INTEGRATING ECOSYSTEM SERVICES AND RISK TO OPTIMIZE ECOLOGICAL SECURITY PATTERNS IN TYPICAL ECOLOGICAL TRANSITION ZONES, CHINA

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Abstract. The ecological security of transition areas faces significant challenges due to the combined effects of climate change and human activities. As a typical ecological transition zone, Sichuan Province in China is highly sensitive to environmental changes. In response to the complexity of the region, this study uses multi-source data to conduct quantitative assessments of the supply capacity, ecological demand, and ecological risk of ecosystem service functions. By integrating widely applied models, the “supply-demand-risk” concept is incorporated into the traditional ecological security pattern framework, enabling multi-indicator synergistic analysis and optimization of ecological security patterns in ecological transition zones. The main results were as follows: pronounced east-west disparities exist in the ecological service supply and demand across Sichuan Province. Medium-level landscape ecological risk was predominantly distributed in the western mountainous areas, while high-level risk zones persisted in eastern urban construction land. Based on the distribution characteristics of ecological source areas, ecological corridors, and nodes in different regions, an optimized ecological spatial configuration called “Three zones, Three belts, and One cluster” was proposed. Within this framework, targeted ecological protection strategies were proposed to support sustainable ecological–social development and strengthen ecological security in transition zones.

Keywords: *supply-demand-risk framework, integrated multi-model approach, landscape connectivity, ecological corridors, Sichuan Province*

Introduction

In recent decades, the rapid socioeconomic development coupled with global climate change has exerted unprecedented pressures on ecosystems, leading to diverse manifestations of ecological degradation and posing a significant threat to ecosystem stability (Shumway et al., 2018). Finding a suitable equilibrium between economic growth and environmental conservation, tapping into and harnessing limited ecological resources, and enhancing regional ecological security have emerged as pivotal concerns in current ecological research and planning endeavors (Yang et al., 2023).

Ecosystem services constitute the material foundation of ecological security, and quantitative evaluations of ecosystem services have revealed the ability to provide Ecological Service Supply (ESS), which either directly or indirectly underpin the natural conditions indispensable for human progress (Ying et al., 2022; Le Provost et al., 2023). However, existing researches have used relatively narrow indicators for evaluating ecosystem service functions. As society and the economy development, the human demand for resource extraction rises rapidly and construction land expands constantly, which often leads to a spatial mismatch between the regional service supply and demand (Zhang et al., 2022). Consequently, when enhancing the comprehensive assessment of ESS via multiple indicators and in combination with the study of Ecosystem Service Demand (ESD), it is necessary to modify the supply–demand dynamics, ensure equilibrium between supply and demand, and reconcile the tensions between the advantages of economic growth and the need for ecological conservation (Liang et al., 2022). In addition, regional ecological security is also influenced by Landscape Ecological Risk (LER). Through the assessment of regional LER, we can evaluate the degree of risk posed by external interference with the ecosystem (Peng et al., 2015). Although scholars have incorporated the LER index into their research on landscape patterns and regional ecological security, conducting effective explorations (Ayre et al., 2012; Xie et al., 2024; Fu et al., 2024), this alone does not directly guide ecological protection actions. Therefore, on the basis of ESS and ESD research, the approach of incorporating LER research to form a spatial integration framework and build a comprehensive Ecological Security Pattern (ESP) can achieve multi-objective collaborative optimization.

The ESP acts as a crucial scientific basis for harmonizing regional ecological conservation and development. Its objective is to facilitate a development trajectory centered around harmonious human-nature relations by eliminating or mitigating human impacts on natural ecosystems. Current ESP research largely follows the workflow of “Ecological sources identification - Resistance surface establishment - Ecological corridors extraction” (Luo et al., 2024). Ecological sources serve as the foundation for ecological land conservation, providing habitats for current species and facilitating the exchange and spread of species (Liu et al., 2022a). In early studies, large areas of forestlands, grasslands, waters, ecological reserves and habitats were classified as ecological sources by subjective methods, overlooking the potential ecological important areas (Chen et al., 2024). Subsequently, numerous researchers included factors such as ecological significance, landscape connectivity, and ecological sensitivity in their approaches to identifying ecological sources. Although the focus of identification was shifted from a single land use type to a broader ecological situation, these approaches failed to reveal the interactive relationship between natural ecology and human society (Gao et al., 2024). The core functionality of the Morphological Spatial Pattern Analysis (MSPA) model lies in employing mathematical morphology algorithms to perform meticulous classification of landscape patterns, thereby enabling the objective and precise identification of spatial structural features within landscape elements, such as core areas, edge zones, and pores. In contrast to traditional subjective delineation methods, this model can more effectively prevent the overlooking of core habitats and markedly enhance the precision of ecological connectivity assessments. At present, many scholars are keen to study the use of MSPA model to identify ecological sources, and examine how the supply and demand for various ecosystem services interact. The resistance surface can reveal the obstacles faced by species migration and ecological flow to a certain extent. Initial research primarily focused on creating resistance surfaces using natural elements like terrain and vegetation. Over time, they began to incorporate additional data, including night light indices and road density, to combine the effects of natural factors with human activities, resulting in a more complete resistance surface (Kang et al., 2021), to quantify the combined blocking effects of natural and anthropogenic factors on ecological flow. Ecological corridors serve as crucial links connecting isolated patches of ecological sources and facilitating the smooth flow of materials and energy. They are essential components in creating an ecological security framework and provide a viable solution to the problem of ecosystem fragmentation (Ding et al., 2024). Building upon the static optimal pathways identified through the traditional Minimum Cumulative Resistance (MCR) model, the integration of circuit theory has effectively characterized biological stochastic movement, species migration randomness, and corridor width variability (Ma et al., 2023; Xu et al., 2023). This methodology has facilitated the categorization of priority conservation corridors and the identification of ecological nodes influenced by human activities or natural topographic constraints. In this context, the transition from single-factor regulation to comprehensive ecosystem management represents an inevitable trend in the development of a new paradigm for ESP (Wang et al., 2022). By comprehensively considering the diversity, integrity, systematicity, and coordination of ecological elements, we provide support for establishing a new ESP that fosters harmonious coexistence between humanity and nature.

Sichuan Province is located in the transitional zone of China’s terrain ladder, and due to its complex and diverse topography, climate, ecosystem, and socio-economic development, it has become a typical ecological transition zone in China. The ecological environment in this region has significant spatial differences, posing special challenges to biodiversity and sustainable development (Li et al., 2025a). Moreover, within the framework of the China strategy for industrial transfer to western regions, Sichuan Province has been designated as a crucial strategic reserve area and a key industrial backup base. Consequently, substantial adjustments are required to its primary productive forces. Nonetheless, the rapid increase in regional economic development, the quick advancement of urbanization, and the continuously growing extent of construction have heightened habitat fragmentation, lead to an increasingly severe spatial mismatch between ESS and ESD. The traditional process of constructing ESP has not adequately addressed the interactions between ESS and ESD (Lin et al., 2023), nor has traditional ESP construction sufficiently considered LER. Therefore, integrating the relationships between ESS and ESD, incorporating ERI, and establishing a comprehensive ESP can human social development in the ecological transition zone under the background of the “Eastward shift of production to the west” initiative. This approach aims to guarantee ecological security, optimize industrial layouts, and promote a balanced growth between natural ecosystems and human communities.

This study focuses on Sichuan Province of China as the research area. Based on the United Nations Millennium Ecosystem Assessment framework, seven indicators were chosen, including Carbon Sequestration (CS), Water Services (WS), Soil Retention (SR), Habitat Quality (HQ), Biodiversity Maintenance (BM), Green Recreation (GR), and Food Supply (FS), the Integrated Ecosystem Service Supply (IESS) capacity was assessed from a spatial perspective. Additionally, the Ecological Risk Index (ERI) was introduced to identify areas characterized by low LER and high ESS capacities, which were subsequently utilized for the identification of ecological sources. Following this, a framework integrating ESS and ESD was proposed, taking into account the “basic-desired-spatial” needs of human society. Finally, these components were integrated to construct the ESP in Sichuan Province, China.

Materials and methods

Study area

Sichuan Province is located in the southwestern region of China (97°21′-108°33′E, 26°03′-34°19′N), covering a total area of 48.60×10^4 km^2 and includes 21 prefecture-level administrative regions (*Fig. 1*). The province exhibits a striking topographical difference, characterized by complex and diverse terrain. The elevation ranges from 199 to 7162 m, spanning subtropical humid and semi-humid climate zones as well as alpine and frigid plateau climate zones. There are 32 national nature reserves in the province, which protect important habitats for wildlife and intact ecosystems.

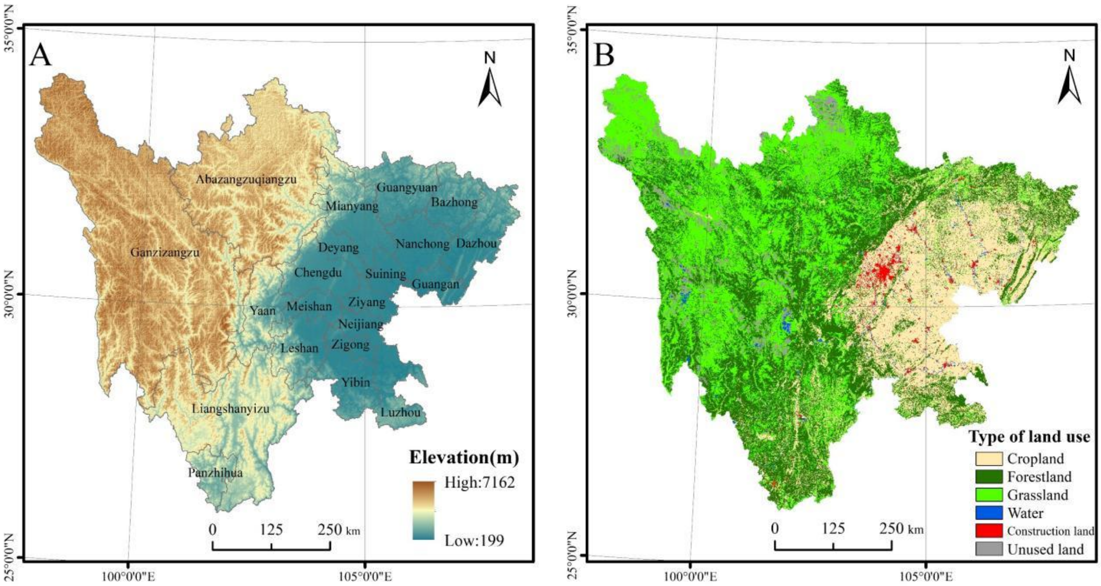

Figure 1. *Geographical overview of Sichuan Province. (A) elevation (generated based on DEM, https://earthexplorer.usgs.gov/), (B) land use types in 2020 (https://www.resdc.cn/)*

Data sources

This study contains multiple data types. All datasets were visualized and resampled to a resolution of 1 km × 1 km. The specific data sources are presented in *Table 1*.

Table 1. *Data attributes and sources*

Data type	Name	Spatial resolution	Unit	Year	Sources
Land use data	Type of land use	30 m	—	2020	https://www.resdc.cn/
Terrain data	DEM	30 m	—	2020	https://earthexplorer.usgs.gov/
	Elevation, slope and aspect	1 km	Elevation: m; slope and aspect: °	2020	Generated based on DEM
Vegetation data	NPP	500 m	kg C/m^2	2020	https://lpdaac.usgs.gov/
	NDVI	1 km	—	2020	https://www.gscloud.cn/
Soil data	Soil texture	—	—	2020	https://www.fao.org/
Meteorological data	Precipitation	1 km	mm	2020	https://www.resdc.cn/
	Evapotranspiration	1 km	mm	2020	http://www.geodata.cn/
	Temperature	1 km	°C	2020	https://data.cma.cn/
Socio-economic data	Food production	—	—	2020	https://tjj.sc.gov.cn/
	Population size	—	persons	2020	https://tjj.sc.gov.cn/
	Population density	1 km	persons/km^2	2020	https://www.worldpop.org/
	GDP per capita	1 km	million CNY	2020	https://geodata.nnu.edu.cn/

Methods

The methodology comprises five main steps: (1) Conduct research on ESS using preprocessed natural and socio-economic data. (2) Analyze ESD of human society. (3) Overlay multiple ESS to obtain integrated IESS, and introduce ERI to achieve spatial expression of Potential Ecosystem Service Provision (PESP). (4) Overlay different ESD to correct the basic resistance surface based on the combination of natural and human social factors and obtain a comprehensive resistance surface. (5) Combine MSPA and landscape connectivity to identify ecological source area, integrating MCR model and circuit theory to extract ecological corridors and conduct ecological network analysis, identifying key ecological nodes in the ecological corridors, constructing and evaluating ESP, and proposing suggestions for ecological optimization strategies based on ESP (*Fig. 2*).

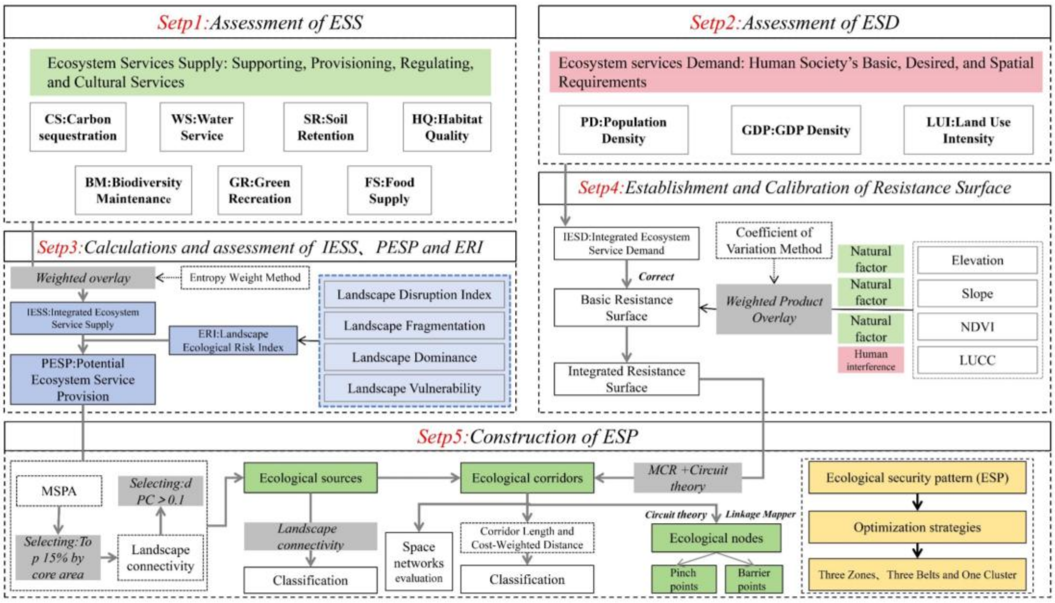

Figure 2. *Framework for the research process*

Ecosystem service supply assessment

This study employed the Carbon Storage module of the InVEST model and carbon density (Wu et al., 2022) to assess the spatiotemporal distribution of terrestrial carbon stocks across Sichuan Province in 2020. The carbon storage is calculated according to *Equation 1*.

$$C = C_{above} + C_{below} + C_{soil} + C_{dead} \qquad \text{(Eq.1)}$$

where: C is total carbon stock; C_{above} is above-ground biomass carbon stock; C_{below} is underground biomass carbon stock; C_{soil} is soil carbon stock; C_{dead} is dead organic carbon stock.

The WS capacity was quantified using the Water Yield module of the InVEST model, and the calculation was performed according to *Equation 2*.

$$Y_i = \left[1 - \left(\frac{A_i}{P_i}\right)\right] \times P_i \qquad \text{(Eq.2)}$$

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where: Y_i, A_i, and P_i represent the annual water yield, actual evapotranspiration, and precipitation, respectively.

The SR service was quantified using universal soil loss equation implemented in InVEST model (Zhang et al., 2025), and the calculation was performed according to *Equation 3*.

$$SR = R \times K \times L \times S \times C \times P \quad \text{(Eq.3)}$$

where: SR represents the soil conservation capacity; R represents the rainfall erosion factor; K represents the soil erodibility factor. L and S are topographical factors; C represents the cover and management factors; P represents the soil and water conservation measure factor.

We assessed HQ using the Habitat Quality module of the InVEST model by integrating land use patterns and threat factors table, the calculation was performed according to *Equation 4*.

$$HQ_{xj} = H_j[1 - (\frac{D_{xj}}{D_{xj} + k^2})] \quad \text{(Eq.4)}$$

where: HQ_{xj} represents the HQ for grid cell x in land-use type j; H_j denotes the habitat suitability of land-use type j; D_{xj} represents the overall threat level at grid cell x for land-use type j; k is the half-saturation constant.

We employed the BM service capacity index as a core evaluation metric, and the calculation was performed according to *Equation 5*.

$$S_{bio} = NPP_{mean} \times F_{pre} \times F_{tem} \times (1 - F_{alt}) \quad \text{(Eq.5)}$$

where: S_{bio} represents the BM service capacity index; NPP_{mean} represents the multiyear average of vegetation net primary productivity; F_{pre} is the multi-year average precipitation; F_{tem} is the multiyear average temperature; F_{alt} is the altitude factor.

The proportion of green space within a defined radius was adopted as the GR indicator. Forestland, grassland, and water bodies were classified as green space components. Using buffer analysis, the percentage of green space within 1 km radius buffer zones was quantified to assess ecological service capacity (Xue et al., 2024).

Refer to the method of introducing value equivalent method to calculate regional ecosystem service value (Wang et al., 2024). Based on the specific situation of the study area (Xie et al., 2015), the food production supply coefficient was revised to obtain the FS value coefficient table for various land types (*Table 2*). Due to the significant impact of construction land on the ecological environment and its lack of direct effect on grain production in the study area, this study excluded its influence of construction land and recognized its ecosystem service value as 0 (Yang et al., 2024). The main grain crops in the study area are wheat, corn, and rice (Liu et al., 2022b). The grain data were used to calculate the service value coefficient of food production per unit area of each land type, and finally the food production service of the whole study area was obtained. The calculation was performed according to *Equation 6*.

$$ESV_f = \sum_{k=1}^{n}(A_k \times V_{kf}) \quad \text{(Eq.6)}$$

where: ESV_f represents the value of food provisioning services provided by the ecosystem; n denotes five types of land; A_k is the area of the k-th land type; V_{kf} refers to the food production service value coefficient of the k-th landscape type in the study area.

The above seven different ESS functions are standardized and weighted by entropy weight method (*Table 3*). Finally, the IESS is obtained by multiplying the weight of each indicator by the standardized data.

Table 2. *Value coefficient of food supply services by different land use types in Sichuan Province*

Type of land use	Cropland	Forestland	Grassland	Water	Construction land	Unused land
Value coefficient	1.105	0.250	0.233	0.655	0.000	0.010

Table 3. *Weights of supply indicators in different ecosystems in Sichuan Province, 2020*

Indicator type	CS	WS	SR	HQ	BM	GR	FS
Weight	0.1379	0.1225	0.2211	0.0638	0.1973	0.1225	0.1350

Ecosystem service demand assessment

Citing previous studies (Liang et al., 2024), this study divides the demand for ecosystem services into three parts: basic needs, expectation demands, and spatial demands for analysis, in order to meet the needs of human activities for ecosystems.

Generated the spatial distribution of Population Density (PD) was generated by calibrating WorldPop data with Sichuan Province’s 2020 Seventh National Population Census data, serving as a proxy for basic needs. The calculation formula was performed according to *Equation 7*.

$$\mathrm{PD} = \mathrm{PD_i} \times \frac{\mathrm{PD_R}}{\mathrm{PD_r}} \tag{Eq.7}$$

where: PD represents the adjusted population density; PD_i denotes population data from the WorldPop database; PD_R refers to population data by administrative division from Sichuan’s Seventh National Population Census; PD_r indicates population data obtained from administrative division-based statistics of PD_i.

GDP per capita reflects the socio-economic strength and human living standards in the region, which indirectly expresses human expected demands for ecosystem services. Introduce the 2020 Sichuan Province Statistical Yearbook was introduced to revise the GDP data of each administrative region were calibrated accordingly, and the calculation was performed according to *Equation 8*.

$$\mathrm{GDP} = \mathrm{GDP_l} \times \frac{\mathrm{GDP_R}}{\mathrm{GDP_r}} \tag{Eq.8}$$

where: GDP represents the adjusted per capita GDP; GDP_r represents the spatial distribution data of raw GDP; GDP_R stands for GDP data in the statistical yearbook.

Land Use Intensity (LUI) can reflect the space demand of human beings to meet their own survival and development (Fu et al., 2025), and the calculation process is presented in *Equation 9*.

$$\mathrm{LUI} = 100 \times \sum_{i=1}^{n} (A_i \times C_i) \tag{Eq.9}$$

where: LUI is the comprehensive index of land use, representing the intensity of land use; n represents different land use types; A_i is the land use type classification index for the i-th land use type; C_i is the proportion of the i-th land use type to the total area.

According to various researchers studying the balance of ESD indicators (Yang et al., 2022), basic needs, expected needs, and spatial needs are all considered equally vital for human survival and progress. The comprehensive demand for ecosystem services is calculated based on the above three different demands, and the calculation process is presented in *Equation 10.*

$$\mathrm{IESD} = \mathrm{PD}' \times \mathrm{GDP}' \times \mathrm{LUI}' \tag{Eq.10}$$

where: IESD represents the Integrated Ecosystem Service Demand. PD’, GDP’ and LUI’ are their respective normalized values.

Landscape ecological risk assessment

Landscape indices including fragmentation, separation, and dominance were calculated using Fragstats 4.2 Spatial analysis of LER was conducted based on ERI calculations in the study (Meng et al., 2025), and the calculation process was presented in *Equations 11–13.* The natural breakpoint classification method was used to classify the ERI in the study area into five categories for analysis: Low risk [0, 0.071), Medium-low risk [0.071, 0.082), Medium risk [0.082, 0.096), Medium-high risk [0.096, 0.122) and High risk [0.122, 0.150).

$$E_i = aC_i + bS_i + cD_i \tag{Eq.11}$$

$$R_i = E_i F_i \tag{Eq.12}$$

$$\mathrm{ERI}_i = \sum \sqrt{R_i \frac{A_{ki}}{A_k}} \tag{Eq.13}$$

where: E_i represents the landscape disturbance index; a, b and c are the weights corresponding to the landscape fragmentation index C_i, landscape separation index S_i and landscape dominance index D_i respectively. Weights were established according to the conditions of the study area, set to 0.6, 0.3 and 0.1 respectively; R_i represents the landscape loss index; F_i represents the landscape vulnerability index; ERI_i represents the risk index of the i-th ecological risk area, and the larger the value, the more serious the LER; A_{ki} represents the area of the i-th land use type in the k-th ecological risk area; A_k represents the area of the k-th risk area. ERI represents the landscape disturbance index.

Ecological security pattern construction

In reference to the current methods of extracting ecological source, this study employs the overlay of the integrated ESS and LER layers to derive the PESP, and the calculation process is presented in *Equation 14.*

$$\mathrm{PESP}_i = \mathrm{IESS}_i \times (1 - \mathrm{ERI}_i) \tag{Eq.14}$$

where: $PESP_i$ represents the potential supply of ecosystem services within the i-th grid; $IESS_i$ denotes the comprehensive supply of ecosystem services within the i-th grid.

The calculated PESP will undergo reclassification using ArcGIS 10.8, employing the natural breakpoint method for grading based on the actual data distribution. Regions with a potential supply of ecosystem services at or above the medium-level will be selected as prospect data and inputted into GuidosToolbox software for MSPA analysis.

An ecological source must attain a specific size to function effectively (Kang et al., 2021), but the current research deficient systematic methods to estimate the threshold of ecological source area (Zhou et al., 2021). Therefore, considering the ecological conditions and area scale of this area, the core area of landscape type based on MSPA output is selected, and the large area patches with the top 15% of the area ranking as the ecological sources (Liu, 2024) utilize Conefor software to calculate the ecological source importance dPC (Lucia and Santiago, 2006; Su et al., 2010; Wu et al., 2012). Finally, the dPC was greater than 0.1 as the threshold for extraction. According to the values of plaque importance index, ecological source can be divided into three levels: first-level (dPC > 10), second-level (1 < dPC ≤ 10) and third-level (dPC ≤ 1) ecological sources (Halimulati et al., 2021).

LUCC, elevation, NDVI, and slope data were selected to create a fundamental resistance surface in Sichuan Province. The resistance value is determined based on a correlation study conducted (Li et al., 2025b). Taking into account the characteristics of the evaluation factors, the data were divided into classified intervals following threshold schemes proposed in previous studies and adjusted appropriately according to the actual conditions of the study area, and each interval was assigned a resistance value ranging from 10 to 100. As the value increases, the resistance also increases. The coefficient of variation approach is used to determine the significance of each factor's weight (*Table 4*), and subsequently, the fundamental resistance surface is constructed by overlaying each factor layer in accordance with its respective weight.

Table 4. *Assignment of weight factors for comprehensive resistance surfaces in Sichuan Province, 2020*

Indicator type	Weight	Categorical intervals	Resistance value	Indicator type	Weight	Categorical intervals	Resistance value
LUCC	0.2972	Forestland, water	10	NDVI	0.2086	>0.7	10
		Grassland	20			0.5–0.7	20
		Cropland	40			0.3–0.5	40
		Unused land	80			0.1–0.3	80
		Construction land	100			<0.1	100
Elevation	0.2569	<800 m	10	Slope	0.2374	<2	10
		800–1600 m	20			2–6	20
		1600–2400 m	40			6–15	40
		2400–3200 m	80			15–25	80
		>3200 m	100			>25	100

The cost of species migration and ecological flows is influenced not only by natural factors such as terrain and vegetation but also significantly by human activity intensity. To reflect the coupling of the social–ecological system, this study adopts an ecological process perspective and introduces IESD as a proxy for human activity pressure to modify the basic resistance surface, and the calculation process is presented in *Equation 15.*

$$Z_i = \frac{IESD_i}{IESD_a} \times F_i \qquad \text{(Eq.15)}$$

where: Z_i represents the corrected ecological resistance value within the i-th grid; $IESD_i$ represents the comprehensive ESD value within the i-th grid; $IESD_a$ represents the average IESD of land use type a within the i-th grid; F_i represents the basic resistance value within the i-th grid.

ArcGIS 10.8’s Link Mapper toolbox was used to identify the least cost path among ecological sources (Wang et al., 2023b). The ratio of corridor length to cost-weighted distance determines the importance of the corridor (Castilho et al., 2015). A lower ratio indicates enhanced ecological efficiency and connectivity of the corridor path. Using the natural breakpoint method, classify ecological corridors based on the ratio of corridor length to weighted cost distance: first-level [0.0213, 27.723), second-level [27.723, 40.356) and third-level [40.356, 63.818) ecological corridors. Higher-level ecological corridors are identified as the most effective conduits among ecological substrates, whereas lower-level corridors are indicative of potential ecological connectivity.

In terms of ecological corridor evaluation, the α index, β index, and γ index are commonly used quantitative evaluation indices (Kong et al., 2010), and the calculation process is presented in *Equations 16-18.*

$$\alpha = \frac{L-V+1}{2V-5} \qquad \text{(Eq.16)}$$

$$\beta = \frac{L}{V} \qquad \text{(Eq.17)}$$

$$\gamma = \frac{L}{3(V-2)} \qquad \text{(Eq.18)}$$

where: L represents the number of corridors; V represents the number of nodes.

Pinch points are critical areas that help prevent the degradation or alteration of ecological spaces. In circuit theory, it refers to the area with high ecological flow density. Once destroyed, it will greatly destroy the connectivity of ESP (Fang et al., 2020). In this study, The Pinch Point Mapper tool was utilized to locate pinch points by running the Circuitscape program based on the current corridors. Barrier points are the areas where ecological flow is easy to be hindered during migration or activity, which can be regarded as key nodes hindering connectivity between source areas. Barrier Mapper tool is used to detect important barrier areas affecting corridor quality, and the high interval of resistance value is regarded as obstacle area to extract barrier points.

Results

Ecological service supply and demand capacity assessment

In Sichuan Province, different types of ESS capabilities exhibit spatial heterogeneity (*Fig. 3*). The research indicates that regions with strong CS are primarily located in the western mountainous areas and along the northern and southern edges of the eastern region, primarily distributed in areas dominated by forestland and grassland. In the east, the CS offered by construction land and cropland is low (*Fig. 3A*). WS shows a pattern of being higher in the east and lower in the west. Furthermore, the regions where the central mountains meet the basins show high water production capacity (*Fig. 3B*). The areas with high SR ability are mainly located in the central region (*Fig. 3C*) while on the eastern and western sides, the SR capacity is low. In the southern part, the SR capacity is greater than that in the northern part. *Figure 3D* shows that HQ and SR are spatially alike. The lower capacity are mainly located in the eastern construction land and cropland. The pattern of BM is high in the east (*Fig. 3E*), the areas with high BM are distributed in the same pattern as those with strong WS. The areas of forestland and grassland can supply more GR (*Fig. 3F*). Cropland is the main provider of FS capacity, mainly distributed in the eastern region (*Fig. 3G*). In general, the central region mainly has land use types like forestland and grassland that are the main providers of IESS. High IESS is also shown in the southern regions. In contrast, the eastern region, which has land use types like construction land and cropland, shows low IESS (*Fig. 3H*).

The PD (*Fig. 3I*), GDP (*Fig. 3J*) and LUI (*Fig. 3K*) are primarily influenced by anthropogenic activities. An increase in these metrics correlates with a heightened level of local economic development in ESD. The IESD based on "basic-expectation-space" presents distribution regarding "high in the east and low in the west" in spatial pattern (*Fig. 3L*). In the east, high IESD values are widely distributed in construction land and cropland types.

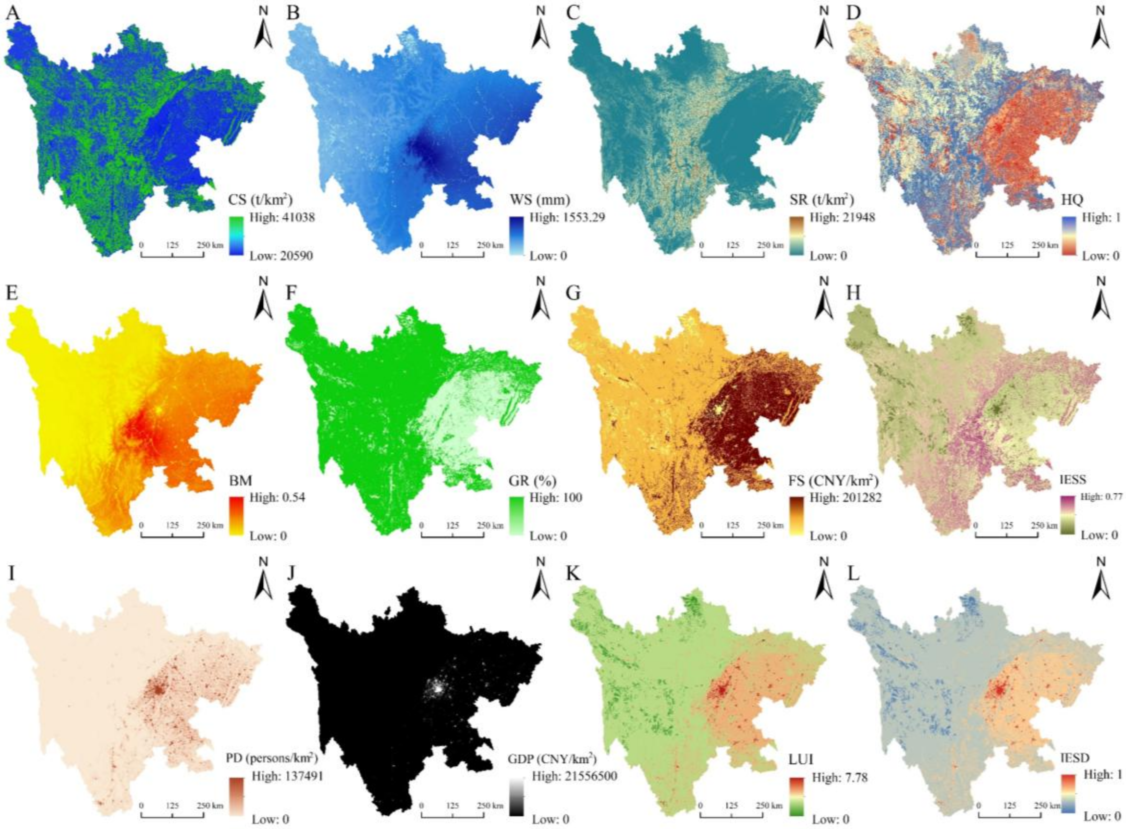

***Figure 3.** Spatial distributions of different supply and demand for ecosystem services in Sichuan Province, 2020 (abbreviations are defined in Table S1)*

Landscape ecological risk assessment

LER distribution exhibits significant spatial heterogeneity (*Fig. 4*). Low-risk areas are primarily concentrated in the east, with only a few scattered patches in the west. These areas cover 9.10×10^4 km^2, accounting for 18.72% of the total landscape area (*Table 5*), and are mainly composed of cropland and unused land. The Medium-low risk areas were mainly situated at the southern and northern edges of the Low risk areas and in the southern part of Sichuan. It was marked by a combination of cropland, forestland, and grassland, accounting for 22.79% of the total landscape area. The medium risk regions are mostly gathered in the western section of Sichuan, mainly consisting of forestland and grassland. The area is up to 27.76×10^4 km^2, which is the main LER level in the study area. It should be noted that the areas designated for construction in the eastern region have high ERI values and present an obvious spatial distribution pattern, which is approximately 1% of the study area.

Table 5. *Area and proportion of different landscape ecological risk levels in Sichuan Province, 2020*

Landscape ecological risk type	Area/×10^4 km^2	Proportion of total plaque area/%
Low risk	9.10	18.72
Medium-low risk	11.08	22.79
Medium risk	27.76	57.11
Medium-high risk	0.50	1.03
High risk	0.17	0.35

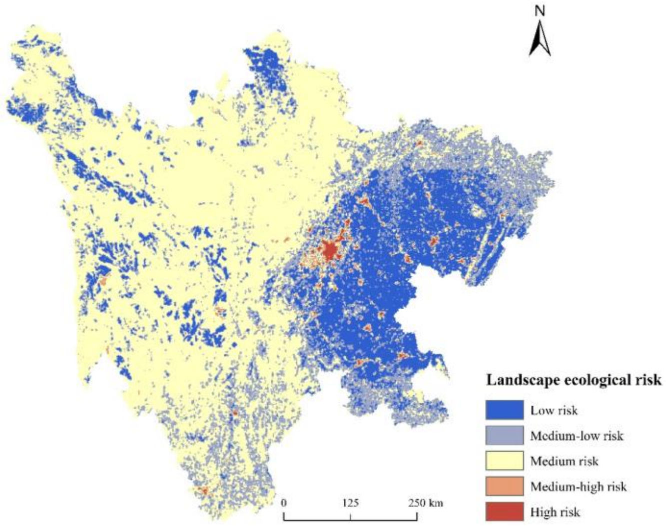

Figure 4. *Spatial distribution of landscape ecological risks in Sichuan Province, 2020*

Ecological security pattern construction

Through the analysis of the PESP superimposed by IESS and ERI, it becomes feasible to identify regions characterized by high IESS and low ERI (*Fig. 5A*). PESP with medium and above grade was selected as foreground data, covering an area of 26.19 × 10^4 km^2. The significant spatial distribution of different landscape types was revealed through the

MSPA model (*Fig. 5B*), with the largest core areas predominantly located in the central region, covering 5.61 × 10^4 km^2, accounting for 25.18% of the foreground area. The bridge areas, serving as structural corridors within the ecological network, are situated around multiple core patches and possess the potential to evolve into ecological sources. These areas cover a total of 7.27 × 10^4 km^2, representing 32.58% of the total foreground area. There are also many isolated areas scattered throughout the region, reflecting ecological patch fragmentation, with a total area of 2.08 × 10^4 km^2, representing 9.33% of the total foreground area. The Perforation areas are 0.38 × 10^4 km^2, accounting for 1.71% of the foreground area. Other landscape types collectively account for 31.20% of the total foreground area.

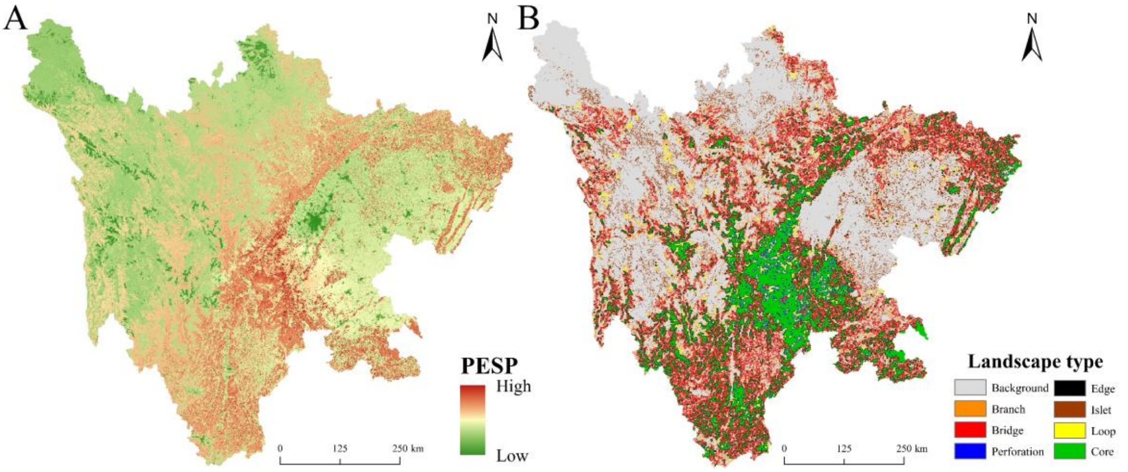

Figure 5. *Spatial distributions of PESP capacity (A) and MSPA-based landscape types (B) in Sichuan Province, 2020*

A total of 216 ecological sources were identified (*Fig. 6A*), covering 4.12 × 10^4 km^2. Primarily distributed in the central and southern parts of Sichuan Province, and on both the northern and southern sides of the eastern region. Specifically, two ecological sources exhibited a dPC exceeding 10, eight ecological sources displayed a dPC ranging from 1 to 10, while the remaining ecological sources had a dPC between 0.1 and 1. The areas of ecological sources land across the three categories were 1.81 × 10^4 km^2, 0.67 × 10^4 km^2 and 1.64 × 10^4 km^2, which are of significant importance, and account for 43.97%, 16.26%, and 39.77% (*Table 6*) of the total area designated as ecological sources. These first-level ecological sources are primarily situated in the central and southern regions of Sichuan Province. They predominantly consist of forestland and grassland, which are advantageous for species dispersal and conservation. The third-level ecological sources are mainly distributed around the first-level and second-level ecological sources and in the edge of eastern Sichuan Province, which contribute less to the regional landscape connectivity and is less important.

Utilizing the IESD, the resistance surface created with the four resistance factors is adjusted (*Fig. 6B*) to acquire a comprehensive resistance surface of the landscape, which further refines the spatial differentiation of resistance conditions and shows the pattern of being “high in the west and low in the east” (*Fig. 6C*). Construction land in the east exhibits the highest resistance values, whereas mountainous regions in the west show moderately high resistance.

Table 6. *Division and proportion of ecological source at different levels in Sichuan Province, 2020*

Ecological sources importance level	Number	Proportion of total plaques/%	Area/×10^4 km^2	Proportion of total plaque area/%
First-level	2	0.93	1.81	43.93
Second-level	8	3.70	0.67	16.26
Third-level	206	95.37	1.64	39.81

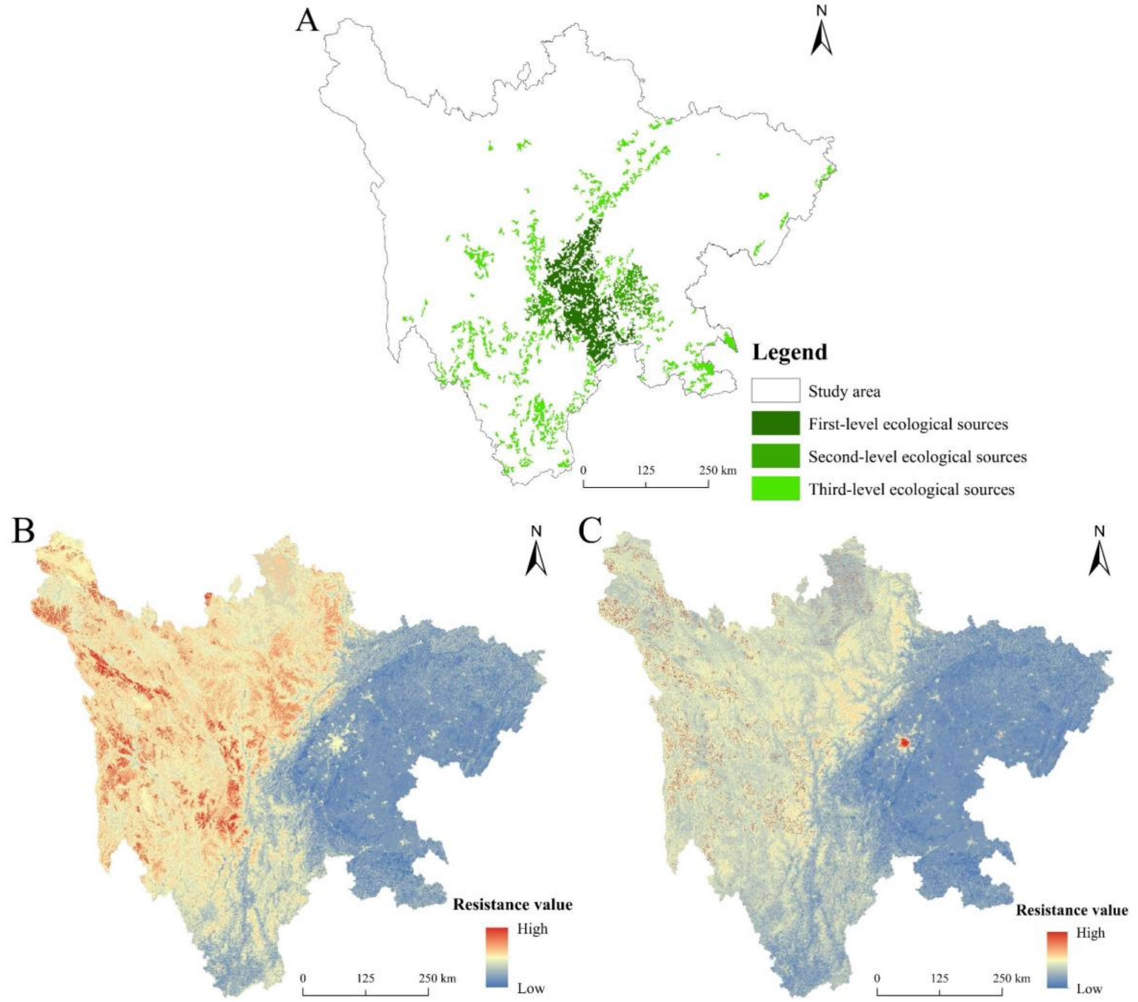

Figure 6. *Spatial distributions of ecological sources level (A), resistance surfaces before (B) and after correction (C) in Sichuan Province, 2020*

The corridor extraction tool was utilized to extract 572 ecological corridors in total (*Fig. 7A*). Among these, 202 ecological corridors are of the first-level. The southern and central ecological source areas are connected by 161 second-level ecological corridors. The western source area is mainly connected with the central and southern source areas by 209 third-level corridors. The spatial network evaluation and analysis of the ecological corridor showed that the α index, β index, and γ index were 0.84, 2.65, and 0.89, respectively, indicating that the ecological network in Sichuan Province has a good degree of connectivity. The complex network structure and high connectivity are conducive to maintaining the stability of the ecosystem and promoting biodiversity.

Maintaining regional biodiversity can be facilitated by appropriately increasing the width of the corridor. The ecological corridor is designed to enhance ecological connectivity in a holistic manner and protecting biodiversity. In consideration of biodiversity protection, a buffer zone 3 km was chosen according to the actual conditions of plains and mountains for the construction of the ecological corridor and the analysis of its landscape structure. It is shown that the first-level ecological corridor mainly consists of cropland, the second-level mainly of forestland, and the third-level mainly of forestland and grassland (*Table 7*). Major landscape types such as cropland, forestland, and grassland form important corridors, making up 29.61%, 41.87% and 24.58% of the total. These three main landscape types, namely cropland, forestland and grassland, and together account for approximately 96.06% of the total corridor area, highlighting their crucial role in species dispersal and habitat connectivity.

Table 7. *Land use structure of corridors at different levels in Sichuan Province, 2020*

Type of land use	**First-level**	**Second-level**	**Third-level**	**Ecological corridors**
	Proportion of area/%			
Cropland	59.67	20.09	2.55	29.61
Forestland	29.46	52.76	49.39	41.87
Grassland	6.58	25.19	43.46	24.58
Water	1.86	1.05	0.46	1.16
Construction land	2.22	0.57	0.11	1.07
Unused land	0.22	0.34	4.03	1.71

There were 1156 ecological nodes found in total (*Fig. 7B, C*), which consisted of 363 pinch points and 793 barrier points. The majority of the critical areas are situated at essential locations that connect significant ecological resources in the eastern and southern regions, and they have a great influence on the relationships among different ecological resources. However, barrier points are predominantly located in the western mountainous regions, where they impede ecosystem flow and obstruct connections between ecological source areas.

Discussion

Analysis and optimization of ecological security pattern

The ecological condition in Sichuan Province exhibits significant differences across various regions. The IESS is elevated in the central and southern mountainous areas, which primarily overlap with regions that have good ecological quality, including forestland and grassland. These findings align with prior research outcomes (Chen et al., 2022). Geographical features greatly hinder the movement of matter and energy, resulting in poor corridor quality and a high-level of LER, with a gradual decline in IESS towards the northwest. The north and south edges of the Sichuan Basin in the east also have high IESS and important ecological corridors distribution areas. However, they are significantly influenced by anthropogenic activities, posing a certain degree of threat to regional ecological connectivity. The spatial concentration of IESD is predominantly observed in the eastern section, mostly concentrated in construction land and cropland, and the corresponding LER level is also very high. Areas with high IESD capabilities are closer to areas with strong IESS, which may cause some resistance to the material and energy flow of ecosystems. However, from the perspective of ESD in human society, short distances are more conducive to improving the efficiency of ecological service acquisition (Koellner et al., 2018). Meanwhile, the IESS capability in southern Sichuan Province is robust, capable of meeting the ESD of human society in the region. The ecological sources in this area exhibit strong connectivity, the ecological corridors are at a medium-level, and the ecological pinch points are densely distributed. There is significant potential for improvement in the ecological environment. Among the landscape types included in the ecological network, cropland accounts for a large proportion. While the cropland ecosystem poses some obstacles to the movement of land-based organisms, the results suggest that it is essential for the movement of materials, energy, and information between the migration paths of these organisms and their ecological origins.

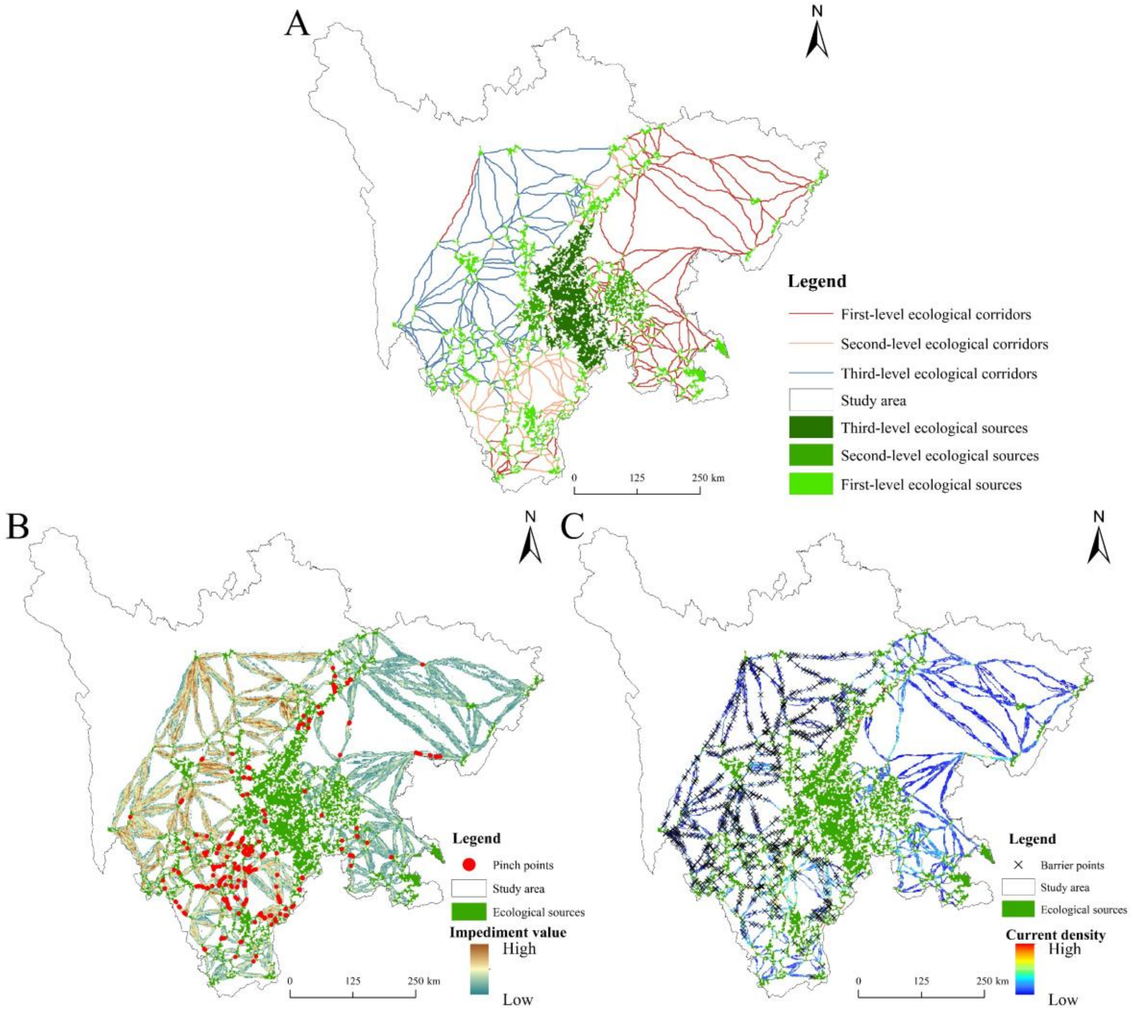

Figure 7. *Spatial distributions of ecological corridors at different level (A), ecological pinch points (B), and barrier points (C) in Sichuan Province, 2020*

This study takes Sichuan Province as a typical region for analysis, and multiple ecological transition zones worldwide face highly similar ecological and social challenges (Wang et al., 2023a; Rogora et al., 2018). In China, the eastern margin of the Qinghai–Tibet Plateau and the Qinling–Huaihe boundary zone serve as important ecological barrier areas, where alpine meadows and montane forests are highly sensitive to climate change and human disturbances, and the ecosystem service functions show significant transitional characteristics and fragility (Zhao et al., 2025). Internationally, the Alps are not only a typical high-mountain region for climate change research, but also an important research target for exploring the impacts of land-use transitions on ecosystems. Tourism expansion, agricultural abandonment, and forest expansion jointly act to produce significant landscape pattern evolution and risk accumulation (Gobiet et al., 2014). Sichuan Province has similar ecological vulnerability and human–land conflicts, while also possessing the uniqueness of a mountain–basin composite system. Through the supply–demand–risk framework, it can not only compensate for the neglect of human needs and risk distribution in traditional ESP construction, but also provide a transferable idea for the study of other types of ecological transition zones. At the same time, in order to further promote the realization of the United Nations Sustainable Development Goals (SDGs) on climate action and terrestrial ecosystems, by means of carbon sequestration, water conservation, and ESP optimization, it also provides ecological support for achieving China's "dual carbon" strategy. Therefore, this study further constructs an ESP containing multiple ecological information, and forms a macro-spatial pattern of "Three Zones, Three Belts and One Cluster" in spatial distribution (*Fig. 8*), which is consistent with the macro-strategy of "Four Zones, Eight Belts, and Multiple Nodes" in Sichuan Province, and provides a spatial optimization scheme for regional development.

The "Three Zones" refer to the core ecological reserve zone in the central and southern mountainous of Sichuan, the ecological restoration zone of northwest plateau in Sichuan, and the ecological reserve zone along the Sichuan Basin. These are defined according to the distribution of ecological resources and resistance surfaces. The release of policy documents— "Red Line Plan for Ecological Protection of Sichuan Province and the Land and Space Planning of Sichuan Province (2021-2035)" provided explicit guidelines for evaluating ecological functions across various regions and for implementing ecological protection measures. The core ecological reserve zone in the central and southern Sichuan mountains covers many ecological protection red lines, such as the ecological protection red line for soil and water conservation in Daxueshan, the ecological protection red line for water source conservation in Minshan, and the ecological protection red line for BM in Qionglai Mountain. At the same time, it plays a crucial role in providing essential ecological services such as WS, BM, and CS. Therefore, as the core protection area of the key ecological source, the development and construction of the area should be properly restricted on the basis of maintaining the original ecology, and the standardized construction and management of the nature reserve, the protection of forest vegetation and forest ecosystem, the control of water and soil loss, the prevention and control of geological disasters, and the connectivity between the source areas should be strengthened. Concurrently, the promotion of cultural and leisure ecotourism should be actively pursued to foster economic development while addressing the well-being needs of local residents. The ecological restoration zone of northwest plateau in Sichuan, forming part of the Qinghai-Tibet Plateau, primarily encompasses Aba Prefecture and Ganzi Tibetan Autonomous Prefecture. This zone is characterized by continuous high-altitude mountains and dramatic elevation differentials between valley floors and peaks.

This region exhibits pronounced climatic zonation that significantly impedes wildlife migration and ecosystem connectivity. As a key restoration area within important ecological reserves such as the source of the Yalong River and the Ruoergai Wetland, it holds significant ecological importance. However, it faces severe environmental challenges including grassland degradation and wetland shrinkage caused by permafrost thawing. Future management should prioritize reducing pastoral and agricultural activities (Yao et al., 2022), and involving specifically improving the safeguarding of connectivity corridors that link southwestern ecological source areas by broadening essential corridors and addressing barrier points. The ecological reserve zone along the Sichuan Basin, which includes multiple ecological protection red lines such as the water conservation Daba Mountain and the sensitive ecological protection red line of rocky desertification in southeastern Sichuan. It has low mountains and hills such as Danshan and Huaying Mountain, connecting the Chengdu Plain with the surrounding mountains of the basin. The area of arable land, forest land, and grassland in this region accounts for a large proportion, and the ecological environment is highly susceptible to human activities, resulting in a decreasing trend in ecological security level This area is also an important area to ensure the connectivity between the eastern ecological source and the central ecological source. In the future, we should focus on protecting the ecological pinch points area, delimit the boundary between basic farmland and mixed forest and grass land, promote mountain restoration and water system management (Cao et al., 2018), safeguard biodiversity, mitigate the effects of rocky desertification, and enhance ecological security.

The “Three Belts” refer to the ecological recreation connectivity belt in the eastern basin, the southern mountain restoration belt, and the western high mountain restoration belt, mainly based on the importance and spatial distribution patterns of ecological corridors. The ecological recreation connectivity belt in the eastern basin functions as a vital connectivity channel linking three directions of ecological sources, with development objectives aimed at establishing ecological recreation corridors that integrate natural and cultural resources while connecting the core ecological reserve zone in the central and southern mountainous of Sichuan and ecological reserve zone along the Sichuan Basin with the ecological demand cluster in the Sichuan Basin. The southern mountain restoration belt, and the western high mountain restoration belt, located south of the core ecological reserve zone in the central and southern mountainous of Sichuan and located east of the ecological restoration zone of northwest plateau in Sichuan, primarily encompass second-level and third-level ecological corridors. These areas face considerable connectivity challenges between ecological sources, necessitating prioritized restoration measures to enhanced protection of forest vegetation, wetlands, and rare wildlife habitats, comprehensive geohazard management in arid valleys and alpine gorges and intensified soil erosion control through slope stabilization initiatives.

The “One Cluster” refers the ecological demand cluster in the Sichuan Basin, which has been defined according to the spatial distribution of IESD. As the primary region for economic growth and agricultural output in Sichuan Province, this region exhibits low HQ due to intensive urbanization and the expansion of cropland. Li et al. (2022) research on ecological health in the southwestern region shows that with population aggregation and economic development leading to ecosystem degradation and reduced health levels, there is a high demand for ecosystem services in the region. In the future, while continuously expanding the scale of construction land with the goal of economic development, we should strengthen the protection of the “three in one” of cultivated land quantity, quality, and ecology, promote the ecological transformation of cultivated land, increase the construction of green infrastructure, improve green space coverage, and protect and manage rivers. At the same time, actively introducing cultural and leisure types of ecotourism to promote economic development and meet the welfare needs of residents. The corridors in this area have a higher level and better quality. It is crucial to safeguard significant ecological hubs within the corridors that link the ecological source areas, such as Nantong City, and Emei Mountain in the southeast. Vegetation buffer zones should be used to reduce human activity interference and enhance ecological mobility.

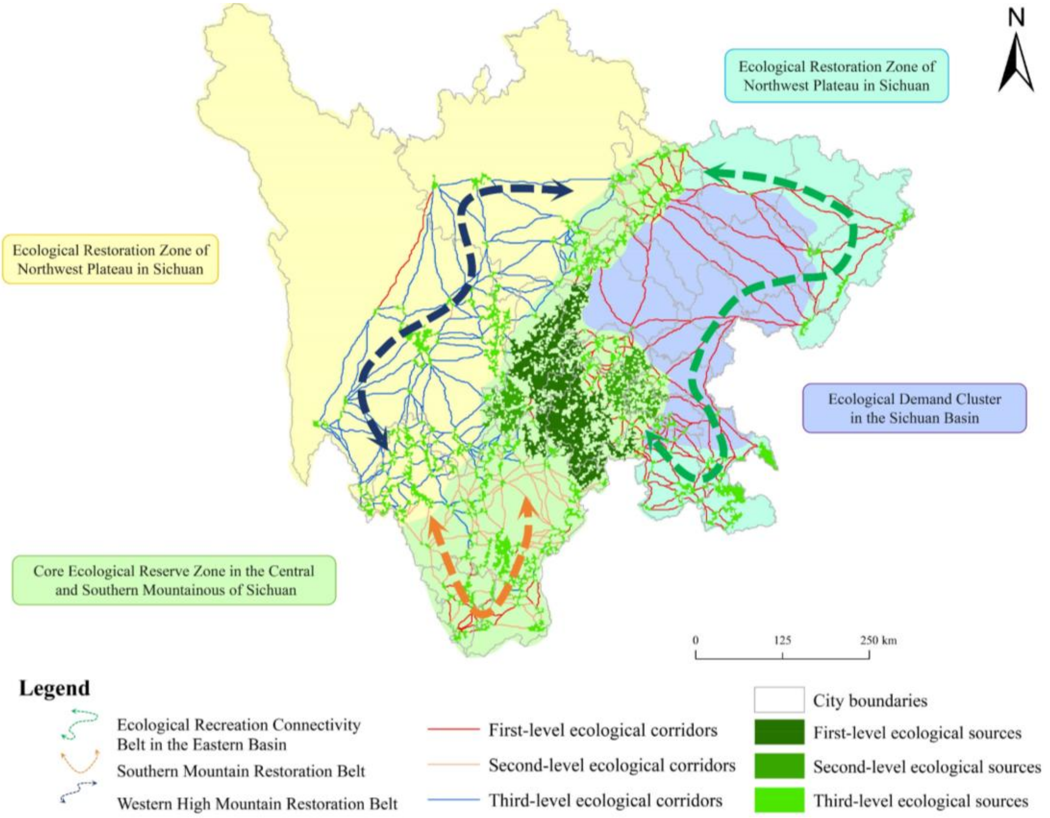

Figure 8. *Optimization strategies for ecological conservation in Sichuan Province based on ESP*

Conclusion

High ESS regions are mainly found in the central, southern, and eastern parts of the study area, which mainly consist of forestland, grassland, and cropland. The eastern portion exhibits high ESD, with higher LER concentrated in urbanized zones. We identified 216 ecological sources areas, spanning 4.12×10^4 km^2, including 2 first-level ecological sources, 8 second-level ecological sources, and 206 third-level ecological sources. Larger aggregated source areas require enhanced corridor connectivity, while smaller, fragmented tertiary sources are spatially dispersed. According to circuit theory, a total of 572 ecological corridors totaling 1.70×10^4 km were identified, stratified as 202 first-level ecological corridors, 161 second-level ecological corridors, and 209 third-level ecological corridors, which exhibit distinct spatial zonation across eastern, southern, and western sectors, the ecological corridors are well connected. Critical ecological nodes comprise 363 pinch points and 793 barrier points.

Building upon these findings, the ESP was preliminarily established. Integrating ecological functions, spatial heterogeneity, and societal demands, an optimization framework termed “Three Zones, Three Belts, and One Cluster” was proposed, establishing a theoretical framework for the integrated and sustainable advancement of ecological conservation and economic development in areas undergoing ecological transition.

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APPENDIX

Table S1. *List of abbreviations*

Abbreviation	Definition
ESS	Ecological Service Supply
ESD	Ecosystem Service Demand
LER	Landscape Ecological Risk
ESP	Ecological Security Pattern
MSPA	Morphological Spatial Pattern Analysis
CS	Carbon Sequestration
WS	Water Services
SR	Soil Retention
HQ	Habitat Quality
BM	Biodiversity Maintenance
GR	Green Recreation
FS	Food Supply
IESS	Integrated Ecosystem Service Supply
ERI	Ecological Risk Index
PESP	Potential Ecosystem Service Provision
PD	Population Density
LUI	Land Use Intensity