

Construction and optimization of ecological security pattern in the mainstream of the Tarim River Basin, China

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Abstract: Scientifically constructing an ecological security pattern (ESP) is an important spatial analysis approach to improve ecological functions in arid areas and achieve sustainable development. However, previous research methods ignored the complex trade-offs between ecosystem services in the process of constructing ESP. Taking the mainstream of the Tarim River Basin (MTRB), China as the study area, this study set seven risk scenarios by applying Ordered Weighted Averaging (OWA) model to trade-off the importance of the four ecosystem services adopted by this study (water conservation, carbon storage, habitat quality, and biodiversity conservation), thereby identifying priority protection areas for ecosystem services. And then, this study identified ecological sources by integrating ecosystem service importance with eco-environmental sensitivity. Using circuit theory, the ecological corridors and nodes were extracted to construct the ESP. The results revealed significant spatial heterogeneity in the four ecosystem services across the study area, primarily driven by hydrological gradients and human activity intensity. The ESP of the MTRB included 34 ecological sources with a total area of 1471.38 km², 66 ecological corridors with a length of about 1597.45 km, 11 ecological pinch points, and 13 ecological barrier points distributed on the ecological corridors. The spatial differentiation of the ESP was obvious, with the upper and middle reaches of the MTRB having a large number of ecological sources and exhibiting higher clustering of ecological corridors compared with the lower reaches. The upper and middle reaches require ecological protection to sustain the existing ecosystem, while the lower reaches need to carry out ecological restoration measures including desertification control. Overall, this study makes up for the shortcomings of constructing ESP simply by spatial superposition of ecosystem service functions and can effectively improve the robustness and stability of ESP construction.

Keywords: ecological source; ecological corridor; river corridor; ecological resistance surface; ecological node; ecological network; kernel density analysis

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1 Introduction

As the fundamental guarantee for sustainable development, ecological security is facing severe

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challenges under the dual pressures of rapid urbanization and industrialization (Li et al., 2024a). Globally, land use changes caused by high-intensity human activities have led to landscape fragmentation and degradation of ecosystem service functions, which are particularly evident in ecologically fragile areas (Winkler et al., 2021; Jiang et al., 2024). Taking the inland river basin located in arid areas as an example, the ecosystems are subject to the dual stresses of water resource constraints and human interference, presenting explicit ecological risks such as sandification, desertification, and soil erosion, and the regional ecological security threshold is approaching a critical state (Zhang et al., 2024). In this context, building an ecological security pattern (ESP) has emerged as a pivotal strategy for achieving nature–society system coordination (Dong et al., 2024b; Gong et al., 2025). By identifying ecological sources, corridors, and nodes, ESP integrates ecological processes with spatial heterogeneity and provides a theoretically robust and practically scalable framework in arid inland river basins.

Early international research on ESP predominantly focused on biodiversity conservation (Dong et al., 2024b; Shu et al., 2024). For example, Conservation International (CI) delineated 35 global biodiversity hotspots to prioritize habitat protection for threatened species (Myers et al., 2000; Mittermeier et al., 2011), while the International Union for Conservation of Nature (IUCN) identified key biodiversity areas (KBAs) through systematic threat assessments (Dong et al., 2024a). Among methodological frameworks for ESP construction, the "ecological source identification-resistance surface construction-ecological corridor extraction" paradigm remains the most widely adopted (Xu et al., 2023). Ecological sources are priority areas that provide important ecological services and maintain biodiversity (Li et al., 2024a). The methods for identifying ecological sources can be divided into qualitative and quantitative categories. The qualitative methods often designate nature reserves, protected areas, or ecologically significant landscapes as sources based on expert judgment. Quantitative approaches, conversely, rely on goal-oriented evaluation systems, such as region-specific ecosystem service importance assessments or urban-scale eco-environmental sensitivity analyses (Oguh et al., 2021). However, these systems frequently overlook trade-offs and synergies between indicators during index aggregation, while ecological sensitivity analyses often employ equal-weighting schemes that fail to capture the weakest link principle—system vulnerability is often governed by single limiting factor (Pan et al., 2023; Qian et al., 2024). Consequently, robust identification of ecological sources must simultaneously account for interdependencies among ecosystem services and constraints imposed by critical ecological thresholds, such as biodiversity loss tipping points or hydrological regime shifts. Traditional ecological resistance surface construction often relies on oversimplified resistance values assigned to single land use type, neglecting the multifaceted impacts of anthropogenic disturbances on ecological flows (An et al., 2021). A robust ecological resistance surface must integrate land cover dynamics, human activity intensity, and climatic gradients to realistically simulate species migration barriers and ecosystem process disruptions (Huang et al., 2021; Wang et al., 2021). As an important connecting channel for biological flow diffusion between ecological sources, ecological corridors effectively connect ecosystem elements and enhance the connectivity and integrity of ecosystems (Wang et al., 2022). Although the minimum cumulative resistance (MCR) model can identify potential migration paths, it is difficult to quantify the randomness of species diffusion and corridor structure parameters (Li et al., 2025). The innovative application of circuit theory makes up for this limitation: by simulating the flow of current in the landscape matrix, ecological pinch points, and ecological barrier points can be accurately identified, and the width requirement of ecological corridors can be quantified (Peng et al., 2018; Li et al., 2019). However, few studies have combined ecological corridors with river systems to jointly build and enhance the internal connectivity of ecosystems, thereby improving the integrity and stability of ecosystems. In general, with the profound changes in the global ecological environment, the construction of ESP is undergoing a paradigm shift from independent regulation of a single factor to integrated management of ecosystems. By coordinating the integrity, systemic relevance, and functional coordination of ecological elements, we can provide scientific support for building a new ESP in which humans and nature coexist in harmony.

The Tarim River Basin (TRB) is recognized as one of the most arid and ecologically vulnerable regions in China, with water scarcity serving as a primary factor of its fragile ecosystem. Characterized by desert-oasis landscapes, its riparian forests and wetlands form a unique corridor-like ecological pattern along riverbanks (Song et al., 2002; Xue et al., 2019). However, due to the combined effects of long-term high-intensity water resource development and utilization and climate change, the mainstream of the Tarim River Basin (MTRB) faces multiple ecological crises, such as obvious degradation of desert vegetation in the riparian zone, significant reduction in species diversity, and serious threats to regional ecological security (Ling et al., 2017). Although emerging research has begun to establish ESPs in arid inland river basins, most studies lack multidimensional consideration of ecosystem sustainability (Mu and Shen, 2022). At the same time, ecological resistance surface construction often overrelies on biophysical factors while overlooking anthropogenic disturbances. In addition, the construction of ecological corridors ignores the connection with river systems, which is not conducive to the sustainable and stable development of arid inland river basins. This gap underscores the urgent need to develop a holistic ESP framework that integrates multiple ecological objectives, including maintaining ecosystem functionality and structural integrity under anthropogenic pressure. The objectives of the study are to: (1) identify ecological sources by assessing ecosystem service importance and eco-environmental sensitivity; (2) couple natural and human activity ecological resistance factors to determine ecological resistance surface; and (3) extract ecological corridors, ecological pinch points, and ecological barrier points based on circuit theory. This optimized the ESP by integrating river corridors with ecological corridors, providing a scientific reference for ensuring the ecological security and sustainable development of the MTRB.

2 Study area and data sources

2.1 Study area

The TRB, as the largest inland river basin in China, is located in the Northwest China. The MTRB (40°29'–40°35'N, 80°45'–87°35'E) originates at the confluence of the Aksu River, Yarkant River, Hotan River, and Kaidu-Kongque River, flowing northwest to southeast through the alluvial fan at the southern foot of the Tianshan Mountains before terminating in Taitema Lake (Xu et al., 2010; Zhang et al., 2020). Spanning 1321.00 km with an average annual runoff of 3.98×10^9 m³, the MTRB is divided into three segments: the upper reaches (495.00 km) from Alaer Hydrologic Station to Yingbazha Hydrologic Station, the middle reaches (398.00 km) from Yingbazha Hydrologic Station to Qiala Hydrologic Station, and the lower reaches (428.00 km) from Qiala Hydrologic Station to Taitema Lake (Fig. 1) (Li et al., 2021). The altitude of MTRB ranges from 850 to 1050 m, featuring a terrain that is high in the north and gentle in the south. It has an extremely arid continental climate, with an average annual precipitation of less than 60 mm, potential evaporation of up to 2000–2900 mm, and an annual average temperature of about 10.7°C (Jiao et al., 2022; Zou et al., 2024). The surface matrix is mainly saline soil and the world's largest contiguous desert riparian forest lies along the river course, primarily composed of *Populus euphratica* Oliv., *Tamarix chinensis* Lour., and *Phragmites australis* (Cav.) Trin. ex Steud. Grassland and woodland are the predominant land cover types in the MTRB (Ling et al., 2016). As a pivotal agricultural region, the irrigated area of MTRB reached 1.31 km² in 2015, comprising 1.07 km² of cropland and yielding 5765 t of grain (Chen, 2019). However, intensive agricultural irrigation in the upper and middle reaches has disrupted regional water-salt balance and caused secondary salinization. Concurrently, vegetation in the lower reaches has severely degraded, gravely endangering regional ecological security.

2.2 Data sources

This study utilized multiple datasets that reflect the land cover, topographical (digital elevation model (DEM) and slope), climatic (temperature, precipitation, and surface reflectance), and socio-economic (net primary production (NPP), distance to roads (including distance to primary

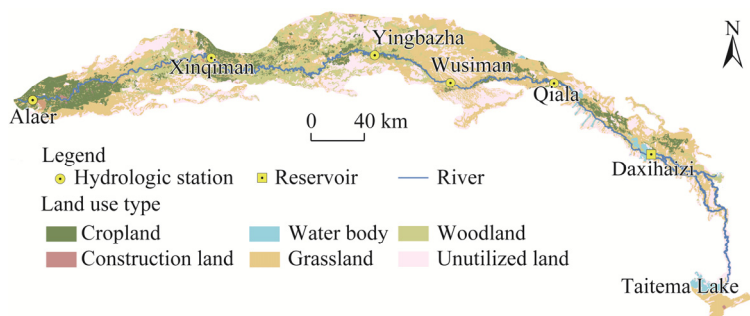


Fig. 1 Overview the spatial distribution of land use in the mainstream of the Tarim River Basin (MTRB) in 2020. The image is from the Resource and Environmental Science Data Center, Chinese Academy of Sciences (<https://www.resdc.cn/>).

road, distance to secondary road, and distance to railway), distance to water body, groundwater depth, and river network density) situations of MTRB in 2020 (Table 1). All spatial datasets were standardized to a unified geographic framework: the World Geodetic System 1984 (WGS 1984) geographic coordinate system with Universal Transverse Mercator (UTM) projection and Zone 46 North, to ensure spatial consistency and minimize geometric distortion across the study area. Additionally, all raster layers were resampled to a 500 m×500 m spatial resolution using the nearest neighbor resampling technique to align data resolutions.

Table 1 Detailed description of data used in the study

Data item	Data source	Resolution
Land cover	GlobeLand 30 (https://www.globeland30.org/)	30 m
Digital elevation model (DEM)	Geospatial Data Cloud (https://www.gscloud.cn)	30 m
Slope	Geospatial Data Cloud (https://www.gscloud.cn)	30 m
Temperature	MOD11A2 product (https://ladswb.modaps.eosdis.nasa.gov)	1 km
Precipitation	Global Resource Data Cloud (www.gis5g.com)	1 km
Surface reflectance	MOD09A1 product (https://ladswb.modaps.eosdis.nasa.gov/)	500 m
Net primary production (NPP)	EARTHDATA (https://ladswb.modaps.eosdis.nasa.gov/)	500 m
Distance to road (primary road, secondary road, and railway)	Open Street Map (http://www.openstreetmap.org/)	500 m
Distance to water body	Open Street Map (http://www.openstreetmap.org/)	500 m
Groundwater depth	The Tarim River Basin Management Bureau	500 m
River network density	Open Street Map (http://www.openstreetmap.org/)	500 m

3 Methodology

The ESP was constructed using an integrated network framework, which comprises ecological sources, ecological resistance surface, ecological corridors, and ecological nodes. The construction process of ESP involved the following sequential steps: (1) identification of ecological sources; (2) construction of ecological resistance surface; and (3) extraction of ecological corridors and nodes (Fig. 2).

3.1 Identification of ecological sources

This study identified ecological sources based on the assessment of ecosystem service importance and eco-environmental sensitivity.

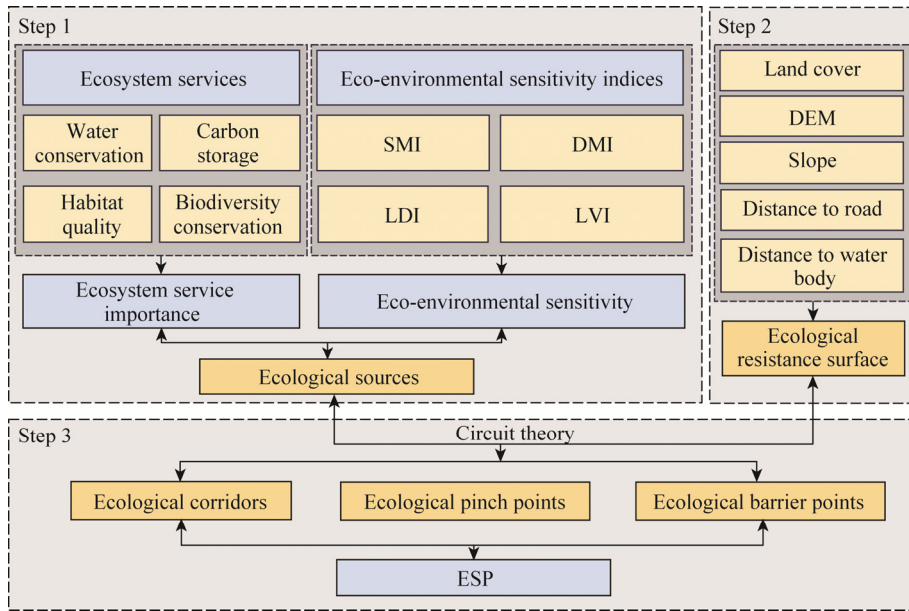


Fig. 2 Construction and optimization framework of ecological security pattern (ESP). DEM, digital elevation model; SMI, salinization monitoring index; DMI, desertification monitoring index; LVI, landscape vulnerability index; LDI, landscape disturbance index.

3.1.1 Assessment of ecosystem service importance

This study assessed the value of ecosystem service importance by taking into account the particulars of the study area and concentrating on four kinds of ecosystem services including water conservation, carbon storage, habitat quality, and biodiversity conservation.

Water conservation, as a critical ecosystem service, is essential for plant growth, climate regulation, and water resource, especially in arid areas where water dependence is heightened (Kan et al., 2020). In this study, based on the actual conditions of the study area and referencing Yang et al. (2020), we utilized groundwater and river network density to reflect the importance of water conservation in arid ecosystems.

Carbon storage is the capacity of ecosystems to absorb and store atmospheric carbon dioxide through natural processes such as photosynthesis, accumulating carbon in vegetation, soil, and other organic matters (Meersmans et al., 2016). The study used the carbon storage module in the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model to evaluate the amount of carbon stored in soil and other natural resources in the MTRB. The formulae used are as follows (Bai and Weng, 2023):

$$C_i = C_{i\text{-above}} + C_{i\text{-below}} + C_{i\text{-soil}} + C_{i\text{-dead}}, \tag{1}$$

$$C_{\text{sum}} = \sum_{i=1}^m A_i \times C_i, \tag{2}$$

where C_i is the total carbon density of land use type i ($t\ C/hm^2$); $C_{i\text{-above}}$ and $C_{i\text{-below}}$ are the vegetation carbon density in the aboveground and belowground of land use type i , respectively ($t\ C/hm^2$); $C_{i\text{-soil}}$ is the soil carbon density of land use type i ($t\ C/hm^2$); $C_{i\text{-dead}}$ is the carbon density in the dead organic matters of land use type i ($t\ C/hm^2$); C_{sum} is the total carbon storage of all land use types ($t\ C/hm^2$); m is the number of land use types; and A_i is the area of land use type i (hm^2). This study adopted the carbon storage data for the four kinds of carbon density connected to various land use types provided by Guo et al. (2021), as detailed below in Table 2.

An essential metric for assessing the health of an ecosystem is habitat quality (Terrado et al., 2016). We adopted the habitat quality module in the InVEST model to assess the condition and quality of habitats within the ecosystem (Gong et al., 2019):

Table 2 Carbon density of different land use types in the mainstream of the Tarim River Basin (MTRB)

Land use type	C_{above} (t C/hm ²)	C_{below} (t C/hm ²)	C_{soil} (t C/hm ²)	C_{dead} (t C/hm ²)
Cropland	3.47	4.12	86.22	1.24
Woodland	36.97	10.91	121.35	2.48
Grassland	0.58	5.13	85.02	0.22
Water body	0.76	0.54	0.00	0.00
Construction land	1.88	1.74	0.00	0.00
Unutilized land	0.54	1.04	43.39	0.00

$$Q_{xi} = H_i \left[1 - \left(\frac{D_{xi}^z}{D_{xi}^z + k^z} \right) \right], \quad (3)$$

$$D_{xi} = \sum_{u=1}^R \sum_{y=1}^{Y_u} \left(\frac{g_u}{\sum_{u=1}^R g_u} \right) \times u_y \times e_{uxy} \times \beta_x \times S_{iu}, \quad (4)$$

where Q_{xi} is the habitat quality value of land use type i in grid x ; H_i is the habitat suitability of land use type i ; D_{xi} is the level of habitat degradation of land use type i in grid x ; k is the semi-saturation coefficient; z is the inherent conversion coefficient of the system with a value of 0.5; Y_u is the total number of grids of threat factor u ; R is the number of habitat threat factor; g_u is the weight of threat factor u ; u_y is the threat factor value of raster y ; e_{uxy} is the influence of the threat factor u of raster y on grid x ; β_x is the anti-interference level of habitat in grid x ; and S_{iu} is the sensitivity of land use type i to threat factor u .

The concept of biodiversity conservation explains how ecosystems support gene, species, and ecosystem diversity, with habitat parameters primarily used as evaluation metrics (Feld et al., 2010). This study used the biodiversity maintenance capacity index to evaluate biodiversity conservation function based on the environmental parameters of the study area. The corresponding formula is as follows (Li et al., 2023):

$$S_{\text{bio}} = \text{NPP}_{\text{mean}} \times F_{\text{pre}} \times F_{\text{tem}} \times (1 - F_{\text{alt}}), \quad (5)$$

where S_{bio} is the biodiversity maintenance capacity index; NPP_{mean} is the average annual net primary productivity (g C/m²·a); F_{pre} is the average annual precipitation (mm); F_{tem} is the average annual temperature (°C); and F_{alt} is the elevation (m). The variables of NPP_{mean} , F_{pre} , F_{tem} , and F_{alt} in this formula were all normalized to 0–1.

We used the min-max normalization to transform water conservation, carbon storage, habitat quality, and biodiversity conservation into dimensionless values in the range of 0–1.

3.1.2 Assessment of eco-environmental sensitivity

The likelihood and seriousness of ecosystem damage or degradation in reaction to external factors, whether natural or man-made, are referred to as ecological environmental sensitivity (Nguyen and Liou, 2019). This study employed salinization, desertification, and landscape ecological risk indices to develop a comprehensive framework for assessing ecological sensitivity and analyzing the region's vulnerability and potential risks.

In arid areas, high temperatures, limited rainfall, and high evaporation rates foster soil salinization, which directly threatens vegetation growth and land productivity (Okur and Örcen, 2020). Building on the work of Lu et al. (2020), this study generated the salinization monitoring index (SMI) to assess soil salinization levels in arid areas by combining the modified soil adjusted vegetation index (MSAVI) with the soil salinity index (SSI). The formulae are as follows:

$$\text{MSAVI} = \frac{2\rho_{\text{NIR}} + 1 - \sqrt{(2\rho_{\text{NIR}} + 1)^2 - 8(\rho_{\text{NIR}} - \rho_{\text{R}})}}{2}, \quad (6)$$

$$\text{SSI} = \sqrt{\rho_{\text{B}} \times \rho_{\text{R}}}, \quad (7)$$

$$\text{SMI} = \sqrt{(\text{MSAVI} - 1)^2 + \text{SSI}^2}, \quad (8)$$

where ρ_{NIR} , ρ_{R} , and ρ_{B} are the reflectance of the near-infrared, blue, and red bands from remote sensing images, respectively.

Land desertification accelerates land degradation and vegetation loss while severely damaging ecosystem functions. This in turn worsens water scarcity and biodiversity loss, posing a threat to the region's sustainable development (Jie et al., 2002; AbdelRahman, 2023). To address this, the study utilized the desertification monitoring index (DMI) proposed by Bai et al. (2022), merged with the sandification feature index (SFI), surface albedo, and MSAVI to offer a thorough depiction of desertification in dry areas. The followings are the matching formulae:

$$\text{SFI} = \frac{\rho_{\text{SWIR1}} - \rho_{\text{B}}}{200 - \rho_{\text{SWIR2}}}, \quad (9)$$

$$\text{Albedo} = 0.356\rho_{\text{B}} + 0.130\rho_{\text{R}} + 0.373\rho_{\text{NIR}} + 0.085\rho_{\text{SWIR1}} + 0.072\rho_{\text{SWIR2}} - 0.0018, \quad (10)$$

$$\text{DMI} = \sqrt{(\text{MSAVI} - \text{MSAVI}_{\text{max}})^2 + (\text{Albedo} - \text{Albedo}_{\text{min}})^2 + (\text{SFI} - \text{SFI}_{\text{min}})^2}, \quad (11)$$

where ρ_{SWIR1} and ρ_{SWIR2} are the reflectance of the shortwave infrared 1 (1628–1652 nm) and shortwave infrared 2 (2105–2155 nm) bands, respectively; $\text{MSAVI}_{\text{max}}$ is the maximum value of the MSAVI; $\text{Albedo}_{\text{min}}$ is the minimum value of surface albedo; and SFI_{min} is the minimum value of the SFI.

The landscape ecological risk index quantifies the risks to landscape ecosystems, comprising two components: landscape vulnerability index (LVI) and landscape disturbance index (LDI). The LVI assesses the susceptibility of ecosystems to external pressures based on land-use vulnerability. Based on the research by Li et al. (2020), the vulnerability values for cropland, woodland, grassland, construction land, water body, and unutilized land are 0.186, 0.084, 0.084, 0.061, 0.270, and 0.399, respectively. The LDI measures the external influences on ecosystems, such as human activities, climate change, and natural disasters, helping identify areas for protection or restoration. The formula is as follows:

$$\text{LDI} = a \times \text{PD} + b \times \text{SP} + c \times \text{FD}, \quad (12)$$

where PD, SP, and FD are the landscape patch density, landscape isolation, and patch fractal dimension, respectively, as derived from moving window analysis in Fragstats 4.2 (Pacific Northwest Research Station, Orleans, USA); and a , b , and c are the weights of landscape patch density, landscape isolation, and patch fractal dimension, respectively, in this study, the a , b , and c were established as 0.5, 0.3, and 0.2, respectively (Li et al., 2020).

We applied the min-max normalization to convert each index into dimensionless data within the range of 0–1. The barrel principle, also known as the short board effect, refers to the classic theory that the comprehensive effectiveness of a system is constrained by its weakest link, i.e., the capacity of a container is determined by the shortest board. In ecological sensitivity assessment, this approach prevents the error of index averaging and precisely identifies the vulnerability threshold of spatial units by recognizing key limiting factors. Based on the raster calculator in ArcGIS v.10.8 software (Environmental Systems Research Institute (ESRI), Redlands, USA), this study performed spatial maximum operations on the four eco-environment sensitivity indices (SMI, DMI, LVI, and LDI), and finally generates a spatial distribution map of eco-environmental sensitivity that highlights the ecological shortcomings of the region. The larger the ecological sensitivity value is, the more sensitive the ecological environment will be. Therefore, this study selected the top 20% of ecologically stable areas as ecological sources.

3.1.3 Determination of priority protection areas

The Ordered Weighted Averaging (OWA) is a multi-criteria decision-making analysis method that is currently used for multiple trade-offs in the importance of ecosystem services. The specific formulae are as follows (Zhao et al., 2020; Gou et al., 2022):

$$\text{OWA}(h_{tm}) = \sum_t w_t S_{tm}, \left(w_t \in [0,1], \sum_t w_t = 1, tm = 1, 2, 3, \dots, n \right), \quad (13)$$

$$w_t = Q_{\text{RIM}}\left(\frac{t}{n}\right) - Q_{\text{RIM}}\left(\frac{t-1}{n}\right), (t = 1, 2, 3, \dots, n), \quad (14)$$

$$Q_{\text{RIM}}(\gamma) = \gamma^\alpha, \alpha \in (0, \infty), \quad (15)$$

where $\text{OWA}(h_{tm})$ is the result of weighted aggregation of the ordered sequence S_{tm} after ascending the order of the ecosystem service attribute value h_{tm} in the m^{th} raster; h_{tm} is the attribute value of pixel t on raster m ; w_t is the ordered weight of S_{tm} ; S_{tm} is the new sequence obtained by banking the attribute values of h_{tm} in ascending order; n is the total number of ecosystem service types; Q_{RIM} is the regular function; γ is the fuzzy measure parameter of OWA operator; and α is the scenario risk, reflecting the decision maker's inclination to minimize uncertainty and taking values in the range of $(0, \infty)$. When $\alpha < 1.0000$, the weight of prioritized factors increases, reflecting a pessimistic risk preference that amplifies landscape ecological risk; conversely, when $\alpha > 1.0000$, the greater weights will be assigned to lower-priority factors, embodying an optimistic preference that alleviates ecological risk; when $\alpha = 1.0000$, it means no preference. According to Gou et al. (2024), we simulated seven different levels of risk: $\alpha = 0.0001, 0.1000, 0.5000, 1.0000, 2.0000, 10.0000$, and $10,000.0000$ to characterize the OWA trade-offs across pessimistic to optimistic decision-making spectrums. The trade-off quantifies the balance of resource allocation across multiple objectives. The formula is as follows (Jiang and Eastman, 2000):

$$\text{Trade-off} = 1 - \sqrt{\frac{n \sum_t \left(w_t - \frac{1}{n}\right)^2}{n-1}} \quad (0 \leq \text{trade-off} \leq 1). \quad (16)$$

Multiple OWA scenarios can generate priority ranking results with different conservation efficiency, providing a multi-dimensional benefit trade-off perspective for ecological protection decision-making. Referring to the research of Zhang et al. (2022), the priority protection areas within the top 20% patches in the scenario were taken as the ecological sources. The expression is defined as follows (Gou et al., 2024):

$$E = \frac{\text{ES}_p}{\text{ES}_e}, \quad (17)$$

where E is the conservation efficiency of the priority protection area; ES_p is the average value of various ecosystem services in the priority protection area; and ES_e is the average value of various ecosystem services in the entire region.

3.1.4 Identification of ecological sources

Considering that some ecological sources are small in scale, fragmented, and highly dispersed, to reasonably determine the minimum area threshold of ecological sources, we determined the relationship between the minimum area threshold of ecological sources and the total number of ecological sources, and the proportion of the area of important ecological sources to the total area of ecological sources by referring to Ding et al. (2022).

3.2 Construction of ecological resistance surface

We chose five factors including land cover, DEM, slope, distance to road (including primary road, secondary road, and railway), and distance to water body to represent resistance in this study (Fu et al., 2020; Cui et al., 2022). We divided each factor into different levels based on the natural breaks method, which identifies natural divisions in the data by maximizing differences between

groups. Once the natural breakpoints were identified, resistance values from 1.00 to 5.00 were assigned to each level, with these values corresponding to the specific intervals defined by the natural breaks (Table 3). Then, we calculated the weight of each factor using the entropy weight method and utilized the raster calculator in the ArcGIS v.10.8 software to build the comprehensive ecological resistance surface.

Table 3 Resistance value of each ecological resistance factor involved in this study

Resistance factor	Resistance value					Weight
	1.00	2.00	3.00	4.00	5.00	
Land cover	Woodland and water body	Grassland	Cropland	Unutilized land	Construction land	0.3415
DEM (m)	765–795	795–825	825–885	885–975	>975	0.0660
Slope (°)	0–5	5–15	15–25	25–35	35–53	0.2168
Distance to road (primary road, secondary, and railway) (m)	>700	400–700	300–400	100–300	<100	0.2823
Distance to water body (m)	<100	100–300	300–500	500–1000	>1000	0.0934

3.3 Extraction of ecological corridors

To accurately assess the feasibility of ecological corridors, we used the Linkage Mapper plug-in in ArcGIS v.10.8, which is grounded in the random walk principle of circuit theory—where electrons simulate species movement across landscapes to identify optimal ecological linkages.

3.4 Extraction of ecological nodes

Ecological nodes include ecological pinch points and ecological barrier points. The ecological pinch points are the high value area of cumulative current, which is the location where the maximum possibility of species migration is simulated. The ecological barrier points are areas where species are greatly hindered by the landscape during the movement between ecological sources (Chen et al., 2023). The Pinchpoint Mapper and Barrier Mapper modules in the Linkage Mapper plug-in were employed to extract ecological pinch points and ecological barrier points in this study, respectively.

3.5 Identification of important and general ecological corridors

The kernel density analysis method enables the quantification of the spatial distribution density of ecological corridors, revealing the connectivity and significance of ecological corridors across different regions (Li et al., 2020). This study used the kernel density analysis module in ArcGIS v.10.8 software to construct a spatial distribution map of ecological corridors. The larger the kernel density is, the more likely it is that the ecological corridor supports species migration and the continuity of ecological processes. For better analysis, this study used the min-max normalization method to normalized the kernel density value to a standard value range of 0–1, and used the natural breaks method to divide the kernel density value into two categories: ecological corridors with a kernel density value greater than 0.8 were classified as important ecological corridors, and ecological corridors with a kernel density value less than 0.8 were classified as general corridors (Li et al., 2020). Important ecological corridors play a key role in ecological processes, while general corridors only support a small number of ecological processes (Li et al., 2010).

4 Results

4.1 Spatial pattern of ecological source

4.1.1 Spatial pattern of ecosystem service importance

Figure 3 shows the spatial distribution of ecosystem services in the MTRB in 2020. Water conservation exhibited the highest intensity in the middle reaches of the MTRB, attributed to the

robust water resource management framework and the pronounced water retention capacity of riparian zones. In contrast, the southern lower reaches and other river-distant areas demonstrated weaker functionality, with water availability less than 20% of the middle reaches' core zone and functional values below 0.3, reflecting severe hydrological constraints. Carbon storage across the MTRB maintained a high overall baseline but was strongly modulated by vegetation distribution patterns. Areas distal to the river channel exhibited sparse vegetation cover and significantly diminished carbon sequestration capacity compared with riparian belts, underscoring the critical role of hydrological proximity in ecosystem productivity. Habitat quality reached peak levels in the middle reaches, supported by dense vegetation cover, abundant water resources, and stable ecological systems. Conversely, the southern and eastern segments of the lower reaches faced structural ecosystem fragility, constrained by water scarcity and monotonous land-use regimes, which collectively impede habitat sustainability. Biodiversity conservation hotspots were concentrated in the northern middle reaches and riparian corridors (functional value of 0.7–0.9), where optimal ecological conditions sustained rich faunal and floral diversity. By stark contrast, downstream regions, subjected to extreme aridity and ongoing ecological degradation, exhibited uniformly low functional values (<0.1), starkly testifying to their heightened ecosystem vulnerability. The overall assessment results of ecosystem service importance showed obvious spatial heterogeneity (Fig. 4). High-value areas were concentrated in the middle reaches of MTRB and the riparian zone. Low-value areas were mainly distributed in the lower reaches and upper reaches of the industrial and agricultural belts.

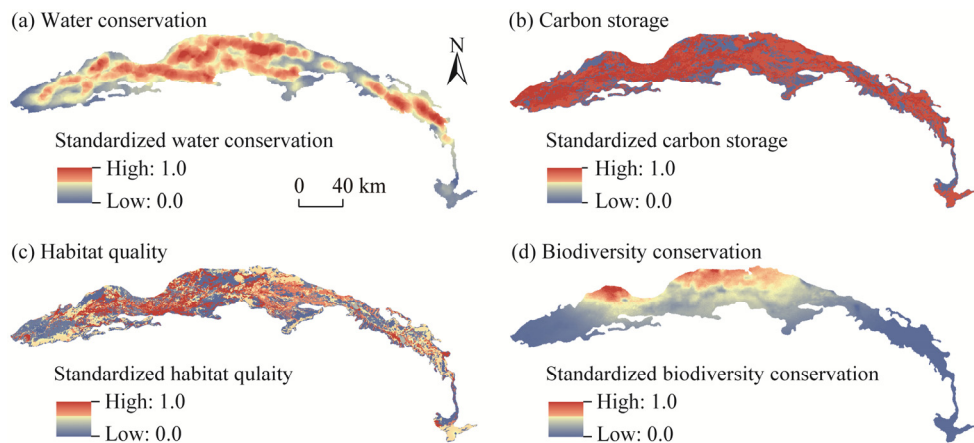


Fig. 3 Spatial distribution of ecosystem service in the MTRB in 2020. (a), water conservation; (b), carbon storage; (c), habitat quality; (d), biodiversity conservation.

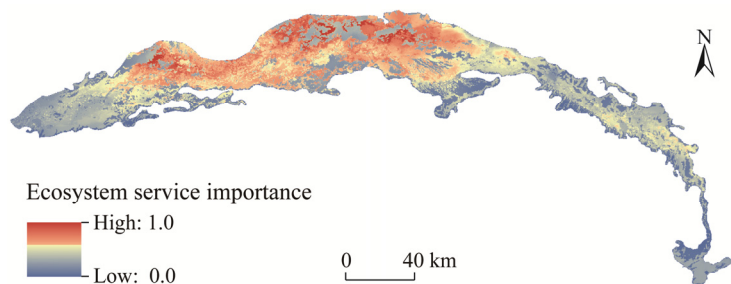


Fig. 4 Spatial distribution of ecosystem service importance in the MTRB in 2020

4.1.2 Spatial pattern of eco-environmental sensitivity

The spatial distribution of eco-environmental sensitivity indices in the MTRB in 2020 is shown in Figure 5. The lower reaches and other river-distant marginal areas exhibited high salinization

intensity, characterized by dominant unutilized land cover that is highly susceptible to environmental fluctuations. Desertification levels were predominantly elevated across the MTRB, with low values confined to water bodies and riparian zones, reflecting the study area's arid climate and dual risks of land and vegetation degradation. The lower reaches demonstrated elevated landscape vulnerability, particularly in unutilized land and river-distant areas with high sensitivity to environmental changes. Notably, landscape disturbance remained relatively low overall, attributable to the high proportion of desert-dominated landscapes under extremely arid conditions and limited human activity intensity. Figure 6 shows the comprehensive eco-environmental sensitivity assessment of the MTRB in 2020. The southern and northern margins of the upper-middle reaches, along with the entire lower reaches, exhibited pronounced sensitivity, while riparian zones and lush vegetation areas showed stronger resistance and resilience to external disturbances, underscoring the critical role of hydrological proximity in ecosystem stability.

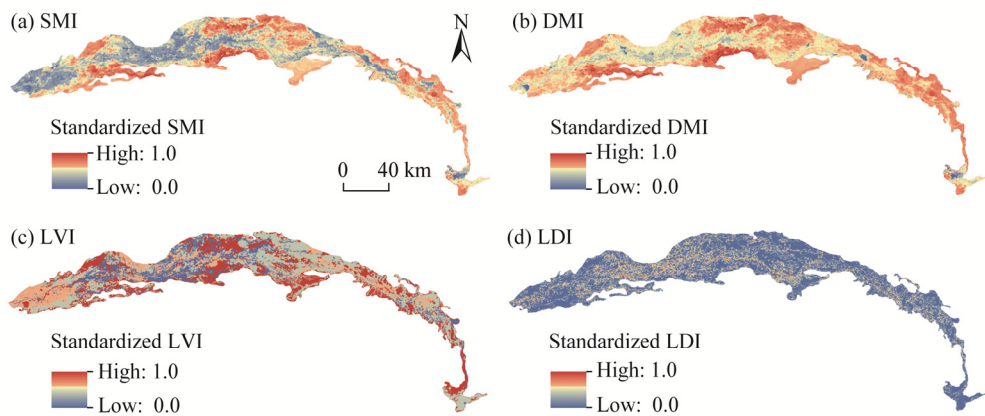


Fig. 5 Spatial distribution of SMI (a), DMI (b), LVI (c), and LDI (d) in the MTRB in 2020

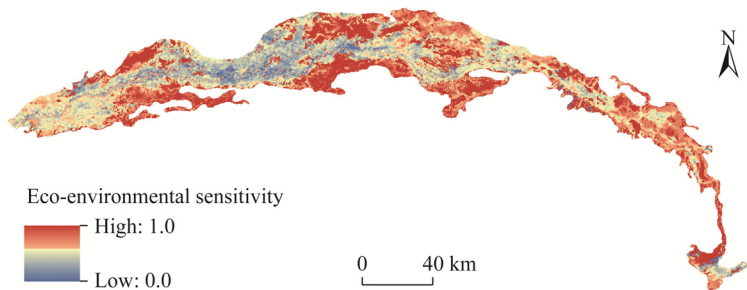


Fig. 6 Spatial distribution of eco-environmental sensitivity in the MTRB in 2020

4.1.3 Ecological source identification

We calculated ecosystem service trade-offs under seven scenarios, as shown in Table 4. As the risk increased, the trade-off value increased first and then decreased. When the ecological risk reaches 1.0000, the weight assigned to each ecosystem service was 0.2500, and the degree of trade-off was maximized. Among the seven risk scenarios, Scenario 4 showed the highest trade-off value, which was 1.0000. In Scenario 1 and Scenario 7, only one kind of ecosystem services was assigned the highest weight, resulting in the lowest trade-off value of 0.0000. For the remaining five scenarios, the order of their trade-off values from highest to lowest is: Scenario 4>Scenario 3>Scenario 5>Scenario 6>Scenario 2.

The conservation efficiency of the four ecosystem services is shown in Table 5. The conservation efficiency of each ecosystem service under the seven scenarios was greater than

1.0000, indicating that these scenarios coordinated the conservation of all ecosystem services. The scenario 7 had the highest conservation efficiency, followed by scenarios 6 and 5. Considering the ecosystem service trade-offs and conservation efficiency, this study selected the top 20% priority protection areas under scenario 5 as ecological sources.

By superimposing the importance of ecosystem services and the eco-environmental sensitivity of ecological sources, we finally obtained 274 ecological sources. Due to the large number of small and broken patches, some ecological sources were eliminated by determining the minimum patch area threshold. As shown in Figure 7, when the minimum patch area increased from 0.00 km² to 7.00 km², the number of corresponding ecological sources gradually stabilized, and the proportion of the area of the remaining ecological sources was always above 80%, indicating that eliminating ecological sources below 7.00 km² would not affect the overall ecological source effect. Therefore, the remaining 34 ecological sources were used as the final ecological sources, with a total area of 1471.38 km², as shown in Figure 8.

Table 4 Ecological risk and trade-offs between ecosystem services under different scenarios

Scenario	Ecological risk	Weight				Ecological trade-off
		Water conservation	Carbon storage	Habitat quality	Biodiversity conservation	
1	0.0001	0.0000	0.0000	0.0000	1.0000	0.0000
2	0.1000	0.0000	0.0550	0.0010	0.9440	0.0740
3	0.5000	0.0620	0.3120	0.1880	0.4380	0.6770
4	1.0000	0.2500	0.2500	0.2500	0.2500	1.0000
5	2.0000	0.5000	0.1590	0.2070	0.1340	0.6610
6	10.0000	0.8710	0.0390	0.0620	0.0280	0.1720
7	10,000.0000	1.0000	0.0000	0.0000	0.0000	0.0000

Table 5 Ecosystem service conservation efficiency under different scenarios

Scenario	Ecological risk	Weight				Conservation efficiency
		Water conservation	Carbon storage	Habitat quality	Biodiversity conservation	
1	0.0001	1.2070	1.2310	1.4890	1.2720	1.3000
2	0.1000	1.2320	1.2560	1.5120	1.2980	1.3250
3	0.5000	1.3010	1.5530	1.7780	1.4220	1.5140
4	1.0000	1.4490	1.6500	1.8160	1.8770	1.6980
5	2.0000	1.5460	1.6670	1.8210	2.2830	1.8290
6	10.0000	1.5350	1.6610	1.8060	2.5510	1.8880
7	10,000.0000	1.5370	1.6540	1.8020	2.5850	1.8950

4.2 Construction of ESP

4.2.1 Determination of ecological resistance surface

The ecological resistance surface of the study area showed the spatial distribution of low resistance values along the riparian zone and high resistance values away from the river, as shown in Figure 9. The minimum resistance value was 1.07 and the maximum was 4.65. The marginal area away from the river was a desert area with sparse vegetation and harsh climate. At the same time, in the upper reaches of the MTRB, due to frequent human activities such as agricultural expansion and dense road networks, the connectivity of the ecosystem decreased and the resistance value was high. Conversely, the abundant water sources and dense riparian vegetation strengthened ecological functions, leading to low resistance values that directly facilitated species migration. It is essential for maintaining ecological processes and biodiversity in the study area.

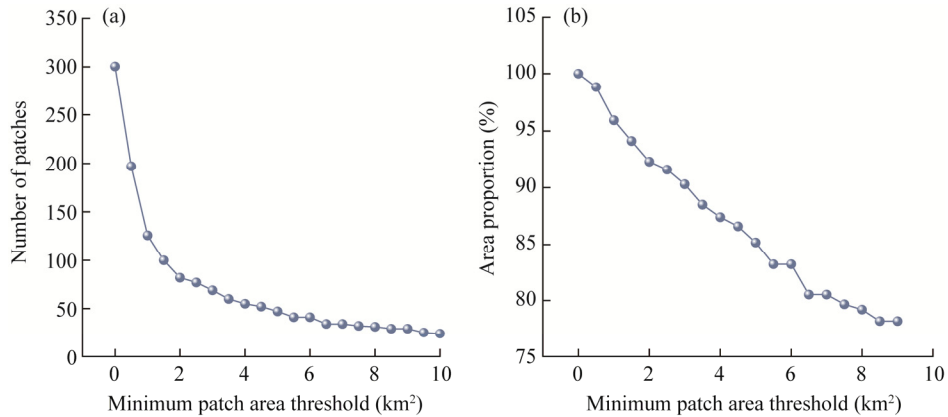


Fig. 7 Effect of the minimum patch area threshold on the number (a) and area proportion (b) of patches

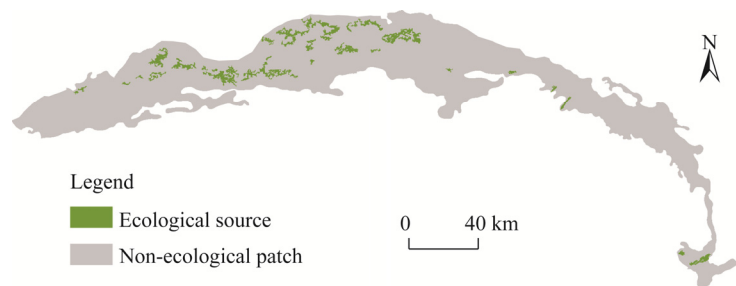


Fig. 8 Spatial distribution of ecological sources in the MTRB in 2020

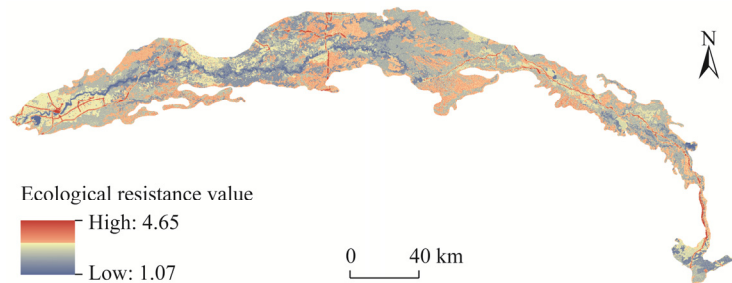


Fig. 9 Spatial distribution of ecological resistance surface in the MTRB in 2020

4.2.2 Construction of ESP

Ecological corridors play a critical role in enhancing regional resilience to extreme weather and anthropogenic disturbances by improving ecosystem connectivity and mitigating ecological fragmentation. This study identified 66 ecological corridors with a cumulative length of 1597.45 km (Fig. 10), ranging from 0.71 to 257.94 km. From the perspective of spatial distribution, the ecological corridors were mainly concentrated in the central region of the upper and middle reaches, showing a network distribution. However, the single land use type and poor ecological environment in the lower reaches resulted in sparse distribution of ecological corridors in a linear manner. Concurrently, 24 ecological nodes were identified, including 11 ecological pinch points and 13 ecological barrier points, which are important hubs for maintaining ecological flow and controlling ecological processes. Ecological nodes were mainly distributed at the intersection of ecological sources and ecological corridors, mainly in the upper and middle reaches. Overall, the spatial heterogeneity in the distribution of ecological corridors and ecological nodes was high, and the stability and sustainability of the ecosystem need to be further strengthened. Meanwhile, it is necessary to strengthen the protection of ecological pinch points and the restoration of ecological barrier points to enhance the connectivity of ecological corridors.

4.3 Optimization of ESP

4.3.1 Connecting ecological corridors and river corridors

This study integrated ecological corridors with river corridors to construct a hierarchical ecological network, thereby enhancing the stability and sustainability of the ecosystem, as shown in Figure 11. Ecological corridors connected to river corridors can provide continuous water resource support for the region, effectively optimize the pattern of vegetation water supply, further expand the area of vegetation restoration, and improve the ecological environment. In addition, the optimized ESP helped to enhance the anti-interference capacity and stability of ecosystem, and further enhanced the regional ecological restoration capacity and resilience. By optimizing the configuration of water resources and ecological space, key ecosystem service functions such as water conservation and carbon storage can be improved, thereby improving the regional ESP and promoting the overall value of ecosystem services.

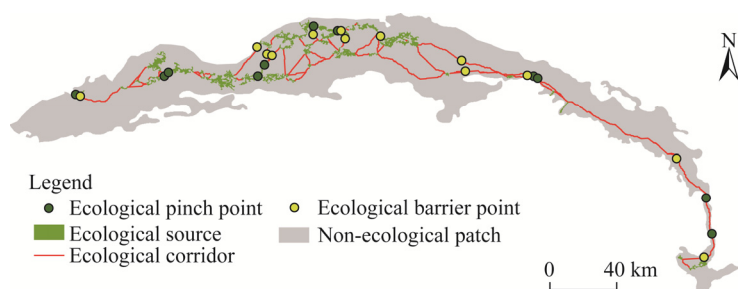


Fig. 10 Distribution of ESP in the MTRB

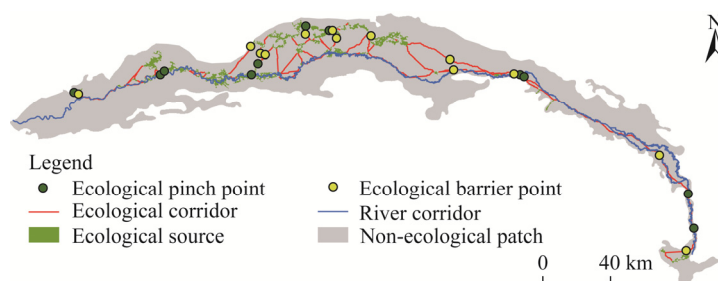


Fig. 11 Optimized layout of ecological corridors with river corridors in the MTRB in 2020

4.3.2 Determine the priority of ecological corridor protection

The kernel density values ranged from 0.00 to 43.75 in the MTRB in 2020. Based on the distribution of kernel density values, finally, we identified 17 important ecological corridors and 49 general ecological corridors, as shown in Figure 12. The important ecological corridors were mainly distributed in the upper and middle reaches. These areas were mainly focused on high kernel density values (>0.8), and had strong ecological functions and connectivity, which effectively promoted the connection between various ecological sources and stabilized the ecosystem. However, there were few important ecological corridors in the lower reaches, only one of which was distributed in Taitema Lake, and the lower reaches were mainly general ecological corridors. The lower reaches of the MTRB were mainly deserts and saline-alkali lands, with poor ecological conditions. At the same time, due to frequent human activities and poor water resource management in the upper and middle reaches, the downstream ecosystem has been continuously damaged.

5 Discussion

5.1 Methodological advantages of constructing ESP in arid areas

The construction of ESP and optimization of regional ecological spatial structures can effectively

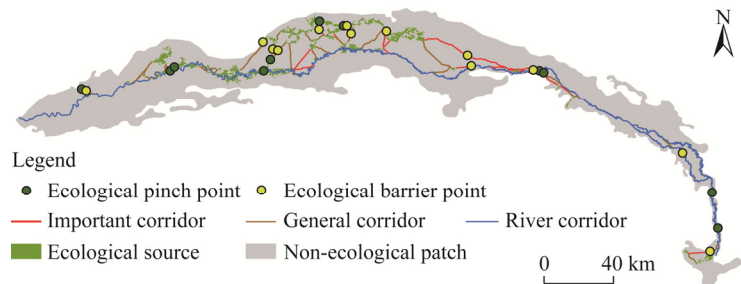


Fig. 12 Distribution of the ESP with the importance of ecological corridors in the MTRB in 2020

mitigate the conflict between socio-economic development and ecological protection in ecologically fragile arid inland river basins (Ding et al., 2022). In the identification of ecological sources, this study employed a comprehensive assessment integrating the ecosystem service importance and eco-environmental sensitivity. Conventional approaches often rely on equal weighting methods to assign fixed weights to indices of ecosystem service importance and eco-environmental sensitivity, which may inadequately capture critical ecological functions or overemphasize secondary factors, thereby introducing biases into results (Ding et al., 2022). Simultaneously, in defining the minimum area threshold for ecological sources, conventional studies have predominantly relied on subjective determination of threshold values to exclude fragmented patches, introducing biases into the spatial extent of extracted ecological sources (Fu et al., 2020). This study addressed the methodological limitations of traditional equal-weighting approaches by implementing the OWA multi-scenario simulation method and short-board effect. This study determined that the optimal spatial configuration of ecological sources was achieved at a minimum patch area threshold of 7.00 km². Using this threshold, 34 ecological sources were identified, spanning a total area of 1471.38 km².

The optimization of ESP should be closely anchored to the extant ecological elements of the study area (Peng et al., 2018), as this contextualization enhances the feasibility of regional ecological sustainability. Water, as a limiting factor for vegetation regeneration, assumes a pivotal role in maintaining ecosystem health and stability in arid inland river basins (Cai et al., 2021). Thus, by leveraging the eco-hydrological characteristics of the MTRB, this study integrated river corridors with ecological corridors to construct a high-efficiency ecological river network, enhancing the holistic functionality of the ecosystem (Hao and Li, 2014). Additionally, kernel density analysis was employed to prioritize ecological corridors, which effectively enhances ecosystem connectivity. Notably, the ESP in the MTRB exhibited significant spatial heterogeneity: the middle and upper reaches featured a higher density of ecological sources and corridors with pronounced aggregation, yielding superior ecological conditions compared with the lower reaches. To curb desertification progression in the downstream, large-scale ecological restoration initiatives—including desertification control and wetland rehabilitation—are imperative. In contrast, the middle and upper reaches require sustained conservation efforts building on existing favorable conditions, such as ecological water conveyance projects and corridor connectivity maintenance.

5.2 Ecosystem management based on ESP in the river basin in arid areas

Due to unreasonable human intervention and fragile ecological environment, environmental problems in arid areas have gained public attention (Zou et al., 2020). To meet the essential requirements of ecological protection and restoration, the ecosystem stability of arid inland river basins must take into account the ecological security layout and water resource distribution. International research in the area of ecological water utilization has concentrated on the precise control of reservoir water storage, the optimization dam discharge timing, and the installation of ecological gates at critical nodes to guarantee sufficient water flow in river basins. Examples include development projects in the Colorado River and Murray-Darling River basins (Mix et al., 2016; Pittock, 2016). Although international efforts, such as the creation of Yellowstone National

Park and the establishment of the International Commission for the Protection of the Danube River (ICPDR), have made progress in building ecological corridors and restoring wetlands and rivers, research on arid river basins remains limited (Chester, 2015; Habersack et al., 2016). In these areas, ecological water utilization is mostly restricted to riparian vegetation, limiting the expansion of green corridors and reducing the efficiency of water utilization, which significantly hampers the improvement of ecosystem functionality. Furthermore, compared with traditional ecological protection strategies, few studies have focused on integrating the spatial layout of ecological security with the optimization of water resource allocation. Therefore, to accomplish regional ecological protection and restoration, this study started with definition and construction of ESP, and optimized ESP by combining different levels of protection of ecological corridors and connecting with river corridors. This study used an "ecological source identification-resistance surface construction-ecological corridor extraction" framework to discover, build, and optimize the ESP for arid watersheds by considering the intricate mechanisms regulating river ecosystems. This framework offers essential guidelines for watershed ecological management aimed at enhancing landscape composition and spatial structure. The ecological functions of corridors vary. Unlike studies that analyze ecological corridors in isolation or consider only river systems, this research combined the overall layout of ecological corridors with river networks to optimize water resource utilization and circulation within the region, thereby enhancing ecosystem connectivity and functionality. The analysis showed that the global integration of the optimized ecological corridors has significantly improved.

5.3 Limitations

Although an effective spatial connection has been established between vegetation distribution and water systems and the overall connectivity of regional ecosystems has been improved, there are still deficiencies in the specific scheduling of water resources. Studies have shown that the implementation of rotational irrigation priorities based on vegetation gradient patterns and the division of ecological zones through ecological gate regulation can not only maximize the protection and restoration of basin vegetation but also achieve accurate and efficient allocation of water resources (Li et al., 2024b). Therefore, future research should further explore how to scientifically and rationally optimize the planning and layout of water resources, and formulate a scientific and reasonable water resource allocation strategy based on the existing configuration to ensure efficient management of water resources and further optimization of ecosystem functions.

6 Conclusions

The construction of ESP is conducive to promoting ecological protection and regional sustainable development. This study identified ecological sources by combining ecosystem service importance eco-environmental sensitivity. The circuit theory and kernel density analysis were used to extract ecological corridors, ecological pinch points, and ecological barrier points, and the importance level of ecological corridors is determined. The ESP in the MTRB in 2020 included 34 ecological sources, 17 important ecological corridors, 49 general ecological corridors, 11 ecological pinch points, and 13 ecological barrier points. The ecological network connectivity in the upper and middle reaches of the MTRB was strong, and the ecosystem was relatively stable, while the ecological sources and ecological corridors in the lower reaches were sparsely distributed and the network structure was relatively simple. In the future, more attention should be paid to the ecological protection of the upper and middle reaches and the restoration of the lower reaches. The research results can provide a scientific basis for curbing the deterioration of the ecological environment and improving the regional ecological function in similar areas, and also provide strong guidance and scientific support for the ecological environment protection and rational spatial planning of arid inland river basins.

Conflict of 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.

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Author contributions

Conceptualization: LING Hongbo; Data curation: QIN Xiaolin, LIU Wei; Methodology: QIN Xiaolin, LIU Wei; Formal analysis: QIN Xiaolin, MENG Xiangdong; Writing - original draft preparation: QIN Xiaolin; Writing - review and editing: LING Hongbo, ZHANG Guangpeng, GONG Yanming; Funding acquisition: LING Hongbo; Resources: LING Hongbo, ZHANG Guangpeng, SHAN Qianjuan; Supervision: LING Hongbo; Visualization: MENG Xiangdong, SHAN Qianjuan. All authors approved the manuscript.

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