

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

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Date: 2025-10-22T00:00:00+00:00

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.

Full Text

Preamble

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 territorial spatial patterns, enhancing 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 nine ecological sources in the region using the Morphological Spatial Pattern Analysis (MSPA) method and landscape connectivity assessment, and extracted ten significant corridors and twenty-six 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 Circuit Theory, thereby constructing the ecological security pattern of the area. Further, we evaluated ecosystem health from 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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Received 2025-03-14; revised 2025-08-16; accepted 2025-08-26

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<http://jal.xjegi.com>; www.springer.com/40333

Citation: CHENG Lanhua, YANG Xianming, PAN Xumei, AN Jingfeng. 2025. Identification and classification of ecological restoration areas in the territorial land space of the Qaidam Basin, China. *Journal of Arid Land*, 17(10): 1402–1424. <https://doi.org/10.1007/s40333-025-0089-4>; <https://cstr.cn/32276.14.JAL.02500894>

1 Introduction

Territorial spatial ecological restoration 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 [?, ?]. 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 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 [?]. 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 [?, ?].

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 territorial land space in China [?, ?, ?]. Guided by constructing an ecological security pattern, comprehensively identifying the key areas for ecosystem restoration according to 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 [?, ?]. The models and methods applied in previous studies mainly included the Morphological Spatial Pattern Analysis (MSPA) method [?, ?], the Minimum Cumulative Resistance (MCR) model [?], Circuit Theory [?, ?], and the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model [?]. Notably, previous studies primarily identified the ecological components in the ecological security pattern and combined them to delineate restoration areas, resulting in a relatively narrow research perspective [?].

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 [?, ?, ?]. 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 [?]. 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 [?], Structure-Function-Process-Development (SFPD) [?], Pressure-State-Response (PSR) [?], Driving force-Pressure-State-Impact-Response (DPSIR) [?], and Vitality-Organization-Resilience (VOR) and Vitality-Organization-Resilience-Service (VORS) [?]. 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 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 [?, ?, ?]. 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 [?], degradation risks [?, ?], and service functions [?].

Constructing an ecological security pattern and scientifically assessing and improving ecosystem health are effective approaches to safeguarding national ecological security and implementing 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 [?]. 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 [?]. Maintaining 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 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.

2.1 Study Area

The Qaidam Basin (Fig. 1 [FIGURE: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 [?]. 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" [?]. 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.

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 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 Communiqué 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>).

2.3.1 Ecological Source Identification

Ecological sources are identified as vital habitat patches within an ecosystem that hold paramount significance for maintaining ecological security in a region [?]; 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 source habitats in a region, utilizes a series of morphological principles to segment, erode, and classify binary raster data into seven distinct and non-overlapping landscape categories [?]. 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 [?]; 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 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 IIC, PC, and dPC values correspond to enhanced landscape connectivity. The larger the dPC value, the greater significance the patch holds in ensuring ecological security [?]. 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 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:

$$IIC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i a_j m_{ij}}{A_L^2}$$

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

$$dPC = \frac{PC - PC_{\text{remove}}}{PC} \times 100\%$$

where A_L is the total area of the landscape (km^2); n represents the number of patches in the region; m_{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 [?]. Drawing upon pertinent studies [?, ?] and expert consultations, we identified the ecological resistance factors by considering both the anthropogenic disturbances and ecological attributes that could affect connectivity between the ecological sources in the Qaidam Basin. Considering land use type and distances from roads and water bodies as the anthropogenic resistance factors, 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 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:

$$R = \sum_{k=1}^m F_k W_k$$

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

Resistance factor	Resistance value	Weight
Anthropogenic resistance		
Land use type	Grassland, water body, snow/ice, and wetland	0.15
	Forestland	0.20
	Shrubland	0.25
	Cropland	0.40
	Impervious	0.60
	Bare land	0.80
Distance from roads (m)	>2000	0.10
	1000-2000	0.30
	500-1000	0.50
	<500	0.70
Distance from water bodies (m)	>2000	0.10
	1000-2000	0.30
	500-1000	0.50
	<500	0.70
Ecological property		
NDVI	>0.5	0.05
	0.3-0.5	0.15
	0.1-0.3	0.25
	<0.1	0.35
DEM (m)	<3000	0.05
	3000-3500	0.15
	3500-4000	0.25
	>4000	0.35
Slope (°)	<5	0.05
	5-15	0.15
	15-25	0.25
	>25	0.35

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 [?]. Among the methods used to identify such corridors, MCR is commonly employed when constructing the corridor system due to its ability to consider the interrelations among various ecological sources [?]. 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:

$$G_{uv} = \frac{M_u M_v}{D_{uv}^2} = \frac{(S_u P_u)(S_v P_v)}{L_{uv}^2 L_{\max}^2}$$

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 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 [?, ?]. 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 [?, ?]. 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 [?].

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 [?, ?], the minimum detection radius was calibrated to 1000 m and the 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 ecosystem service functions in the region into the VORS model (Fig. 2 [FIGURE:2]). Ecosystem vitality (EV), ecosystem organization (EO), and ecosystem resilience (ER), which were essential indicators of the pristine health (PH) of the ecosystem [?], 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 [?, ?]. 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) [?]. Generally, LH can be evaluated by 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 [?], and it can be assessed via resistance and recovery coefficients assigned to different land use types [?]. 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 [?, ?]. 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 [?]. 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 related literature [?] and 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/($\text{hm}^2 \cdot \text{a}$). Consequently, we derived the unit-area ecosystem service values of different land use types in the Qaidam Basin (Table 2). Concerning previous studies [?, ?] 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:

$$EHI = PH \times CESI$$

$$PH = EV \times EO \times ER$$

$$EO = 0.35LH + 0.35LC + 0.30IPC$$

$$LH = 0.10AWMPFD + 0.25SHDI$$

$$LC = 0.10CONT + 0.25FI_1$$

$$IPC = 0.03CI_1 + 0.07FI_2 + 0.03CI_2 + 0.07FI_3 + 0.03CI_3 + 0.07FI_4$$

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

$$CESI = \sum_{h=1}^n \sum_{t=1}^m (P_{ht} \times A_h)$$

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 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 land use type h ; P_{ht} denotes the ecosystem service value per unit area of land use type h for ecosystem service type t (CNY/($\text{hm}^2 \cdot \text{a}$)); A_h denotes the area of land use type h (hm^2); $CESI_t$ designates the ecosystem service value of 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 ecosystem service type t (CNY/($\text{hm}^2 \cdot \text{a}$)). 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 inverse metrics; conversely, the remainder were considered positive indicators. Prior to analysis, normalization was applied to all metrics to standardize their scales [?].

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.

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 Madoi County, Qumarleb County, Dulan County, Ulan County, and Delingha City, and were largely contiguous with local hydrological systems. The edges and perforations followed in terms of area, contributing significantly to mitigating 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, nine significant ecological sources were ultimately selected, cumulatively spanning an area of 35,194.9 km^2 , primarily comprising grassland and aquatic ecosystems. Among these, the largest ecological source encompassed 23,319.2 km^2 of area, comprising 8.5% of the total area of the Qaidam Basin, featuring Donggi Cona Lake and the southeastern fringing grasslands; its intact natural ecosystem and high ecosystem service values

render it 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 high-resistance regions predominantly distributed along the southern and northern fringes, forming a semi-circular pattern (Fig. 3

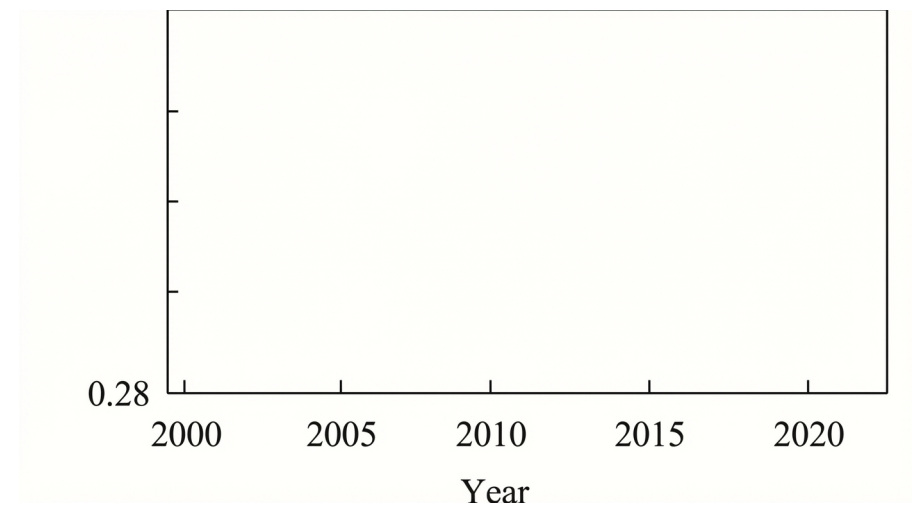


Figure 1: Figure 3

). With higher elevations and steeper slopes, the predominant land use type in these regions was primarily bare land, indicating lower ecological stability. Conversely, 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.

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 [FIGURE:4]). By filtering paths with an interaction force greater than 400.0, ten 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 species dispersal. Meanwhile, 26 general corridors, extending for 4719.1 km (82.8% of the total length), spanned more extensively, serving to enhance spatial service values among diverse ecological sources. Interestingly, we observed no ecological corridor links between Aksay Kazak Autonomous County, Mangya City, and Ruoqiang County in the northwestern region of the Qaidam Basin, highlighting the reduced connectedness and integrity of natural ecosystems in these areas.

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 [FIGURE:5]). Considering the ecological corridor distribution pattern, we identified a total of 114 ecological “pinch points” as 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. Additionally, we identified 42 barrier points as key restoration areas (encompassing 42.0 km²) to enhance connectivity of ecological corridors. These barrier points were predominantly situated in the southeastern part of the Qaidam Basin, specifically in Dulan County and Ulan County, where land use types consisted primarily of bare land, grassland, snow/ice, and water body. Furthermore, a few ecological barrier points coincided with 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 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 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 conservation zones, important corridors were designated as conservation corridors, general corridors were designated as restoration corridors, ecological “pinch points” were designated as control zones, and barrier points were designated as restoration areas. This strategic framework formed the ecological security pattern for the Qaidam Basin.

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

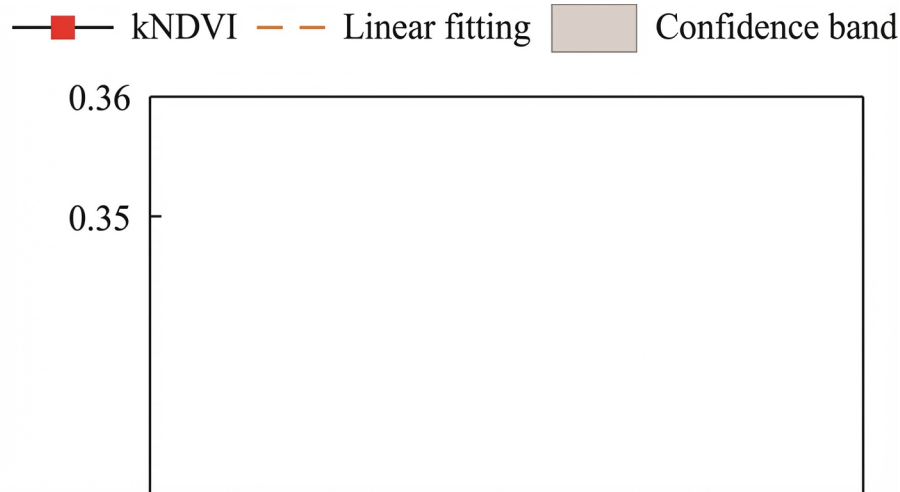


Figure 2: Figure 6

). From the perspective of variations in area and area percentage corresponding to each EHI category, the overall EHI showed an initial decrease followed by 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 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 relatively weak area, coupled with the decline of the percentage of ordinary area (from 12.7% to 2.2%); the other was the decrease of the percentage of strong area for ER (from 98.0% to 28.3%), primarily due to 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, cou-

pled with slow recovery rates. From 2003 to 2013, the Qaidam Basin experienced accelerated economic and social growth, which increased human interference in its ecosystems. The reduction in structural integrity and functional stability of the ecosystem led to a decline in overall ecosystem health in this region.

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 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, areas that were previously weak area were 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 environmental conservation efforts strengthened significantly 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 spatial disparity of 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, regions with declining ecosystem health were widely distributed, and small parts of 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 [?]. Additionally, these areas contain numerous large salt lakes (e.g., Qarhan Salt Lake, East Taijnar Lake, West Taijnar Lake, and Da Qaidam Salt Lake) [?]. Due to rapid economic and social development, as well as market forces, salt lake resources in the Qaidam Basin experienced large-scale exploitation during 2003–2013 [?]. During this phase, long-term and large-scale extraction of brine caused water levels in some salt lakes to drop and lake areas to shrink significantly. Numerous salt fields and evaporation ponds were constructed around the salt lakes, altering surface runoff and resulting in increased soil salinity. Additionally, salt residue produced from salt-lake re-

source processing occupied extensive land areas and could also spread with the wind, further aggravating soil salinity in surrounding areas and posing risks to plant communities [?]. High industrial water consumption (e.g., for ore dressing and processing) exacerbated pressure on already scarce water resources, further intensifying the trend of desertification. Consequently, EHI in these areas significantly declined, particularly in terms of ecosystem structural complexity and the capability of ecosystem structure and function to recover to initial states after experiencing external stress.

From 2003 to 2013, compared to the northeastern, southwestern, and southeastern fringe regions, the interior and northwestern areas of the basin depicted greater decline in EO and ER magnitudes (Fig. 8a [FIGURE:8], 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 ecosystem health within the ecological vulnerable areas of the basin was the primary driver of overall ecological degradation 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 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, urbanization and industrialization encroached on grassland and cropland areas, resulting in a decrease in CESI in the majority of these areas. This decrease was most evident in the southeastern region, where the negative impact of declining CESI on EHI outweighed the beneficial impact of EV improvement, limiting small parts of improved EHI area to the northeastern and southwestern fringe areas.

Between 2013 and 2023, EHI-enhanced areas exhibited broad spatial coverage, and regions with the largest improvement in EHI were primarily located within the basin interior (Fig. 8b, f, i, and l). Meanwhile, small parts of regions with EHI degradation were predominantly located in the northeastern, southwestern, and southeastern fringe areas of the basin, with particular concentration in the northeastern sector. The improvements in EO and ER magnitudes were greater than the decreases in EV and CESI magnitudes observed across the majority of interior and northwestern areas during this period; therefore, EHI values in these areas improved. With the adoption of the “Regulations on the Exploitation, Utilization, and Protection of Salt Lake Resources in Qinghai Province” plan, stricter environmental policies have transitioned to sustainable development practices for salt lake resource exploitation [?], indicating that under the influence of natural environmental changes on the Qinghai–Xizang Plateau and national and provincial ecological protection policies, human activities had reduced impact in the interior and northwestern regions during 2013–2023. Therefore, the complexity of ecosystem structure increased, and the capacity of ecosystem structure and function to return to initial states under

external stress significantly enhanced. In the northeastern, southwestern, and southeastern fringe areas of the basin, decreases in ER and CESI had a more substantial negative impact on EHI compared to positive effects induced by EV and EO improvements, leading to EHI decline in these regions from 2013 to 2023. The most pronounced decline occurred in the northeastern fringe region, particularly due to extensive coal resource exploitation. Ongoing urbanization and industrialization in the northeastern, southwestern, and southeastern fringe areas led to increased human activity interference within the ecosystem [?].

Consequently, compared to 2003, EV, ER, and CESI in 2023 decreased in the majority of areas in the interior and northwestern regions, with their adverse effects on EHI outweighing the positive effects of EO improvement. Conversely, EV and EO increased in the majority of areas in the northeastern, southwestern, and southeastern fringe areas, wherein their positive impacts surpassed risks from declining ER and CESI. Thus, during 2003–2023, EHI in the interior and northwestern regions decreased, while that in the northeastern, southwestern, and southeastern fringe areas increased, widening regional disparities by 2023 (Figs. 6 and 8). Moreover, EO depicted enhancement and ER depicted degradation by 2023 (compared to levels in 2003) in the majority of interior and northwestern regions, suggesting that in the more fragile interior and northwestern regions, 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 across the interior and fringe of the basin (Fig. 9 [FIGURE:9]), covering a total area of 6034.7 km² (Table 4). These key ecological restoration areas varied in natural and humanistic environments; some were traversed by important ecological corridors but belonged to low-EHI areas. To promote circulation of matter and energy within the basin and sustain ecosystem stability, 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 restoration. The area of the corridor connectivity zone was 1775.0 km², accounting for 29.4% of key ecological restoration areas. This zone was mainly distributed in the interior and southeastern parts of the basin and comprised low-EHI areas located along ecological corridors, 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 ecological restoration areas was significantly low. In the southeastern part of the Qaidam Basin, the population was relatively widely distributed. Thus, during development of residential areas, traffic routes should be reasonably planned, and excessive encroachment on urban space, including cropland and water areas, should be minimized to reduce 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 ecological restoration. 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 primary restoration targets can include mitigating soil salinity, increasing vegetation coverage, and immobilizing aeolian sand. Specifically, ecological rehabilitation of tail brine ponds in salt lake exploitation areas can involve lining pond walls with High-Density Polyethylene (HDPE) geomembrane-clay composite barriers to effectively mitigate brine seepage and facilitate 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 grid cells, can effectively decrease evaporation, inhibit capillary salt transport, and reduce topsoil salinity. Moreover, before the rainy season, shallow-tilling of land and broadcasting 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 ecological restoration in cropland areas, ecological landscape resources should be well-maintained. Reducing pesticide and fertilizer use to prevent and control cropland pollution, as well as developing water-saving agriculture, organic agriculture, and oasis ecological characteristic agriculture, should be vigorously promoted to coordinate agricultural production with ecological balance and enhance the ability of cropland areas to maintain metabolism and primary production. According to regional natural conditions and ecological value of crops, the agricultural planting structure should be adjusted appropriately to increase 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, resistance to species migration can be reduced and landscape connectivity and ecological functions of the cropland ecosystem boosted by establishing forest-grass belts of reasonable width around cropland areas. Wetland ecosystem restoration requires an integrated strategy combining natural shoreline preservation, dredging to reconnect with fluvial-lacustrine systems, aquatic vegetation restoration, and microhabitat improvement, ultimately facilitating comprehensive functional recovery of aquatic ecosystems. Snow/ice ecosystem restoration should focus on maintaining stability of quantity, structure, and overall func-

tions to counteract warming and humidifying trends on the Qinghai-Xizang Plateau.

The artificial restoration zone was distributed in the northeastern region of Delingha City, as well as in border areas between Delingha City and Aksay Kazak Autonomous County and between Qumarleb County and Golmud City. This zone covered an area of 2243.5 km², accounting for 37.2% of key ecological restoration areas. The dominant land use types were bare land, grassland, and cropland. The ecosystem health of this zone was at a weak level, with serious ecological degradation caused by long-term resource exploitation and industrial production. The ecosystem structure was severely damaged, and the ability to restore structure and function to initial states under external stress was poor. Therefore, priority should be given to enhancing ecological restoration and redevelopment of abandoned industrial and mining lands. For grassland ecosystems in this zone, degraded grassland restoration and protection of natural secondary grasslands are important. Particular emphasis should be placed on strengthening cultivation and protection of grassland vegetation, increasing planting of shrub and grass vegetation with low water consumption and high stress resistance, to raise vegetation coverage and improve grassland community structure, thereby enhancing overall landscape connectivity and providing favorable ecological space for species inhabitation, reproduction, and migration. For cropland ecosystems, developing water-saving agriculture, organic agriculture, and oasis ecological characteristic agriculture should be vigorously promoted to coordinate agricultural production with ecological balance. For bare land resulting from land degradation, corresponding biotechnological measures should be adopted to promote planting of forage grasses tolerant to salt and alkali. For water areas such as snow and ice, focus should be on maintaining stability of quantity, structure, and overall functions.

The ecological recovery zone should focus on conserving snow/ice areas and reducing human interference such as grazing. The area of the ecological recovery zone was 1685.0 km², accounting for 27.9% of key ecological restoration areas. It was predominantly located along the western fringe of the basin, with primary land use types being snow/ice, bare land, and grassland. A significant reduction was observed in ecosystem service value, and the ecosystem's ability to restore structure and function to initial states under external stress decreased from 2003 to 2023. As the ecological foundation was relatively fragile, extensive grazing methods and unordered settlement expansion patterns during the study period led to environmental deterioration. Human activity intervention should be moderately reduced, and an ecological governance policy emphasizing natural restoration supplemented by artificial intervention should be adopted. Notably, conservation of snow and ice recharge areas should be prioritized. Minimizing or avoiding external interference with natural states of snow/ice ecosystems should be the main strategy. Furthermore, delineating buffer zones in core snow/ice areas to prohibit mining, infrastructure construction, and tourism activities and moderately regulating human mountaineering activities to minimize foot traffic should be priorities. Key efforts should focus on advancing vegetation restora-

tion 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 local economies through eco-tourism and livestock product processing to reduce reliance on grasslands; (3) carrying out projects to enclose degraded grasslands; and (4) aerial seeding or manual reseeding 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 reseeding by conducting routine assessments of grassland areas. All efforts should aim to increase vegetation coverage, improve water conservation, enhance supply capacity of ecological products, and restore health of grassland ecosystems. In addition, utilizing regional resource advantages and clean energy (such as photovoltaics and wind energy) should be actively adopted to enhance ecological and economic benefits of areas with low ecosystem health levels and mitigate adverse impacts of improving human production and living standards on the ecosystem.

The ecological enhancement zone should focus on addressing water scarcity and human interference problems. The area was 331.2 km², accounting for 5.5% of key ecological restoration areas. This zone was primarily distributed in Dulan County and Madoi County, with dominant land use types being bare land, snow/ice, and grassland. The surrounding ecological environment essentially had 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 regional ecological security due to significant ecological function. Restoration should focus on alleviating water pressure and pressure from human activities. Water pressure can be alleviated through coordination of agricultural and industrial water use, protection of ecological base flow, construction of micro water-harvesting systems (e.g., via use of plastic sheets and reservoirs), and collection of rainwater in key vegetation areas for irrigation. For degraded grassland and snow/ice areas, fencing and enclosure should be installed to reduce human interference. Owing to significance of this zone to ecological security construction, expansion trends and spatial trade-off relationships between production, living, and ecological spaces should be comprehensively considered in the future. To preserve integrity and stability of existing ecological functions, we suggest demarcating 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 ecological landscape pattern and improve comprehensive ecosystem service value of the basin.

Furthermore, we suggest implementing targeted restoration strategies for different land use types within ecological “pinch points” and ecological barrier points. First, areas covered by ecological “pinch points” and barrier points predominantly involved grassland ecosystems. In such areas, implementing restoration of degraded grasslands and protecting natural secondary grasslands is important. Particular emphasis should be placed on strengthening cultivation and

protection of grassland vegetation, increasing planting of shrub and grass vegetation with low water consumption and high stress resistance, to raise vegetation coverage and improve grassland community structure, thereby enhancing overall landscape connectivity and providing favorable ecological space for species inhabitation, reproduction, and migration. Second, several regions covered by ecological “pinch points” and barrier points were bare lands. Considering that the Qaidam Basin is located inland in northwestern China and has a typical plateau continental climate, corresponding biotechnological measures should be adopted to promote planting of salt and alkali-tolerant forage grasses and rehabilitate degraded areas. For water areas such as snow and ice, focus should be on maintaining stability of quantity, structure, and overall functions to counteract warming and humidifying trends on the Qinghai-Xizang Plateau [?]. Moreover, regional pollution prevention and control should be strengthened to gradually restore ecological functions.

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

4 Conclusions

This study integrated ecological security pattern and ecosystem health assessment to identify key areas for ecological restoration and proposed differentiated and targeted restoration strategies in the Qaidam Basin. The overall EHI revealed an initial decrease (2003-2013) followed by 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, with spatial differences widening from 2003 to 2023. This study identified four types of key ecological restoration areas. The corridor connectivity zone was distributed within the interior and southeastern regions, wherein mitigating soil salinity, increasing vegetation coverage, and adjusting 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 border areas between Delingha City and Aksay Kazak Autonomous County and between Qumarleb

County and Golmud City. Priority should be given to enhancing ecological restoration and redevelopment of abandoned industrial and mining lands. The ecological recovery zone was distributed along the western fringe of the basin. Focus should be on conserving snow/ice areas by minimizing or avoiding human activity interferences, improving vegetation coverage of grassland areas, and utilizing region's resource advantages to develop clean energy industries. The ecological enhancement zone was geographically concentrated in Dulan County and Madoi County; focus should be on alleviating water pressure in key vegetation areas, reducing human interference in degraded grasslands and snow/ice areas, and constructing an ecological space network system with complex functions and diverse hierarchies. The majority of areas covered by ecological "pinch points" and barrier points involved grasslands; focus should be on strengthening cultivation and protection of grassland vegetation. In bare land resulting from land degradation, corresponding biotechnological measures should be adopted to promote planting of forage grasses tolerant to salt and alkali.

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

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.

Acknowledgements: This research was supported by the National Natural Science Foundation of China (41961045) and the Shanxi Province Basic Research Program (202103021223253).

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.

References

- Bureau of Statistics of Haixi Mongolian and Tibetan Autonomous Prefecture. 2003-2023. Statistical Communique on National Economic and Social Development of the Haixi Mongolian and Tibetan Autonomous Prefecture. [2025-05-30]. <http://tjj.qinghai.gov.cn/tjData/cityBulletin/>. (in Chinese)
- Bureau of Statistics of Qinghai Province, Survey Team of the National Bureau of Statistics in Qinghai. 2004-2024. Qinghai Province Statistical Yearbook. Beijing: China Statistics Press. (in Chinese)
- Cao X F, Liu Z S, Li S J, et al. 2022. Identification of key areas of ecological protection and restoration based on the pattern of ecological security: A case of Songyuan City, Jilin Province. *China Environmental Science*, 42(6): 2779-2787. (in Chinese)
- Chen J, Zhao C C, Zhao Q, et al. 2023. Construction of ecological network in Fujian Province based on morphological spatial pattern analysis. *Acta Ecologica Sinica*, 43(2): 603-614. (in Chinese)
- Chen W X, Zhao X L, Zhong M X, et al. 2022. Spatiotemporal evolution patterns of ecosystem health in the Middle Reaches of the Yangtze River Urban Agglomerations. *Acta Ecologica Sinica*, 42(1): 138-149. (in Chinese)
- Chen X, Peng J, Liu Y X, et al. 2017. Constructing ecological security patterns in Yunfu City based on the framework of importance-sensitivity-connectivity. *Geographical Research*, 36(3): 471-484. (in Chinese)
- Deng X C, Zhu C L, Shi Y F, et al. 2018. The current situation of Qinghai salt lake lithium resources development and the suggestions for lithium industry. *Journal of Salt Lake Research*, 26(4): 11-18. (in Chinese)
- Dou H M, Zhao R F, Chen X D, et al. 2024. Identification of priority areas for territorial space ecological restoration in arid area of Northwest China: A case study of Zhangye City in Heihe River basin. *Chinese Journal of Applied Ecology*, 35(2): 469-479. (in Chinese)
- Fan Y W, Du H Q, Lu S L, et al. 2023. Modelling of sand/dust emission process in the Zhuonai Lake Watershed, the source of the Yangtze River. *Geographical Science*, 43(12): 2247-2256. (in Chinese)
- Feng X Q, Du Z Y, Tao P Y, et al. 2024. Construction of green space ecological network in Xiongan New Area based on the MSPA-InVEST-MCR model. *Applied Sciences*, 14(22): 10760, doi: 10.3390/app142210760.
- Fu B J, Chen L D, Ma K M, et al. 2001. Principles and Applications of Landscape Ecology. Beijing: Science Press. (in Chinese)

Geng J, Zhang X Y, Guo X N, et al. 2021. Sources of soluble salts in dustfall and their impact on resources and environment in the Qaidam Basin. *Acta Geologica Sinica*, 95(7): 2082-2098. (in Chinese)

Gong J L, Li H B, Yang H P. 2024. Identification and classification of ecological restoration areas in territorial land space of Wuhan metropolitan area under the perspective of ecological security patterns and ecological vulnerability. *Geographical Science*, 44(10): 1809-1817. (in Chinese)

Guo J, Wei X J, Zhang F Q, et al. 2025. Remote sensing assessment of ecosystem health and its key driving factors: A case study of the Urban Agglomeration in the Middle Reaches of the Yangtze River. *Environment Science*, 46(7): 4545-4557. (in Chinese)

Han X L, Liang D H. 2024. Economic analysis of China highland barley industry in China. *Food and Nutrition in China*, 30(1): 14-18. (in Chinese)

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Technical Report. IPBES Secretariat. Bonn, Germany.

Jia H W, Yan C Z, Xing X G. 2021. Evaluation of eco-environmental quality in Qaidam Basin based on the ecological index (MRSEI) and GEE. *Remote Sensing*, 13(22): 4543, doi: 10.3390/rs13224543.

Lai X Y, Yu H R, Liu G H, et al. 2023. Construction and analysis of ecological security patterns in the southern Anhui region of China from a circuit theory perspective. *Remote Sensing*, 15(5): 1385, doi: 10.3390/rs15051385.

Li J H, Chen W L, Wang Y. 2025. Construction of ecological security pattern based on the trade-off between the ecological value and realization potential of ecological product value: taking Haixi Prefecture as an example. *Resources and Environment in the Yangtze Basin*, 34(5): 1097-1112. (in Chinese)

Li J L, Lei Q H, Hu D W, et al. 2024a. Characterization of spatial and temporal correlation between human activity intensity and ecosystem service value in the Yangtze River Economic Zone. *Resources and Environment in the Yangtze Basin*, 33(9): 1992-2003. (in Chinese)

Li K X, Zhang L, Li H, et al. 2024b. Identification of the key regions of spatial ecological restoration in the Northwest Shanxi based on the MSPA model and circuit theory. *Arid Zone Research*, 41(9): 1593-1604. (in Chinese)

Li X, Zheng Y, Chen A Y, et al. 2024c. Identification of ecological restoration priority areas based on ecological security patterns and risk assessment: A case study of Shenmu City. *Acta Ecologica Sinica*, 44(19): 8784-8797. (in Chinese)

Lin L G, Wei X D, Luo P P, et al. 2023. Ecological security patterns at different spatial scales on the Loess Plateau. *Remote Sensing*, 15(4): 1011, doi: 10.3390/rs15041011.

- Liu S K, Qin X H, Lu R C, et al. 2024. Dynamic interactive responses of urbanization and ecosystem health in land border areas in China. *China Land Science*, 38(9): 122-134. (in Chinese)
- Liu Y, Huang T T, Zheng X. 2022a. A method of linking functional and structural connectivity analysis in urban green infrastructure network construction. *Urban Ecosystems*, 25(3): 909-925.
- Liu Y M, Xu N Y, Zeng H. 2022b. Ecosystem health assessment and its scale dependence in the coastal region of the East China Sea. *Acta Ecologica Sinica*, 42(24): 9913-9926. (in Chinese)
- Meng Z Q, Long L B, She Q N, et al. 2018. Assessment of ecological conditions over China's coastal areas based on land use/cover change. *Chinese Journal of Applied Ecology*, 29(10): 3337-3346.
- National Development and Reform Commission. 2004-2024. Compilation of National Agricultural Products Cost and Benefit Data. Beijing: China Statistics Press. (in Chinese)
- Ouyang X, Chen J, Wei X, et al. 2024. Exploring key types and threshold effects of land use change impact on ecosystem health in Changsha-Zhouzhou-Xiangtan Urban Agglomeration. *Geographical Science*, 44(11): 1946-1954. (in Chinese)
- Pinto U, Maheshwari B L, Ollerton R L. 2013. Analysis of long-term water quality for effective river health monitoring in peri-urban landscapes—a case study of the Hawkesbury-Nepean river system in NSW, Australia. *Environmental Monitoring and Assessment*, 185(6): 4551-4569.
- Rao H H, Pan T, He M Y, et al. 2025. Progress in the study of potassium, lithium, and boron salt resources in salt lakes of the Qaidam Basin on the Qinghai-Tibet Plateau. *Acta Geoscientica Sinica*, 46(2): 376-396. (in Chinese)
- Stober I, Zhong J, Bucher K. 2023. From freshwater inflows to salt lakes and salt deposits in the Qaidam Basin, W China. *Swiss Journal of Geosciences*, 116(1): 5, doi: 10.1186/s00015-023-00433-4.
- Su M R, Xie H, Yue W C, et al. 2019. Urban ecosystem health evaluation for typical Chinese cities along the Belt and Road. *Ecological Indicators*, 101: 572-582.
- Tian R, Zhao Z Q, Song D Y. 2025. Identification of ecological restoration of territorial space based on ecosystem degradation risk and ecological security pattern: A case study of the Chang-Zhu-Tan Metropolitan Area. *Environmental Science*, 46(3): 1608-1620. (in Chinese)
- Wang W Q, Liu X, Liu C H, et al. 2024. Impacts of grazing pressure on ecosystem health in the agro-pastoral intertwined areas of northern China. *Acta Ecologica Sinica*, 44(14): 6288-6300. (in Chinese)
- Wang Y H, Zhao A Z, Liu X F, et al. 2025. Analysis of spatial and temporal evolution of ecosystem health and its driving factors on the Loess Plateau.

Environmental Science, 46(7): 4558–4567. (in Chinese)

Xie G D, Zhang C X, Zhang L M, et al. 2015. Improvement of the evaluation method for ecosystem service value based on per unit area. *Journal of Natural Resources*, 30(8): 1243–1254. (in Chinese)

Yang J, Xie B P, Wang T B, et al. 2023. Identification and optimization strategy of ecological security pattern in Maiji District of Gansu, China. *Ecological Indicators*, 157: 111309, doi: 10.1016/j.ecolind.2023.111309.

Yang L J, Zhang L L, Zhang F N, et al. 2024. A study on the resilience of ecological networks in the Loess Plateau from the perspective of ecological security patterns. *Acta Ecologica Sinica*, 44(22): 10471–10485. (in Chinese)

Yang Q Y, Zhang H Z, Tang Q. 2022. Ecological restoration zoning of territorial space in Chongqing City based on adaptive cycle model. *Acta Geographica Sinica*, 77(10): 2583–2598. (in Chinese)

Yang R J, Meng W, Shu J M, et al. 2017. Ecological civilization construction for the saline industry in the Qaidam Basin. *Strategic Study of CAE*, 19(4): 48–54. (in Chinese)

Yang Y K, Wang Y, Cheng X, et al. 2020. Establishment of an ecological security pattern based on connectivity index: A case study of the Three Gorges Reservoir Area in Chongqing. *Acta Ecologica Sinica*, 40(15): 5124–5136. (in Chinese)

Zeng C, Cheng Y J, Lü T Y. 2022. Research on land-space ecological restoration zoning based on ecosystem health: A case study of the urban agglomeration in the middle reaches along the Yangtze River. *Journal of Natural Resources*, 37(12): 3118–3135. (in Chinese)

Zhang H T, Li J L, Tian P, et al. 2022. Construction of ecological security patterns and ecological restoration zones in the city of Ningbo, China. *Journal of Geographical Sciences*, 32(4): 663–681.

Zhao Y L, Han R, Cui N, et al. 2021. The impact of urbanization on ecosystem health in typical karst areas: A case study of Liupanshui City, China. *International Journal of Environment Research and Public Health*, 18(1): 93, doi: 10.3390/ijerph18010093.

Zhou G J, Huan Y Z, Wang L Q, et al. 2023. Linking ecosystem services and circuit theory to identify priority conservation and restoration areas from an ecological network perspective. *Science of the Total Environment*, 873: 162261, doi: 10.1016/j.scitotenv.2023.162261.

Zhu Q, Cai Y L. 2024. Impact of ecological risk and ecosystem health on ecosystem services. *Acta Geographica Sinica*, 79(5): 1303–1317. (in Chinese)

Figures

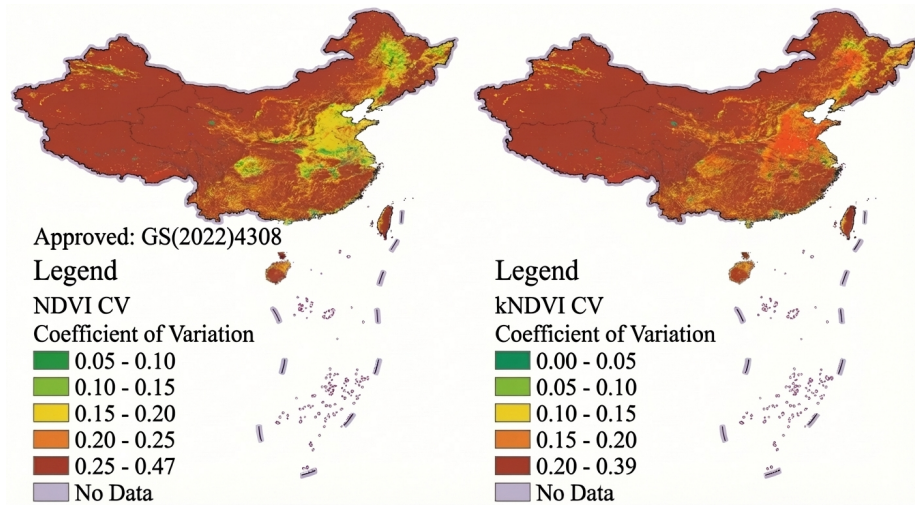


Figure 3: Figure 12

Source: ChinaXiv – Machine translation. Verify with original.

Map Approval Number: GS(2022)4308

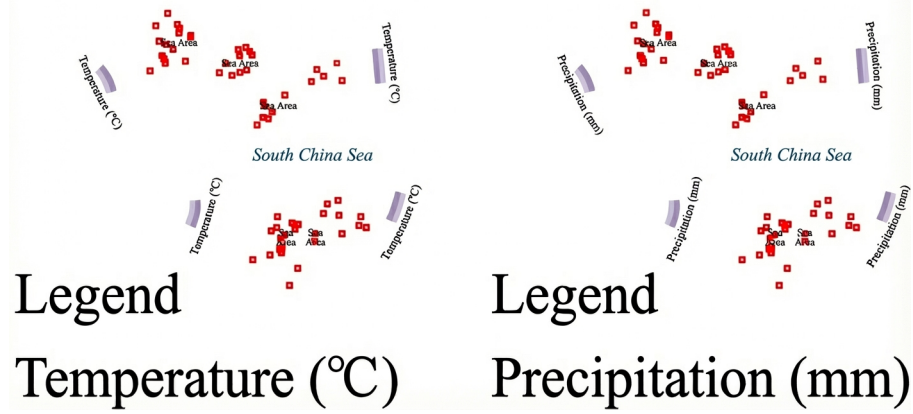


Figure 4: Figure 18

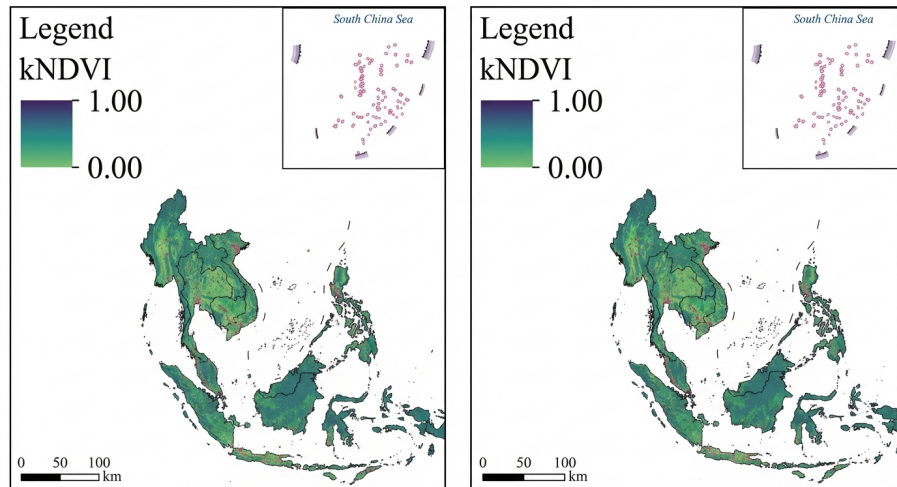


Figure 5: Figure 46

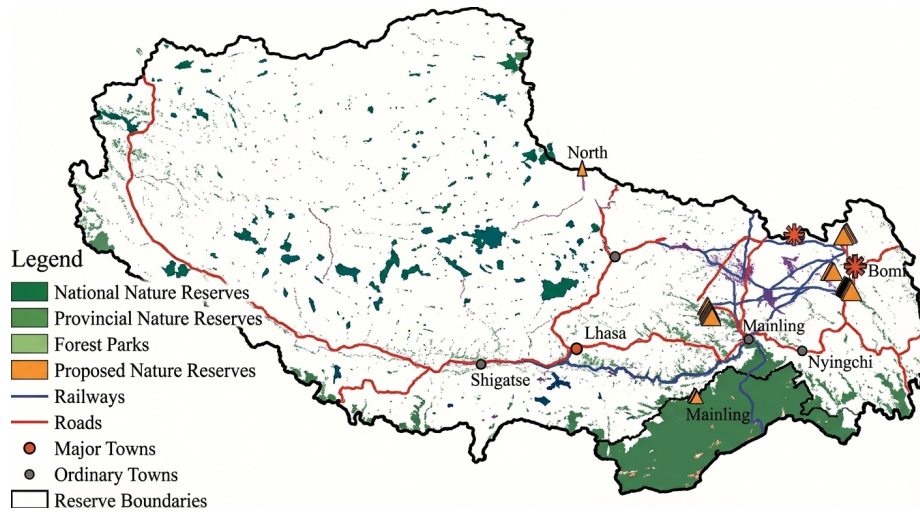


Figure 6: Figure 53