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Spatial-temporal dynamics and evolution of ecological security in a rapid urbanization city, Southwest China

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The main goal of constructing ecological security patterns (ESPs) is to identify ecological sources, corridors and nodes that play significant roles in sustainable development on a regional scale. Although there are many studies on the construction of ESPs, there is no consensus in terms of research methodology and systematic frameworks for integrated landscape management. Based on land use data from 2000, 2010, and 2020 of Chongqing Municipality in southwest China, we evaluated the spatial-temporal variation of ESPs by integrating InVEST and Circuit Theory. Results showed that: (a) Habitat quality varied through space, with habitat quality being lower in the western and central regions and higher in the southeastern and northeastern regions. (b) The area of lower quality habitat across different time periods was more than 46%, and habitat quality over the last two decades has generally been low with no significant improvement. (c) From 2000 to 2020, ecological sources were primarily distributed in the mountainous areas with high habitat quality and fractional vegetation coverage in the northeast and southeast. The regions identified ecological sources in 2000, 2010, and 2020 accounted for 31.37, 33.53, and 32.7% of Chongqing Municipality, respectively. (d) The ESPs were composed of ecological sources dominated by forests, connected by continuous ecological corridors. The current ESPs of Chongqing Municipality included 20 ecological nodes, 17 continuous ecological corridors and 23 ecological sources. We strongly suggest the local governments strengthen the protection of the identified ecological nodes, ecological corridors, ecological sources, and protection gaps, and focus on strengthening the construction and management of the ecological corridor network system to promote species diffusion and gene exchange. Our findings are helpful for policy makers to introduce appropriate measures to objectively guide urban expansion *via* rational and sustainable development of land resources and improve the level of ecological security for Chongqing Municipality.

KEYWORDS

ecological security pattern, ecological corridor, landscape connectivity, circuit theory, Chongqing Municipality

Introduction

China has undergone the most significant and fastest urbanization process in world history and has made remarkable achievements in development since the 1970s. The country's urban resident population increased from 170 million to 730 million from 1978 to 2013, and the urbanization rate rose from 17.9 percent to 53.7 percent (Zhang, 2016). Urbanization promotes rapid economic and social development and improves human quality of life. However, reckless development and the excessive use of land resources can degrade regional ecosystems and their services (Feist et al., 2017; Peng et al., 2018a,b). Adverse outcomes for water conservation, soil conservation, biodiversity, and climate regulation can threaten regional ecological security (McCarty, 2001; Díaz et al., 2006; Menon et al., 2007; Dong et al., 2018). Therefore, understanding the interactions of landscape structure, ecological process, landscape function and ecological security patterns (ESPs) from the perspective of landscape ecology has become an urgent issue (Liu et al., 2022). The construction of ESPs has become one of the most important national strategies for the coordination of ecological protection and economic development in modern-day China and is vital for strengthening the management of priority ecological areas and key ecological function zones (Xiao et al., 2020; Li et al., 2021; Liu et al., 2022).

Species survival and reproduction is dependent on habitat quality (Mammola et al., 2019). Thus, habitat quality can be seen as an essential component of regional ecological security (Hao et al., 2019; Zhang et al., 2021). While rapid urbanization can bring economic benefits, it often involves encroachment on large patches of habitat, leading to landscape fragmentation (Zhou et al., 2021). This fragmentation causes a reduction in the area of internal habitat patches, a truncation of ecological corridors, and an increase in the isolation of habitat patches (Luo et al., 2021). Decreased habitat connectivity interferes with standard ecological processes, resulting in a shift in ecosystem services (Mitchell et al., 2013). Human activities and land use changes alter the pattern and structure of ecosystems and the quality of habitats and their ecosystem processes, thus weakening ecosystem services (Peng et al., 2018b). Therefore, formulating an ESP is a vital component for safeguarding a landscape's ecological factors amid rapid economic development. In 2001, the United Nations launched the Millennium Ecosystem Assessment, a program that studied the impact of changes in ecosystem services on human livelihoods. The study found that 15 of the 24 global ecosystem services were degrading, and regional and global ecological securities were threatened (Fu and Zhang, 2014). In 2005, the International Geosphere-Biosphere Program (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) released a joint core program—the Global Land Program (GLP), which prioritized research on the response of landscape structure and services to land use change. At present, urban landscape ecology focuses on the evolutionary process of landscape patterns, their driving mechanisms, and the construction of ESPs (Chen and Wang, 2020; Xiao et al., 2020). Although some progress has been made in the study of landscape ecology, it is difficult to apply its related research to landscape management. In particular, neglect of the relationship between the spatial pattern of ecological elements and the interaction between multiple landscape services has limited landscape planning and design (Zhang, 2016).

ESP construction aims to balance the relationship between nature conservation and economic development (Peng et al., 2018a,b). By studying the concordant ecosystem of nature-society, relevant thresholds and hierarchies of human impacts on ecosystems can be determined, and regional ESP construction and ecosystem restoration approaches can be obtained. Currently, the methods of ESP construction primarily include source-resistance surface construction, multi-factor superposition planning and "pressure-state-response" analysis (Zhao et al., 2006; Peng et al., 2018a; Guo et al., 2019). There are three main processes for ESP construction: identifying ecological sources, computing resistance surfaces and identifying ecological corridors (Huang et al., 2020; Wang et al., 2020). Methods used to identify ecological corridors include the gravity model, minimum cumulative resistance (MCR) model, and the Circuit Theory (CT) model (Zhang et al., 2017; Guo et al., 2019; Wang et al., 2020). Compared with other mathematical models, the Circuit Theory model boasts better performance in simulating the diffusion of species restricted by landscape resistance (Dai et al., 2021). Therefore, this model has been widely applied in the construction of ecological network patterns and ESPs (Wang et al., 2020). Previous studies constructing ESPs have been done for the establishment of protected areas, functional zoning of nature reserves, understanding of ecosystem function, process and biodiversity, and evaluation of ecosystem services (Zhao and Xu, 2015; Wang and Pan, 2019; Zheng et al., 2021).

Several studies about ESP construction have been carried out on regional habitat quality, mainly done at more minor scales, such as an ecological environment quality assessment of a nature reserve (Liu et al., 2009; Zheng et al., 2021). However, the study of habitat quality has expanded to urban levels and across more significant regions, such as assessing the spatial-temporal evolution of habitat quality for national parks and determining urban ecological security and carrying capacity (Peng et al., 2018a; Wang et al., 2021). Two research methods can be used to assess these metrics. In the first method, habitat quality parameters in a specific area are collected *via* a field survey and an evaluation system to determine habitat quality (Balasooriya et al., 2009). In the second, various ecological models, such as MaxEnt, Ecological Niche Factor Analysis (ENFA), and InVEST models, are used to examine habitat quality (Hirzel et al., 2001; Moreira et al., 2018; Dai et al., 2019; Rather et al., 2020). The InVEST model has many advantages, such as multiple modules, fewer operating parameters, ease of access to fundamental data, quantitative evaluation, and spatial visualization. Thus, it has been widely used in the assessment of ecosystem services (Zheng et al., 2021).

Chongqing Municipality, as an important ecological barrier of the upper reaches of the Yangtze River, plays an irreplaceable role in maintaining ecological security of the middle and lower reaches of the Yangtze River. To identify the ESPs for Chongqing Municipality is the first step to build the solid ecological barrier of the upper reaches of the Yangtze River. As a sensitive and vulnerable area of the ecosystem in the Yangtze River Basin, Chongqing Municipality has a prominent contradiction between ecological protection and economic development. As one of the South-Central China biodiversity hotspots (Myers et al., 2000), the city has worked toward the preservation of biodiversity conservation, and the number of wild animals and plants has recovered (Chongqing Forestry Bureau, 2021).[1] However, as the youngest municipality in China, the rapid economic development has also brought tremendous pressure on the local ecological environment. Therefore, achieving the balance between ecological protection and economic development has become a problem that must be faced and solved. This study adopted the InVEST model to dynamically evaluate the habitat quality of Chongqing Municipality in the past two decades, identified the ecological corridors in different periods based on the Circuit Theory model, and finally constructed the ESP of Chongqing Municipality. The results are expected to provide theoretical and methodological support for formulating ecological protection strategies such as protected area planning, ecological corridor network construction and ecological restoration.

Materials and methods

Study area

Chongqing Municipality is located in southwestern China along the upper reaches of the Yangtze River (**Figure 1**). It is approximately 82,400 km^2 and governs 26 districts, 8 counties, and 4 autonomous counties (Northeastern area including Wanzhou, Wushan, Wuxi, Chengkou, Kaizhou, Fengjie, Yunyang, Liangping, and Zhongxian; Southeast area including Qianjiang, Xiushan, Youyang, Pengshui, and Wulong; Central area including Fuling, Changshou, Dianjiang, Fengdu, and Shizhu; Southeastern area including Nanchuan and Qijiang; Western area including Jiangjin, Yongchuan, Hechuan, Tongliang, Dazu, Rongchang, Bishan, and Tongnan; Central urban area including Yuzhong, Dadukou, Jiangbei, Shapingba, Jiulongpo, Nan'an, Beibei, Yubei, and Ba'nan). As of November 2020, the permanent resident population of Chongqing Municipality was approximately 32 million. Chongqing Municipality is located in the subtropical humid monsoon climate zone, with a relatively rich annual precipitation average, ranging from 1,000 to 1,350 mm in most areas. Precipitation is concentrated from May through September, accounting for roughly 70% of annual precipitation. The terrain of Chongqing Municipality descends gradually from north and south toward the Yangtze River valley. Hills and low mountains dominate the western and central regions, and the southeast is close to two large mountain ranges, Daba Mountain and Wuling Mountain. Its proximity to mountains lends itself to the nickname "Mountain City." The vertical difference in climate is severe, and zonal vegetation types include evergreen broad-leaved forest and coniferous forest, which provide habitat for wildlife. There are more than 6,000 species of plants in the area, including rare tree species such as metasequoia (*Metasequoia glyptostroboides* Hu & W. C. Cheng) and Cathaya (*Cathaya argyrophylla* Chun et Kuang), which are known as "living fossils." The forest coverage rate of Chongqing Municipality was approximately 50% in 2020. There are more than 800 species of wild terrestrial vertebrates and more than 4,300 species of invertebrates, among which 11 species are under Chinese national first-class key protection, such as clouded leopard (*Neofelis nebulosa*), François's Langur (*Trachypithecus francoisi*) and forest musk deer (*Moschus berezovskii*); and 47 species are under Chinese national second-class key protection,

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[1] http://lyj.cq.gov.cn/zwxx_237/mtbd/202110/t20211014_9808355.html

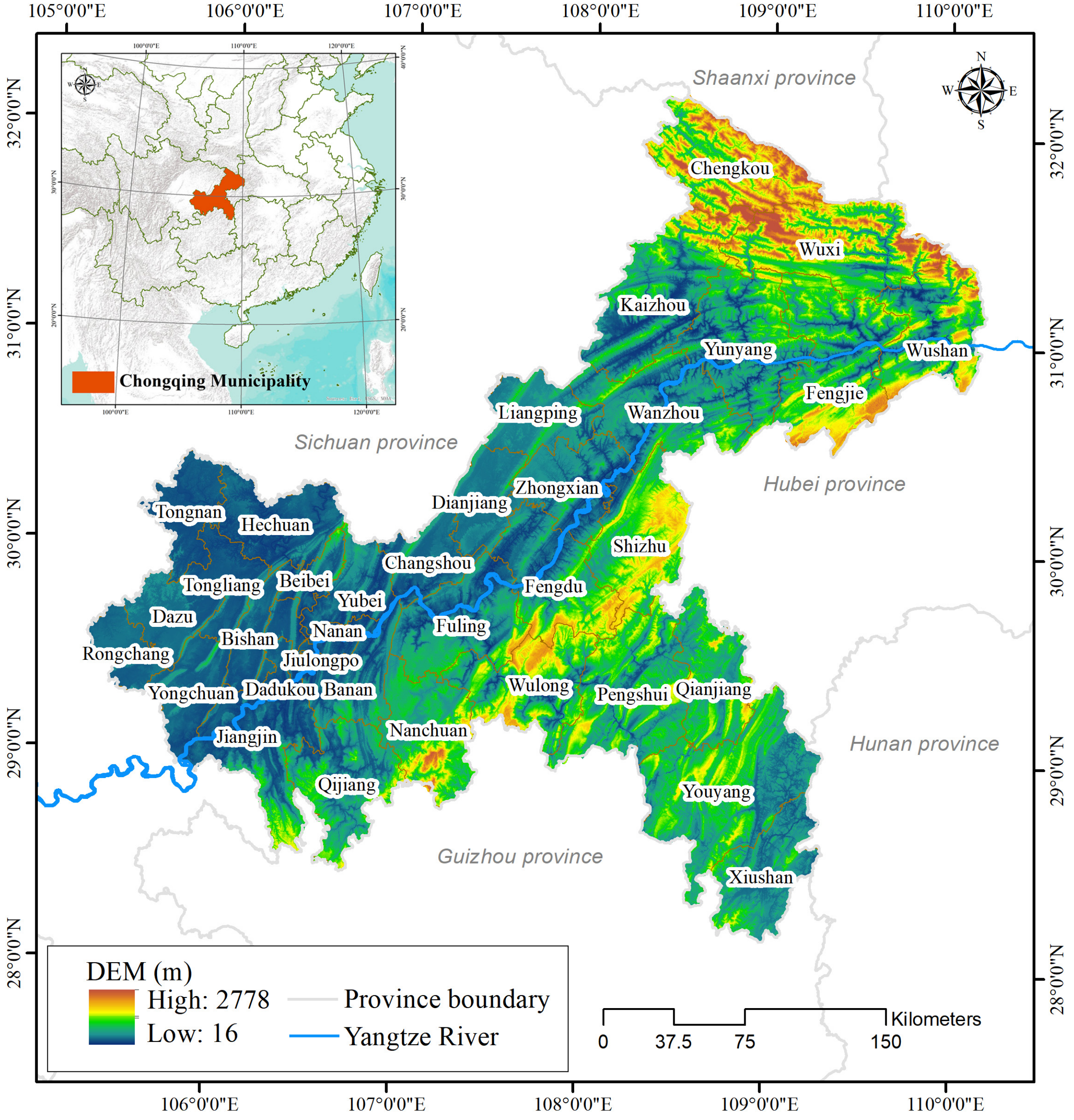

FIGURE 1
The geographical location of Chongqing Municipality, China.

such as golden pheasant (*Chrysolophus pictus*), long-eared owl (*Asio otus*), Himalayan goral (*Naemorhedus goral*), and large Indian civet (*Viverra zibetha*) (Chongqing Forestry Bureau, 2021; "see text footnote 1").

Data sources

We used GlobeLand30-2000, GlobeLand30-2010, and GlobeLand30-2020, developed by the National Center for Basic Geographic Information of China (30 m spatial resolution; **Figure 2**).[2] GlobeLand30 was developed using Pixel-Object-Knowledge method based on the U.S Landsat images (TM5, ETM+) and China Environmental Disaster Reduction Satellite images (HJ-1) with a resolution of 30 m (Chen et al., 2015). Globeland30 is one of the world's highest resolution global land cover data. It can more accurately measure the spatial

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[2] http://www.globallandcover.com/

distribution of various types of global land cover and the changes in 10 years. Globeland30 provides basic data support for the simulation of earth ecosystem evolution and global change research. It also reveals the changes in the global ecological environment and resources caused by anthropogenic activities, which provides an essential basis for in-depth analysis of human-earth conflicts and scientific formulation of global sustainable development (Chen et al., 2017). The data includes ten first-class land types: cultivated land, forest, grass, shrub, wetland, water, tundra, artificial surface, bare land, and ice.

Research framework of ecological security patterns

ESPs are usually composed of the ecological nodes, ecological corridors and ecological sources that play essential roles in the ecosystem (Peng et al., 2018a; Dai, 2022). Based on land use data and human interference factors, we have evaluated the habitat quality using the InVEST model and identified vital ecological sources in different periods. The negative exponential transformation function was used to convert habitat suitability into a landscape resistance layer. Circuit Theory modeling was utilized to identify ecological corridors, and the ecological nodes were the intersection points of more than two ecological corridors. The final ESPs were then constructed based on the identified ecological nodes, ecological corridors and ecological sources.

Habitat quality assessment

We used InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model to evaluate the habitat quality of Chongqing Municipality in 2000, 2010, and 2020. InVEST was developed by the Natural Capital Project Team of Stanford University to evaluate the value and spatial distribution of ecosystem service functions to assist ecological planning and management decisions (Nelson et al., 2009; Sharp et al., 2018). Biodiversity is closely related to the production of ecosystem services. Biodiversity has spatial characteristics in nature. Thus, it can be calculated by analyzing land use and land cover (LULC) and its threat to biodiversity. In the InVEST model, habitat quality and habitat scarcity, as the reflection of biodiversity, can be expressed by evaluating the scope of various habitat types or vegetation types in a specific area and the degradation degree of these vegetation types (Zheng et al., 2021). The dynamic assessment of habitat quality for Chongqing Municipality was realized by the Habitat Quality Module (HQM) of the InVEST model (Qiu and Turner, 2013; Sharp et al., 2018; Nematollahi et al., 2020). The core of HQM is that different land use types may become threat sources of biodiversity and habitat quality, and then associate habitat quality with threat sources and calculate the adverse impact of threat sources on habitat quality. In this study, the habitat quality was calculated according to the degree of habitat degradation. The spatial attenuation of the threat to the ecological source can be expressed by linear or exponential

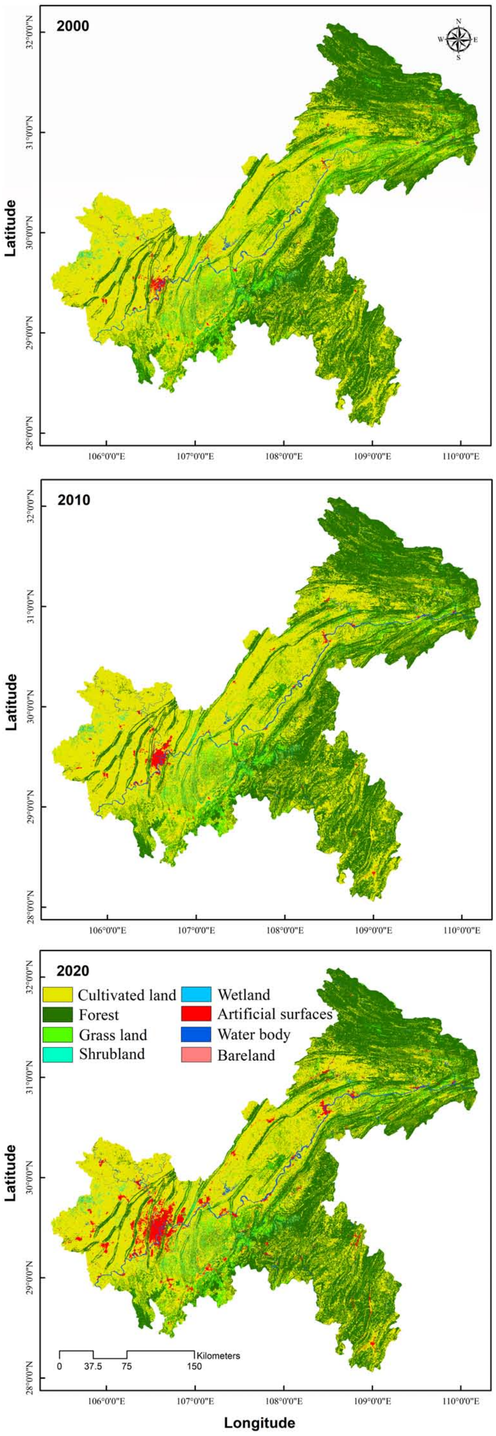

FIGURE 2
Land use and land cover of Chongqing Municipality in 2000, 2010, and 2020.

distance attenuation function, and its calculation formula is:

$$\text{If linear } \mathrm{i}_{\mathrm{rxy}} = 1 \left(\frac{d_{xy}}{d_{rmax}} \right) \tag{1}$$

$$\text{If exponential } \mathrm{i}_{\mathrm{rxy}} = exp \left[\left(\frac{2.99}{d_{rmax}} \right) d_{xy} \right] \tag{2}$$

where d_{xy} is the linear distance between habitat grid x and y, and d_{rmax} is the maximum effective distance for the threat of artificial surfaces, bare land and cultivated land.

In this study, the quality of habitat in different periods was calculated according to the following formula:

$$Q_{xj} = H_j \left[1 \left(\frac{D_{xj}^{z}}{D_{xj}^{z} K^{z}} \right) \right] \tag{3}$$

H_j is the suitability of habitat quality of grid j; K is the semi saturated property constant, which is generally half of the maximum value of D_{xj}; z is the default parameter value, which is usually 2.5.

The operation of InVEST model was based on the land use type data (grid format), threat sources (grid format), a CSV file of threat sources and a CSV file of sensitivity of land use types to different threat sources. In this study, the parameters in the two CSV files were assigned according to the user guide of InVEST model and previous studies (**Tables 1**, **2**; Nelson et al., 2009; Qiu and Turner, 2013; Sharp et al., 2018; Zheng et al., 2021). Furthermore, in order to more intuitively display the spatial distribution characteristics of habitats with different quality, the outputs of the InVEST model were divided into five grades in ArcGIS 10.1, respectively lowest (0–0.2), lower (0.2–0.4), secondary (0.4–0.6), higher (0.6–0.8), and highest (0.8–1) (Zheng et al., 2021).

Ecological sources

The ecological source is an essential habitat for species survival and dispersal. It can provide necessary ecological services and show continuity and integrity in landscape patterns (Peng et al., 2018a). Therefore, identifying ecological sources is a crucial step in the construction of ESPs. In most cases, taking the object to be protected as the source can be an ecosystem with different types of biological species, ethnic communities and habitats, which is generally symbolic, and sufficient to characterize the different habitats in the study area (Xiao et al., 2020). Ecological sources usually contain different types of habitats and have the characteristics of ecosystem diversity. Therefore, the strict protection of ecological sources is of great significance to protect most species and ecosystems in the whole region (Peng et al., 2018a). Based on the outputs of the InVEST model and the minimum home range of the umbrella species in the study area, the grid cells with a habitat quality index greater than 0.8, strong habitat patch continuity and area greater than 10 km^2 were selected as the key ecological sources (Zheng et al., 2021; Dai, 2022).

Resistance surface

In the natural ecosystem, the flow and transmission of material and energy and the species migration are affected by land cover types, ecological, environmental factors and anthropogenic disturbance factors, which have a specific resistance to the process of ecological connectivity (Dai et al., 2021). The use of species in the environment can be regarded as the process of spatial coverage and competitive management. They must overcome their corresponding resistance to achieve their coverage and management. The resistance surface also shows the trend of species and ecological flow diffusion. Because species encounter different resistance values in diverse

TABLE 1 Influence range and weight of threat factors.

Threat factor	Maximum influence distance (km)	Weight	Spatial attenuation type
Cultivated land	3	0.7	Linear
Bare land	2	0.6	Linear
Artificial surfaces	5	0.9	Exponential

TABLE 2 Sensitivity of different habitats to threat factors.

Land use type	Habitat suitability	Cultivated land	Bare land	Artificial surfaces
Cultivated land	0.3	0	0.5	0.25
Forest	0.9	0.5	0.45	0.7
Grass land	0.6	0.5	0.55	0.35
Shrub	0.8	0.5	0.3	0.8
Wetland	0.7	0.8	0.5	0.5
Water body	0.8	0.65	0.4	0.55
Artificial surfaces	0	0	0	0
Bare land	0	0	0	0

landscapes, identification of resistance has become the primary content of overcoming resistance in species diffusion path. Quantifying the effects of a heterogeneous landscape on species diffusion and gene flow is one of the main components of landscape ecology (An et al., 2020). Landscape resistance models are usually used to quantify landscape heterogeneity, including the Circuit Theory model and Least-cost Distance Model (Adriaensen et al., 2003; McRae et al., 2008). The model is based on the migration resistance of different variables according to matrix permeability, and then the diffusion resistance between populations is calculated (Li et al., 2019). In order to link habitat suitability index (HSI) with low movement resistance, this study took the reciprocal of HSI index and converted HSI into resistance value by using a negative exponential transformation function (Dai et al., 2019; Li et al., 2019). The calculation formula is as follows:

$$\text{If HSI} > \text{Threshold} \rightarrow \text{Suitable habitat} \rightarrow \text{Resistance} = 1 \tag{4}$$

$$\begin{aligned} &\text{If HSI} < \text{Threshold} \rightarrow \text{Non} - \text{suitable habitat}/ \\ &\text{Matrix} \rightarrow \text{Resistance} = e^{\frac{\ln(0.001)}{\text{threshold}} \times \text{HSI}} \times 1000 \end{aligned} \tag{5}$$

Where HSI represents the HSI, which is the results calculated by the InVEST model. 0.8 is the threshold value to distinguish suitable habitat from non-suitable habitat. When HSI ≥ 0.8, it is regarded as suitable habitat, and when HSI < 0.8, it is regarded as non-suitable habitat.

Ecological corridors

The Circuit Theory model has proved to be scientific and stable in the practice of ecological protection (Peng et al., 2018a,b). Therefore, this study selects this model to identify the ecological corridor. Based on the HSI map output by InVEST model, the Circuit Theory model was used to simulate ecological corridors in Chongqing Municipality for different periods. Circuit theory is based on the random walk theory, which combines circuit and motion ecology. First, the landscape is taken as a resistance layer, and then the current mode is used to simulate the motion mode of random walker between the source cells and the target cells of the landscape (McRae et al., 2008). Circuit Theory models are usually used to simulate wildlife migration, identify connection areas with crucial ecological significance, and focus on their protection and management, such as ecological corridor identification, species gene flow simulation (LaPoint et al., 2013; Li et al., 2019; Dai et al., 2021). According to the data structure of graph theory, the Circuit Theory model assigns a low resistance value to the habitat patches that can promote the ecological process and a high resistance value to the habitat patches that hinder the ecological process. Circuitscape is an open-source program based on Circuit Theory to build heterogeneous landscape connectivity. This study used Circuitscape 4.0[3] to identify the ecological corridors, and the operating parameters of Circuitscape were set to: (1) model mode: Paired patterns; (2) calculation mode: use average conductance instead of resistance for connections between cells, run in low-memory mode; (3) image output options: cumulative and max current maps, set focal node currents to zero; and (4) other model parameters: default. The effective resistance was iteratively calculated for all paired nodes.

Results

Spatial-temporal variation of habitat quality

The spatial distribution of habitat quality in Chongqing Municipality in 2000, 2010, and 2020 was varied. Habitat quality in the northeast and southeast was higher than in the western and central regions. In the regions with high habitat quality and rich biodiversity, forest was the dominant land use type. The regions with secondary habitat quality were predominantly located in the south, which was affected by dual factors of rocky desertification and human disturbance. Regions with lower habitat quality were primarily distributed in the west, where human activities are frequent. Areas with the lowest habitat quality were mainly located in the western part of the region, where human activities were frequent and highway density was high (**Figure 3**).

The average coverage of low-quality habitat in the study area with all three time periods combined was more than 46%. The proportion of area consisting of lower quality habitats was more significant than that of higher and highest quality habitats in different periods, indicating that habitat quality in Chongqing Municipality was generally at a low level from 2000 to 2020 and that there has been no substantial improvement (**Table 3**). A comparison of variation in habitat quality between different periods showed that the area of lowest quality habitat increased by 36.09% from 2000 to 2010 and that habitat quality in the western region decreased. The area of higher and highest quality habitat increased by 5.1 and 2.72%, respectively. From 2010 to 2020, habitat quality declined, with the lowest quality habitat increasing by 219.46%. From 2000 to 2020, habitat quality decreased significantly, as shown by the lowest quality habitat increasing by 334.76%, while the higher and highest quality habitat only increased by 24.98 and 2.36%, respectively. The decrease in habitat quality was mainly concentrated in the western and northern regions but also in some areas along the Yangtze River (**Table 4** and **Figure 3**).

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[3] https://circuitscape.org/

Spatial-temporal patterns of resistance surface and ecological sources

In 2000, 2010, and 2020, the resistance values of landscape resistance patches in the west of the study area were higher than in the northeast and southeast. Habitat patches with high resistance values were mainly distributed in the western, central, and northern regions of the study area. Human activities were frequent, and the ecological environment was damaged to a greater extent, resulting in low connectivity between different habitat patches. Habitat patches with low resistance values were concentrated in the mountainous areas of the southeast and northeast, where the fractional vegetation coverage was relatively high, the habitats were less disturbed by human activities, and the ecosystem was more integrated than that of the western region. From 2000 to 2020, habitat patches with high landscape resistance expanded spatially. The western urban area expanded into the surrounding suburbs and the banks of the Yangtze River. Ecological sources were mainly distributed in the northeast and southeast of the study area during different periods. In 2000, 2010, and 2020, the total area of ecological sources were 25858.02, 227640.86, 226958.35 km^2, accounting for 31.37, 33.53, and 32.7% of the total area, respectively. Compared to 2010, the area of ecological sources in 2020 decreased, which was mainly concentrated in the western region (Figure 4).

Characteristics of ecological corridors and ecological security pattern

The ecological corridors connected the west, northeast, and southeast of the study area in a "spider web" shape (Figure 5). The spatial distribution of ecological corridors in different periods was varied, showing that there were more corridors in the eastern and southern regions. However, the habitat connectivity in these regions was relatively low. From 2000 to 2020, the number of ecological corridors in the southeast of the study area decreased, while the change in other areas was not as noticeable. The current ESPs of Chongqing Municipality were composed of ecological sources dominated by forests, which were connected by continuous ecological corridors. These included 20 ecological nodes, 17 continuous ecological corridors, and 23 ecological sources (Figure 6). The ESPs were composed of several key ecological sources, including Yunwu Mountain, Jinyun Mountain, Zhongliang Mountain, and Mingyue Mountain in the western region; Tiefeng Mountain, Fangdou Mountain, Qiyue Mountain, and Wushan Mountain in the eastern and northeastern region; and Dalou Mountain in the southeastern region. At present, 57.65% of protected areas are distributed in important ecological sources and 42.35% of protected areas are distributed in non-ecological sources. In addition, there was an important protection gap in the eastern region that was not in a protected area. Although not in the range of an essential ecological

TABLE 3 Habitat conditions of Chongqing Municipality in different periods.

Category	Habitat suitable index	2000		2010		2020	
		Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)	Area (km^2)	Percentage (%)
Lowest	0–0.2	608.81	0.74	828.54	1.01	2646.84	3.21
Lower	0.2–0.4	40618.97	49.27	40649.73	49.31	38418.64	46.6
Secondary	0.4–0.6	5941.63	7.21	4694.54	5.69	4927.31	5.98
Higher	0.6–0.8	1523.88	1.85	1601.66	1.94	1904.62	2.31
Highest	0.8–1	33745.33	40.93	34664.15	42.05	34541.21	41.9

TABLE 4 Habitat changes at different stages in Chongqing Municipality.

Category	Habitat suitable index	2000–2010		2010–2020		2000–2020	
		Area change (km^2)	Change rate (%)	Area change (km^2)	Change rate (%)	Area change (km^2)	Change rate (%)
Lowest	0–0.2	219.73	36.09	1818.3	219.46	2038.03	334.76
Lower	0.2–0.4	30.76	0.08	−2231.09	−5.49	−2200.33	−5.42
Secondary	0.4–0.6	−1247.09	−20.99	232.77	4.96	−1014.32	−17.07
Higher	0.6–0.8	77.78	5.1	302.96	18.92	380.74	24.98
Highest	0.8–1	918.82	2.72	−122.94	−0.35	795.88	2.36

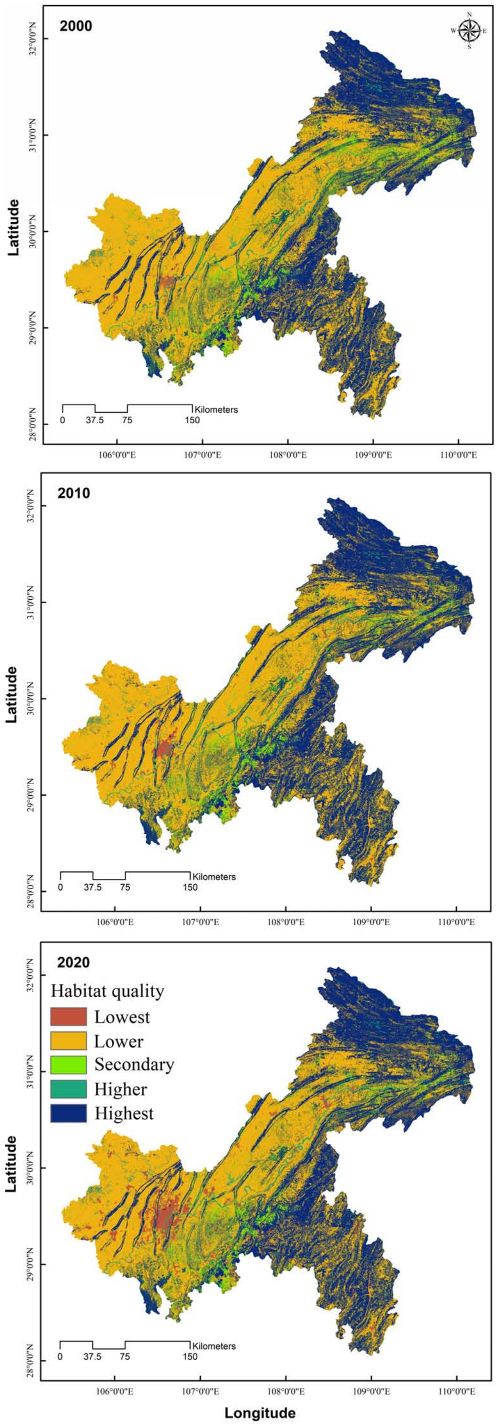

FIGURE 3
Spatial distribution of habitat quality of Chongqing Municipality in 2000, 2010, and 2020.

source, it appears to serve as a "stepping stone" that connects important ecological sources in the northeast and southeast (**Figure 6**).

Discussion

This study revealed the spatial-temporal variation characteristics of habitat quality and ecological corridors in Chongqing Municipality over the past two decades. It provided a basis for the scientific construction of the ESPs for Chongqing Municipality. ESPs construction is a pivotal step to alleviate the contradiction between economic development and ecological protection (Dabelko and Dabelko, 1995; Yu, 1996; Esbah et al., 2009; Steffen et al., 2015; Mao et al., 2018). Our study was trying to identify the spatial distribution of ESPs in Chongqing Municipality, and provide the basis for the government to formulate the ecological protection strategies in the process of urbanization. First, we used the InVEST model to dynamically evaluate the habitat quality of Chongqing Municipality in 2000, 2010, and 2020. We then used the habitat quality layer as the foundation of ESP construction and combined the Circuit Theory model to analyze the ecological security characteristics. Many researchers used the InVEST model to evaluate habitat quality and analyze ecological sources based on model outputs and landscape ecology methods (Peng et al., 2018a; Xiao et al., 2020). This method is relatively scientific, which can reduce the interference of subjective factors (Zheng et al., 2021). Moreover, the construction method of ecological corridors and ESPs based on the Circuit Theory model has been relatively mature and achieved results in practical ecological management and biodiversity conservation (Peng et al., 2018a).

The results showed that the ESPs of Chongqing Municipality were made up of 23 ecological sources, 17 ecological corridors and 20 ecological nodes. The core ecological sources were mainly distributed in large mountainous areas, and the forest accounted for a large proportion of the identified habitat patches. Compared with other provinces and cities in Southwest China (Peng et al., 2018a), Chongqing's ESPs showed that the density of ecological corridors was more concentrated, but the area of ecological sources and the number of ecological nodes were relatively small, which may be mainly affected by Chongqing's terrain and socio-economic development level. According to the density and distribution of the ecological corridors, the core ecological sources can be divided into three geographical groups: west, southeast and northeast. The priority ecological corridors were mainly distributed in the west of the study area. As the habitat quality of ecological corridors directly determines the degree of species dispersal and the frequency of gene exchange, the protection and landscape restoration of ecological corridors should be strengthened. The spatial distribution of habitat quality in Chongqing Municipality was significantly different, with the characteristics of high in the northeast and southeast and low in western and central regions. In different periods, the area of low suitable habitat quality was more than 46%. The habitat quality was generally at a low level in the past two

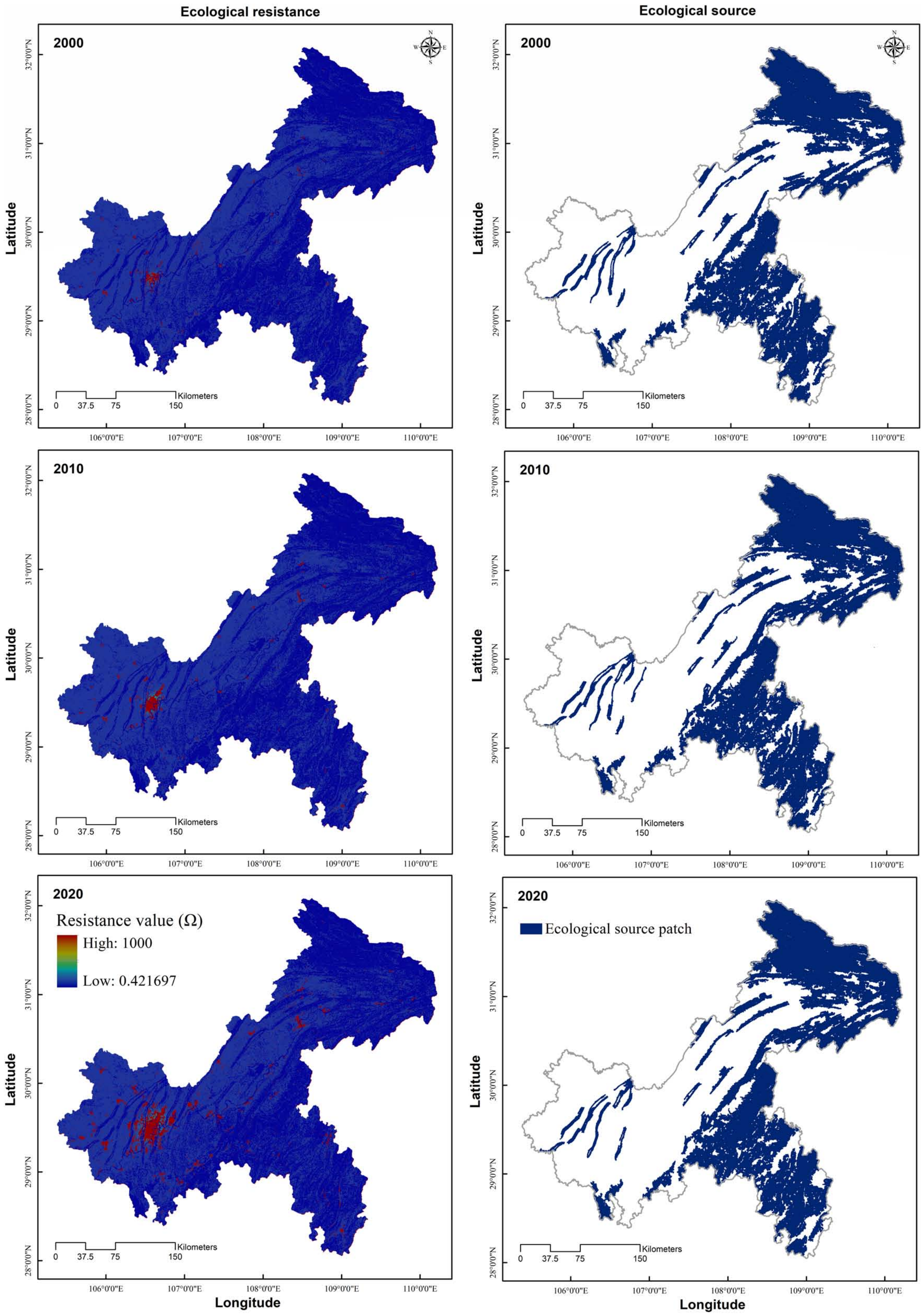

FIGURE 4
The ecological resistance layers and ecological source patches of Chongqing Municipality in 2000, 2010, and 2020.

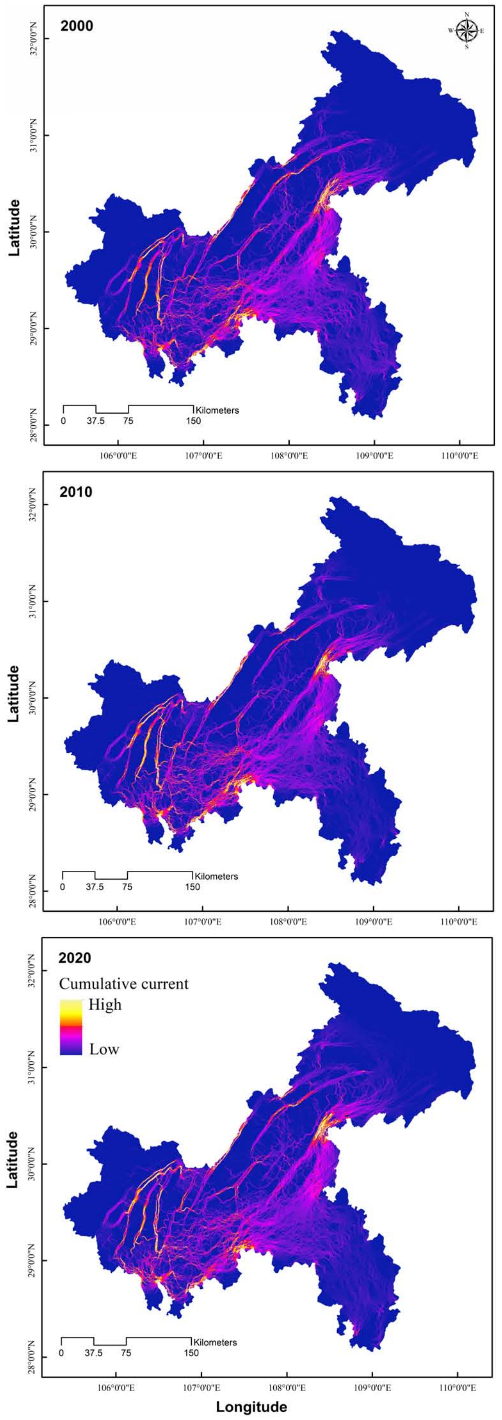

FIGURE 5
Spatial distribution of ecological corridors of Chongqing Municipality in 2000, 2010, and 2020.

decades, with no significant improvement in habitat quality. The reasons might include: (1) Change in land use types: from 2000 to 2020, the two types of land use types of artificial surface and bare land in Chongqing Municipality changed considerably, manifested in the increase of distribution area and the expansion of distribution scope. These two land use types directly impact the ESPs of Chongqing Municipality. The increase in artificial surface area was mainly caused by urban development, while the increase in bare land area included both human and natural factors. Human factors included the destruction of surface vegetation, which leads to land denudation, while the natural factor was rocky desertification, especially in Southeast Chongqing Municipality. (2) The quality of forest habitat and landscape connectivity decreased: from 2000 to 2020, the fragmentation of forest in Chongqing Municipality increased, and the connectivity and aggregation decreased, indicating that the integrity and connectivity of forest ecosystem were poor and changing the ESPs.

Although there are many studies on the construction of ESPs, there is still a lack of research methods and systematic frameworks for integrated landscape management (Xiao et al., 2020). In previous studies, a single ecological model was often used to assess regional ecosystem service capacity and habitat quality, such as SolVES, MaxENT, and InVEST. Despite many studies on ecological source identification based on ecological models, there are still relatively few studies on the identification of ecological security space based on multiple models. In addition, the scientific identification of ecological corridors, which plays an important role in maintaining ecosystem integrity and regional ecological security, was often ignored in the assessment of regional ecological security. Based on the ecological environment data and anthropogenic interference data, our study used the InVEST model and Circuit Theory model to build an ESP identification framework. In addition, considering the specific ecological problems and geospatial differences of Chongqing Municipality, we selected the indices with ecological significance to evaluate the spatial-temporal dynamics and evolution of ecological security. For example, the evaluation of biodiversity is the main index to evaluate ecological security, and it also plays a crucial role in reflecting important ecological space (Inoye, 2003). At the same time, we used interdisciplinary knowledge and comprehensive landscape management methods to consider the priority reserves of ecological corridors and took the ecological sources as the core part of ecological corridor construction. As the ecological space suffers from the pressure of high-intensity human interference, strengthening the key protection of the identified ecological sources and ecological corridors is far more effective than blindly implementing ecological protection measures, especially in developing countries such as China. However, identifying the priority ecological reserve is complicated because of the restriction of spatial heterogeneity within the ecosystem and geographical environment. Therefore, the scientific evaluations and identification of ESPs are still challenging.

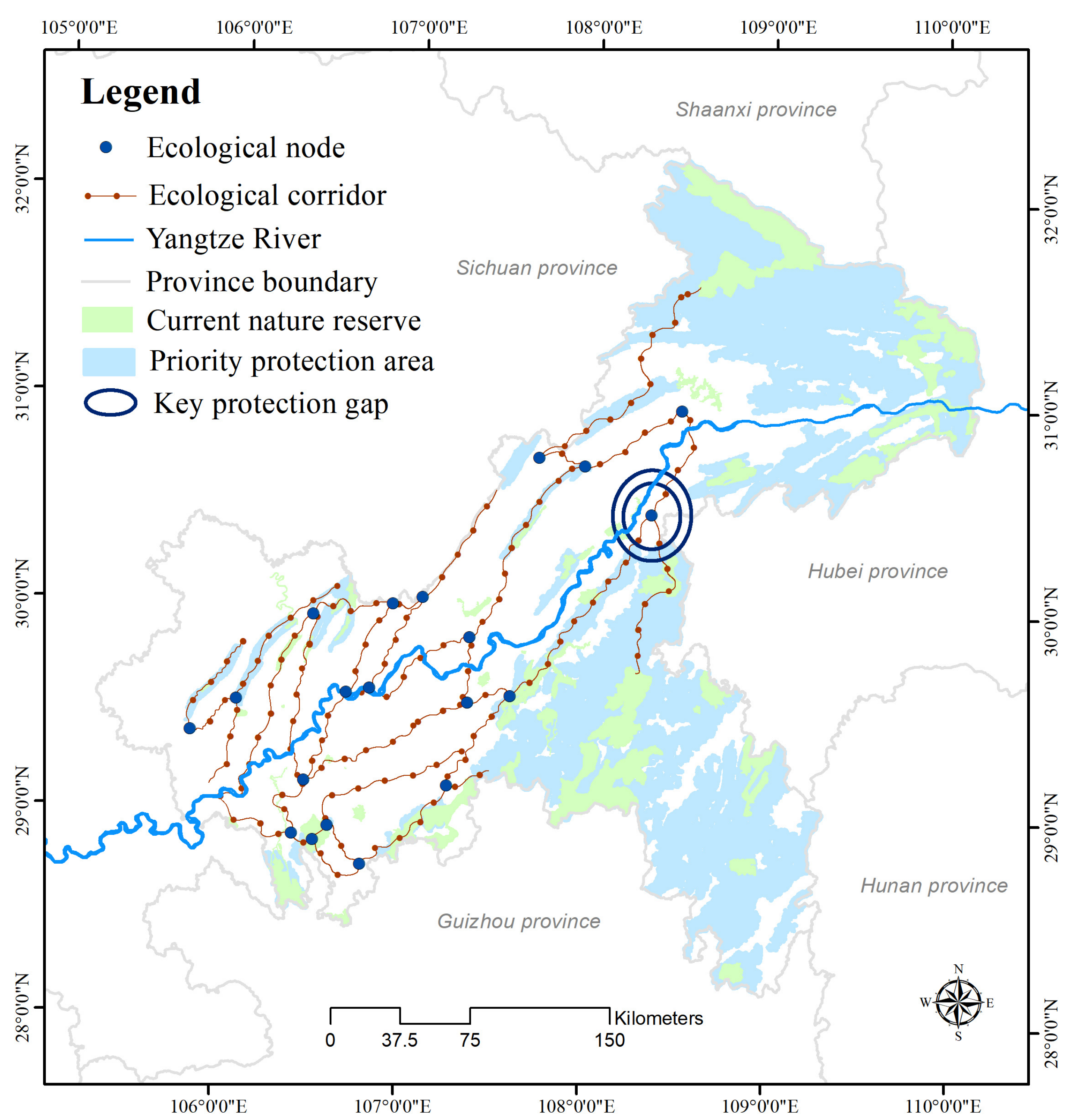

FIGURE 6
Spatial distribution of ecological security pattern of Chongqing Municipality. The ecological corridors were simulated by the Circuit Theory model based on the habitat quality and ecological resistance layer of 2020. The priority protection area are the intersection area of the ecological source patches of Chongqing Municipality in 2000, 2010, and 2020. The ecological nodes are the intersection points of more than two ecological corridors.

We demonstrated the stability of research results from three aspects. Firstly, to ensure the rationality of the findings, we overlaid them with the current distribution of all protected areas of Chongqing Municipality. The results showed that most of the protected areas were located in patches of important ecological sources, and the overlap area between protected areas and ecological sources was more than 57%. Secondly, from the perspective of species conservation, the abundance of endangered species is higher in the northeast and southeast mountain regions of Chongqing Municipality, while the abundance of terrestrial endangered species is lower in the west (Chongqing Forestry Bureau, 2021; "see text footnote 1"). Furthermore, the results indicated that the major ecological sources were primarily located in the northeast and southeast areas of the study area, which was consistent with the geographical distribution of endangered species. Thirdly, in order to verify the feasibility of identified ecological corridors, we overlaid the land use map and ecological corridors. Results showed that the ecological corridors were primarily distributed in areas of forest and shrub, which indicated that it was feasible to establish or protect the ecological corridors under actual real-life conditions.

Conclusion and recommendations

Throughout the process of rapid city expansion, there is an urgent need to determine the critical ecological space and priority ecological reserves (Peng et al., 2018a; Wang et al., 2020; Xiao et al., 2020). This research identified the key ecological sources, ecological nodes, ecological corridors and protection gaps in Chongqing Municipality based on the InVEST and Circuit Theory model. The ESPs of Chongqing Municipality were composed of ecological sources dominated by forests, which were connected by continuous ecological corridors. Our study has made some innovations in the identification of ecological nodes, ecological corridors and ecological sources, which plays a guiding role in building ESPs. On the regional scale, the research findings would help policy makers introduce corresponding ecological protection measures, objectively guide and limit disordered urban expansion and human activities, and further improve the ecological security of Chongqing Municipality. At the national level, the method used in this paper is beneficial to other researchers in identifying and delimiting ecological functional areas.

To objectively guide and limit the disorderly urban expansion and human activities and to protect the ESPs of Chongqing Municipality, the following measures are suggested: (1) Strengthen the protection and management of the 23 identified ecological sources. Present ecological sources were mainly distributed in the northeast of Daba Mountain and Wuling Mountain, which were dominated by forests. It is crucial to protect the landscape connectivity of these forests and the nearby ecological function. (2) The protection gap should be included in the management of protected areas. Some important ecological sources are not in the current protected area system, so it is necessary to integrate these ecological sources into the adjacent protected area system. For example, new nature reserves need to be built in the Three Gorges Region and Daba Mountain or the scope of current nature reserves should be adjusted to incorporate the identified gaps and key ecological sources into the existing protected area system. (3) The local government should give priority to the construction and management of the ecological corridor network system and strengthen the protection of 17 ecological corridor clusters and 20 ecological nodes determined in this study so as to promote species diffusion and gene exchange in the northeast, southeast and western ecological areas of Chongqing Municipality. (4) Strengthen the landscape restoration of ecologically fragile areas in Southeast Chongqing Municipality. It is necessary to strengthen the ecological restoration of rocky desertification areas, such as restoring vegetation through artificial afforestation, soil improvement and artificial grass planting to curb the expansion and spread of rocky desertification.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

DL: manuscript concept. YcD: primary authorship. YyD, CD, YL, GS, and BZ: additional review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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