

Identification and classification of ecological restoration areas in the territorial land space of the Qaidam Basin, China

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Abstract: Territorial spatial ecological restoration is a crucial prerequisite for optimizing the territorial spatial patterns, enhancing the ecosystem functions, and achieving sustainable development at the regional scale. The Qaidam Basin, located in the alpine arid region of the Qinghai–Xizang Plateau, China, is experiencing desertification, biodiversity loss, soil erosion, and environmental pollution. Selecting the Qaidam Basin as the study area, we identified 9 ecological sources in the region using the Morphological Spatial Pattern Analysis (MSPA) method and the landscape connectivity assessment, and extracted 10 significant corridors and 26 general corridors using the Minimum Cumulative Resistance (MCR) and Gravity models. Then, we determined 114 ecological "pinch points" and 42 ecological barrier points by employing the Circuit Theory, thereby constructing the ecological security pattern of the area. Further, we evaluated the ecosystem health of the Qaidam Basin during 2003–2023 using the Vitality–Organization–Resilience–Service (VORS) model. Finally, we integrated ecosystem health assessment and ecological security pattern to comprehensively identify the key areas for ecological restoration in the Qaidam Basin. The results revealed that the ecosystem in the basin fluctuated toward a healthier state from 2003 to 2023. The average ecosystem health index (EHI) for the basin decreased from 0.34 in 2003 to 0.28 in 2013, followed by a substantial recovery to 0.36 in 2023. Higher EHI values were found in the northeastern, southeastern, and southwestern fringes and lower values were located in the basin interior and northwestern region. During 2003–2023, the areas that exhibited a decrease in EHI were primarily located in the interior and northwestern regions of the basin, while those that exhibited an increase in EHI were located in the northeastern, southeastern, and southwestern fringes, demonstrating expanded spatial differences. This may be attributed to the fact that once an eco-environment is damaged, the ecological recovery of the vulnerable areas within the eco-environment will be slow and difficult. This study identified four types of ecological restoration areas, including corridor connectivity, artificial restoration, ecological recovery, and ecological enhancement zones, covering a total area of 6034.7 km², and proposed targeted ecological restoration strategies according to these different categories. Our findings can serve as a valuable reference for optimizing the territorial spatial patterns, enhancing the ecosystem functions, and promoting sustainable development in the Qaidam Basin.

Keywords: ecological security pattern; ecosystem health; ecological restoration; Morphological Spatial Pattern Analysis (MSPA); Minimum Cumulative Resistance (MCR); Vitality–Organization–Resilience–Service (VORS) model; Qaidam Basin

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1 Introduction

The ecological restoration of territorial land space denotes a process wherein the concepts and methods of system and integrity are integrated into ecological restoration practices, based on the internal mechanisms and succession laws of ecosystems. This encourages a shift from the perspective of restoration by a single factor to that of regionally coordinated governance that considers all elements and the entire process. The aim is to restore damaged, degraded, or destroyed ecosystems to a healthy state and enhance their comprehensive service capabilities (Yang et al., 2022; Gong et al., 2024). Over the last decade, with the swift advancement of industry, urbanization, and climate change, the passive compression of ecological space, fragmentation of landscape patterns, sharp decline in biodiversity, and degradation of ecosystem functions pose significant risks to the ecological security in China. In its Global Assessment Report on Biodiversity and Ecosystem Services released in 2019, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) highlighted that the world is experiencing accelerated species extinction and unprecedented natural biodiversity decline; large-scale ecosystem restoration is crucial for curbing species extinction and mitigating the effects of climate change (IPBES, 2019). Strengthening the stability, diversity, and sustainability of ecosystems, as well as expediting the implementation of major projects aimed at protecting and restoring significant ecosystems, are given equal importance in the report of the 20th National Congress of the Communist Party of China. The identification and classification of ecological restoration areas in territorial land space can offer a strategic direction for the layout of ecological restoration engineering projects, which is an essential precondition for conducting ecological restoration in an orderly manner, optimizing the ecological security pattern of territorial land space, enhancing the ecosystem functions, and achieving regional sustainable development (Cao et al., 2022; Yang et al., 2022).

At present, the research framework of "constructing the ecological security pattern—identifying ecological restoration spaces—conducting ecological restoration diagnosis" has been established for the ecological restoration zoning of the territorial land space in China (Cao et al., 2022; Yang et al., 2022; Gong et al., 2024). Guided by constructing an ecological security pattern, comprehensively identifying the key areas for ecosystem restoration according to the regional differences and then, proposing targeted and differentiated restoration strategies is a significant issue in territorial land space zoning, which requires immediate attention for ecological restoration and protection and is also a current research hotspot. The ecological security pattern originates from landscape ecological planning, and a research framework of "identifying ecological source areas—extracting ecological corridors—determining ecological "pinch points" and barrier points—constructing the ecological security pattern" has been developed in previous studies (Cao et al., 2022; Zhou et al., 2023). The models and methods applied in previous studies mainly included the Morphological Spatial Pattern Analysis (MSPA) method (Chen et al., 2023; Li et al., 2024b), the Minimum Cumulative Resistance (MCR) model (Yang et al., 2024), the Circuit Theory (Zhang et al., 2022; Li et al., 2024b), and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (Feng et al., 2024). Notably, previous studies primarily identified the ecological components in the ecological security pattern and combined them to delineate the restoration areas, resulting in a relatively narrow research perspective (Tian et al., 2025).

Ecosystem health reflects the structure and functional state of an ecosystem, encompassing various health elements, such as vitality, organization, and resilience; it is a pivotal ecosystem management issue in macro-ecological research (Pinto et al., 2013; Liu et al., 2022b; Zhu and Cai, 2024). A healthy ecosystem is typically characterized by normal ecological processes, stable biodiversity, appropriate resource utilization, and the ability to adapt to environmental changes. Since the introduction of the concept of ecosystem health, the related research field has witnessed an evolutionary process, progressing from the exploration of conceptual connotations and

extended theories to quantitative assessments (Liu et al., 2022b). At present, the majority of studies on ecosystem health focus on conducting quantitative assessments by establishing evaluation indicator systems and frameworks; the evaluation frameworks mainly include the Natural–Social–Economic Subsystem (Meng et al., 2018), Structure–Function–Process–Development (SFPD) (Su et al., 2019), Pressure–State–Response (PSR) (Wang et al., 2025), Driving force–Pressure–State–Impact–Response (DPSIR) (Zhao et al., 2021), Vitality–Organization–Resilience (VOR) (Guo et al., 2025), and Vitality–Organization–Resilience–Service (VORS) (Chen et al., 2022). The Natural–Social–Economic Subsystem model rarely explores the interaction relationship between ecosystems and human needs. In contrast, the PSR and DPSIR models do not evaluate the natural attributes and integrity of ecosystems. The VORS model evaluates the ecosystem service functions based on the VOR model, and it features clear measurement criteria and abundant ecological information; it not only assesses the natural attributes of ecosystems, but also explores the relationships between anthropogenic social activities and natural ecosystems. To some extent, the VORS model compensates for the shortcomings of other models, therefore having been widely applied in assessing ecosystem health (Zeng et al., 2022; Liu et al., 2024; Wang et al., 2024). To meet the actual needs of ecological restoration at the regional level, the specific practice of ecological restoration zoning in territorial land space often relies insufficiently on a set of generally applicable assessment procedures. This necessitates a more comprehensive and integrated assessment system that is tailored to the specific conditions of a region, to ensure and guarantee the efficacy and durability of ecological restoration efforts. In recent years, a few researchers attempted to comprehensively identify the ecological restoration zoning of territorial land space from the perspective of integrating ecological security patterns with ecological vulnerability (Gong et al., 2024), degradation risks (Li et al., 2024c; Tian et al., 2025), and service functions (Yang et al., 2023). Constructing an ecological security pattern and scientifically assessing and improving ecosystem health are effective approaches to safeguarding national ecological security and implementing the ecological civilization strategies. These efforts are crucial for sustaining the integrity of ecosystem structure and processes, enhancing the service capacity of ecosystems, and improving the human happiness index (Guo et al., 2025). However, the research perspective of combining ecological security patterns with ecosystem health remains unexplored.

The Qaidam Basin, one of the three major inland basins in China, is located in the alpine arid region of the Qinghai–Xizang Plateau. The basin is rich in salt lakes and oil and gas resources; however, its ecological environment is extremely fragile. For several years, the basin has faced severe problems, including desertification, soil salinization, biodiversity depletion, soil erosion, and environmental pollution, mainly due to the influence of global warming, resource exploitation, and urban construction (Li et al., 2025). Maintaining the regional ecological security in this region is a key issue that requires urgent attention and solutions, both in the present and for the foreseeable future. Taking the Qaidam Basin as the study area, we first formulated an ecological security pattern of the territorial land space in this region by applying the MSPA model, landscape connectivity assessment, MCR model, and Circuit Theory. Second, based on the VORS model, we evaluated the ecosystem health of the study area. Finally, we explored the research perspective of combining ecological security patterns with ecosystem health to identify and classify ecological restoration areas and proposed ecological restoration strategies based on the local conditions in the territorial land space of the Qaidam Basin. The findings can serve as a reference for maintaining the overall balance and promoting sustainable development of the ecosystem in the Qaidam Basin.

2 Materials and methods

2.1 Study area

The Qaidam Basin (Fig. 1), located in the northeastern part of the Qinghai–Xizang Plateau, is adjacent to the Kunlun Mountains in the south and connects with the Altun Mountains and Qilian

Mountains in the north. With an average elevation of approximately 3000 m, the Qaidam Basin covers roughly 800.0 km from east to west and 300.0 km from north to south, totaling an area of approximately 274,800.0 km². The basin has a plateau continental climate, which is characterized by scarce precipitation, high evaporation, water resource shortages, and relatively serious soil salinization problems, resulting in a fragile ecosystem (Jia et al., 2021). As one of China's three main inland basins, the basin has a wealth of numerous mineral resources, including salt, petroleum, natural gas, coal, and uranium ore. In particular, the salt mine resources in this region rank first in China, earning it the title of "treasure basin" (Stober et al., 2023). Relying on the regional resource advantages, the Qaidam Basin Circular Economy Pilot Zone was established in 2010 and became one of the first batches of circular economy industrial pilot parks in China.

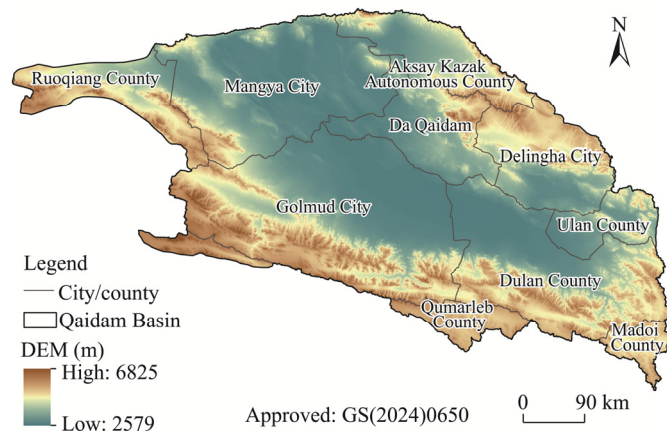


Fig. 1 Overview of the Qaidam Basin based on the digital elevation model (DEM). Note that the figure is based on the standard map (GS(2024)0650) of the Map Service System (<https://bzdt.ch.mnr.gov.cn/>), and the boundary of the standard map has not been modified.

2.2 Data sources

In this study, the land use data were sourced from the 30 m annual land cover dataset and its dynamics in China from 1985 to 2024 released by the Wuhan University, China (<http://zenodo.org/records/15853565>). The digital elevation model (DEM) data were derived from the Geographic Space Data Cloud (<http://www.gscloud.cn>), with a spatial resolution of 30 m. The slope was derived from the DEM data. The road and river data were acquired from the OpenStreetMap website (<http://www.openstreetmap.org>). The Normalized Difference Vegetation Index (NDVI) data covering the period 2003–2023 with a spatial resolution of 1000 m were acquired from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (<http://www.resdc.cn>). The Net Primary Productivity (NPP) of vegetation data were acquired from the MOD17A3 NPP product of the National Aeronautics and Space Administration (NASA) (<http://urs.earthdata.nasa.gov>), available annually from 2003 to 2023, with a spatial resolution of 500 m. The vector boundary of the Qaidam Basin was provided by the National Glacier, Permafrost, Desert Science Data Center (<http://www.ncdc.ac.cn>). All the raster datasets were resampled uniformly, with their projections and geographic coordinates converted to ensure consistency and compatibility across all spatial analyses. Socioeconomic data were used to calculate the ecosystem-service values, which were sourced from the Statistical Communique on National Economic and Social Development of the Haixi Mongolian and Tibetan Autonomous Prefecture (Bureau of Statistics of Haixi Mongolian and Tibetan Autonomous Prefecture, 2003–2023), Qinghai Province Statistical Yearbook (Bureau of Statistics of Qinghai Province and Survey Team of the National Bureau of Statistics in Qinghai, 2004–2024), Compilation of National Agricultural Products Cost and Benefit Data (National Development and Reform Commission, 2004–2024), and Huinong Network (<http://www.cnhnb.com>).

2.3 Methods

2.3.1 Ecological source identification

Ecological sources are identified as vital habitat patches within an ecosystem that hold paramount significance for maintaining the ecological security in a region (Chen et al., 2017); when it comes to creating an ecological security pattern, they form the base elements. Notably, MSPA, a method commonly employed in ecological studies to identify the source habitats in a region, utilizes a series of morphological principles to segment, erode, and classify the binary raster data into seven distinct and non-overlapping landscape categories (Chen et al., 2023). Based on the MSPA model, this study selected the following land use types in the Qaidam Basin as the foreground data for 2023: forestland, shrubland, grassland, water body, snow/ice, and wetland. The other land use types (cropland, impervious land, and bare land) were considered as background data. By employing the GuidosToolbox 3.0 software and adopting an eight-connectivity approach, the edge width was set to 30 m to delineate seven landscape categories: core, islet, perforation, edge, loop, bridge, and branch. The core areas, characterized as sizable ecological patches within the foreground, exhibited high ecosystem service values (Cao et al., 2022); therefore, the largest 30 patches within the core areas were preliminarily selected as the ecological sources in the study area. To further refine the selection of ecological sources, the landscape connectivity assessment, which involved evaluating the strength of the connectivity between different landscape elements, was integrated with the MSPA model. Note that the integral index of connectivity (IIC), probability of connectivity (PC), and delta Probability of Connectivity (dPC; %) are the most widely used indicators of landscape connectivity, and increased ICC, PC, and dPC values correspond to enhanced landscape connectivity. The larger the dPC value, the greater of significance the patch holds in ensuring ecological security (Lai et al., 2023). In this study, we assessed the connectivity of the ecological sources using the Conefor 2.6 software, while setting the connectivity distance threshold for patches at 5000 m and the probability of connection at 0.5. Those with a larger dPC values (>1.1) were prioritized for designation as the ultimate ecological sources. The formulas used for calculating the IIC, PC, and dPC can be expressed as follows:

$$IIC = \frac{1}{A_L^2} \sum_{i=1}^n \sum_{j=1}^n \frac{a_i a_j}{1 + ml_{ij}}, \quad (1)$$

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

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

where A_L is the total area of the landscape (km^2); n represents the number of patches in the region; ml_{ij} denotes the shortest path connection value between patches i and j (km); a_i and a_j are the areas of patches i and j (km^2), respectively; p_{ij}^* is the maximum value of the product of all path probabilities between patches i and j ; and PC_{remove} is the potential connection index following patch removal.

2.3.2 Ecological resistance surface construction

The ecological resistance surface denotes the impediments encountered during the processes of species migration and energy flow between ecological sources (Yang et al., 2020). Drawing upon pertinent studies (Gong et al., 2024; Li et al., 2024c) and expert consultations, we identified the ecological resistance factors by considering both the anthropogenic disturbances and ecological attributes that could affect the connectivity between the ecological sources in the Qaidam Basin. Considering the land use type and the distances from roads and water bodies as the anthropogenic resistance factors, the NDVI, DEM, and slope were identified as the major ecological property resistance elements. Lower values assigned for the resistance factors indicate lesser hindrance. This study developed a comprehensive ecological resistance evaluation index

system (Table 1). The weight of each ecological resistance factor was established by applying the Analytic Hierarchy Process (AHP) in the YAAHP 10.1 software, and the resultant values were subjected to consistency ratio tests. Simultaneously, a synthesized ecological resistance surface was created by integrating all factors using the weighted index summation method in ArcGIS 10.8. The equation for ecological resistance surface (R) can be expressed as follows:

$$R = \sum_{k=1}^m (F_k \times W_k), \quad (4)$$

where m represents the number of resistance factors; F_k denotes the coefficient of resistance factor k ; and W_k is the weight of resistance factor k .

Table 1 Comprehensive ecological resistance evaluation index system developed in this study

Type	Resistance factor	Resistance value					Weight
		1	3	5	7	9	
Anthropogenic resistance	Land use type	Grassland, water body, snow/ice, and wetland	Forestland and shrubland	Cropland	Impervious area	Bare land	0.32
	Distance from roads (m)	>2000	1500–2000	1000–1500	500–1000	0–500	0.05
	Distance from water bodies (m)	0–500	500–1000	1000–1500	1500–2000	>2000	0.13
Ecological property	NDVI	0.8–1.0	0.6–0.8	0.4–0.6	0.2–0.4	0.0–0.2	0.08
	DEM (m)	2579–3048	3048–3589	3589–4134	4134–4641	>4641	0.27
	Slope (°)	0.0–5.9	5.9–12.5	12.5–21.1	21.1–31.5	>31.5	0.15

Note: NDVI, Normalized Difference Vegetation Index; DEM, digital elevation model.

2.3.3 Ecological corridor extraction

Ecological corridors serve as vital links or bridges between ecological sources, providing the pathways of least cost for species migration and energy flow (Fu et al., 2001). Among the methods used to identify such corridors, MCR is commonly used when constructing the corridor system, due to its ability to consider the interrelations among various ecological sources (Gong et al., 2024). Based on the MCR model, we first employed the Cost Distance tool in ArcGIS 10.8 to generate the potential ecological corridors that link the ecological sources in the region. Subsequently, we calculated the interaction forces between each pair of sources by applying the Gravity model. The links with stronger mutual interactions were identified as critical ecological corridors, whereas others were categorized as general corridors. The formula for the Gravity model is given below:

$$G_{uv} = \frac{M_u M_v}{D_{uv}^2} = \frac{\left(\frac{\ln(S_u)}{P_u}\right) \times \left(\frac{\ln(S_v)}{P_v}\right)}{\left(\frac{L_{uv}}{L_{\max}}\right)^2} = \frac{L_{\max}^2 \ln(S_u) \ln(S_v)}{L_{uv}^2 P_u P_v}, \quad (5)$$

where G_{uv} is the force of mutual interaction between the ecological sources u and v ; M_u and M_v represent the masses representing the ecological significance or attractiveness of sources u and v , respectively; D_{uv} is the standardized value of the potential corridor resistance between the ecological sources u and v ; S_u and S_v are the areas of ecological sources u and v , respectively (m^2); P_u and P_v are the resistance values of ecological sources u and v , respectively; L_{uv} is the cumulative resistance value of the corridor between the ecological sources u and v ; and L_{\max} stands for the maximum cumulative resistance of all corridors.

2.3.4 Determining the ecological "pinch points" and barrier points

Ecological "pinch points" are parts of the trail that cannot be replaced or those that pass through with high probability during the species migration within the ecological corridors, playing a

pivotal role in maintaining the overall connectivity of the ecological networks within a region. They can be used as priority areas to prevent ecological degradation and promote ecological restoration (Dou et al., 2024; Gong et al., 2024). Ecological barrier points are areas where the passage of a species between ecological sources is hindered, typically found at junctures where ecological corridors exhibit discontinuity. An essential step is to find these barrier points and then, remove or mitigate them, to enhance landscape permeability and connectivity to the environment (Cao et al., 2022; Gong et al., 2024). The Circuit Theory, adapted from the field of electrical engineering, conceptualizes species as analogous to electrons and the landscape as a conducting medium. Drawing upon the random walk behavior of electrons within circuits, this approach models the dispersal process of species across their ecological sources. By skillfully capturing the complexities of species migration and movement, this approach provides an accurate depiction of their actual translocations within authentic ecological situations (Liu et al., 2022a).

In this study, we identified the ecological "pinch points" and barrier points using the Circuitscape program grounded in Circuit Theory, along with the Pinchpoint Mapper and Barrier Mapper tools available in ArcGIS 10.8. Drawing upon relevant ecological corridor planning in the Qaidam Basin, the current corridors were set at a width of 10.0 km using the Pinchpoint Mapper tool in the "All-to-One" mode through iterative experimentation. The natural break approach was employed to classify the current density results into five classes, with the highest class designated as the ecological "pinch points". Based on the Barrier Mapper tool and the results of previous studies (Cao et al., 2022; Lin et al., 2023), the minimum detection radius was calibrated to 1000 m and maximum detection radius was set to 4000 m (with a radius step value of 1000 m). We identified areas that were likely to pose a greater threat to the ecological corridor connectivity of the Qaidam Basin by employing the Barrier Mapper tool. Those areas were divided into five categories utilizing the natural break approach, and the category with the highest value was identified as the ecological barrier points.

2.3.5 Ecosystem health assessment framework construction

An ecological health assessment framework was built by integrating the ecosystem service functions in the region into the VORS model (Fig. 2). Ecosystem vitality (EV), ecosystem organization (EO), and ecosystem resilience (ER), which were essential indicators of the pristine health (PH) of the ecosystem (Zhu and Cai, 2024), were used to assess the integrity and sustainability of the ecosystems within the study area. EV, defined as the capacity to maintain self-renewal and primary productivity, is commonly quantified through NPP or NDVI (Liu et al., 2024; Ouyang et al., 2024). This study selected NPP to avoid redundancy in our metrics. EO reveals the structural intricacy of ecosystems, and higher values correlate with greater PH; it is primarily characterized by landscape heterogeneity (LH), landscape connectivity (LC), and important patch connectivity (IPC) (Zeng et al., 2022). Generally, LH can be evaluated by the Shannon's diversity index (SHDI) and area-weighted mean patch fractal dimension (AWMPFD). SHDI is used to quantify ecosystem diversity and AWMPFD is employed as a measure of the intricacy of landscape patches, with higher values corresponding to greater LH. LC can be quantified by the overall landscape contagion index (CONT) and fragmentation index (FI). The CONT index evaluates the propensity of dominant landscape types to cluster, with higher values indicating superior LC. Furthermore, FI can quantify the degree of landscape fragmentation, typically exhibiting a negative correlation with LC. The landscapes of the Qaidam Basin are primarily characterized by grasslands, water bodies, and croplands, which serve as crucial ecological connectivity functions and are identified as important patches. Moreover, IPC is quantitatively assessed by incorporating both the cohesion index (CI) and the FI of the important patches. CI primarily assesses the spatial aggregation or isolation patterns among heterogeneous patch types, demonstrating a positive relationship with IPC. Finally, ER denotes the capacity of an ecosystem to recover its composition and function under the influence of external stresses (Wang et al., 2024), and it can be assessed via resistance and recovery coefficients assigned to

different land use types (Liu et al., 2024). Ecosystem service functions, which denote the provision of material benefits and support offered to humans by nature, have become integral indicators in ecological health evaluations. They include provisioning, regulating, supporting, and cultural services, typically measured by ecosystem service values (Zeng et al., 2022; Ouyang et al., 2024). This study employed the Ecosystem Service Valuation Equivalent Scale established by Xie et al. (2015), while drawing upon relevant research on ecosystem service valuation conducted recently (Li et al., 2024a). Taking into account the actual conditions of the Qaidam Basin, *Lycium barbarum*, highland barley, and wheat were selected as the main crops of the region. Using the average yields per unit area of the three crops in the Haixi Mongolian and Tibetan Autonomous Prefecture in the last decade and the national average price of wheat as foundational data, as well as referring to the related literature (Han and Liang, 2024) and the agricultural product price fluctuation data published by Huinong Network, the average prices for highland barley and *Lycium barbarum* were considered to be 4.23 and 48.00 CNY/kg, respectively. The economic value of one standard unit of ecosystem service in the Qaidam Basin was calculated to be 6869.76 CNY/(hm²·a). Consequently, we derived the unit-area ecosystem service values of different land use types in the Qaidam Basin (Table 2). Concerning previous studies (Liu et al., 2024; Wang et al., 2024) and the actual ecosystem health status of the Qaidam Basin, five levels were used to classify the ecosystem health index (EHI), EV, EO, ER, and composite ecosystem services index (CESI) (Table 3). The specific formulas to calculate these indices can be expressed as follows:

$$EHI = \sqrt{PH \times CESI}, \quad (6)$$

$$PH = \sqrt[3]{EV \times EO \times ER}, \quad (7)$$

$$EO = 0.35LH + 0.35LC + 0.30IPC = (0.10AWMPFD + 0.25SHDI) + (0.10CONT + 0.25FI_1) + (0.03CI_1 + 0.07FI_2 + 0.03CI_2 + 0.07FI_3 + 0.03CI_3 + 0.07FI_4), \quad (8)$$

$$ER = 0.4 \times \sum_{h=1}^n A_h^* \times C_{\text{resistant},h} + 0.6 \times \sum_{h=1}^n A_h^* \times C_{\text{resilient},h}, \quad (9)$$

$$CESI = \sum (P_h \times A_h), \quad (10)$$

$$CESI_t = \sum (P_{ht} \times A_h), \quad (11)$$

where FI_1 symbolizes the overall fragmentation index; CI_1 and FI_2 , CI_2 and FI_3 , as well as CI_3 and FI_4 denote the patch cohesion and fragmentation indices specific to grassland, water body, and cropland, respectively; A_h^* signifies the proportion of area covered by the land use type h in the study area (%); $C_{\text{resistant},h}$ and $C_{\text{resilient},h}$ represent the resistance and resilience coefficients, respectively, associated with the land use type h ; P_h denotes the ecosystem service value per unit area of land use type h (CNY/(hm²·a)); A_h denotes the area of land use type h (hm²); $CESI_t$ designates the ecosystem service value of the ecosystem service type t in the study area (CNY); and P_{ht} is the individual ecosystem service value of land use type h per unit area for the ecosystem service type t (CNY/(hm²·a)). All landscape pattern indices were computed using the "Landscape Metrics" module in Fragstats 4.2. Among these indices, FI_1 , FI_2 , FI_3 , and FI_4 represent the inverse metrics; conversely, the remainder were considered positive indicators. Prior to analysis, normalization was applied to all metrics to standardize their scales (Wang et al., 2024).

2.3.6 Identification and zoning of ecological restoration areas

With the help of ArcGIS 10.8, we identified the areas with weak and relatively weak levels of ecosystem health in the Qaidam Basin in 2023. Further, according to the EHI, these areas were classified into five categories, using the natural break method. Taking the first two categories as the base map and combining them with the distribution of ecological corridors within the region, four key ecological restoration areas were finally demarcated, namely, the corridor connectivity zone, artificial restoration zone, ecological recovery zone, and ecological enhancement zone.

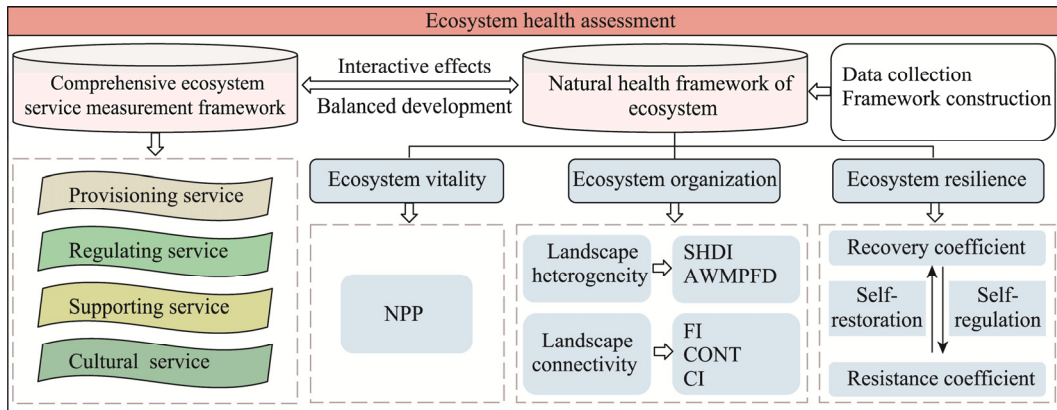


Fig. 2 Ecosystem health assessment framework of the Qaidam Basin. NPP, net primary productivity; SHDI, Shannon's diversity index; AWMPFD, area-weighted mean patch fractal dimension; FI, fragmentation index; CONT, the overall landscape contagion index; CI, cohesion index.

Table 2 Ecosystem service values of each land use type per unit area in the Qaidam Basin

Type	Ecosystem service	Ecosystem service value (CNY/(hm ² ·a))							
		Crop-land	Forest-land	Shrub-land	Grass-land	Water body	Snow/ice	Bare land	Wetland
PS	Food production	5839.3	1511.3	1305.3	687.0	5495.8	0.0	0.0	3503.6
	Raw material production	2747.9	3572.3	2954.0	961.8	1580.0	0.0	0.0	3434.9
	Water supply	137.4	1854.8	1511.3	549.6	56,950.3	14,838.7	0.0	17,792.7
RS	Gas regulation	4602.7	11,678.6	9686.4	3503.6	5289.7	1236.6	137.4	13,052.6
	Climate regulation	2473.1	34,829.7	29,059.1	9205.5	15,731.8	3709.7	0.0	24,731.1
	Environmental purification	687.0	10,235.9	8793.3	3022.7	38,127.2	1099.2	687.0	24,731.1
	Hydrological regulation	1854.8	22,945.0	23,013.7	6732.4	702,364.7	48,981.4	206.1	166,454.4
SS	Soil conservation	7075.9	14,151.7	11,816.0	4259.3	6388.9	0.0	137.4	15,869.2
	Maintaining nutrient cycling	824.4	1099.2	893.1	343.5	480.9	0.0	0.0	1236.6
	Biodiversity	893.1	12,915.2	10,785.5	3847.1	17,517.9	68.7	137.4	54,065.0
CS	Aesthetic landscapes	412.2	5633.2	4740.1	1717.4	12,983.9	618.3	68.7	32,494.0

Note: PS, provisioning service; RS, regulating service; SS, supporting service; CS, cultural service. Note that the ecosystem service values of impervious area per unit area were all zero.

Table 3 Classification of various ecosystem indices in this study

Index	Weak	Relatively weak	Ordinary	Relatively strong	Strong
Ecosystem health index (EHI)	0.00–0.20	0.20–0.35	0.35–0.50	0.50–0.75	0.75–1.00
Ecosystem vitality (EV)	0.00–0.02	0.02–0.04	0.04–0.06	0.06–0.13	0.13–1.00
Ecosystem organization (EO)	0.00–0.44	0.44–0.45	0.45–0.48	0.48–0.51	0.51–1.00
Ecosystem resilience (ER)	0.00–0.06	0.06–0.20	0.20–0.40	0.40–0.55	0.55–1.00
Composite ecosystem services index (CESI)	0.00–0.01	0.01–0.04	0.04–0.06	0.06–0.09	0.09–1.00

3 Results and discussion

3.1 Construction of ecological security pattern

3.1.1 Ecological source identification

In the MSPA results, the core areas represented the largest proportion of the prospective elements within the Qaidam Basin, accounting for 77.3% of the entire area. These core areas were

predominantly situated along the southeastern rim of the basin, particularly in the Madoi County, Qumarleb County, Dulan County, Ulan County, and Delingha City, and were largely contiguous with the local hydrological systems. The edges and perforations followed in terms of the area, contributing significantly to mitigating the external spatial impacts on the core areas and exhibiting pronounced edge effects. Bridges and islets occupied 2.0% and 1.5% of the prospective elements, respectively, suggesting relatively smooth energy flows between the core areas. Upon assessing the landscape connectivity of the top 30 largest core areas, 9 significant ecological sources were ultimately selected, cumulatively spanning an area of 35,194.9 km², primarily comprising grassland and aquatic ecosystems. Among these, the largest ecological source encompassed 23,319.2 km² of area, comprising 8.5% of the total area of the Qaidam Basin, featuring the Donggi Cona Lake and the southeastern fringing grasslands; its intact natural ecosystem and high ecosystem service values render it as a critical patch for regional ecological security.

3.1.2 Ecological resistance surface formation

This study acquired a composite ecological resistance surface of the Qaidam Basin based on the integrated weighted overlay analysis of the anthropogenic resistance factors and ecological property resistance elements detailed in Table 1. The composite ecological resistance values in the basin exhibited pronounced spatial variability, with the high-resistance regions predominantly distributed along the southern and northern fringes, forming a semi-circular pattern (Fig. 3). With higher elevations and steeper slopes, the predominant land use type in these regions was primarily bare land, indicating lower ecological stability. Conversely, the low-resistance areas were concentrated in the southeastern sector of the basin, featuring grassland as the dominant land use type. These areas exhibited higher NDVI values, denoting lush vegetation cover and enhanced ecological connectivity.

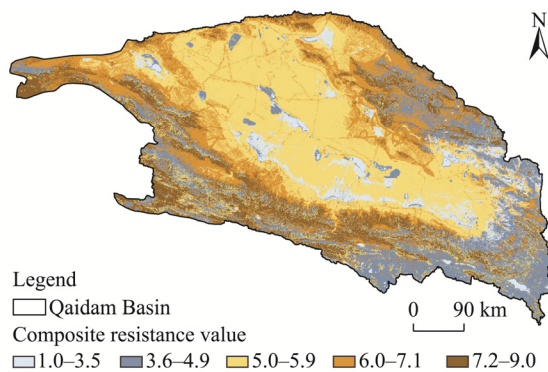


Fig. 3 Ecological resistance surface based on the composite ecological resistance values in the Qaidam Basin

3.1.3 Ecological corridor extraction

Building upon the composite ecological resistance surface data, we simulated the pathways of species migration and energy flow between the identified ecological sources using the MCR model. In total, 36 potential ecological corridors spanning a distance of 5702.7 km were delineated in the Qaidam Basin, with the longest corridor extending 762.4 km, constituting 13.4% of the aggregate corridor length. Based on the Gravity model calculations, we derived an interaction matrix among the identified sources (Fig. 4). By filtering the paths with an interaction force more than 400.0, 10 significant corridors emerged, with a total length of 983.6 km, which represented 17.2% of the overall corridor network. Predominantly linking Delingha City, Ulan County, and Dulan County, these corridors served as pivotal conduits for the dispersal of species. Meanwhile, 26 general corridors, extending for 4719.1 km (82.8% of the total length), spanned more extensively, serving to enhance the spatial service values among the diverse ecological sources. Interestingly, we observed no ecological corridor links between the Aksay Kazak Autonomous County, Mangya City, and Ruoqiang County in the northwestern region of the Qaidam Basin, highlighting the reduced connectedness and integrity of the natural ecosystems in these areas.

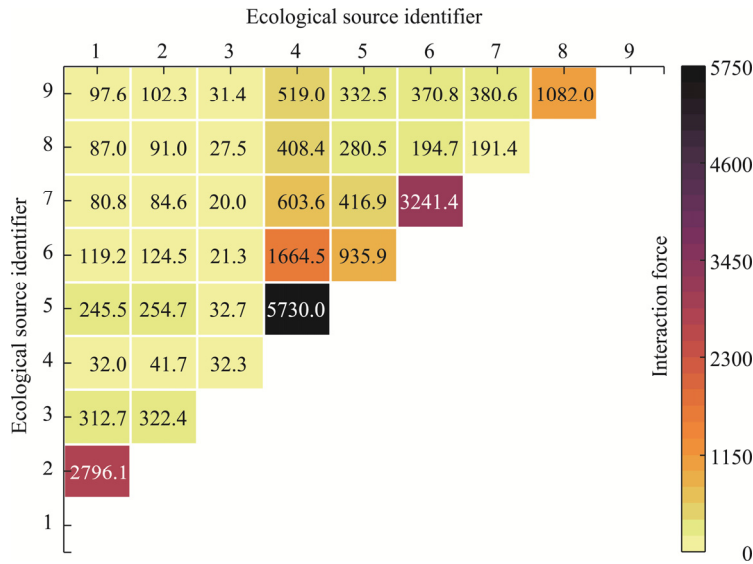


Fig. 4 Interaction matrix of ecological sources in the Qaidam Basin based on the Minimum Cumulative Resistance (MCR) and Gravity models. Numbers 1–9 denote the ultimately identified ecological sources.

3.1.4 Ecological security pattern construction

The ecological "pinch points" were predominantly clustered in the north of Golmud City, east of the Da Qaidam Administrative Committee, and northwest of Delingha City (Fig. 5). Considering the ecological corridor distribution pattern, we identified a total of 114 ecological "pinch points" as the priority regions for conservation and protection against ecological degradation. The major land use types in these regions were predominantly grassland and bare land, covering an area of 114.0 km². Besides, we identified 42 barrier points as the key restoration areas (encompassing 42.0 km²) to enhance the connectivity of ecological corridors. These barrier points were predominantly situated in the southeastern part of the Qaidam Basin, specifically in the Dulan County and Ulan County, where the land use types consisted primarily of bare land, grassland, snow/ice, and water body. Furthermore, a few of the ecological barrier points coincided with the ecological "pinch points" located in the northeast of Delingha City and southeast of Ulan County, characterized primarily by grassland and bare land. These regions served as the core areas for ecological function (significant corridors for species migration), while featuring limited soil and water conservation capacity due to their high elevations and steep slopes. Characterized by a high proportion of bare land, these regions demonstrated relatively weak natural recovery capabilities. Human activities (e.g., resource exploitation and environmental pollution) could readily trigger both functional degradation and recovery obstacles in these regions, rendering them as vulnerable bottlenecks (barrier points) within the ecosystem. Special attention should be given to these regions during ecological restoration efforts, particularly in these overlapping areas. Building upon this analysis, in this study, ecological sources were designated as the conservation zones, important corridors were designated as the conservation corridors, general corridors were designated as the restoration corridors, ecological "pinch points" were designated as the control zones, and barrier points were designated as the restoration areas. This strategic framework formed the ecological security pattern for the Qaidam Basin.

3.2 Ecosystem health assessment

3.2.1 Temporal variations of ecosystem health

The average EHI values for the basin decreased from 0.34 in 2003 to 0.28 in 2013, followed by a substantial recovery to 0.36 in 2023 (Fig. 6). From the perspective of the variations in the area and the area percentage corresponding to each EHI category, the overall EHI showed an initial

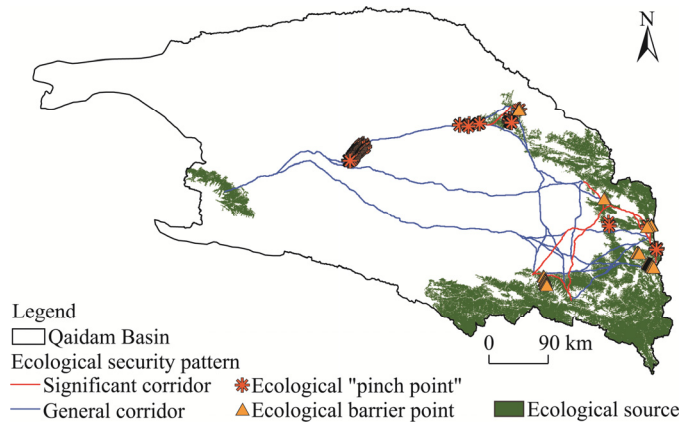


Fig. 5 Ecological security pattern constructed for the Qaidam Basin

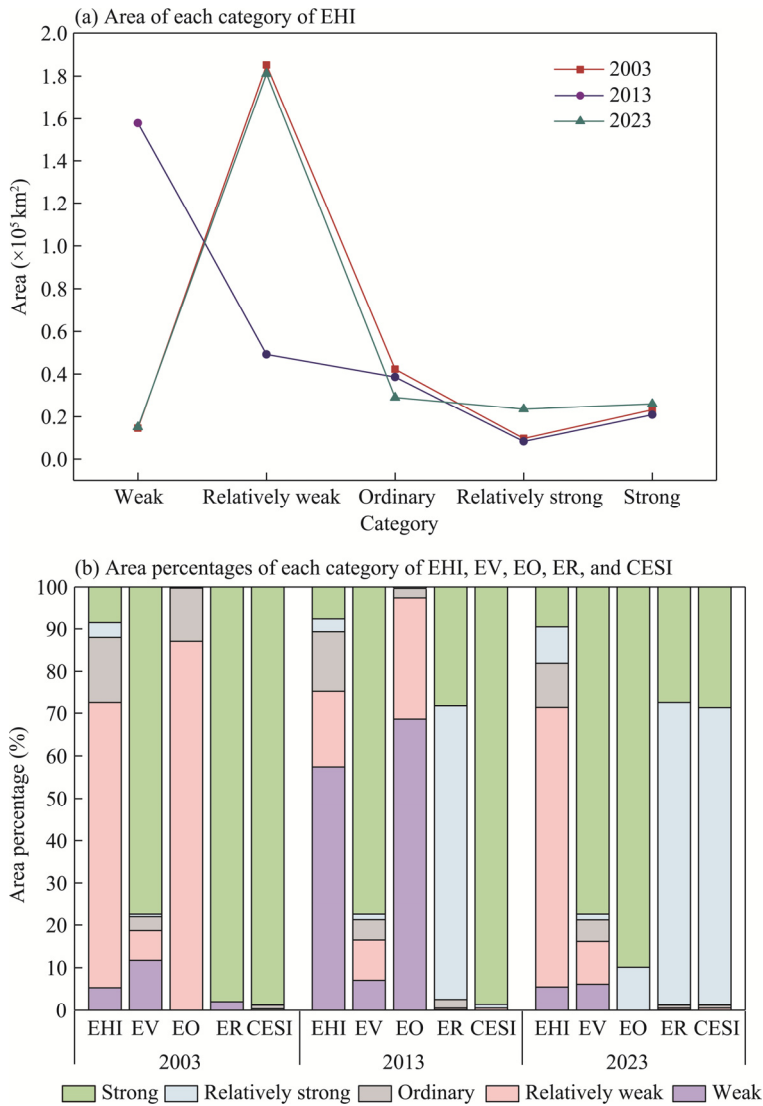


Fig. 6 Statistics on areas of ecosystem health index (EHI) categories (a) and area percentages of EHI, ecosystem vitality (EV), ecosystem organization (EO), ecosystem resilience (ER), and composite ecosystem services index (CESI) categories (b) in the Qaidam Basin from 2003 to 2023

decrease, followed by a subsequent recovery, indicating a fluctuating transition to a healthier state from 2003 to 2023. However, by 2023, the entire basin remained predominantly in a sub-healthy condition. Spatially, higher EHI values emerged in the northeastern, southeastern, and southwestern fringes and lower EHI values emerged in the interior and northwest of the basin. Isolated high-value areas characterized by robust ecosystem health could be discerned within the basin, whereas urban centers located along the periphery tended to exhibit lower EHI values.

The EHI category experiencing the most significant reduction in coverage was the relatively weak area, decreasing from 67.3% in 2003 to 17.9% in 2013, essentially transforming into the weak area (Figs. 6 and 7). Two factors primarily drove the observed changes during this period: one was the expansion of the percentage of weak area for EO (from 0.0% to 68.6%), primarily converted from the relatively weak area, coupled with the decline of the percentage of ordinary area (from 12.7% to 2.2%); the other one was the decrease of the percentage of strong area for ER (from 98.0% to 28.3%), primarily due to the conversion into relatively strong area (Fig. 6b). Notably, the location of the Qaidam Basin on the Qinghai–Xizang Plateau endows it with inherently fragile ecosystems that are highly sensitive to anthropogenic disturbances and natural environmental shifts, coupled with slow recovery rates. From 2003 to 2013, the Qaidam Basin experienced accelerated economic and social growth, which increased the human interference in its ecosystems. The reduction in the structural integrity and functional stability of the ecosystem led to a decline in the overall ecosystem health in this region.

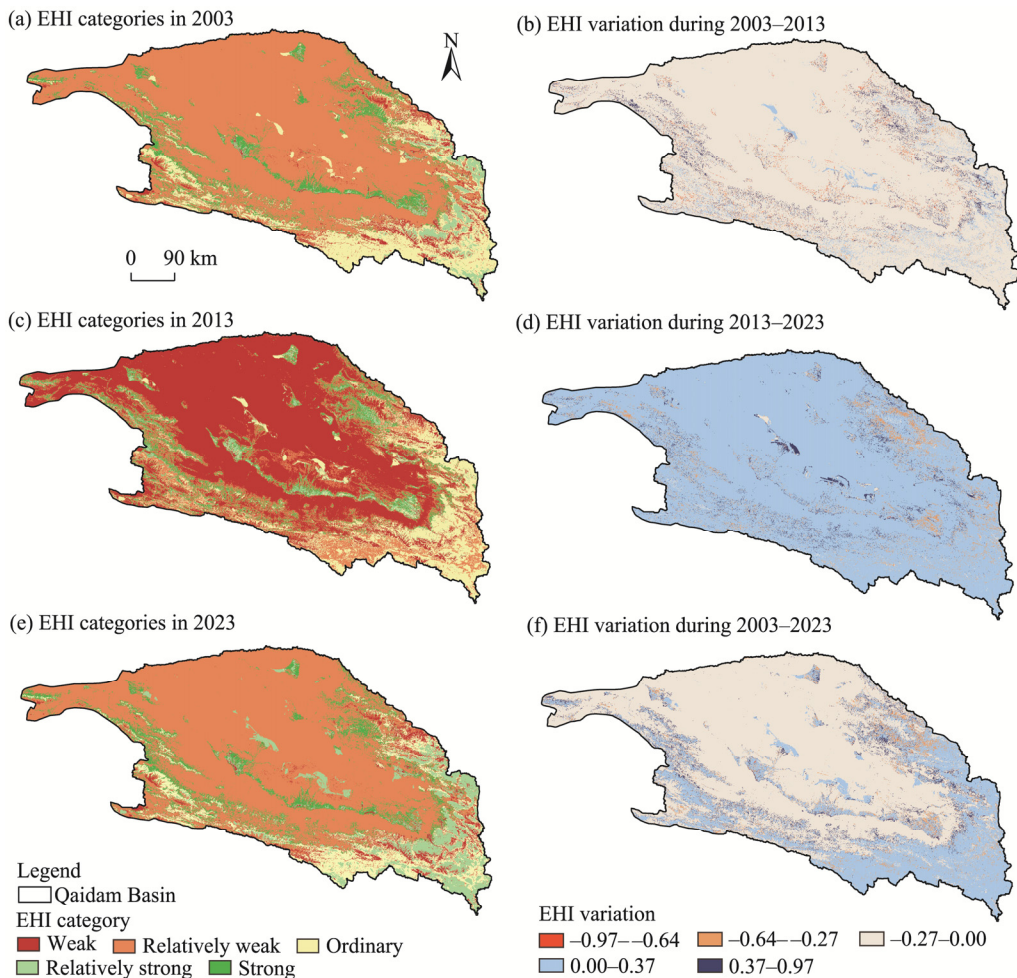


Fig. 7 Spatial distributions of EHI categories in 2003, 2013, and 2023 (a, c, and e) and variations in EHI during periods of 2003–2013, 2013–2023, and 2003–2023 (b, d, and f) across the Qaidam Basin

Between 2013 and 2023, the percentage of relatively weak area (as per the EHI) recovered from 17.9% to 65.9%, that of relatively strong area increased from 3.0% to 8.6%, and that of weak area decreased from 57.4% to 5.5%. The overall improvement in EHI during this period was primarily driven by the transformation of the EO in the region—composed initially of 68.6% weak area, 28.9% relatively weak area, and 2.2% ordinary area—into a new composition of 89.9% strong area and 10.1% relatively strong area. Within the basin, the areas that were previously weak area was restored to relatively weak area between 2013 and 2023, but the average EHI in 2023 was still lower than that in 2003. On the southeastern fringe of the Qaidam Basin, the majority of ordinary area primarily transitioned to relatively strong area between 2013 and 2023, and the EHI increased significantly compared to that in 2003. This implied that the environmental conservation efforts significantly strengthened during this period. The southeastern fringe of the Qaidam Basin had a healthy ecological baseline, characterizing ecosystems with high structural integrity and functional stability. The majority of areas with ecological sources located on the southeastern fringe showed greater improvement in EHI, leading to a notable increase in the spatial disparity of the ecosystem health throughout the Qaidam Basin during 2013–2023. However, we noted no discernible improvement in the central districts of counties in the basin, and the basin-scale ecosystem health remained at an ordinary level until 2023. These central districts, marked by dense populations, experienced increased pressure due to ongoing urbanization.

3.2.2 Spatial variations of ecosystem health

From 2003 to 2013, the regions with declining ecosystem health were widely distributed, and the small parts of the regions with improving ecosystem health were mostly found in the northeastern and southwestern fringe areas (Figs. 6–8). The majority of the interior and northwestern regions of the Qaidam Basin were covered by desert (the Gobi desert), with scarce precipitation (<100 mm/a), vigorous evaporation, and low vegetation coverage, resulting in extremely fragile ecosystems in these areas (Li et al., 2025). Additionally, these areas contain numerous large salt lakes (e.g., the Qarhan Salt Lake, East Taijnar Lake, West Taijnar Lake, and Da Qaidam Salt Lake) (Rao et al., 2025). Due to rapid economic and social development, as well as market forces, the salt lake resources in the Qaidam Basin experienced large-scale exploitation during 2003–2013 (Deng et al., 2018). During this phase, long-term and large-scale extraction of brine caused the water levels in some salt lakes to drop and the lake areas to shrink significantly. Numerous salt fields and evaporation ponds were constructed around the salt lakes, altering the surface runoff and resulting in increased soil salinity. Additionally, the salt residue produced from salt-lake resource processing occupied extensive land areas and could also spread with the wind, further aggravating the soil salinity in the surrounding areas and posing risks to the plant communities in these areas (Geng et al., 2021). The high industrial water consumption (e.g., for ore dressing and processing) exacerbated the pressure on the already scarce water resources in these areas, further intensifying the trend of desertification in this region. Consequently, the EHI in these areas significantly declined, particularly in terms of ecosystem structural complexity and the capability of the ecosystem structure and function to recover to their initial states after experiencing external stress.

From 2003 to 2013, compared to the northeastern, southwestern, and southeastern fringe regions, the interior and the northwestern areas of the basin depicted greater decline in the EO and ER magnitudes (Fig. 8a, e, h, and k). Notably, EV exhibited further decline in the interior and northwestern regions and an increase in the northeastern, southwestern, and southeastern fringe areas. These indicated that the drop in the ecosystem health within the ecological vulnerable areas of the basin was the primary driver of the overall ecological degradation in the basin during 2003–2013. The northeastern, southwestern, and southeastern fringe areas of the Qaidam Basin, mainly characterized by grassland and cropland, had relatively complete ecosystem structures and stronger stability. The decline in the EO and ER was not significant in these areas, and the ability to maintain metabolism and primary production improved under the influence of natural environmental changes. However, these attributes were mostly noted in oasis areas with relatively

concentrated population and industries. During this period, the urbanization and industrialization encroached on the grassland and cropland areas, resulting in a decrease in the CESI in the majority of these areas. This decrease was most evident in the southeastern region, where the negative impact of the declining CSEI on EHI outweighed the beneficial impact of EV improvement on EHI, limiting small parts of the improved EHI area to the northeastern and southwestern fringe areas.

Between 2013 and 2023, the EHI enhanced areas exhibited broad spatial coverage, and the regions with the largest improvement in EHI were primarily located within the basin interior (Fig. 8b, f, i, and l). Meanwhile, the small parts of regions with EHI degradation were predominantly located in the northeastern, southwestern, and southeastern fringe areas of the basin, with a particular concentration in the northeastern sector. The improvements in the EO and ER magnitudes were greater than the decreases in the EV and CESI magnitudes observed across the majority of the interior and northwestern areas in the basin during this period; therefore, the EHI value of these areas improved. With the adoption of the "Regulations on the Exploitation, Utilization, and Protection of Salt Lake Resources in Qinghai Province" plan, the stricter environmental policies have transitioned to sustainable development practices for salt lake resources exploitation (Yang et al., 2017), indicating that under the influence of natural environmental changes on the Qinghai–Xizang Plateau and the national and provincial ecological

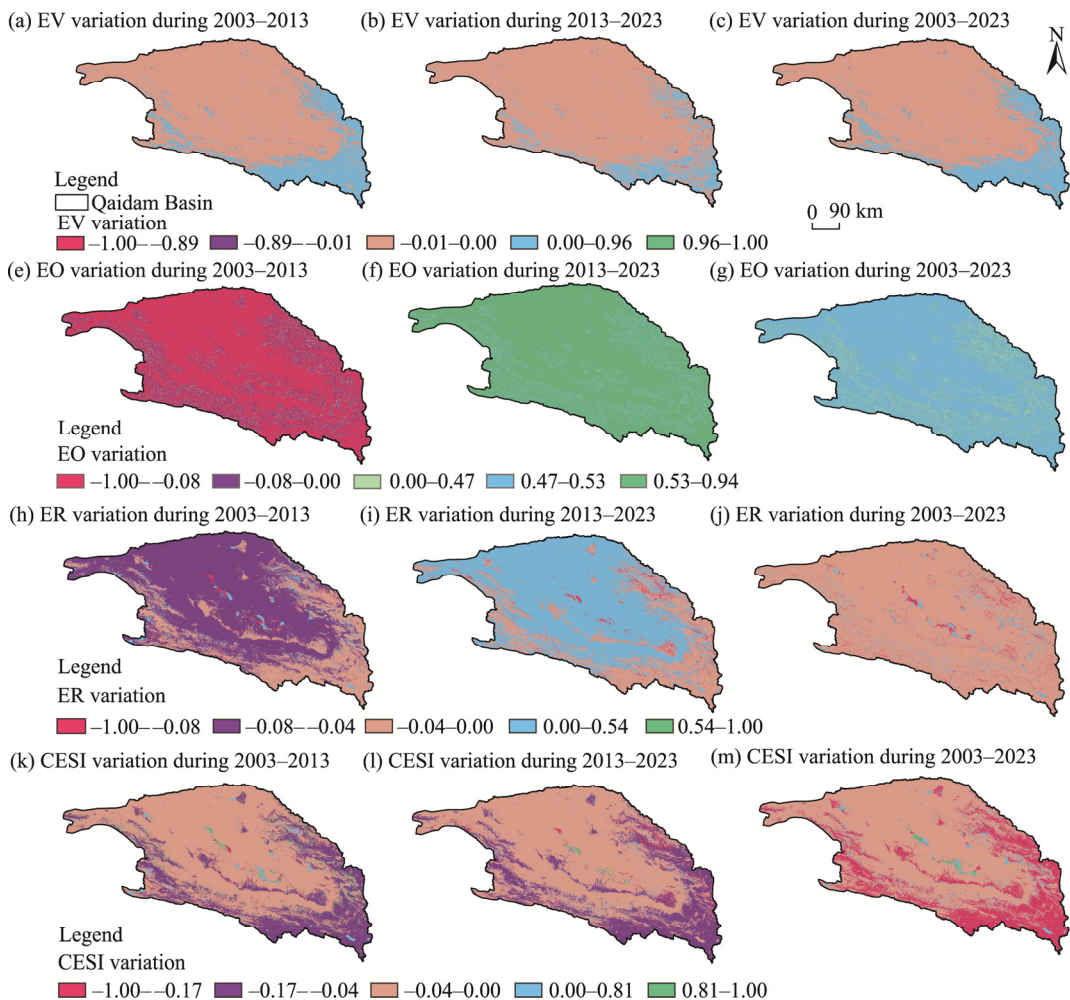


Fig. 8 Variations in EV (a–c), EO (e–g), ER (h–j), and CESI (k–m) in the Qaidam Basin during periods of 2003–2013, 2013–2023, and 2003–2023

protection policies, human activities had a reduced impact in the interior and northwestern regions of the Qaidam Basin during 2013–2023. Therefore, the complexity of the ecosystem structure increased, and the capacity of the ecosystem structure and function to return to the initial state under external stress significantly enhanced. In the northeastern, southwestern, and southeastern fringe areas of the basin, the decreases in the ER and CESI had a more substantial negative impact on EHI, compared to the positive effects induced by EV and EO improvements, leading to a decline in EHI in these regions from 2013 to 2023. The most pronounced decline occurring in the northeastern fringe region, particularly due to the extensive coal resource exploitation in the region. The ongoing urbanization and industrialization in the northeastern, southwestern, and southeastern fringe areas of the basin led to an increase in the human activity interference within the ecosystem (Li et al., 2025).

Consequently, compared to 2003, the EV, ER, and CESI in 2023 decreased in the majority of areas in the interior and northwestern regions of the basin, with their adverse effects on EHI outweighing the positive effects of EO improvement. Conversely, the EV and EO increased in the majority of areas in the northeastern, southwestern, and southeastern fringe areas of the basin, wherein their positive impacts surpassed the risks from declining ER and CESI. Thus, during 2003–2023, the EHI in the interior and northwestern regions of the basin decreased, while that in the northeastern, southwestern, and southeastern fringe areas of the basin increased, widening the regional disparities by 2023 (Figs. 6 and 8). Moreover, the EO depicted enhancement and the ER depicted degradation by 2023 (compared to the levels in 2003) in the majority of the interior and northwestern regions, suggesting that in the more fragile interior and northwestern regions of the basin, once the ecosystem deteriorates, ecological restoration will be slower and more challenging.

3.3 Zoning and targeted strategies for ecological restoration areas

The corridor connectivity zone, artificial restoration zone, ecological recovery zone, and ecological enhancement zone identified in the study scattered in the interior and fringe of the basin (Fig. 9), covering a total area of 6034.7 km² (Table 4). These key ecological restoration areas varied in natural and humanistic environments, some of which were traversed by important ecological corridors but belonged to low-EHI areas. To promote the circulation of matter and energy within the basin and sustain the stability of the ecosystem, we suggest implementing targeted ecological restoration projects in these zones.

The corridor connectivity zone was regarded as a vital area for ecological restoration in the Qaidam Basin, where comprehensive land improvement measures could be implemented to optimize the ecological network structure and ensure ecosystem connectivity and stability during the restoration of this zone. The area of the corridor connectivity zone was 1775.0 km², accounting for 29.4% of the key ecological restoration areas. This zone was mainly distributed in the interior and southeastern parts of the basin, and comprised of low-EHI areas located along the ecological corridor, characterized by the following main land use types: cropland, bare land, grassland, wetland, and snow/ice. Multiple ecosystems were traversed in the corridor connectivity zone, including but not limited to cropland, bare land, and grassland ecosystems. Moreover, the EHI of this zone within the ecological restoration areas was significantly low. In the southeastern part of the Qaidam Basin, the population was relatively widely distributed. Thus, during the development of residential areas, traffic routes should be reasonably planned, and excessive encroachment on urban space, including cropland and water areas, should be avoided to minimize the influence of human activities on ecological corridors. In this zone, bare land was widespread, with a fragile environmental foundation. Frequent salt-lake resource development activities, coupled with poor and slow-improving ecosystem health, pose challenges to the ecological restoration in this region. Ecological restoration in this zone should strike a balance between maintaining ecological connectivity and adapting to extreme environmental conditions, by employing natural regeneration processes in conjunction with targeted human interventions. The

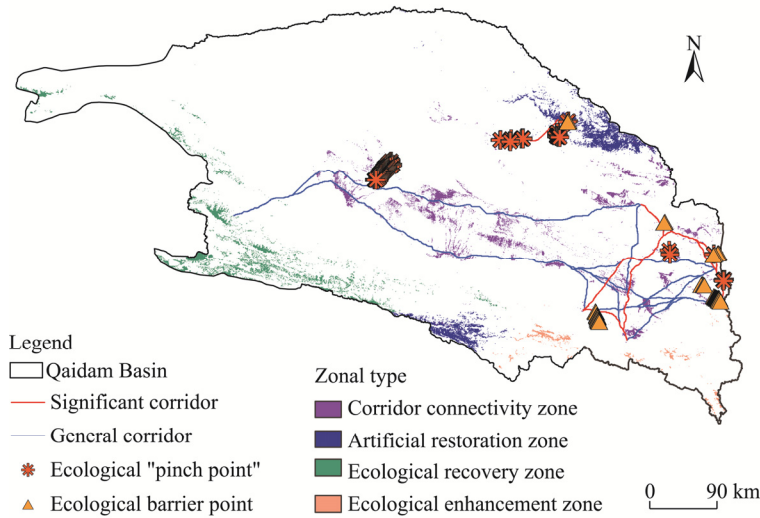


Fig. 9 Classification of the ecological restoration areas in the Qaidam Basin

Table 4 Areas of the ecological restoration zones in the Qaidam Basin

Zonal type	Area (km ²)									
	Total	Crop-land	Forest-land	Shrub-land	Grass-land	Water body	Snow /ice	Bare land	Impervious area	Wetland
Corridor connectivity zone	1775.0	851.0	5.3	1.6	143.2	4.6	110.3	543.5	2.8	112.7
Artificial restoration zone	2243.5	0.0	0.0	0.0	168.1	2.7	507.0	1565.6	0.0	0.1
Ecological recovery zone	1685.0	0.0	0.0	0.0	111.6	2.2	979.6	591.6	0.0	0.0
Ecological enhancement zone	331.2	0.0	0.0	0.0	22.7	0.1	55.1	253.3	0.0	0.0
Total	6034.7	851.0	5.3	1.6	445.6	9.6	1652.0	2954.0	2.8	112.8

primary restoration targets can include mitigating soil salinity, increasing vegetation coverage, and immobilizing aeolian sand. Specifically, ecological rehabilitation of tail brine ponds in the salt lake exploitation areas can involve lining the pond walls with a High-Density Polyethylene (HDPE) geomembrane-clay composite barrier, to effectively mitigate brine seepage and facilitate the sustainable repurposing of saline tailings. Sand-fixing checkerboards using highland barley or *Triticum aestivum* straw or *Phragmites australis*, with 2–5 cm diameter gravel uniformly distributed within the grid cells can effectively decrease evaporation, inhibit capillary salt transport, and reduce topsoil salinity. Moreover, before the rainy season, shallow-tilling of the land and broadcasting the seeds of native salt-tolerant xerophytes (e.g., *Nitraria tangutorum* and *Artemisia desertorum*) can help achieve moderate and systematic vegetation restoration. The corridor connectivity zone mainly involves cropland and water areas (snow/ice and wetland). During the ecological restoration process in cropland areas, the ecological landscape resources of these areas should be well-maintained. Reducing the use of pesticides and fertilizers to prevent and control the pollution in cropland, as well as developing water-saving agriculture, organic agriculture, and oasis ecological characteristic agriculture, should be vigorously promoted to coordinate the agricultural production with the ecological balance to enhance the ability of the cropland areas and maintain their metabolism and primary production. According to the regional natural conditions and the ecological value of crops, the agricultural planting structure should be adjusted appropriately to increase the service value of the cropland ecosystem. For instance,

salt-tolerant cash crops (e.g., *Lycium barbarum*, *Chenopodium quinoa*, and *Suaeda salsa*) can be cultivated through optimized planting systems, including quinoa-green manure rotation for nitrogen fixation and *Lycium-Tamarix* intercropping for windbreak synergy, thereby achieving synergistic ecological and socioeconomic benefits. In addition, the resistance to species migration can be reduced and the landscape connectivity and ecological functions of the cropland ecosystem can be boosted by establishing forest-grass belts of reasonable width around the cropland areas. Wetland ecosystem restoration in this zone requires an integrated strategy that combines natural shoreline preservation, dredging to reconnect with fluvial-lacustrine system, aquatic vegetation restoration, and microhabitat improvement, ultimately facilitating the comprehensive functional recovery of the aquatic ecosystems in the basin. The snow/ice ecosystem of the corridor connectivity zone was predominantly arranged in the northeastern and southeastern fringe areas of the basin, where the vulnerability of these ecosystems was amplified by intensive anthropogenic pressures. Phased regulatory interventions should be strengthened to alleviate the adverse impacts of human activities on the snow/ice ecosystems in the basin.

The artificial restoration zone, characterized by high elevations, arid conditions, and higher intensity of resource exploitation, requires targeted efforts to focus on the ecological well-being of residents and the supply of ecological products, and artificial restoration methods can be the most viable option. The area of the artificial restoration zone was 2243.5 km², accounting for 37.2% of the key ecological-restoration areas. This zone was distributed in the northeast of Delingha City, the border area between the Delingha City and Aksay Kazak Autonomous County, and the border area between the Qumarleb County and Golmud City. The primary types of land use were bare land, snow/ice, and grassland. These regions depicted a higher intensity of resource exploitation, such as coal mines, salt lakes, and nephrite deposits, along with relatively frequent human activities, which led to severe habitat destruction, grassland degradation, and ecosystem instability. Through landform reshaping, soil reconstruction, recovery of forest and grass vegetation, collaborative treatment of pollutants, and construction of mine parks, the ecosystem and its functions can be rapidly restored and regenerated. Specific implementation pathways may include the following aspects: (1) transforming the steep slope of the open-pit mine (original slope >45°) into a stepped platform to reduce the risk of landslides and then, digging a drainage ditch (50 cm×30 cm) inside the platform to guide the rainwater to the sedimentation tank, to prevent soil erosion and reshape the landform; (2) using "gangue+slag" to backfill the bottom, "geomembrane+clay" to construct an isolation layer, and "loess+humus+desulfurization gypsum" to formulate a nutrient layer of soil to backfill the open-pit mine, and applying the biochar to immobilize the heavy metal pollutants in the soil, thereby achieving soil reconstruction; (3) selecting high-elevation and cold-suitable species, such as *Elymus dahuricus* and *Artemisia desertorum*, and digging "fish scale pits" to alleviate drought stress and achieve the recovery of forest and grass vegetation; and (4) in accordance with the regional natural and social conditions, transforming the deep pit into a stepped garden to form an artificial structure from the water-filled pit and then, carving representative or national culture pattern on the solidified surface of the gangue hill, installing photovoltaic panels on the slope, and transforming the dressing plant into a mining museum to construct a mining park. The restored landscape patches can be integrated with the surrounding natural environment. Furthermore, landscape reshaping and redevelopment should be carried out on abandoned industrial and mining lands, and new industries can be clustered by leveraging the regional advantages to explore new development models for resource-based regions. The key point of ecological restoration in the snow/ice areas of the zone is to protect the original hydrological functions of snow and ice. High-reflectivity materials can be laid to cover the exposed ice surface, reflecting solar radiation and reducing the temperature of the ice surface. In addition, passive heat rods can be installed around the roads or facilities in the mining area, to conduct underground heat and maintain the stability of the frozen soil.

The ecological recovery zone should emphasize natural restoration supplemented by artificial intervention based on the foundation of a fragile ecosystem and the realistic plight of extensive

grazing. The area of the ecological recovery zone in this study was 1685.0 km², accounting for 27.9% of the key ecological restoration areas. It was predominantly located along the western edge of the Qaidam Basin, with the primary land use types being snow/ice, bare land, and grassland. A significant reduction was observed in the ecosystem service value of this zone, and the ecosystem's ability to restore its structure and function to the initial state under external stress decreased from 2003 to 2023. As the ecological foundation of this zone was relatively fragile, the extensive grazing methods and unordered settlement expansion patterns during the study period led to the deterioration of the ecological environment. Based on this aspect, human activity intervention should be moderately reduced, and an ecological governance policy for national territorial space that emphasizes on natural restoration supplemented by artificial intervention should be adopted during the process of ecological restoration in this zone. Notably, the conservation of snow and ice recharge areas should be prioritized. Minimizing or avoiding external interference with the natural state of the snow/ice ecosystems in the snow/ice areas should be the main strategy for restoring this region. Furthermore, delineating the buffer zones in the core snow/ice areas to prohibit mining, infrastructure construction, and tourism activities and moderately regulating human mountaineering activities to minimize foot traffic should be a priority in the snow/ice areas. The key efforts in this zone should focus on advancing vegetation restoration in alpine grasslands. Specific measures may include: (1) implementing sustainable grazing systems, such as seasonal grazing bans, resting grazing, and rotational grazing (summer/autumn grazing with winter/spring rest); (2) diversifying the local economies through eco-tourism and livestock product processing, to reduce the reliance on grasslands; (3) carrying out projects to enclose degraded grasslands; and (4) aerial seeding or manual reseeded of native plants with well-developed root systems that can withstand cold and drought (e.g., *Stipa*, *Artemisia*, and *Carex*) prior to the rainy season. Drones may also be used for precision reseeded, by conducting routine assessments of grassland areas. All efforts should be aimed at increasing vegetation coverage, improving water conservation, enhancing the supply capacity of ecological products, and restoring the health of the grassland ecosystems. In addition, utilizing regional resource advantages and clean energy (such as photovoltaics and wind energy) should be actively adopted in the ecological recovery zone, to enhance the ecological and economic benefits of the areas with low ecosystem health levels and mitigate the adverse impacts of improving human production and living standards on the ecosystem.

The ecological enhancement zone should focus on addressing the problems of water scarcity and human interference. In this study, the area of the ecological enhancement zone was 331.2 km², accounting for 5.5% of the key ecological restoration areas. This zone was primarily distributed in the Dulan County and Madoi County, with the dominant land use types being bare land, snow/ice, and grassland. The surrounding ecological environment of this zone had essentially no serious ecological or environmental issues. Moreover, the ecological enhancement zone and its surrounding regions were key ecological sources, playing a crucial role in establishing the regional ecological security pattern due to their significant ecological function. Ecological restoration in this zone should focus on addressing the problems of water scarcity and the pressure from human activities. The water pressure in this zone can be alleviated through the coordination of agricultural and industrial water, protection of the ecological base flow, construction of micro water-harvesting systems (e.g., via the use of plastic sheets and reservoirs), and collection of rainwater in the key vegetation areas (for irrigation). For the degraded grassland and snow/ice areas, fencing and enclosure should be installed to reduce human interference. Owing to the significance of this zone to the ecological security construction, the expansion trends and spatial trade-off relationships between the production, living, and ecological spaces in this zone should be comprehensively considered in the future. To preserve the integrity and stability of the existing ecological functions, we suggest demarcating the key protection areas with red lines and implementing targeted control measures. Furthermore, constructing an ecological space network system with complex functions and diverse levels can help optimize the ecological landscape pattern and improve the comprehensive ecosystem service value of the basin.

Furthermore, we suggest implementing targeted restoration strategies for different land use types within the ecological "pinch points" and ecological barrier points. First, the areas covered by ecological "pinch points" and ecological barrier points in the Qaidam Basin predominantly involved grassland ecosystems. In such areas, implementing the restoration of degraded grasslands and protecting the natural secondary grasslands is important. Particular emphasis should be placed on strengthening the cultivation and protection of grassland vegetation, increasing the planting of shrub and grass vegetation with low water consumption and high-stress resistance, to raise the vegetation coverage rate and improve the grassland community structure, thereby enhancing the overall landscape connectivity and providing a favorable ecological space for the inhabitation, reproduction, and migration of species in the basin. Second, several regions covered by ecological "pinch points" and ecological barrier points were bare lands. Considering that the Qaidam Basin is located inland in the northwestern region of China and has a typical plateau continental climate, corresponding biotechnological measures should be adopted in these areas to promote the planting of salt and alkali-tolerant forage grasses and rehabilitate the degraded areas. For water areas, such as those covered by snow and ice, the focus should be on maintaining the stability of the quantity, structure, and overall functions of these areas to counteract the warming and humidifying trend on the Qinghai–Xizang Plateau (Fan et al., 2023). Moreover, regional pollution prevention and control should be strengthened to gradually restore the ecological functions of these areas.

From the perspective of territorial spatial zoning, we intend to emphasize on maintaining the ecosystem integrity and diversity in the region to implement cross-regional ecological restoration, via the application of differentiated and targeted ecological restoration strategies. The effectiveness of this approach has been demonstrated in various macro- and medium-scale ecological restoration zoning studies (Zeng et al., 2022; Gong et al., 2024; Li et al., 2024b). Furthermore, we propose that sustainable grazing management—rotational grazing, seasonal bans, and grassland enclosures—could effectively enhance the vegetation coverage in the degraded arid grasslands of the Qaidam Basin. These results concur with the findings of Wang et al. (2024) regarding the impacts of grazing pressure on the ecosystem health in the agro-pastoral intertwined areas of northern China and the conclusions of Li et al. (2025) regarding the construction of ecological security pattern in the Haixi Mongolian and Tibetan Autonomous Prefecture.

4 Conclusions

This study integrated the ecological security pattern and ecosystem health assessment to identify the key areas for ecological restoration and proposed differentiated and targeted restoration strategies in the Qaidam Basin. The overall EHI of the basin revealed an initial decrease (2003–2013), followed by a subsequent recovery (2013–2023), resulting in a fluctuating transition to a healthier state during 2003–2023. In addition, it showed a development trend of higher health status in the northeastern, southeastern, and southwestern fringes and lower health status in the interior and northwestern regions of the basin, and the spatial difference widened from 2003 to 2023. This study identified four types of key ecological restoration areas. The corridor connectivity zone was distributed within the interior and the southeastern regions of the basin, wherein mitigating soil salinity, increasing vegetation coverage, and adjusting the agricultural planting structure appropriately could ensure ecosystem connectivity and stability. The artificial restoration zone was distributed in the northeastern region of Delingha City, as well as in the border areas between Delingha City and Aksay Kazak Autonomous County and between Qumarleb County and Golmud City. Priority should be given to enhancing the ecological restoration and redevelopment of abandoned industrial and mining lands. The ecological recovery zone was distributed along the western fringe of the basin. The focus should be on conserving snow/ice areas by minimizing or avoiding human activity interferences, improving vegetation

coverage of the grassland areas, and utilizing the region's resource advantages to develop clean energy industries. The ecological enhancement zone was geographically concentrated in the Dulan County and Madoi County; in this region, the focus should be on alleviating the water pressure in the key vegetation areas, reducing human interference in the degraded grasslands and snow/ice areas, and constructing an ecological space network system with complex functions and diverse hierarchies. The majority of the areas covered by the ecological "pinch points" and ecological barrier points involved grasslands; in these regions, the focus should be on strengthening the cultivation and protection of grassland vegetation. In addition, in the bare land that resulted from land degradation, corresponding biotechnological measures should be adopted to promote the planting of forage grasses that are tolerant to salt and alkali.

To a certain extent, the approach used in the study focused on remedying the one-sidedness of identifying ecological restoration areas solely based on the ecological security pattern. Notably, our study can serve as a reference for restoring the degraded ecosystems in the Qaidam Basin. However, with its rugged terrain and complex landforms, the Qaidam Basin contains extensive undeveloped and bare lands that experience multi-level ecological risks; thus, the improvement and optimization of undeveloped ecosystems is a pivotal challenge in the terrestrial spatial ecological restoration in this region. Future research can focus on multi-perspective, multi-level, and long-term time series, while considering the ecological risks, ecosystem health, and ecological security patterns, to enhance the overall understanding of the ecological security and service value of the ecosystem and promote the implementation of terrestrial spatial ecological restoration projects in the Qaidam Basin.

Conflicts 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: CHENG Lanhua, YANG Xianming; Methodology: CHENG Lanhua; Software: CHENG Lanhua; Validation: CHENG Lanhua, YANG Xianming; Formal analysis: CHENG Lanhua; Investigation: CHENG Lanhua, YANG Xianming, AN Jingfeng; Resources: CHENG Lanhua; Data curation: CHENG Lanhua; Writing - original draft preparation: CHENG Lanhua; Writing - review and editing: CHENG Lanhua, YANG Xianming; Visualization: CHENG Lanhua; Supervision: CHENG Lanhua, YANG Xianming, PAN Xumei, AN Jingfeng; Project administration: YANG Xianming; Funding acquisition: YANG Xianming, PAN Xumei, CHENG Lanhua. All authors approved the manuscript.

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