecological sources and served as ecological barriers in the north and in the southeast and as an ecological hub in the middle. Different land use policies and ecological protection policies were proposed for forest protection, comprehensively considering the internal ecological status and external ecological threats. In summary, this study provided a new method for the construction of regional ESP, and could provide references for land use planning and ecological security protection.

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Appendix A. Supplementary Materials of ES Assessment

Table A1. Ecological services used to extract ecological patches.

Ecosytem Service	Formula	Explanation	Parameter Reference
Water Yield (*Wc*)	$Y_{xj} = \left(1 - AET_{xj}/P_x\right) \times P_x$ $AET_{xj}/P_x = \left(1 + \omega_x R_{xj}\right)/\left[1 + \omega_x R_{xj} + \left(1/R_{xj}\right)\right]$	Y_{xj} is the water yield of grid x in land-use type j(mm); AET_{xj} is the actual annual average evapotranspiration of grid x in land-use type j(mm); P_x is the annual precipitation of grid x(mm); R_{xj} is the dimensionless Budyko dryness index of grid x in land-use type j, which is the ratio of potential evapotranspiration to precipitation; ω_x is the ratio of annual water demand to annual precipitation for different land-use types.	[65,66]
Biodiversity Conservation (*Bc*)	$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\omega_r / \sum_{r=1}^{R} \omega_r\right) r_y i_{rxy} \beta_x S_{jr}$ $i_{rxy} = 1 - \left(d_{xy}/d_{r\ max}\right) \quad if\ liner$ $i_{rxy} = exp\left(-(2.99/d_{r\ max}) d_{xy}\right)\ if\ exponential$	Q_{xj} is the habitat quality of grid x in land-use type j; D_{xj} is the stress level of grid x in land-use type j; H_j is the habitat suitability of land-use type j; k is a half-saturation constant, which usually takes half of the maximum D_{xj}; z is a normalized constant and usually takes the value 2. 5; R is the number of threat factors; y is the number of grids for threat factor r; Y_r is the number of grids occupied by stress factors; ω_r is the weight of the threat factor, ranging from 0 to 1; r_y is the threat factor value of grid y; i_{rxy} is the habitat threat level of grid x from threat factor r on grid y; β_x is the accessibility level of grid x, with values ranging from 0 to 1; S_{jr} is the sensitivity of habitat type j to threat factor r; d_{xy} is the linear distance between grid x and grid y and d_{rmax} is the maximum influence distance of threat factor r.	[67,68]
Soil Conservation (*Sc*)	$A_c = A_r - A$ $A_r = R \times K \times L \times S$ $A = R \times K \times L \times S \times C \times P$	A_c is the amount of soil conservation(t/(hm^2·a); A_r, A is the amount of potential soil erosion, actual soil erosion (t/(hm^2·a); R is the rainfall erosivity factor (MJ·mm/(hm^2·h·a)); K is the soil erodibility factor (t·hm^2·h/hm^2·MJ·mm); L is the slope length factor; S is the slope degree factor; C is the vegetation cover and management factor; P is the soil and water conservation measure factor. With reference to previous studies, the P-values of cultivated land, forest land, grassland, water area, construction land and unused land are 0.35, 0.8, 1, 0, 0, 1, respectively.	[69,70]
Carbon Sequestration (C*c*)	$C_i = C_{i(above)} + C_{i(below)} + C_{i(dead)} + C_{i(soil)}$ $C = \sum_{i}^{n} C_i \times S_i$	C_i is the total carbon density of land-use type i (t/hm^2); $C_{i(above)}$ is the aboveground biomass carbon density (t/hm^2); $C_{i(below)}$ is the underground biomass carbon density (t/hm^2); $C_{i(dead)}$ is the carbon density in dead organic matter (t/hm^2); $C_{i(soil)}$ is the soil carbon density (t/hm^2); C is the total carbon storage(t); S_i is the area of land-use type i (hm^2); n is the number of land-use types.	[71,72]

Appendix B. Supplementary Materials of ES Assessment

Table A2. Landscape element types of MSPA and their ecological meanings.

Element Types	Ecological Meanings
Core	Large habitat patches in foreground data pixels and can provide larger habitats for species as ecological sources, which are of great significance for biodiversity conservation.
Islet	Isolated and broken small patches that are not connected to each other. The connectivity between the patches is relatively low, and the possibility of internal material and energy exchange is less.
Perforation	Transition zone between core area and non-green landscape patch; the inner patch edge.
Edge	The transition zone between the core area and the main non-green landscape patch area.
Bridge	The narrow area connecting the core; important for biological migration and landscape connection.
Loop	Corridors connecting the same core area are shortcuts for species migration in the same core area.
Branch	Only one side is connected to the edge, bridge, loop or the perforation.

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