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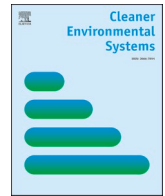
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# How to harmonize the ecological security pattern and economic production space of the Chengdu-Chongqing urban agglomeration? A Study on Sustainable Development Modeling

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## ABSTRACT

Sustainable urban agglomerations aim to provide ecologically sound and economically thriving environments for human habitation. The construction of ecological security pattern (ESP) can effectively coordinate the relationship between ecological preservation and economic development. However, the traditional research of ESP has not considered enough economic production activities. This study uses the 2021 Chengdu-Chongqing Urban Agglomeration (CCUA) as a case study. It introduces an industrial measurement based on machine learning to characterize the economic production pattern (EPP) in the context of ESP, and establishes a sustainable development pattern (SDP) by resolving conflicts between ESP and EPP on the same map. The results showed that: (1) The ESP of the CCUA was characterized by “external encirclement and internal linkage”. (2) The EPP of the CCUA presented the characteristics of “dual-core drive, axis series connection”. (3) Ecological-economic conflicts are mainly reflected in the vulnerability of low-grade ecological resources to economic activities and the serious ecological issues in economically active areas. (4) Finally, the construction of the SDP of “one Development Main Axis, two Economic Development Cores, two Industrial Development Belts, five Ecological Axis and five Ecological Barrier Areas” can promote coordination of ecological preservation and economic development. The research results of this paper bring a new perspective and new ideas for the study of ecological security pattern, including interdisciplinary integration, and multi-method integration, and the spatial characteristics shown can provide important reference opinions and strategic guidance for urban sustainable development planning and design more effectively.

## 1. Introduction

Ecological security and economic production are an interdependent organic entity. Ecological security acts as the foundation of economic production, with its impairment restricting economic development (Li et al., 2025). Economic production may undermine the ecology but can also feedback to ecological security via technological innovation, industrial upgrading, and rational layout, requiring dynamic balance to achieve sustainable development (Tang et al., 2023; Wei et al., 2024). During the last few decades, urbanization has led to good economic development, but has also led to a decline in ecosystem health and degradation of ecosystem services, causing a slew of ecological and environmental issues, more making the coordination of economic

development and environmental protection a global challenge (Bardhan et al., 2015; Charfeddine, 2017, Van Niekerk et al., 2019; Sun et al., 2020). As the highest spatial form of organized urban development upon maturity, urban agglomerations—characterized by a high degree of internal urban integration—will be the first to confront ecological security challenges, grapple with more pronounced resource constraints and environmental pressures (Ghosh et al., 2021, Li et al., 2023; Tang et al., 2024), while also functioning as one of the most critical carriers for global economic development (Fang and Yu, 2017). To achieve both ecological protection and economic development within urban agglomerations, it is vital to evaluate the ecological security pattern (ESP) and economic production pattern (EPP) and reveal their spatial relationship. This is essential for regional sustainable development and the

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formulation of spatial planning and policy management. Maintaining a balance between the ecology and the economy will enhance the well-being of humanity (Hernández et al., 2024). The sustainable development of ecological preservation and economic growth, and their interactions, is an important research topic worldwide (Sun et al., 2020). Ecological security (ES) is a vital element of sustainable urban development (Peng et al., 2019). Constructing an ESP is an effective approach to achieving the ES (Dai et al., 2021). The ESP provides comprehensive consideration of the interactions between ecological processes and landscape patterns (Klar et al., 2012), which is an important initiative to coordinate ecosystem protection with economic development (Peng et al., 2018). At present, the policy of ESP has become one of the important national strategies in China for coordinating the ecosystem protection and economic development (Peng et al., 2018). Currently, the construction of ESP has formed one research paradigm including the identification of ecological source, and ecological corridor (Yu, 1996, Peng et al., 2018; Jia et al., 2023). At present, it is mainly based on the function of some assessment indicators such as ecosystem service importance, ecological sensitivity, and landscape connectivity to identify ecological sources maturely (Su et al., 2016; Peng et al., 2018; Bai and Guo, 2021). Ecological corridors are the ecological energy flow channels connecting ecological sources, extracted using the Minimal Cumulative Resistance (MCR) Model or Circuit Theory (Gao et al., 2022; Kang et al., 2022).

Economic production activities are the most significant in human activities. However, the traditional regression analysis paradigm used in economics cannot be applied to analyze spatial landscape patterns, which makes it difficult to directly bring EPP into the existing ESP (Dai et al., 2021). If we can treat economic activities as an independent pattern and combine it with the ESP, it may help us understand the contradiction and relationship between ecological preservation and economic development, and enable us to make more accurate decisions on the sustainable development of urban agglomerations. In economic geography theory, the most significant feature of economic activity distribution is industrial spatial agglomeration (Krugman, 1991; Clark and Porter, 1991). In the new era, the forms of industrial space are constantly breaking through traditional administrative boundaries, gradually forming a new pattern of urban agglomerations with core cities as hubs and coordinated development of multiple urban industries. Currently, there are the Ellison and Glaeser index (EGI) and the Duranton and Overman index (DOI) in the mainstream industrial co-agglomeration measurement indicators (Ellison and Glaeser, 1997; Duranton and Overman, 2008, Delgado et al., 2016). However, both indices have certain limitations, such as spatial scale issues or computational complexity (Huang et al., 2024). Luckily, Billings and Johnson proposed an industrial co-agglomeration method based on the Wasserstein distance, which could solve the problems existing in previous methods (Billings and Johnson, 2016). Then, Wasserstein distance was introduced into the field of machine learning (Arjovsky et al., 2017; Carlsson et al., 2018). At present, Liu has measured the industrial agglomeration index of 21 urban agglomerations in China based on Bill's method and drawing on the improvements of this method in the field of machine learning (Chen et al., 2020). Thus, machine learning-based industrial co-agglomeration can characterize EPP. Integrating ESP and EPP via GIS enables regional planning balancing ecological preservation and economic development. This study advances the existing paradigm by proposing an "Ecological-Economic Bidirectional Optimization" framework, with the ESP and the EPP as its two core components. The framework establishes a closed-loop process encompassing spatial diagnosis, mechanism analysis, SDP construction, and strategy adaptation, thereby emphasizing the targeted and adaptive nature of optimization strategies. Notably, the SDP is conceptualized not as a static planning outcome but as a dynamic system that develops differentiated optimization schemes according to the distinct characteristics of ESP and EPP across regions (e.g., core cities versus ecological barrier zones). By highlighting continuous adjustment and mutual adaptation between

ecological and economic systems, this framework transcends the limitations of traditional paradigms of "identification–diagnosis–optimization" and provides a novel analytical perspective for coordinated development within urban agglomerations.

The Chengdu-Chongqing Urban Agglomeration (CCUA) is one of China's five national urban agglomerations, a strategic support for the Yangtze River Economic Belt, and a key "fourth growth pole" for high-quality development (Bian et al., 2021; Li et al., 2023). At the same time, the CCUA is also located in an important ecological barrier area in the upper reaches of the Yangtze River, which is crucial to maintaining national ecological security. Against the backdrop of its ecological and economic challenges, this study proposes a CCUA sustainability framework integrating ecological preservation and economic development from a transdisciplinary perspective. The specific objectives of this study were to (1) identify the ESP by using the MCR, (2) explore the EPP by the Wasserstein distance algorithm of machine learning, (3) identify areas of conflict by merging the two models mentioned above and propose a model for the development of sustainable urban agglomerations, and (4) carry out favorable and detailed planning and design of the space under the guidance of the former.

## 2. Materials and methods

### 2.1. Study region

The CCUA is located between 101°95'-108°98'E and 27°67'-32°32'N in the upper reaches of the Yangtze River and in the Sichuan Basin (Fig. 1). The CCUA encompasses 15 cities in Sichuan and 29 counties (districts) in Chongqing. The region spans an area of  $1.86 \times 10^7$  ha, with construction land covering approximately  $7.34 \times 10^5$  ha, and a population of around  $9.6 \times 10^7$  (as of 2019). The construction land area is approximately  $7.34 \times 10^5$  ha. As one of the most urbanized and economically dynamic regions in western China, the CCUA has made significant strides in economic and social development. It has made significant progress in economic and social development in the region. In the current industrial spatial pattern of the CCUA, Chengdu and Chongqing serve as the core industrial zones, with Mianyang, Deyang, and Jiangjin acting as key nodes. Within advanced manufacturing, industrial clusters such as computers and automobiles have emerged prominently, while the biopharmaceutical industry continues to expand. The regional topography is primarily characterized by plains, hills, and mountains. In recent years, urban expansion has posed threats to local ecosystems, and the trend of ecological degradation has not been fundamentally reversed. Therefore, identifying the ESP and EPP and analyzing the conflict areas between them will contribute to the sustainable development of the CCUA.

### 2.2. Data sources

This study made use of six datasets, including land use data, topographic data (DEM), NDVI data, soil data, meteorological data, and industry data. Table 1 presented the specific resolution, type and source of each data. All data were converted into a unified projection coordinate system (WGS, 1984\_UTM) and the closest neighbor algorithm was used to interpolate or resample the data into a  $500 \text{ m} \times 500 \text{ m}$  resolution. Industrial data excludes non-surviving enterprises, individual businesses, and enterprises with incomplete information. Enterprises latitude and longitude data is obtained using Baidu Maps API.

### 2.3. Methods

This study highlights the win-win situation of ecological preservation and economic development. It not only emphasizes the optimization of the ESP, but also points out the green development of regional industries. The construction method is divided into four steps (Fig. 2). The first step is to identify the source of ecosystem services. Select areas

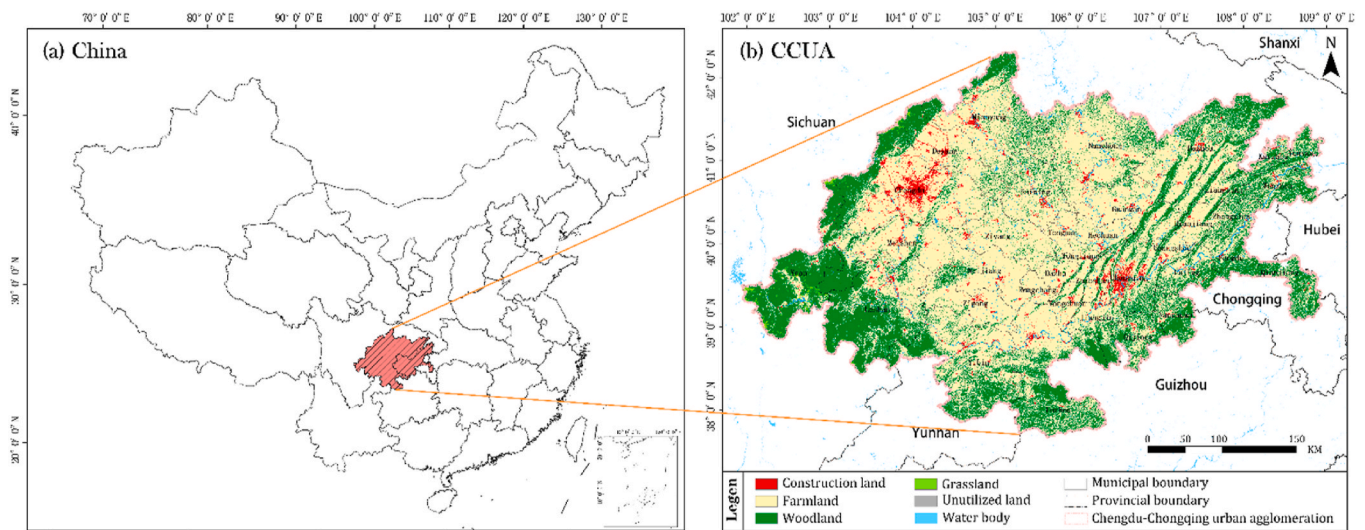


Fig. 1. Geographical location and land cover and of the study area.

**Table 1**  
Data source and description of the study area.

Data	Description	Sources
Land use data	Land use with 10m spatial resolution in 2021	<a href="https://esa-worldcover.org/en">https://esa-worldcover.org/en</a>
Topographic data	Digital elevation model with 90m spatial resolution	<a href="http://www.resdc.cn">http://www.resdc.cn</a>
NDVI data	Annual NDVI with 250m spatial resolution in 2021	<a href="http://www.resdc.cn">http://www.resdc.cn</a>
Soil data	Soil type with 500m spatial resolution in 1995	<a href="https://www.geodata.cn/main/">https://www.geodata.cn/main/</a>
Meteorological data	Temperature, precipitation, potential evaporation in 2021	<a href="http://data.cma.cn/">http://data.cma.cn/</a>
Industry data	Non-individual enterprises in the manufacturing industry in 2021	<a href="https://www.tianyancha.com/">https://www.tianyancha.com/</a>

with high ecosystem services as ecological sources, and evaluate the importance of ecological sources based on the possible connectivity index. The second step is to construct an ecological network based on the MCR. Determine the ecological resistance factor of the ecological source, construct the ecological resistance surface, use the MCR to identify the ecological network, and classify the importance of the ecological network. The third step is to identify the EPP based on machine learning. Use the co-aggregation index to divide the “core-edge” industry, and use “kernel density” tool analysis to characterize the EPP characteristics. The fourth step is to construct a regional comprehensive pattern based on the ESP and EPP.

### 2.3.1. Identification of ecological sources based on ecosystem services

Ecosystem services refer to the various benefits that humans obtain from ecosystems (Costanza et al., 1998). They are widely used in ecological planning at regional and urban scales because they can better reflect human needs and ecological functions (Hansen and Pauleit, 2014, Liu et al., 2016). Their measurement, evaluation and management are important links and decision-making tools for understanding the connection between ecosystems and human well-being (McPhearson et al., 2022; Fang et al., 2023; Wei et al., 2024).

The selection of ecosystem service types refers to the “Guidelines for Delineating Ecological preservation Red Lines in China” (2017) and the “Sichuan Provincial Land Space Ecological Restoration Plan” (2021–2035). Four ecosystem services, including water supply, soil conservation, habitat quality and carbon storage, were selected for quantitative analysis. The specific quantification methods are as follows:

Water supply was estimated by water yield module in the InVEST

model, which was as follows:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x \quad (1)$$

Where  $Y_{xj}$  is the annual water supply (mm) of a grid cell  $x$  for a land use type  $j$ ;  $AET_{xj}$  is the actual evapotranspiration (mm); and  $P_x$  is the annual precipitation of grid cell  $x$  (mm).

Soil conservation was estimated by SDR module in the InVEST model, which was as follows:

$$SC_x = R_x \times K_x \times LS_x(1 - C_x \times P_x) + SDR_x \quad (3)$$

Where  $SC_x$  is the soil conservation of grid cell  $x$ ;  $R_x$  is the precipitation erosion factor;  $K_x$  is the soil erodibility;  $LS_x$  is the slope length factor;  $C_x$  and  $P_x$  are the vegetation cover factor and soil conservation factor, respectively; and  $SDR_x$  is the sediment retention.

Habitat quality was estimated by Habitat Quality module in the InVEST model, which was as follows:

$$Q_{xj} = H_{xj} \times \left(1 - \frac{D_{xj}^2}{D_{xj}^2 + K^2}\right) \quad (2)$$

Where  $Q_{xj}$  is the habitat quality index of grid cell  $x$  in land use type  $j$ ;  $D_{xj}$  is the degree of habitat degradation, which is the level of stress on organisms of grid cell  $x$  in land use type  $j$ ;  $H_{xj}$  is the habitat adaptability of grid cell  $x$  in land use type  $j$ ; and  $K$  is the half-saturation constant.

Carbon fixation was estimated by Carbon Fixation module in the InVEST model, which was as follows:

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (4)$$

Where  $C_{total}$  is the total carbon storage in the study area;  $C_{above}$  is the above-ground carbon storage;  $C_{below}$  is the carbon storage of underground organisms;  $C_{soil}$  is the carbon storage of soil; and  $C_{dead}$  is the carbon storage of organic matter.

The above ecosystem service evaluation results were unified to the range of 0–1 according to the deviation standardization method, and finally the weights of each service layer were superimposed to obtain the comprehensive ecosystem service function layer. The GIS natural breakpoint method was used to divide it into three levels: extremely important, relatively important, and generally important. The extremely important areas in the comprehensive ecosystem service evaluation and the patches with an area of more than 10 km<sup>2</sup> were extracted as ecological source areas.

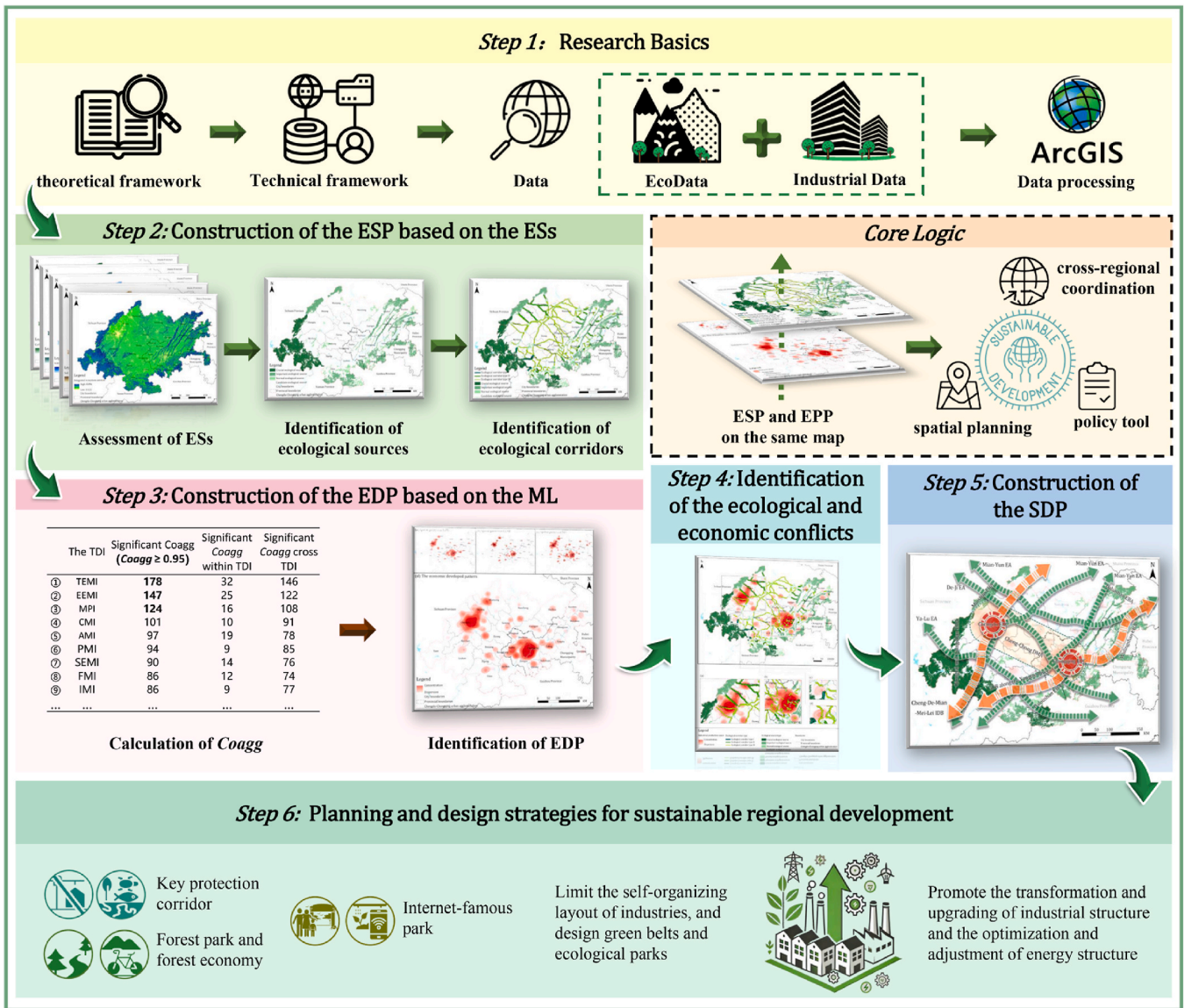


Fig. 2. Graphical abstracts.

2.3.2. Classification of ecological sources based on landscape connectivity

Landscape connectivity evaluation is an effective way to judge the strength of connectivity between landscape patches. Maintaining good landscape connectivity has a very positive effect on maintaining the stability of the ecosystem and biodiversity. This study uses two landscape indices, Probability of Connectivity (PC) and patch Importance Index (dPC), to simulate the seven commonly used thresholds at the regional scale in the Conefor 2.6. The connectivity probability is set to 0.5, and the optimal distance threshold is determined by the change trend of the index. The method was as follows:

$$PC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i a_j p_{ij}^*}{A_L^2} \quad (5)$$

$$dPC = 100\% \times \frac{PC - PC_{max}}{PC} \quad (6)$$

PC represents the possible connectivity index; n represents the total number of ecological sources; a<sub>i</sub> and a<sub>j</sub> represent the area of sources i and j; p<sub>ij</sub><sup>\*</sup> is the maximum probability of diffusion between patches i and j; A<sub>L</sub> is the total area of the landscape. dPC represents the change in the

possible connectivity index, which can evaluate the importance of the element to the overall landscape connectivity. The larger the value, the more important the ecological source is in the overall pattern (Zeng et al., 2024).

2.3.3. Construction of comprehensive resistance surface based on multiple factors

The comprehensive ecological resistance surface describes the difficulty of species migration in different habitat patches and reflects the horizontal resistance of ecological processes to species (Cui et al., 2020). The higher the level of ecosystem services, the smaller the resistance to species spread and the smaller the resistance value (Peng et al., 2018). In this study, four factors, namely land use type, slope, elevation and ecosystem services, were selected to construct a comprehensive resistance surface (Table 2). The relative importance of each factor was evaluated by expert scoring method, and the Analytic Hierarchy Process (AHP) was used to determine the weight.

2.3.4. Extraction of ecological corridors based on the MCR

The MCR can identify the potential channel with the least resistance between ecological flow from one ecological source to another. After the

**Table 2**  
Resistance factor weights.

Evaluation Factor	Resistance value					Weight
	5	15	50	75	100	
Land use	Forest land	Waters and Grassland	Agricultural land	Bare land	Construction land	0.45
Slope	<5°	5–15°	15–25°	25–35°	>35°	0.1
DEM	<200m	200–500m	500–1000m	1000–1500m	>1500m	0.12
Ecosystem services	Level 1	Level 2	Level 3	Level 4	Level 5	0.33

ecological source and the comprehensive ecological resistance surface are established, the minimum cumulative resistance surface is generated using the cost distance tool. Based on this, the MCR can extract the minimum cost path between the source areas. The method was as follows:

$$MCR = \text{fmin} \sum_{j=m}^{i=m} (D_{ij} \times R_i) \tag{7}$$

where  $D_{ij}$  represents the spatial distance of a species from source point  $j$  to landscape patch  $i$ ; and  $R_i$  is the ecological resistance of spatial unit  $i$  to a species migration.

The ecological corridors connecting important ecological sources are designated as key corridors due to their significant role in supporting species exchange and ecosystem functions (Li et al., 2025). Based on existing research, the ecological corridor is divided into three types (Li et al., 2025). A type I corridor is defined as the lowest cost path between crucial ecological source and other types. A type II corridor is defined as the path with the lowest cost between the important ecological source and other types. The rest are all type III corridor. The type I corridor is more important than the others.

### 2.3.5. Industrial co-agglomeration based on machine learning

There are two steps to measure the industrial co-agglomeration index by machine learning method. First, the Wasserstein distance of the spatial distribution of two industries is solved. However, when solving the Wasserstein distance, the original calculation method is to use a linear programming solution, which is more complicated and the calculation results are uncertain. In order to solve the above problems, a method using fixed point iteration in matrix expansion algorithm and increasing entropy regularization constraint was proposed, which was as follows:

$$W_p(\mu(x), \nu(y)) := \left( \inf_{\gamma(x,y) \in \Gamma(\mu,\nu)} \int_{R^n \times R^n} d(x,y)^p \gamma(x,y) dx dy - \alpha \Omega(\gamma) \right)^{1/p} \tag{8}$$

Where,  $\Omega(\gamma)$  is defined as the entropy constraint of the joint distribution  $\Gamma(\mu, \nu)$ :

$$\Omega(\gamma) = - \int_{R^n \times R^n} \gamma(x,y) \ln \gamma(x,y) dx dy \tag{9}$$

Where:  $W_p(\mu(x), \nu(y))$  represents the Wasserstein distance,  $\Gamma(\mu, \nu)$  is the set of all possible joint probability distributions combined by the spatial distributions. For each possible joint probability score, sample  $\gamma(x,y)$  to get a sample  $x$  and  $y$ , and calculate the distance between the pair of samples, so you can calculate the expected value of the sample distance under the joint density distribution, and the lower bound  $\inf$  on this expected value is the Wasserstein distance to look for.

Construction of industrial co-agglomeration index based on the counterfactual sample set of statistical significance. In order to judge whether there is statistical co-agglomeration between two industries in space, counterfactual samples need to be constructed by Monte Carlo method to construct the co-agglomeration index between industry  $j$  and  $k$ . The simulated industrial location set  $\tilde{k}$  for industry  $j$  is randomly selected on  $R^n$ , which is generated by extracting  $N_k$  location points from

the enterprise location information of all industries in the space. The Wasserstein distance between industry  $j$  and simulated industry  $\tilde{k}$  is denoted as  $W_{j,\tilde{k}}$ , and this random selection process will be repeated 1000 times. The real  $W_{j,k}$  is compared with the 1000 counterfactual results, and the number of occurrences that violate the null hypothesis ( $W_{j,k} < W_{j,\tilde{k}}$ ) in the simulation results is denoted as  $n$  times, and then the industrial co-agglomeration index is  $Coagg_{j,k} = n/1000$ .

The industrial spatial network can be divided into “core-edge” industries. The core industry of the EPP is structurally dominant in the network, meaning it has the largest concentration of other industries in a certain area. This dominance attracts industries with business or production relations to the core industry, resulting in spatial clustering. Additionally, from an industrial structural perspective, these industries are at the center and interact most frequently with other industries. From a regional policy-making perspective, these industries deserve the most attention. This study summarizes the notable industries in the CCUA, calculates the frequency of each three-digit industry, further sums up the frequency of the Two-Digit Industries (TDIs), and then obtains the top three core industries in the urban agglomeration industry space.

Kernel density analysis intuitively reflects the distribution and agglomeration of elements. The density map quickly determines the distribution characteristics, primacy and attractiveness of the elements in the region, playing an important role in macro-regional scale research. This study therefore takes the core industry as a representative example and uses the kernel density tool in ArcGIS to portray the industrial space of the Chengdu-Chongqing Twin Cities Economic Circle in geospatial terms. In the kernel density analysis, the output pixel size is  $500 \text{ m} \times 500 \text{ m}$ , consistent with the basic data. The search range uses the system's default value.

## 3. Results

### 3.1. Spatial pattern of ecosystem services and ecological sources

All four ecosystem services in the CCUA for 2021 exhibited spatial heterogeneity (Fig. 3). The spatial distribution of these services showed both similarities and differences. Specifically, water conservation services generally exhibited a spatial pattern of high values in the center and lower values at the edges, with high-value areas primarily concentrated around Meishan. At the municipal scale, Nanchong City had the highest total value of water conservation services. However, the other three ecosystem services (carbon storage, habitat quality and soil conservation) all showed an overall characteristic of low middle and high edge. At the municipal scale level, Ya'an City had the first total value of all three ecosystem services, and Qianjiang city was the second.

The comprehensive ecosystem services obtained based on the superposition of equal weights also showed the overall characteristic of low middle and high edge (Fig. 4). At the city scale, the top three integrated ecosystem service values were Ya'an, Qianjiang and Nanchuan city in order. The integrated ecosystem service results were categorized into four grades of extremely important, more important, generally important and others using the natural breakpoint method. The extremely important areas covered 26,744.20  $\text{km}^2$ , accounting for

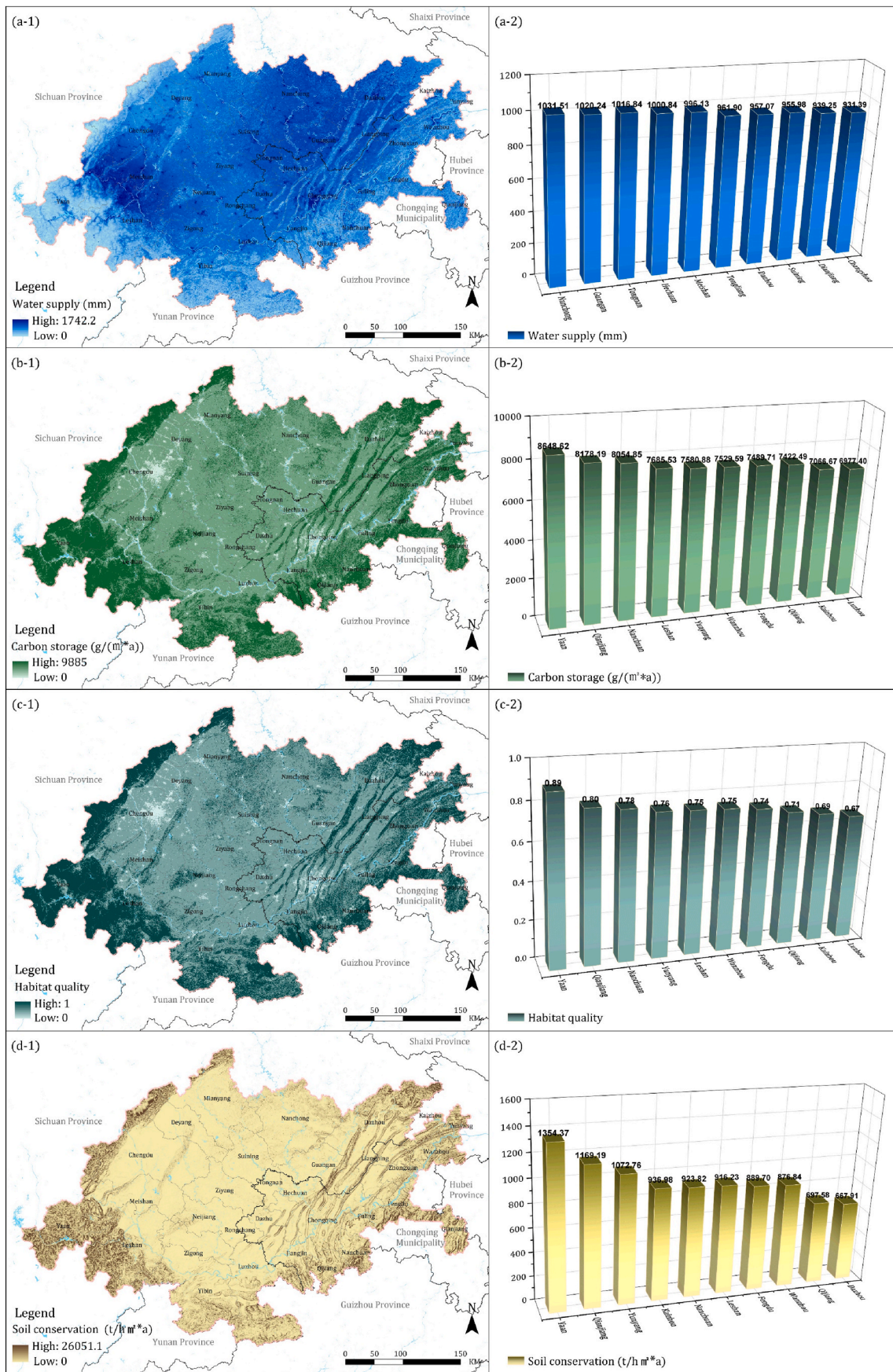


Fig. 3. The spatial patterns of ESs (Left) and their municipal statistics (Right) in the CCUA.

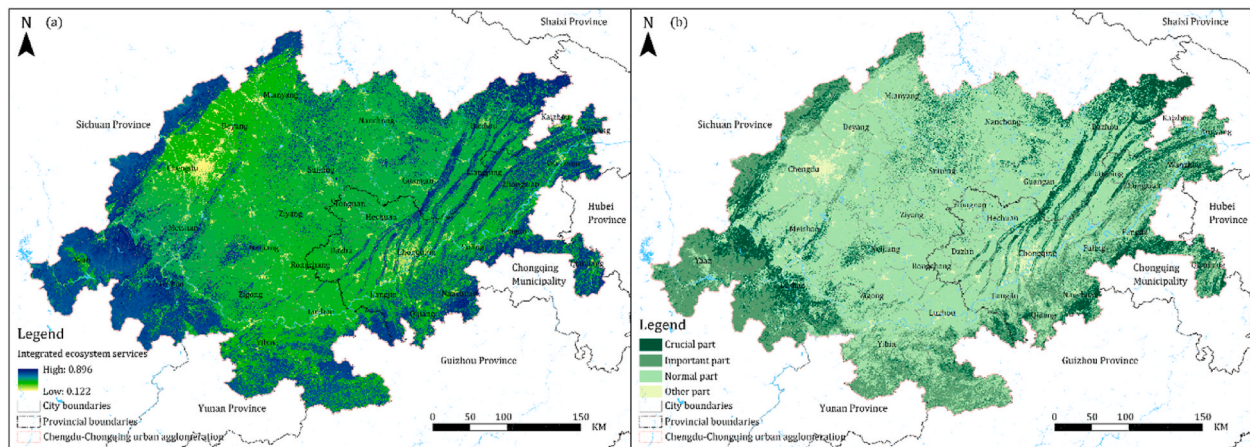


Fig. 4. The results of integrated ecosystem services (a) and ecological function importance classification (b).

14.61% of the total area of the study region, and were mainly concentrated in the southwest and east of the study area. The extremely important areas were all located in the mountainous and forested areas far away from the city, which were rich in topography and had little anthropogenic interference, and can provide a diverse ecological environment for organisms. The more important areas, with a total area of 33615.63 km<sup>2</sup>, accounted for 18.36% of the total area of the study area, and were mainly distributed in the vicinity of the extremely important areas for ecosystem services, which could play a good buffering role in

their surroundings. The generally important area covered 117631.03 km<sup>2</sup>, accounting for 64.25% of the total area, basically covering the central part of the area, which was an important grain and oil production area of the urban agglomeration, with up to 80% of the cultivated area. Overall, the spatial heterogeneity of ecosystem service functions was inextricably linked to the natural geography and socioeconomic development of the study area itself.

Combined with the results of ecosystem service importance grading, the extremely important areas for ecosystem services were selected as

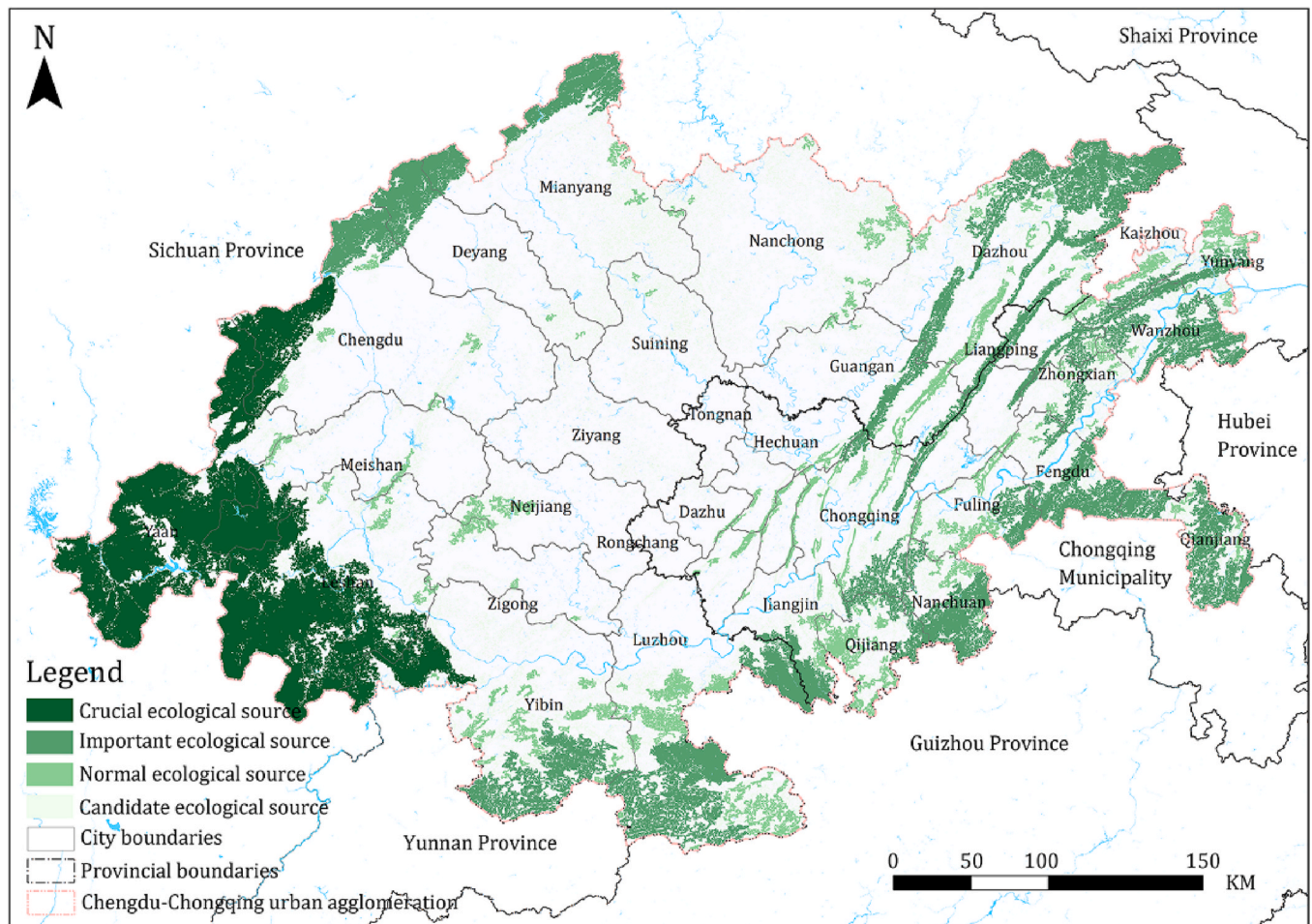


Fig. 5. The ecological sources of the CCUA.

alternative sources, and then those with an area larger than 10 km<sup>2</sup> were selected as ecological sources, and a total of 206 ecological sources were extracted, with a total area of 49,067.68 km<sup>2</sup> (Fig. 5), which accounted for 27.34% of the total area of the study area, and were mainly located at the edge of the urban agglomerations and the eastern part of the city. Based on the results of landscape connectivity calculation, the importance of each ecological source was calculated, and then the dPC was divided into three levels using the natural segment point method, i.e., the corresponding ecological source was classified into three levels. Ecological sources with  $0 < dPC \leq 1.565$  were treated as an ordinary ecological source,  $11.565 < dPC \leq 8.487$  were treated as an important ecological source, and those with  $dPC > 8.487$  were treated as an ecologically important source. Sources, obtaining 2 extremely important sources (20667.77 km<sup>2</sup>), 15 secondary sources (20408.25 km<sup>2</sup>), and 189 tertiary sources (7991.67 km<sup>2</sup>), which accounted for 42.12%, 41.59%, and 16.29% of the total area of the ecological sources, respectively. According to the results of the study, the primary source land accounted for a larger proportion of the ecological source land, and the area of individual source land was also larger, mainly distributed in Luzhou in the south and Ya'an and Leshan in the southwest, and at the same time, it had better ecological function and structural integrity, constituting the main ecological source land of the CCUA; the secondary source land was surrounded in the vicinity of the primary source land; and the tertiary source land was distributed in the cultivated land in the study area in a sporadic way, with small and the tertiary source lands were scattered in the cultivated area of the study area, with small area and fragmentation, and poor landscape connectivity.

### 3.2. Spatial pattern of resistance surface and ecological network

The resistance value of the integrated resistance surface in the CCUA showed a spatial pattern of low-high-low from east to west (Fig. 6). Specifically, the areas with high resistance values were mainly in the Chengdu Urban Agglomeration, the northern part of the Sichuan South Urban Agglomeration and the central urban area of Chongqing. These areas were mainly the main development areas of the urban

agglomerations, with high urbanization levels and high intensity of anthropogenic disturbances. As a result, ecological resistance barriers appeared in these regions.

In this study, 157 ecological corridors were identified, totaling 6322.40 km (Fig. 7). The ecological corridors in the whole area showed lattice-like characteristics. The ecological corridors constructed by the least resistance model reflected the maximum possibility of potential species flow, and most of the extracted corridors deviated from the straight line of the geometric center of the ecological source, choosing the more distant paths with less comprehensive ecological resistance. The orientation of these corridors was predominantly southeast-northwest, demonstrating strong ecological connectivity in this direction. Meanwhile, in the southern part of the region, the same strong gravitational force between the sources of raw material sources and more corridors. According to the results of corridor grading, there were 4 ecological corridor type I, 27 ecological corridor type II, and 126 ecological corridor type III. Ecological corridor type I were concentrated in the west, mainly connecting the Qionglai Mountains and Liangshan Mountains and other important areas of national ecological functions, with a total length of 132.12 km. Ecological corridor type II were distributed in the northeast and east of the region, mainly concentrated in the Minshan Mountains, Dabashan Mountains, Wuling Mountains, and other important areas for biodiversity protection and water conservation, with a total length of 905.90 km. Ecological corridor type III were widely distributed, with a total length of 5284.37 km. Although the ecological corridor type III accounts for the largest proportion, the number of ecological corridor type III was also higher than that of the other corridors. Although the proportion of ecological corridor type III was the largest, the interaction force between source areas was small, and the corridors were easy to block after being disturbed. On the whole, the ecological corridor type I were significantly shorter than the latter two, effectively connecting important ecological sources that were relatively close to each other, while the ecological corridor type II and ecological corridor type III connected a wide range of areas.

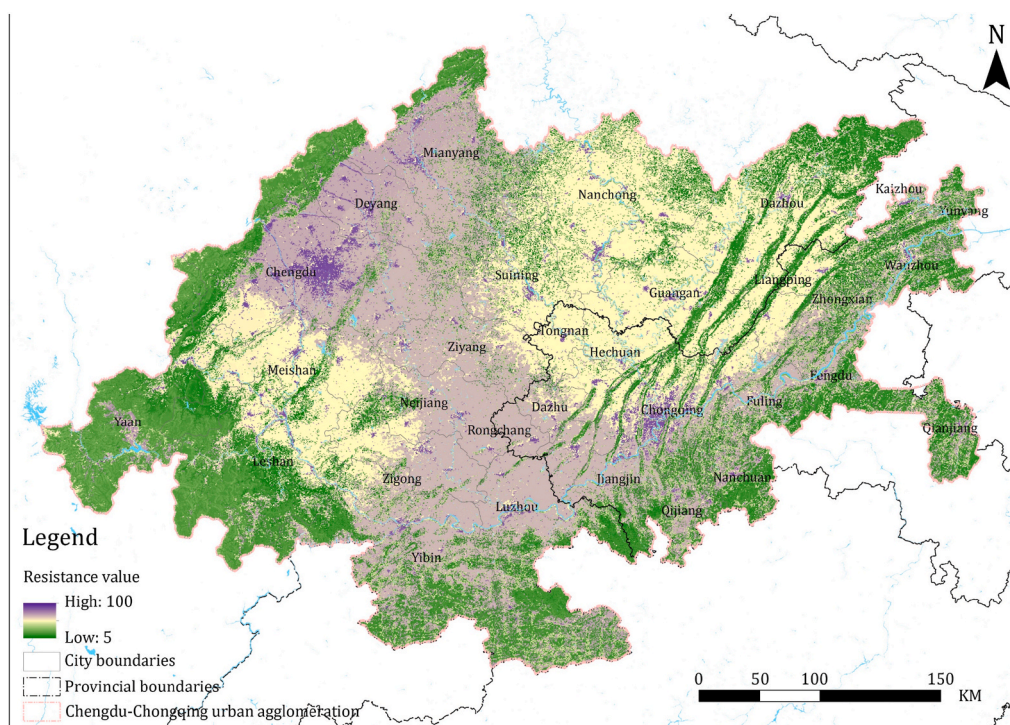


Fig. 6. The ecological resistance surface of the CCUA.

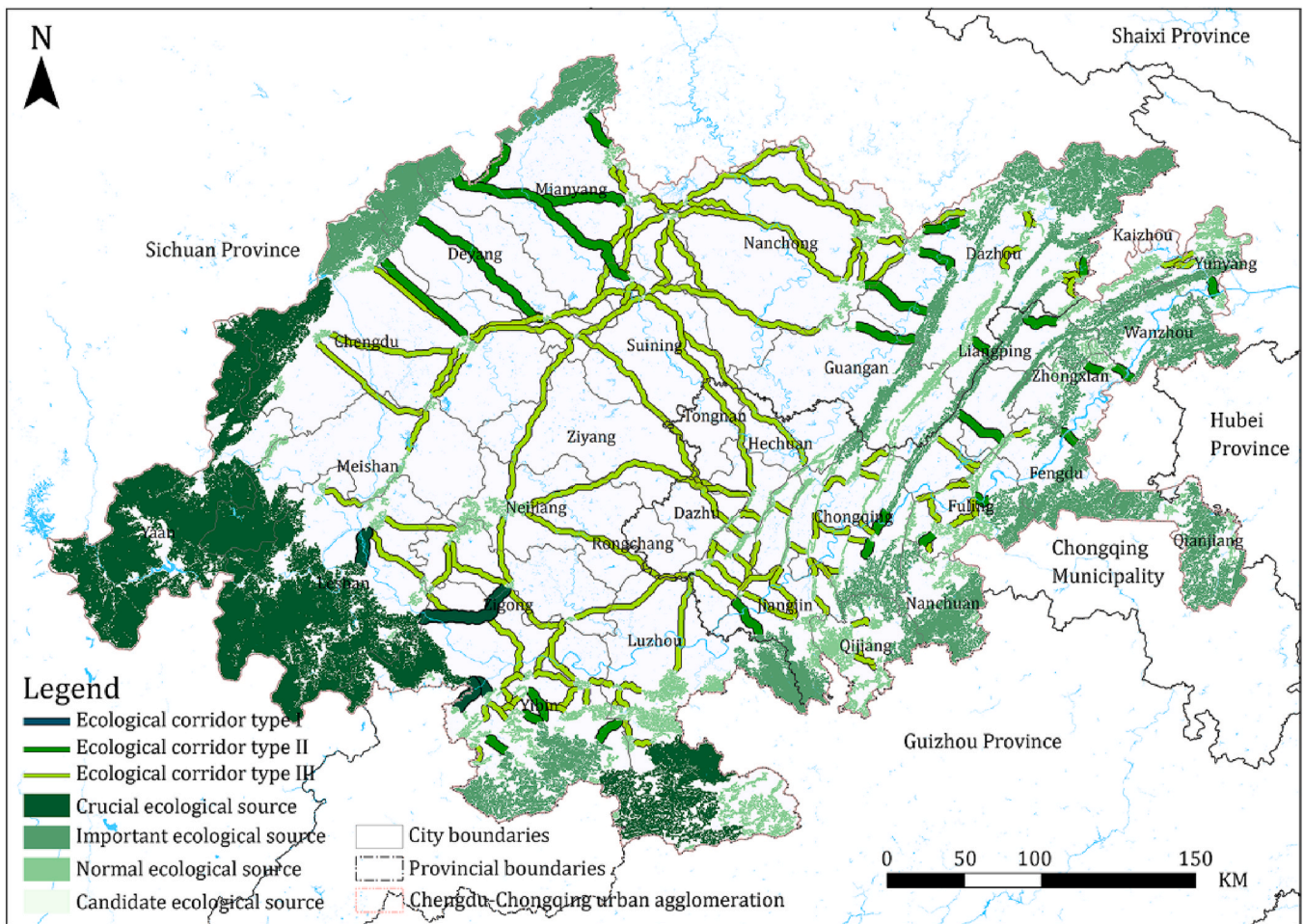


Fig. 7. The ecological network of the CCUA.

**Table 3**  
Statistics of manufacturing industries co-agglomeration in the CCUA.

TDis	Pairs of Coagg	Pairs of Coagg within TDis	Pairs of Coagg cross TDis	The number of significant Coagg	The number of significant Coagg within TDis	The number of significant Coagg cross TDis	Mean value of Coagg
1 Transportation Equipment Manufacturing Industry	1629	81	1548	178	32	146	0.221
2 Electronic Equipment Manufacturing Industry	1629	81	1548	147	25	122	0.381
3 Metal Products Industry	1629	81	1548	124	16	108	0.439
4 Chemical Manufacturing Industry	1448	64	1384	101	10	91	0.421
5 Automobile Manufacturing Industry	1267	49	1218	97	19	78	0.292
6 Pharmaceutical Manufacturing Industry	1448	64	1384	94	9	85	0.346
7 Special Equipment Manufacturing Industry	1629	81	1548	90	14	76	0.486
8 Furniture Manufacturing Industry	1086	36	1050	86	12	74	0.273
9 Instrumentation Manufacturing Industry	1086	36	1050	86	9	77	0.287
10 Textile Industry	1448	64	1384	80	27	53	0.202
11 General Equipment Manufacturing Industry	1629	81	1548	70	10	60	0.407
12 Printing Industry	543	9	534	57	5	52	0.619
13 Arts and Sports Goods Manufacturing Industry	1086	36	1050	51	7	44	0.291
14 Electrical Machinery and Equipment Manufacturing	1448	64	1384	50	8	42	0.501
15 Food Manufacturing Industry	1448	64	1384	45	9	36	0.248
...	...	...	...	...	...	...	...

### 3.3. Spatial pattern of industrial co-agglomeration

This study measured the spatial co-agglomeration relationships between 181 three-digit industries of 31 categories of manufacturing TDIs within the spatial scope of the CCUA. Here was a total of 32,761 pairs of three-digit industrial co-agglomeration indices. In this study, the co-agglomeration among three-digit industries within different TDIs was defined as cross TDI co-agglomeration, and the co-agglomeration among three-digit industries under the within TDI was defined as same-digit industrial co-agglomeration. The results showed that the minimum value was 0 with a frequency of 2865 (8.75%) and the maximum value was 1 with a frequency of 638 (1.94%). In addition, there were 1738 (5.30%) indices of industrial co-agglomeration that were significantly co-agglomerated in a statistically significant way. Of the 31,516 results of cross-digit industrial co-agglomeration, 1438 (4.56%) were statistically significantly co-agglomerated. Of the 1245 results for same-digit industry co-integration, 298 (23.94%) were statistically significant.

Based on the above data, it can be judged that the level of same-digit industrial cohesion in the CCUA was significantly higher than the level of total industrial cohesion and cross-digit industrial cohesion. It can be seen that the core industries of the network at the level of the CCUA mainly included Transportation Equipment Manufacturing Industry, Electronic Equipment Manufacturing Industry and Metal Products Industry (Table 3). Therefore, this study used these three types of industries as representatives and used the kernel density in ArcGIS software to visualize and characterize the industrial space of the CCUA and superimpose them to get the industrial space pattern of the urban agglomeration.

Obviously, the regional industrial pattern presents a “point-axis” structure (Fig. 8). On the one hand, there were two industrial axes in the urban agglomeration, namely, the development axis of the Chengdu urban agglomeration (Mianyang-Deyang-Chengdu-Meishan-Leshan), and the development axis of the Yangtze River urban agglomeration (Yibin-Zigong-Luzhou-Dazu-Chongqing central city-Fuling). On the

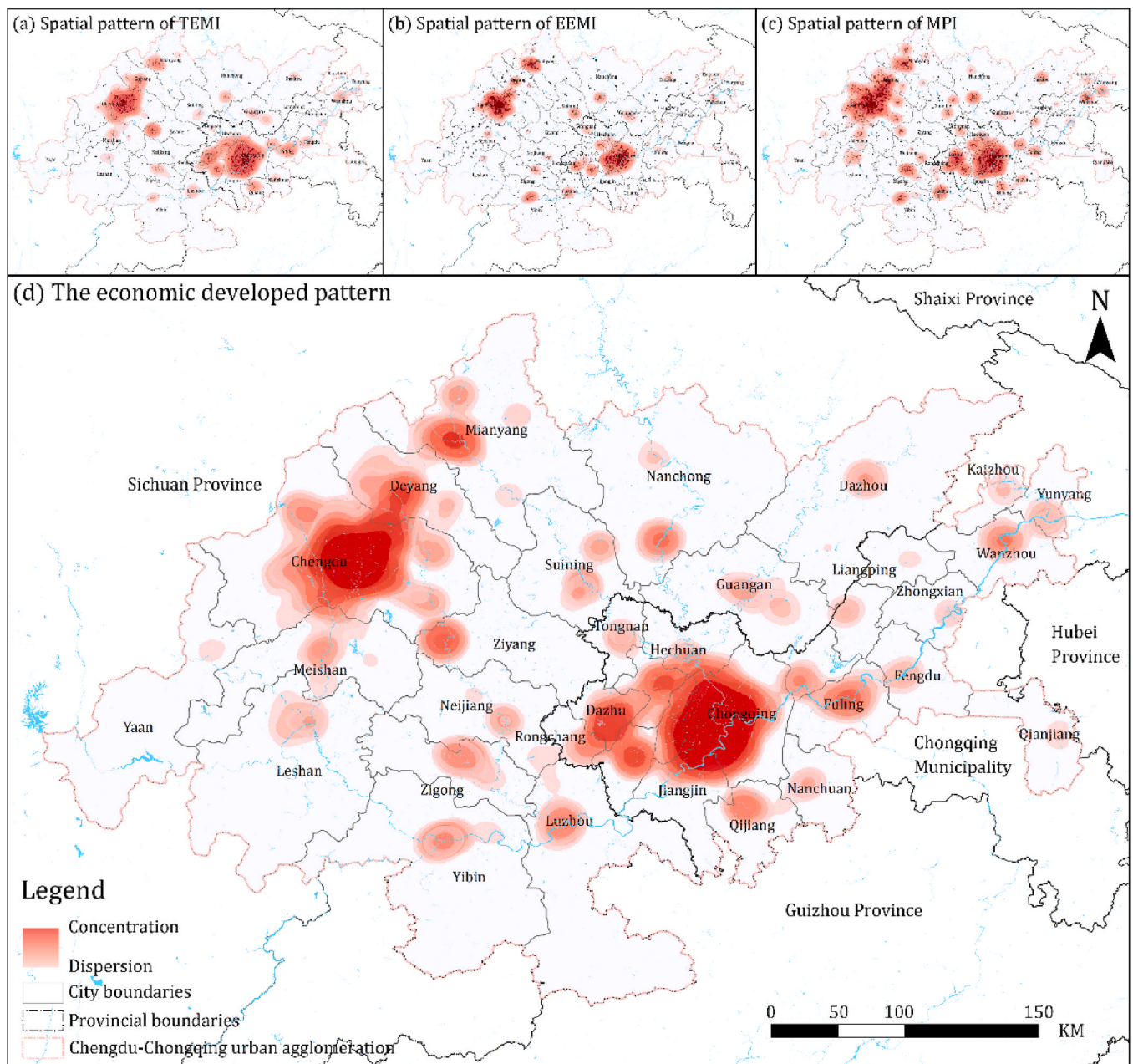


Fig. 8. The spatial patterns of industrial co-agglomeration in the CCUA.

other hand, the urban agglomeration had five-point set spaces with active economic activities. Among them, the Chengdu Urban Agglomeration and the Chongqing Urban Agglomeration had the most active economic production activities and the largest radiation, which were the core of the two industrial axes. There were three other urban agglomerations in the region that were also economically active, namely the southern Sichuan economic zone (Yibin, Zigong, Luzhou and Neijiang), the eastern Sichuan Economic zone (Nanchong, Suining and Guang'an) and the Da-Wan economic zone (Dazhou and Wanzhou). From the spatial pattern, it can be seen that there were active economic cooperation activities across municipal and provincial boundaries within the urban agglomeration, and the development of cities was closely linked to each other. The large cities better drove the development of the surrounding small and medium-sized ones. On the contrary, the southwestern and northeastern parts of the urban agglomeration were less economically active, the number of core industries was smaller, and the development radiation of large cities to them was weaker. Overall, the urban agglomeration had a deep industrial base and was dominated by high-tech industries, mainly developing the transportation equipment industry, the electronic information industry and the energy and material industry. The agglomeration of the metropolitan area with the central cities of Chengdu and Chongqing as its core was obvious. However, there were fewer dense urban areas and a large number of small cities.

### 3.4. Spatial pattern of ecological and economic conflicts

By comparing the ESP and EPP on the same base map of the study area, obvious spatial conflicts can be found (Fig. 9). The conflict areas were mainly distributed around the ecological corridor type II and type III in the ESP, and on the "point-axis" structure in the EPP. Among them, the largest conflict areas were mainly within the Chengdu Urban Agglomeration and Chongqing Urban Agglomeration (Fig. 8(a) and (b)). In the Chengdu Urban Agglomeration, there were three ecological corridor type III and two ecological corridor type II running through the urban construction and agricultural development areas of Chengdu, Deyang, and Mianyang, and the length of the corridors was greater than 60 km (Fig. 9(a)). Especially in Mianyang, where the conflict between ecological preservation and economic development was obvious, and the secondary corridors run through the urban construction core (Fig. 9(a)). It was feared that the corridor will be blocked if there was no intervention in it. In addition to this, there was also a risk of ecological source areas being disturbed by economic activities, mainly in the west of the Chengdu Urban Agglomeration, where there were extremely important ecological source areas. In the Chongqing Urban Agglomeration, the ecological sources were more broken and the ecological corridors were shorter and mostly ecological corridor type III. Ecological sources and corridors were subject to high-intensity disturbance from economic development, and a number of ecological sources and corridors in the center of Chongqing had been isolated from economic activities and had lost contact with surrounding sources (Fig. 9(b)). This could lead to serious impediments to species migration. Meanwhile, it was worth noting that the conflict situation in other densely populated urban areas should not be ignored. For example, in Leshan, Yibin and Zigong, it can be seen that there were primary ecological corridors in conflict with EPP (Fig. 9(c) and (d)). In addition, river corridors such as the Yangtze, Minjiang and Jinsha rivers within the urban agglomeration also flow through the cities and had areas of overlap with the economic production grid. In addition, the cities of Yunyang, Wanzhou and Fuling in the eastern part of the region also had conflicts to varying degrees. Overall, in terms of ecological resources, the ecological corridor type I and crucial source were disturbed, but the performance was not serious. Conflicts with economic development were mainly in the corridor, normal source, and some of the corridor type III. In terms of economic development, the problem of ecological-economic conflicts was more obvious in large and medium-sized cities, and still occurs in the urban

construction areas of these cities.

## 4. Discussion

### 4.1. Analysis of ecological-economic conflicts

The ecological-economic conflicts observed in the CCUA are not coincidental; they arise from the interplay of multiple driving factors, with land cover changes, policy orientations, and industrial characteristics serving as core mechanisms (Düben and Krause, 2022; Li et al., 2024; Luo et al., 2025). Moreover, these factors form a chain reaction that amplifies the intensity of ecological-economic conflicts.

#### 4.1.1. Policy driving: guidance of development orientation

Policy orientation has intensified the spatial competition between ecological and economic interests. As a nationally designated strategic urban cluster, the Sichuan-Chongqing metropolitan area has long prioritized economic growth targets in regional development policies, implementing preferential measures such as land supply and tax incentives for key industries (Fang et al., 2025). This has accelerated the concentration of manufacturing in core cities, yet policy implementation has lacked effective ecological constraints (Wang et al., 2025). Meanwhile, ecological conservation policies have primarily focused on macro levels, lacking detailed spatial guidance for conflict zones. This has resulted in the overlap of high-intensity economic production spaces with ecological resources.

#### 4.1.2. Land cover change: direct spatial occupation

The rapid expansion of construction land is a key driver of ecological space compression (Chen et al., 2023). In core economic zones like the Chengdu Plain and central Chongqing, the continuous increase in land allocated for industrial parks, infrastructure, and residential areas directly erodes surrounding low-level ecological resources. As the foundational framework of regional ecological networks, the fragmentation and loss of these resources disrupts connectivity to higher-level ecological sources, leading to the isolation of ecological corridors (Luo et al., 2025). For instance, Class III ecological corridors in the Chengdu-Deyang-Mianyang region are interspersed with urban construction land and farmland. Continuous occupation reduces the effective width of these corridors, increasing barriers to species migration (Wang et al., 2022).

#### 4.1.3. Industrial type characteristics: differences in ecological impact

Industrial types and agglomeration patterns determine the intensity of ecological-economic conflicts. Core industries such as transportation equipment manufacturing, electronic equipment manufacturing, and metal products manufacturing exhibit distinct ecological impact characteristics. Metal products manufacturing and transportation equipment manufacturing demand extensive land and generate environmental emissions (Wang et al., 2025). Their concentration in industrial parks drives the expansion of pollution hotspots, degrading the quality of surrounding ecological corridors. While the electronics manufacturing sector has lower pollution emissions, its demand for clean energy, water resources, and supporting infrastructure construction intensifies pressure on regional ecological services such as water supply and soil conservation (Wang et al., 2023). Concurrently, industrial clustering further squeezes surrounding ecological space.

Moreover, these three types of mechanisms govern conflicts in distinct regions. Core cities are primarily shaped by policy guidance and industrial drivers. Their high-intensity industrial clusters directly encroach upon ecological spaces. In contrast, for node cities, the primary cause of ecological-economic conflicts is land use changes, as these cities are situated along key development axes. Ecological barrier zones are characterized by a strong policy orientation toward ecological conservation; however, local demands for industrial development persist, creating a tension between ecological protection constraints and the

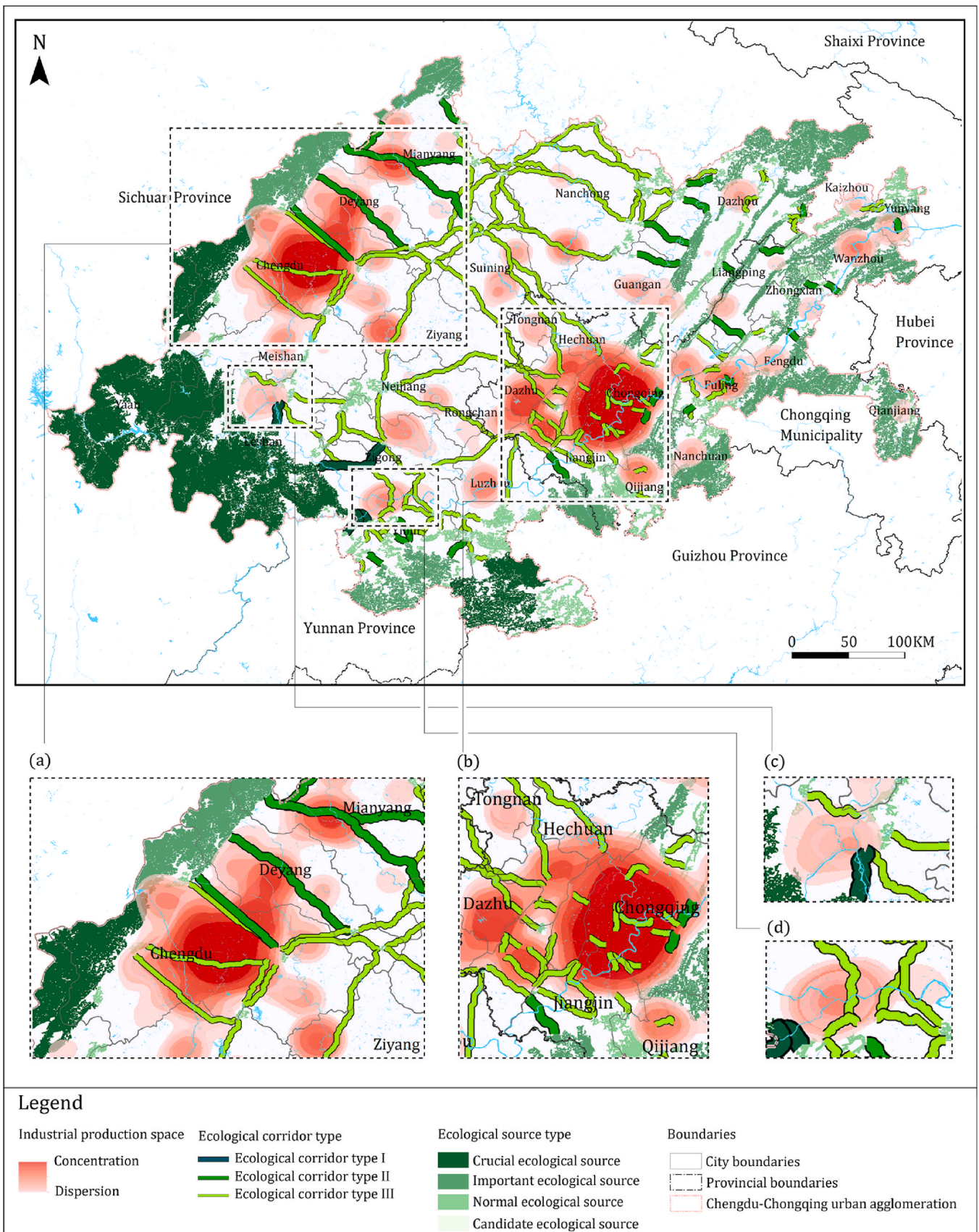


Fig. 9. The spatial patterns of ecological and economic conflicts in CCUA.

need for industrial growth.

4.2. Construction of the sustainable development pattern in the CCUA

4.2.1. Overall framework design of SDP

First, the SDP should adhere to the principle of “ecological priority and green development.” Within the ESP, an ecological barrier system with a “three-sided enclosure and northern opening” characteristics should be constructed based on the ecological sources distribution characteristics of “more at the edges and less in the middle.” Five ecological axis should be constructed based on the ecological corridors and sources, with segmented protection implemented in conjunction with land use and resource characteristics. In the EPP, based on the spatial characteristics of core industries, a development main axis and two industrial development belts should be constructed, centered on Chengdu and Chongqing. Simultaneously, cities at the intersection of the ESP and the EPP should make comprehensive development plans that clearly define the functional roles and boundaries of industrial core zones, industrial development belts, and ecological axis. These plans should reasonably lay out industries, and reserve sufficient ecological buffer space. In summary, this study identified the Chengyu Urban Agglomeration’s sustainable development framework of “one Development Main Axis, two Economic Development Cores, two Industrial

Development Belts, five Ecological Axis and five Ecological Barrier Areas” (Fig. 10). This result is consistent with official documents and other relevant content. Additionally, it overlays ecological and environmental protection strategies with economic development strategies on the same base map, providing spatial guidance for balancing high-level protection with high-quality development. This pattern can serve as a strategic roadmap for the sustainable development of the CCUA, guiding more detailed planning and design for cities.

4.2.2. Refined planning and design strategies under the SDP guidance

Planning and design should follow the guidance of the SDP. In the ESP, the development of a multifaceted system for corridor planning and design is illustrated in Fig. 11. The ecological corridors type I should be protected intact. Additionally, they should create a primary protection corridor for important ecological barriers. The corridor type II prioritize ecological preservation and can be used as urban structural green infrastructure, such as green belts and green wedges around the city, to create a demonstration corridor for ecologically prioritized green development. The corridors type III should be aimed at ecological preservation and smart recreation. These corridors should fully exploit the natural and humanistic backgrounds of cities and towns and create demonstration corridors of ecological and humanistic charm in park cities. In areas adjacent to economic activity and in agricultural zones,

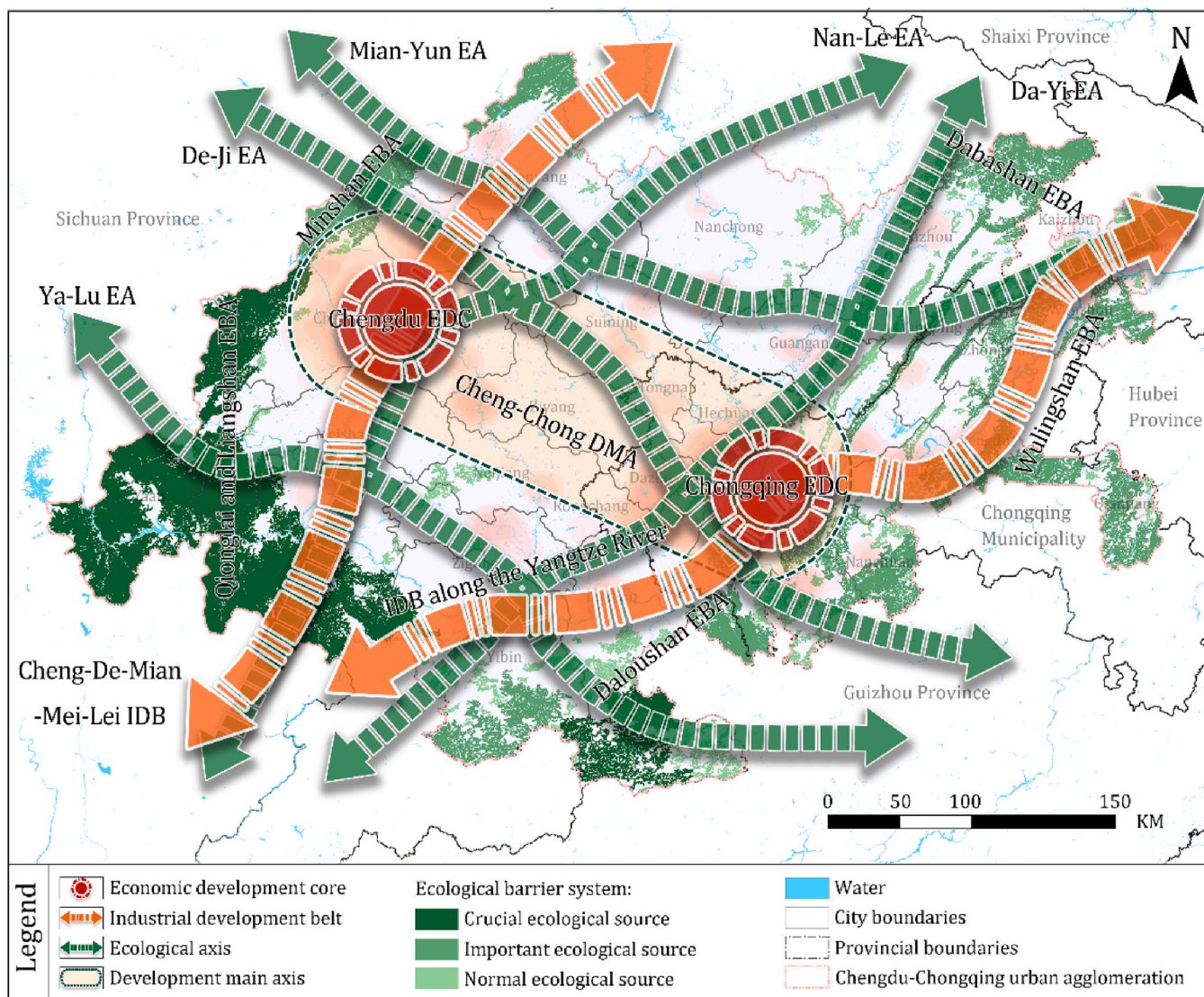


Fig. 10. The sustainable development pattern of CCUA.

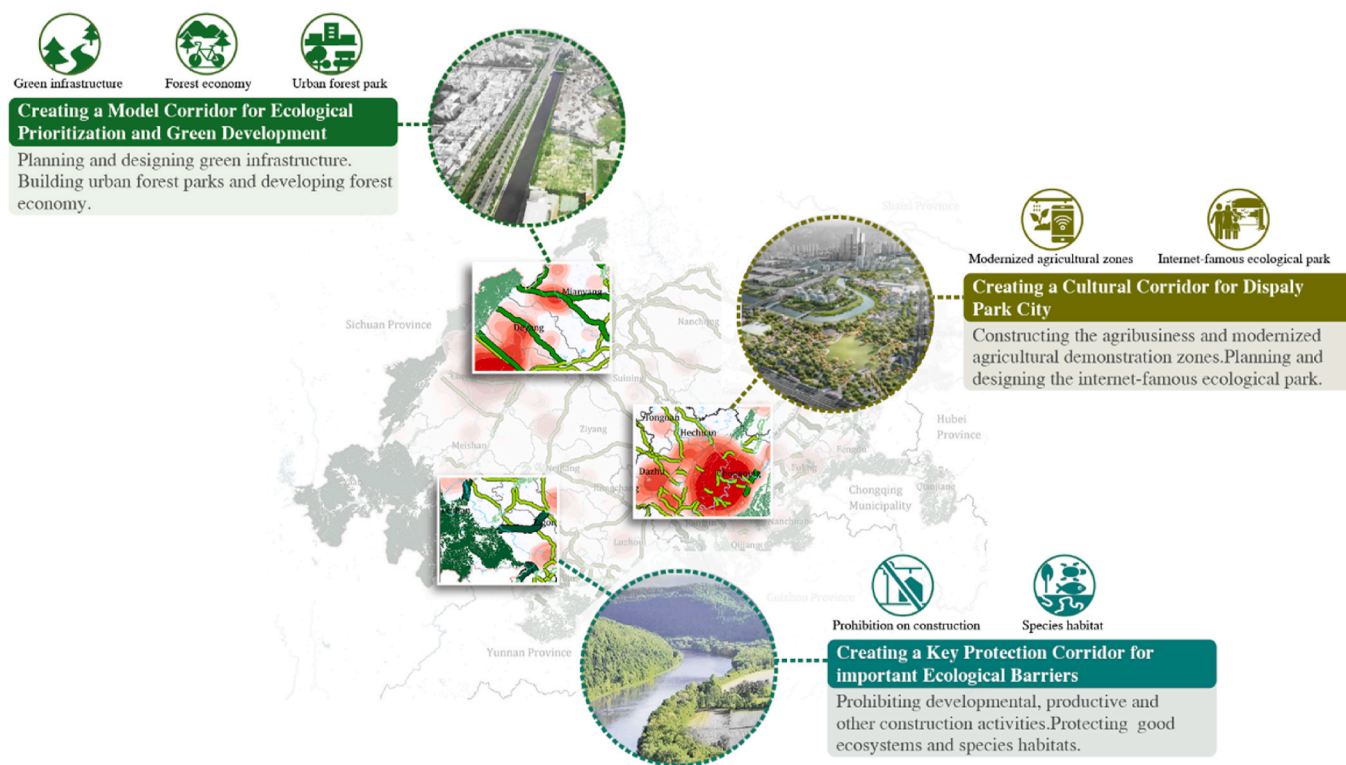


Fig. 11. The spatial planning and design of ecological corridors.

the construction of agricultural complexes and modern demonstration zones is to be initiated. The objective of this initiative is twofold: first, to ensure the integrity of the ecological network is maintained, and second, to address the needs of both urban and rural development.

In regard to industrial layout, the following measures should be implemented: first, restrictions should be imposed on self-organizing models; second, the development of ecological tourism in urban areas within ecological barrier zones should be promoted; and third, the relocation of industrial core zones to surrounding areas should be encouraged to drive regional development. In order to address the conflict between the suburban layout of traditional manufacturing industries and ecological corridors, a layout model combining concentration and dispersion is being implemented. This objective entails the establishment of diverse spatial carriers, including development zones, education and research institution hubs, and the revitalization of obsolete industrial zones. The scale of industrial land units is being regulated, and green belts, ecological parks, and bridges are being planned between enterprises to ensure landscape connectivity and species migration.

In regard to industrial structure, the promotion of the green transformation of industry and energy structure is imperative. This will facilitate the green upgrading of traditional industries, the strict control of new production capacity in the petrochemical and iron and steel industries, the cultivation of green emerging industry clusters such as new-generation information technology and biomedicine, the research of green technologies, and the construction of carbon-neutral laboratories and green engineering research centers.

#### 4.2.3. Alignment with regional policy framework

The core contribution of this study is to break the separate planning paradigm of ESP and EPP, and construct the SDP that is highly compatible with regional policy contexts and has strong operability. The proposed SDP closely aligns with the core objectives of key official documents, forming a complementary relationship with existing regional policies. This study establishes "two Economic Development

Cores" and "two Industrial Development Belts", aligning with the objectives of the Chengdu-Chongqing Economic Circle Development Plan. The study strategy refines industrial layout, responding to the official document's requirement to "optimize the spatial distribution of industries." By clarifying industrial and ecological conservation requirements, this study addresses the planning gap in refined coordination between industry and ecology, thereby enhancing industrial layout guidelines. The proposed "five Ecological Axis and five Ecological Barrier Areas" align with the ecological framework of the Chengdu-Chongqing Economic Circle Ecological Environment Protection Plan, strengthening cross-regional environmental governance. Building upon macro-level policy directives, the study introduces ecological buffer zone designs to enhance implementation rigor.

#### 4.3. Research innovations and future prospects

##### 4.3.1. Core innovations

Current research on the ESP focuses on the spatial characteristics of ecosystems but does not adequately consider their interactions with socio-economic systems (Li et al., 2022). The study of ESP should be combined with regional development strategies and other practical issues to rationally construct planning objectives under specific scenarios (Li et al., 2023). Additionally, although theoretical discussions on ecological security pattern planning have produced abundant results, there is still a lack of case studies on transforming theoretical results into actual projects (Dong et al., 2024). The effectiveness of applying the relevant theories in practice needs improvement. Against this background, this study innovates and complements research on ecological security patterns in terms of methodology and results.

In terms of theory and methodology, this study introduces the "Ecological-Economic Bidirectional Optimization" framework, which overcomes the limitations of traditional linear research paradigms such as "identification–diagnosis–optimization". It clarifies the dynamic interaction between the ESP and EPP, emphasizing that the optimization of these two systems is not a one-time planning process but an ongoing

cycle of adjustments based on feedback mechanisms. This approach enriches the theoretical foundation for eco-economic coordination and provides a versatile analytical tool for urban agglomerations facing the challenge of balancing ecological conservation with economic development. At the methodological level, machine learning is utilized to characterize industrial agglomeration patterns, overcoming the limitations of traditional economic indicators in capturing spatial dynamics and achieving cross-scale integration between economic and ecological analyses.

In terms of results, this study constructs a closed-loop system encompassing spatial diagnosis, mechanism analysis, pattern construction, and strategy adaptation. By identifying regionally dominant eco-economic conflict mechanisms, the proposed SDP approach enables differentiated optimization of the ESP and EPP, making the planning schemes more targeted and actionable. Moreover, it underscores that the implementation of the SDP provides valuable feedback for further adjustments to both ESP and EPP, thereby creating a dynamic optimization cycle.

#### 4.3.2. Future prospects and limitations

There are some limitations in this study. Firstly, we have neglected the width characteristics of ecological corridors. The width of ecological corridors not only determines the success rate of migration of key species, but also has a direct impact on the edge effect (Xie et al., 2023). Meanwhile, the subsequent analysis of other industries such as the service industry can be supplemented to more comprehensively reveal the spatial characteristics of the regional economic. In addition, this study only analyzed based on single time data. The study of temporal and spatial evolution helps to reveal the development and change rules of ecological networks and industrial space, which can lead to more effective planning and design strategies (Düben and Krause, 2022, Wei et al., 2025).

## 5. Conclusion

The framework proposed in this study incorporated considerations of the ecological and environmental impacts of economic production activities. Centered on the feedback logic between development and conservation, it broke through the limitations of traditional research paradigms, and proved that the research on ecological network was a multi-model, multi-method and multi-technology research, which was the result of the mutual game of interests of all parties. In addition, the superimposed spatial characteristics of the two patterns were more effective in providing important references for urban sustainable development planning and design. The conclusions were as follows:

- (1) The ESP of the CCUA was characterized by “external encirclement and internal linkage”.
- (2) The EPP of the CCUA presented the characteristics of “dual-core drive, axis series connection”.
- (3) Ecological-economic conflicts were mainly reflected in the fact that low-grade ecological resources were more vulnerable to economic activities, and ecological and environmental problems were serious in economically active areas.
- (4) The SDP consisted of “one DMA, two EDC, two IDB, five EA and five EBA”, which could strengthen planning leadership.

This result aligns with the core objectives of official documents, validating the correctness of the research direction. Furthermore, the plan addresses the scientific question of “how to promote high-quality development through high-level conservation” in spatial planning, offering more refined theoretical and practical guidance for regional sustainable development. By integrating into the regional spatial planning system, refining cross-regional coordination mechanisms, and aligning policy tool chains, the study effectively advances the coordinated ecological and economic development of the CCUA, providing valuable

insights and universal analysis tool for other urban agglomerations facing similar ecological-economic challenges.

## CRedit authorship contribution statement

**Ao Kang:** Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Ying Huang:** Validation, Methodology, Data curation. **Jiajing Li:** Methodology, Formal analysis, Data curation. **Xinyu Lin:** Visualization, Resources, Formal analysis. **Xiaoyu Gan:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All the co-authors agreed to participate in the research. All the co-authors agreed to publish the manuscript.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2026.100401>.

## Data availability

Data will be made available on request.

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