

Spatiotemporal evolution of ecosystem services and ecological connectivity optimization in arid Northwest China

Authors: HE Jing, YU Yang, SUN Lingxiao, LI Chunlan, GUO Zengkun, LU Yuanbo, Ireneusz MALIK, Malgorzata WISTUBA, YU Yang

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Abstract

Northwest China serves as a critical ecological barrier region for maintaining national water, energy, and food security, as well as transboundary ecological governance. However, under the dual pressures of climate change and human activities, ecosystem services (ESs) are facing severe challenges in this region. Based on multi-source remote sensing and statistical data during 2000-2020, this study investigated the spatiotemporal evolution characteristics of four key ESs (water yield, habitat quality, carbon storage, and food provisioning) in Northwest China using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. Integrating morphological spatial pattern analysis (MSPA) and circuit theory, we identified ecological sources, corridors, pinch points, and barriers, and further designed three optimization scenarios (bottleneck optimization, high-resistance corridor buffering, and barrier removal optimization) to enhance landscape connectivity. The results revealed that ES supply and demand exhibited marked spatial heterogeneity, with high-supply areas concentrated in the southeastern sectors. Ecological sources primarily distributed in the southeastern and northern sectors, and ecological resistance surfaces continuously intensified. Water yield and habitat quality demands were increasing, food provisioning demand was decreasing, and carbon storage demand was surging. A total of 61 ecological sources (8% of the study area), 142 ecological corridors (24,957 km in total length), 237 ecological pinch points, and 89 barrier zones were identified. Among the three optimization scenarios, barrier removal achieved optimal connectivity improvement across all distance thresholds, with the probability of connectivity index improvement reaching up to 4%. This study provides scientific foundations and spatial decision support for ecological network optimization and sustainable governance in arid and semi-arid areas.

Full Text

Preamble

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Spatiotemporal evolution of ecosystem services and ecological connectivity optimization in arid Northwest China

HE Jing^{1,2}, YU Yang^{1,2,3*}, SUN Lingxiao^{1,2}, LI Chunlan^{1,2}, GUO Zengkun^{1,3}, LU Yuanbo^{1,3}, Ireneusz MALIK², Malgorzata WISTUBA²

State Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China; Polish-Chinese Centre for Environmental Research, Institute of Earth Sciences, University of Silesia in Katowice, Katowice 40-007, Poland; University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

Northwest China serves as a critical ecological barrier region for maintaining national water, energy, and food security, as well as transboundary ecological governance. However, under the dual pressures of climate change and human activities, ecosystem services (ESs) are facing severe challenges in this region. Based on multi-source remote sensing and statistical data during 2000–2020, this study investigated the spatiotemporal evolution characteristics of four key ESs (water yield, habitat quality, carbon storage, and food provisioning) in Northwest China using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. Integrating morphological spatial pattern analysis (MSPA) and circuit theory, we identified ecological sources, corridors, pinch points, and barriers, and further designed three optimization scenarios (bottleneck optimization, high-resistance corridor buffering, and barrier removal optimization) to enhance landscape connectivity. The results revealed that ES supply and demand exhibited marked spatial heterogeneity, with high-supply areas concentrated in the southeastern sectors. Ecological sources primarily distributed in the southeastern and northern sectors, and ecological resistance surfaces continuously intensified. Water yield and habitat quality demands were increasing, food provisioning demand was decreasing, and carbon storage demand was surging. A total of 61 ecological sources (8% of the study area), 142 ecological corridors (24,957 km in total length), 237 ecological pinch points, and 89 barrier zones were identified. Among the three optimization scenarios, barrier removal achieved optimal connectivity improvement across all distance thresholds, with the probability of connectivity index improvement reaching up to 4%. This study provides scientific foundations and spatial decision support for ecological network optimization and sustainable governance in arid and semi-arid areas.

Keywords

ecosystem services (ESs); landscape connectivity; Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model; morphological spatial pattern analysis (MSPA); circuit theory; barrier removal scenario Citation: HE Jing, YU Yang, SUN Lingxiao, LI Chunlan, GUO Zengkun, LU Yuanbo, Ireneusz MALIK, Malgorzata WISTUBA. 2026. Spatiotemporal evolution of ecosystem services and ecological connectivity optimization in arid Northwest China.

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Introduction

Arid and semi-arid areas cover vast areas of the global land surface and serve as critical yet

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HE Jing et al.: Spatiotemporal evolution of ecosystem services and ecological... fragile barriers for maintaining global ecological security (Costanza et al., 1997; Pan et al., 2022).

As the core of the Eurasian hinterland, Northwest China presents a unique dual attribute: it is an important strategic corridor connecting China with Central and West Asian countries and an ecologically sensitive area constrained by severe water shortages and interlaced “mountain-basin” landscape (Ding et al., 2023; Li et al., 2024c). Although a “warming-wetting” climate trend has been observed in recent years (Zhang et al., 2021; Chen et al., 2023), this has not altered the fundamental arid baseline condition in this region. Conversely, under the compound pressure of rapid urbanization, energy-based construction, and agricultural expansion, the region faces severe risks of exacerbated habitat fragmentation and a spatial mismatch of water and soil resources (Heng et al., 2022; Li et al., 2024c; Zhao et al., 2025). Therefore, constructing a resilient ecological security pattern (ESP) is particularly urgent for balancing development and protection in this ecologically fragile zone. However, the direct application of generic ESP frameworks to arid landscapes faces significant adaptive challenges, highlighting the necessity of optimizing methodologies specifically for the unique characteristics of arid regions.

Existing frameworks often focus on the static assessment of ecosystem service (ES) supply but overlook the extreme spatial mismatch of supply and demand that characterizes arid regions (Zubaida, 2024; Qin et al., 2025). For instance, water retention functions are mainly confined to high-elevation areas, whereas water demand is highly concentrated in distant oasis cities (Chen et al., 2022; Yin et al., 2023). Without an integrated analysis of the ES supply-demand ratio (ESDR), the protection strategies developed often fail due to their detachment from actual societal needs. Although traditional connectivity analysis can identify existing potential corridors, it often lacks a quantitative comparison of the efficacy of different restoration strategies. Previous studies have predominantly focused on identifying and protecting existing ecological pinch points in the high-resistance landscape matrix of arid regions (Peng et al., 2017; Liu et al., 2023a; Guo et al., 2025). However, few studies have explored whether reducing resistance in critical areas is more effective in improving overall connectivity than simply protecting the status quo.

To address the above challenges, we integrated the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, morphological spatial pattern analysis (MSPA), and circuit theory to construct a systematic ESP framework suitable for the complex habitats of Northwest China.

The ESDR index was introduced to precisely diagnose ecological deficits and design three strategies to identify the optimal restoration strategy. Focusing on the period from 2000 to 2020, we aim to answer the following three core questions: (1) under the dual drivers of climate change and human activities, what are the spatiotemporal evolution characteristics of the supply-demand balance for key ESs (water yield (WY), habitat quality (HQ), carbon storage (CS), and food provisioning (FP))? (2) in the highly heterogeneous landscape matrix of Northwest China, what are the spatial distribution patterns of critical pinch points and barrier zones that restrict ecological flows? and (3) which of the three optimization restoration strategies can improve the overall regional landscape connectivity with optimal efficiency? Significantly, this work offers a robust theoretical basis for reconciling the conflict between ES supply and demand, promoting sustainable regional development in arid and semi-arid areas.

Study area and data sources

Study area

Northwest China ($32^{\circ}11' - 49^{\circ}33'N$, $73^{\circ}21' - 108^{\circ}46'E$; Fig. 1 [Figure 1: see original paper]) comprises Shaanxi Province, Gansu Province, Qinghai Province, Ningxia Hui Autonomous Region, and Xinjiang Uygur Autonomous Region (hereinafter referred to as the “five northwestern provinces”). The region covers a total area of approximately 3.1×10^6 km², which accounts for 32% of China’s total land area. Extending deep into the Eurasian hinterland, Northwest China serves as a vital overland corridor connecting China with Central Asia, West Asia, and Europe, holding significant strategic importance. The region is characterized by a typical temperate continental arid and semi-arid climate. Owing

to its considerable distance from the ocean, moisture-bearing air masses rarely reach the area, resulting

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in annual precipitation below 400 mm in most regions and severe water scarcity issues. The topographical features of this region are complex and diverse, dominated by plateaus, basins, mountains, and plains, exhibiting an alternating “mountain-basin” distribution pattern. The terrain shows pronounced elevation variations, creating a fragile ecological environment (Shi et al., 2003).

1 Overview of the study area based on elevation data (a) and land use data in 2020 (b). The boundary is based on the standard map (GS(2023)2767) of the Map Service System (<https://bzdt.ch.mnr.gov.cn/>) marked by the Ministry of Natural Resources of the People’s Republic of China, and the boundary has not been modified.

Data sources

This study integrated heterogeneous datasets detailed in Table 1 , including land use, population density, elevation, soil, precipitation, temperature, carbon emission inventory, road network, and gross domestic product (GDP). The regional water utilization data for the five northwestern provinces were sourced from the Water Resources Bulletins of each respective province during 2000–2020 (Gansu Provincial Water Resources Department, 2000–2020; Ningxia Hui Autonomous Region Water Resources Department, 2000–2020; Qinghai Provincial Water Resources Department, 2000–2020; Shaanxi Provincial Water Resources Department, 2000–2020; Xinjiang Uygur Autonomous Region Water Resources Department, 2000–2020). The

Datasets used in this study

Temporal coverage

Original resolution

Land use

1990, 2000, 2010, and

Resource and Environmental Science Data Platform

<https://www.resdc.cn/DOI/DOI.aspx?DOIID=54>

Population density (persons/km²)

WorldPop Project, University of Southampton

<https://hub.worldpop.org/geodata/summary?id=3>

Administrative boundaries

National Geographic Information Resource Catalog Service System

<http://www.webmap.cn>

Elevation (m)

Geospatial Data Cloud, CNIC, Chinese Academy of Sciences

<http://www.gscloud.cn>

FAO Soils Portal

<http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/en/>

National Earth System Science Data Center <https://www.geodata.cn>

Temperature (°C) 1990–2020

National Qinghai Tibet Plateau Science Data Center <https://cstr.cn/18406.11.Meteoro.tpcd.270961>

Carbon emission inventory

Carbon Emission Accounts & Datasets

<https://www.ceads.net/news/20211262.html>

Road network

OpenStreetMap Contributors

<http://www.openstreetmap.org>

Resource and Environmental Science Data Platform

<https://www.resdc.cn/DOI/DOI.aspx?DOIID=33>

Precipitation

(104 CNY/km²)

Source

Official URL

Note: “-” means no spatial resolution. GDP, gross domestic product; CNIC, Computer Network Information Center; FAO, Food and Agriculture Organization of the United Nations.

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crop yield data and per capita food consumption data for the five northwestern provinces were sourced from the Statistical Yearbooks of each respective province during 2000–2020 (Bureau of Statistics of Ningxia Hui Autonomous Region, 2000–2020; Bureau of Statistics of Xinjiang Uygur Autonomous Region, 2000–2020; Gansu Provincial Bureau of Statistics, 2000–2020; Qinghai Provincial Bureau of Statistics, 2000–2020; Shaanxi Provincial Bureau of Statistics,

2000-2020). All spatial layers were standardized to a 1000-m resolution to resolve scale mismatches. Categorical data (e.g., land use) were aggregated using the majority rule, whereas continuous data (e.g., elevation) were processed via mean aggregation, ensuring spatial consistency for all model inputs.

Methods

WY supply and demand quantification

The InVEST-Budyko model calculates pixel-scale water fluxes using precipitation data and land cover dynamics (Yin et al., 2023). This model links terrain modifications to hydrological shifts through biophysical parameter simulations, expressed as follows:

$$AET_{x,y} = (1 - \alpha) \times P_x, \quad AET_{x,y}$$

$$1 + \omega_x R_{x,y} + \alpha R_{x,y} + R_{x,y}$$

$$\omega_x = Z \cdot WY$$

$$AWC_x + 1.25,$$

$$R_{x,y} =$$

$$k_{x,y} \cdot ET0_x$$

where $WY_{x,y}$ denotes the WY for land use type y in grid cell x (mm); $AET_{x,y}$ denotes the annual actual evapotranspiration for land use type y in grid cell x (mm); P_x denotes the annual precipitation of grid cell x (mm); $R_{x,y}$ denotes the Budyko dryness index for land use type y in grid cell x ; ω_x and $Z \cdot WY$ are the empirical parameters to characterize the underlying surface; AWC_x denotes the vegetation effective water content of grid cell x (mm), depending on soil depth and texture; $k_{x,y}$ denotes the solar radiation for land use type y in grid cell x ($MJ/(m^2 \cdot d)$); and $ET0_x$ denotes the evapotranspiration of vegetation of grid cell x (mm).

This study categorized regional water utilization patterns into three primary sectors: residential consumption, manufacturing requirements, and agricultural irrigation demands. Sector-specific metrics were aggregated to derive the hydrological service demand (Chen et al., 2022), formalized as follows:

$WY_d = P \times X + G \times Y + A_c \times Z$, where WY_d denotes the total water demand (m^3); P denotes the population density (persons/ km^2); X denotes the individual residential water use coefficient ($m^3/person$); G denotes the GDP (104 CNY/ km^2); Y denotes the industrial water intensity ($m^3/104$ CNY); A_c denotes the cultivated land spatial distribution indices; and Z denotes the agricultural irrigation water quota (m^3/km^2).

HQ supply and demand

The biodiversity assessment component within the InVEST analytical framework delineates the ecosystem integrity by measuring ecological degradation

intensity. This approach integrates geospatial patterns of anthropogenic stressors, ecosystem sensitivity thresholds, and adaptive landscape capacities to derive conservation indices by incorporating three core parameters (Chen et al., 2024): maximum influence distance of threat sources, relative weights of threat factors, and sensitivity of habitat types to specific threats. Based on regional ecological characteristics and

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literature review (Li et al., 2024b), we identified four primary threat sources—urban land, cropland, bare land, and road (highways and railroads)—and conducted spatial reconstruction and standardization of raw land use data using ArcGIS 10.8. HQ was calculated by assessing the negative impacts of threat sources on habitats. The HQ for land use type y in grid cell x ($HQ_{x,y}$) is expressed as follows: $HQ_{x,y} = \frac{H_y}{D_{x,y} + k z}$ where H_y denotes the habitat suitability score for land use type y , reflecting ecosystem compatibility; $D_{x,y}$ denotes the habitat degradation level of grid cell x for land use type y , quantifying anthropogenic impacts; z is a scaling parameter, which is typically fixed at 2.5 in the InVEST model and serves as a shape parameter in the half-saturation function to define the non-linear relationship between the degradation score and habitat quality; and k denotes the half-saturation constant governing stress-response relationships. The HQ index is scaled between 0.0 and 1.0; values approaching 1.0 signify optimal ecological conditions, whereas lower values indicate diminished habitat functionality. All sensitivity parameters and threat factor weights in the model (Table 2) were determined through bibliometric analysis and expert consultation (He et al., 2024; Li et al., 2024b).

Land use type

Habitat suitability

Cropland Forestland Grassland Urban land Bare land Water bodies

Sensitivity of land use types to habitat threat factors Urban land

Susceptibility Bare land Cropland

This study quantitatively evaluated HQ demand from the perspective of development activities (Fu et al., 2022). Development-driven demand refers to the reduction in habitat maintenance services due to direct habitat occupation for human production and living activities. After the volatility index was eliminated, the demand can be normalized as follows:

$HQ_{dx} = C_x \times P_x \times G_x$, $d \min HQ_{dx} = HQ_{d \max} - HQ_{d \min}$ where HQ_{dx} denotes the HQ demand of grid cell x ; C_x denotes the proportion of urban land for grid cell x ; P_x denotes the population density of grid cell x (persons/hm²); G_x denotes the GDP of grid cell x (104 CNY/km²); HQ_{dx}^* denotes the HQ

demand index of grid cell x ; and HQ_{dmax} and HQ_{dmin} are the maximum and minimum values of HQ demand, respectively.

CS service and emission-driven demand

Terrestrial CS reflects the ecological functionality of land cover and can be quantified through four fundamental reservoirs: aboveground biomass (C_{above} ; t/hm²), belowground biomass (C_{below} ; t/hm²), soil organic matter (C_{soil} ; t/hm²), and dead organic matter (C_{dead} ; t/hm²). The InVEST carbon sequestration model computed the aggregate CS (t/hm²) for each grid cell as follows:

$CS = C_{above} + C_{below} + C_{soil} + C_{dead}$. In this study, all four carbon pools were incorporated into the calculation to ensure a comprehensive assessment of regional CS. The carbon density parameters for each land use type (Table 3) were derived from a synthesis of local field surveys and relevant literature specific to the arid and semi-arid areas of Northwest China (Zhang et al., 2018; Han et al., 2022; Li et al., 2024c).

Regional CS requirements were determined through individual carbon footprint metrics scaled by population distribution patterns (Shi et al., 2020):

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$$CS_d = P \times D_{cp}$$

where CS_d denotes the demand for CS service (t/km²); and C_{cp} denotes the per capita carbon emissions (t/person).

Land use type Cropland Forestland Grassland Water bodies Urban land Bare land

C_{above} (t/hm²)

Carbon density for different land use types C_{below} (t/hm²)

C_{soil} (t/hm²)

C_{dead} (t/hm²)

Note: C_{above} denotes the carbon density in aboveground biomass; C_{below} refers to the carbon density in belowground biomass; C_{soil} indicates the carbon density in soil organic matter; C_{dead} represents the carbon density in the dead organic matter.

FP supply and demand

Empirical studies have demonstrated the strong correlation of Normalized Difference Vegetation Index (NDVI) with agricultural productivity (Lyu and Wu, 2023; Yin et al., 2023). This study spatially allocated crop yields by calculating each arable pixel's NDVI ratio relative to regional croplands. Given NDVI's

effectiveness in reflecting grain output and the primary production role of croplands, the following equation can reliably estimate the FP service (Cao et al., 2020):

$FP_x = (NDVI_x / NDVI_{sum}) \times FP_{sum}$, where FP_x denotes the crop yield attributed to the arable grid cell x (104 t); FP_{sum} denotes the annual aggregate crop yield (104 t); $NDVI_x$ denotes the NDVI for the arable grid cell x ; and $NDVI_{sum}$ denotes the cumulative NDVI across all arable grid cells.

Population size and distribution are key factors influencing food demand. This study adopted a population-based food demand assessment method, calculating food demand through population density and per capita food demand (Jin et al., 2024). The specific formula is as follows:

$FP_d = F_{cp} \times P$, where FP_d denotes the food demand (t/km²); and F_{cp} denotes the per capita food consumption (t/person).

ESDR index

The ESDR index assesses the equilibrium between ecological provisioning capacities and anthropogenic requirements. Numerical outcomes reveal ES deficits ($ESDR < 0.000$), surpluses ($ESDR > 0.000$), or equilibrium states ($ESDR = 0.000$), providing a systematic metric for sustainability evaluation (Ma et al., 2024). The calculation formula is as follows: $-D_{human} ESDR = (S_{actual} + D_{actual}) / 2$ where S_{actual} and D_{actual} denote the actual supply and human demand of a specific ES, respectively; and S_{max} and D_{max} denote the maximum supply and demand values within the study area, respectively.

ESP construction

3.6.1 Ecological source identification

Ecological sources are strategic regions with high-intensity ES output capacities, identified using a multi-criteria spatial decision framework. First, based on the standardized supply values (0.0–1.0) of the four ESs (WY, HQ, CS, and FP), we classified the ecological service capacity into five levels (low, relatively low, medium, relatively high, and high) via the Jenks natural breaks classification. Ecological advantage zones with three or more high-value services (\$ \$0.7) were extracted through spatial overlay.

Concurrently, MSPA was applied to establish a landscape connectivity identification system: land use data were firstly binarized into an ecological matrix (where forestland, grassland, and

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water bodies were assigned value 1) and a nonecological matrix (where cropland and urban land were assigned value 0), and then processed through Guidos-

Toolbox 3.0 to generate seven landscape elements. Core areas (500.0 km²) were prioritized as key nodes for landscape connectivity, ensuring the integrity of ecological processes in sources. Finally, ArcGIS spatial overlay analysis coupled high-value ecological service zones with landscape cores to construct an ecological source spatial database for Northwest China. This dual-track validation mechanism could effectively balance ecological function intensity and landscape structural stability requirements.

3.6.2 Ecological resistance surface modeling

The ecological resistance surface model quantifies the impediment to species movement, dispersal, and energy exchange across a landscape. Its spatial heterogeneity results from the combined effects of the underlying natural environment and anthropogenic pressures (Forman and Alexander, 1998; McRae et al., 2008). The surface construction followed a rigorous technical workflow. First, all raster datasets were standardized to a common projection coordinate system and resampled to a 1000-m spatial resolution to ensure consistency in the spatial analysis. Second, each factor was reclassified and assigned an initial resistance value based on a “relative resistance levels” standardization system. Specifically, resistance intensity was categorized into five nonlinear levels (1, 20, 50, 80, and 100), representing a spectrum of scenarios ranging from “nearly barrier-free” to “complete blockage”. The relative order and magnitude of these assigned values were informed by previous seminal studies (e.g., Adriaensen et al., 2003; Sawyer et al., 2009; Yuan et al., 2025), ensuring the classification’s ecological validity.

Subsequently, this study employed a combined subjective–objective weighting method integrating the Analytic Hierarchy Process (AHP) and Entropy Weight Method (EWM) to minimize the subjectivity of the initial assignments. The AHP component incorporates a priori ecological knowledge, whereas the EWM is entirely data-driven, objectively revealing the information content of each factor across different years. We generated final combined weights (Table 4) that balance expert knowledge with the data’s inherent spatiotemporal heterogeneity by coupling them, thereby making the weight allocation more scientific and robust. Finally, the comprehensive ecological resistance surfaces for 2000, 2010, and 2020 were generated by applying a weighted sum calculation on the ArcGIS 10.8 platform. This involved multiplying each factor layer by its corresponding final weight and then aggregating the results.

3.6.3 Ecological corridor and pinch point identification

In this study, a landscape conduction network model was constructed based on circuit theory. The ecological source was likened to the power node, the landscape resistance parameter was converted to the resistance value, and the ecological flow potential was mapped to the current intensity (Yang et al., 2024). The Linkage Mapper tool set was used to perform multidimensional ecological network analysis (Yang et al., 2020). The technical process can be divided into two steps: (1) corridor identification and classification; and (2) strategic node identification. We extracted the potential ecological corridor network using a minimum-cost path algorithm, and quantified the ecological flow transmission intensity of each corridor based on the current flow centrality index. To reveal the regional ecological connectivity hierarchy, the corridors

were divided into key, important, and general ecological corridors via the Jenks natural breaks classification according to the current intensity threshold. For strategic node identification, the current density grid was generated by Pinch-point Mapper, and the top 5% area of current density was extracted by the Jenks natural breakpoint method as the ecological pinch point. Such a “stepping stone” area plays a pivotal role in maintaining the continuity of cross-scale ecological processes. Barrier Mapper was also used to detect the spatial mutation boundary of landscape impedance value and locate the priority repair barrier area that hindered biological migration.

This method innovatively introduces the circuit conduction mechanism into landscape ecology and breaks through the linear limitation of the traditional minimum-cost path by simulating the nonlinear diffusion characteristics of current, providing a spatial quantitative decision basis for ecological network optimization in complex terrain.

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Resistance factor

Land use

Elevation (m)

Slope (°)

Normalized Difference Vegetation Index (NDVI)

Population density (persons/km²)

Distance to highways (m)

Distance to railroads (m)

Ecological resistance factors and weights in Northwest China Feature

Ecological resistance value

Forestland Grassland and water bodies Cropland Bare land Urban land <1000 >4000 <2000 8000-20,000 20,000-50,000 50,000-150,000 >8000 >8000

Weight interval (2000-2020)

3.6.4 Optimization scenario design, connectivity indicator calculation, and uncertainty analysis To evaluate the effects of different optimization strategies on landscape connectivity, measured by the probability of connectivity (PC), integral index of connectivity (IIC), and equivalent connectivity (EC; hm²), we considered three scenarios based on the original resistance surface: bottleneck optimization (Sce1), high-resistance corridor buffering (Sce2), and barrier removal optimization (Sce3). We performed resistance surface modifications under each scenario in ArcGIS v.10.8. The optimized resistance surfaces were then processed using Linkage Mapper and Circuitscape to run connectivity models,

and the resulting connectivity metrics were compared with those of the original landscape.

To assess changes in landscape connectivity under different distance thresholds and scenarios, PC and IIC were calculated using Conefor 2.6 and subsequently converted to EC values (EC(PC) and EC(IIC), respectively). EC represents the area of a single fully-connected patch that would provide the same level of connectivity as the existing landscape. Connectivity analyses were performed under four cost-weighted distance (CWD) thresholds (150,000, 200,000, 300,000, and 500,000), representing the maximum dispersal distance within which patches are considered connected. For each threshold, EC(PC) and EC(IIC) values were computed for the original landscape and three optimization scenarios.

Given the high sensitivity of connectivity indicators to threshold selection and resistance parameters, we performed a Monte Carlo uncertainty analysis to quantify potential variability.

Key cost values in the resistance surface were randomly perturbed by $\pm 20\%$ for 500 iterations,

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and EC(PC) and EC(IIC) values were recalculated for each scenario and threshold. The mean improvement rate, absolute gain in EC(PC), and 95% bootstrap confidence intervals (CIs) were reported for each threshold. Multi-threshold mean improvement and area-under-curve values were also computed to assess robustness across thresholds. Statistical significance was tested using permutation tests, and effect sizes (Cliff's delta) were calculated to evaluate ecological relevance. 3.6.5 Optimization scenario selection and performance evaluation Under each scenario, the selected patches and corridors were determined by ranking their connectivity contribution values (dPC and dIIC) in Conefor 2.6, ensuring that optimization targets prioritized elements with the greatest contributions to overall network connectivity.

To quantify optimization performance, the PC-based improvement rate (RPC; %) was calculated using the formula as follows: $(EC(PC)_{\text{scenario}} - EC(PC)_{\text{original}}) / EC(PC)_{\text{original}} \times 100\%$, $RPC =$ where $EC(PC)_{\text{scenario}}$ and $EC(PC)_{\text{original}}$ denote the EC(PC) values of the optimization scenario and original landscape, respectively.

Besides relative improvements, absolute increases in EC(PC) were calculated to facilitate the interpretation of ecological significance. All improvement rates were reported along with their 95% CIs and significance levels under the Monte Carlo simulation described above. 3.6.6 Analysis of temporal changes in ESs We employed a repeated-measures analysis of variance (ANOVA) to quantitatively assess the dynamic changes of ESs in 2000, 2010, and 2020. This method effectively controls for individual differences among the study units, allowing for

a precise examination of the changes in each service over time. In the analysis, “year” (2000, 2010, and 2020) was the within-subject factor, whereas the four ES indicators served as the respective dependent variables. We first performed the Mauchly’s test of sphericity. When the assumption was violated ($P < 0.050$), Greenhouse–Geisser correction was applied. If the overall ANOVA result was significant ($P < 0.050$), post-hoc pairwise comparisons with Bonferroni correction were performed to identify which specific years differed significantly. All statistical analyses were performed using the pingouin library in Python v.3.12, with the significance level (α) set to 0.05.

Results

ES supply assessment

Dynamics of four key ESs—WY, HQ, CS, and FP—from 2000 to 2020 revealed markedly divergent trends. First, FP exhibited a continuous and highly significant increase ($P < 0.001$).

Concurrently, WY demonstrated a significant “rise-then-fall” pattern ($P < 0.010$), peaking in 2010 before declining to near-initial levels. Among the remaining services, HQ exhibited a trend of degradation in the later period; although the overall change during 2000–2020 was not statistically significant ($P > 0.050$), it underwent a statistically significant decline between 2010 and 2020 ($P < 0.010$). Unlike these services, CS remained highly stable throughout the study period ($P > 0.050$).

For WY, geospatial analysis revealed a pronounced latitudinal gradient, with elevated hydrological outputs clustered in southern mountainous territories, such as Ankang City and Hanzhong City in Shaanxi Province, Golog Tibetan Autonomous Prefecture and Haixi Mongolian Tibetan Autonomous Prefecture in Qinghai Province, and Aksu Prefecture and Altay Prefecture in Xinjiang Uygur Autonomous Region (Fig. 2a [Figure 2: see original paper]). Notably, marked WY increases were recorded in transitional ecotones, including Gannan Tibetan Autonomous Prefecture and Longnan City in Gansu Province, Yulin City in Shaanxi Province, and Kizilsu Kirgiz Autonomous Prefecture, Aksu Prefecture, and Altay Prefecture in Xinjiang Uygur Autonomous Region. The late-stage WY decline indicated dual pressures of decreasing total water resources and rising demand, necessitating vigilance against future supply–demand imbalances. High-supply zones were

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clustered in southern regions and ecologically sensitive areas, highlighting the strong dependence of water distribution on physiographic conditions. Supply increases in Yulin City of Shaanxi Province and Longnan City of Gansu Province may correlate with ecological measures such as cropland-to-forestland conversion and soil conservation, indicating that policy interventions can locally enhance water supply capacity.

For HQ, the average HQ index exhibited a slight declining trend over the study period.

High-supply areas included Golog Tibetan Autonomous Prefecture, Huangnan Tibetan Autonomous Prefecture, and Hainan Tibetan Autonomous Prefecture in Qinghai Province, Gannan Tibetan Autonomous Prefecture and Longnan City in Gansu Province, and Shangluo City, Ankang City, Yan' an City, and Hanzhong City in Shaanxi Province (Fig. 2b). The low-supply zones encompassed Tiemenguan City, Aksu Prefecture, Bayingol Mongolian Autonomous Prefecture, Shuanghe City, Shihezi City, Hotan Prefecture, Hami City, and Turpan City in Xinjiang Uygur Autonomous Region, and Jiayuguan City and Jiuquan City in Gansu Province.

The spatial patterns of HQ consistently showed lower values in central zones and higher values peripherally, with high-supply regions particularly concentrated in the southeast.

2 Spatiotemporal variation in ecosystem service (ES) supply in Northwest China from 2000 to 2020. (a1-a3), WY; (b1-b3), HQ; (c1-c3), CS; (d1-d3), FP. WY, water yield; HQ, habitat quality; CS, carbon storage; FP, food provisioning. FP was calculated and visualized at the prefecture-level city scale.

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For CS, the region' s average CS remained highly stable, showing only negligible fluctuations across the three time points. Low-supply areas concentrated in Aksu Prefecture, Kizilsu Kirgiz Autonomous Prefecture, Kashgar Prefecture, Karamay City, Bayingol Mongolian Autonomous Prefecture, Hotan Prefecture, Hami City, and Turpan City in Xinjiang Uygur Autonomous Region, Haixi Mongolian and Tibetan Autonomous Prefecture in Qinghai Province, and Jiayuguan City and Jiuquan City in Gansu Province (Fig. 2c). High-supply areas clustered in Shangluo City, Baoji City, Tongchuan City, Hanzhong City, Ankang City, Xi' an City, and Yan' an City in Shaanxi Province, and Longnan City, Gannan Tibetan Autonomous Prefecture, and Tianshui City in Gansu Province.

For FP, the total supply in Northwest China exhibited a substantial and continuous upward trend. Spatially, high-supply zones were mainly concentrated in the northern Xinjiang Uygur Autonomous Region border areas and the Shaanxi and Gansu Loess Plateau regions, with typical examples including Tacheng Prefecture in Xinjiang Uygur Autonomous Region and Yulin City in Shaanxi Province (Fig. 2d). Low-supply zones were predominant in the central part of Northwest China, especially in desert areas unsuitable for crop cultivation. From 2000 to 2020, increased supply in northern Xinjiang Uygur Autonomous Region led to a shift in high-supply clusters.

These clusters moved from being densely concentrated at the southeastern and northwestern edges towards more peripheral distributions, with sporadic patches

also appearing in the central region.

ES demand assessment

The total WY and HQ demands increased. The WY demand maintained a persistent spatial pattern of high values in the northwestern sectors, with the high-demand zones consistently concentrated in Xinjiang Uygur Autonomous Region, Ningxia Hui Autonomous Region, and parts of Shaanxi Province (Fig. 3 [Figure 3: see original paper]). The total demand for FP decreased, whereas the CS demand exhibited substantial growth. Elevated CS demand predominated in the southeastern regions, whereas lower CS demand characterized the northwestern areas, decreasing radially from central urban cores.

ES supply and demand varied spatially, indicating notable heterogeneity: supply exhibited “high in the east–low in the north” patterns, whereas demand peaked in urbanized zones and diminished in suburban peripheries. High-demand areas for WY, HQ, CS, and FP primarily encompassed Xi’an City and Xianyang City in Shaanxi Province, Lanzhou City in Gansu Province, and Urumqi City in Xinjiang Uygur Autonomous Region with dense populations and intensive economic activities. Distinctively, elevated WY demand concentrated in Ili Kazak Autonomous Prefecture, Kashgar Prefecture, Aksu Prefecture, Altay Prefecture, and Hotan Prefecture of Xinjiang Uygur Autonomous Region, highlighting arid Northwest China’s substantial agricultural water requirements.

Quantitative relationships between ES supply and demand

during 2000–2020. The average ESDR for WY increased from -0.118 to -0.061 , representing a 48% growth rate. The overall spatial pattern exhibited “high in the southwest–low in the northwest” characteristics, with a prominent central gap. High-ESDR zones expanded from the southeast to the northwest. Severe deficits persisted in urban cores, whereas deficit conditions alleviated in parts of Ningxia Hui Autonomous Region, Gansu Province, and Shaanxi Province.

HQ’s average ESDR increased from 0.008 to 0.042 . The spatial configuration demonstrated “high in the center–low in the periphery”, with high-ESDR zones expanding northwestward from the southeast. CS’s average ESDR declined from 0.038 in 2000 to -0.304 in 2020, indicating progressive deterioration. All urban cores experienced persistent deficits, whereas natural zones maintained relatively stable surpluses. FP’s average ESDR increased from -0.028 to 0.297 .

Spatially, the trend shifted from “high in the northwest” to “low in the center–high in the periphery”. Despite significant ESDR improvements, most regions—particularly urbanized areas—remained in deficit.

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3 Spatiotemporal variation in ES demand in Northwest China from 2000 to 2020. (a1–a3), WY; (b1–b3), HQ; (c1–c3), CS; (d1–d3), FP. All ES demand indicators were mapped at the prefecture-level city scale.

Spatial characteristics of ecological sources

Ecological sources in Northwest China were identified using MSPA with a minimum patch area threshold of 500.0 km² (Fig. 5 [Figure 5: see original paper]). These sources predominantly comprised cropland, forestland, and grassland, accounting for 52%, 26%, and 17% of the total ecological sources, respectively.

Pronounced spatiotemporal evolution was observed: the total source area increased by 37,819.0 km², with its proportion increasing from 7% to 8%. In 2020, 61 ecological sources were identified, covering 247,519.0 km² (8% of the study area). The largest source patch covered 118,628.0 km² and was located in the southern Qinghai Province. Spatially, the ecological sources displayed a highly uneven distribution pattern. They were primarily concentrated in the southwestern and northern parts of the study area. Meanwhile, the eastern part contained only two ecological sources. The central and southeastern regions, dominated by bare land and cropland and characterized by limited high-value ESs, were devoid of ecological sources.

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4 Spatiotemporal variation in ES supply-demand ratio (ESDR) for four ES types from 2000 to 2020. (a1-a3), WY; (b1-b3), HQ; (c1-c3), CS; (d1-d3), FP. All ESDR were mapped at the prefecture-level city scale.

Spatial distribution of ecological sources in Northwest China in 2000 (a), 2010 (b), and 2020 (c)

Ecological resistance surface construction

The resistance patterns exhibited marked intensification during 2000-2020, with gradual

HE Jing et al.: Spatiotemporal evolution of ecosystem services and ecological... increases across the region. High-resistance zones in Xinjiang Uygur Autonomous Region were concentrated around the Taklimakan Desert periphery, whereas low-resistance zones were clustered in the forestlands of the Tianshan Mountains and Altay Mountains. The high-resistance zones in Shaanxi Province were dominated by the urbanized clusters in the Guanzhong Plain, contrasting with low-resistance zones in the Qinling Mountains' nature reserves. The high-resistance zones in Qinghai Province occurred in Qaidam Basin' s deserts and saline-alkali lands, whereas low-resistance zones were concentrated in the Qilian Mountains and Three-River-Source reserves. The high-resistance zones in Gansu Province emerged along the Hexi Corridor' s urban-oasis fringes, countered by low-resistance forestlands in the Qilian Mountains and Altun Mountains. The high-resistance zones in Ningxia Hui Autonomous Region were concentrated in Yinchuan Plain' s urban land-cropland complexes, with low-resistance zones in the forestlands of the Helan Mountains and Liupan Mountains. In summary, ecological resistance surfaces demonstrated

pronounced spatiotemporal evolution from 2000 to 2020, showing gradient increases from interior to peripheral regions. Further, the primary drivers of resistance changes were human activities. Consequently, strategic constraints on urban expansion directions are imperative to prevent further encroachment into high-resistance zones.

6 Spatial distribution of ecological resistance in Northwest China in 2000 (a), 2010 (b), and 2020 (c)

Spatiotemporal distribution of ecological corridors

Ecological risks of corridors were assessed through the ratio of cumulative resistance to path length, with corridors classified into three tiers via the Jenks natural breaks classification (Fig. 7 [Figure 7: see original paper]).

The key ecological corridors were the lowest-risk zones with minimal unit resistance and high quality (e.g., forest core areas and low-human-disturbance regions), predominantly distributed in northeastern sectors. Conversely, the general ecological corridors were the highest-risk zones characterized by elevated resistance per unit length, reflecting poor corridor quality (e.g., low migration efficiency and severe habitat fragmentation), concentrated in the southwestern urbanized areas.

The results demonstrated that ecological corridors primarily comprise forestland, cropland, and grassland. Central regions exhibited higher ecological resistance, impeding ecological flows, with only general ecological corridors traversing the high-resistance zones. Conversely, key ecological corridors were clustered in low-resistance areas and concentrated in the northwestern and southeastern sectors, with the longest corridor spanning from Zhongwei City in Ningxia Hui Autonomous Region to Hami City in Xinjiang Uygur Autonomous Region. In 2020, we identified 142 ecological corridors, totaling 24,958 km in length and ranging from 5 km (shortest) to 1234 km (longest).

Ecological pinch points and barrier zones

Ecological pinch points are essential channels in corridors. They have a high concentration of biological flow and little landscape resistance. If these nodes are damaged, they might break the connection between ecological sources. Thus, they need to be conserved and restored first. There were 237 ecological pinch points in Northwest China (Fig. 8 [Figure 8: see original paper]). They were mainly located along

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Spatial distribution of ecological corridors in Northwest China in 2000 (a), 2010 (b), and 2020 (c)

Spatial distribution of ecological security pattern in Northwest China in 2000 (a), 2010 (b), and 2020 (c)

major corridors. Most of these areas comprised bare land (47%), grassland (37%), and cropland (8%). The vegetation systems in these areas help with biological migration and make the corridors more stable. Several pinch points were clustered together in the southern sectors. In these areas, the corridors and sources were mixed up to form network structures, which greatly improved the ecological connectivity. It is crucial to protect and optimize these corridors in a smart way to promote the migration of species between sources and the exchange of information.

This study identified 89 ecological barrier zones concentrated in the central and northern regions. These zones were mainly covered by bare land and transportation networks. The composition of these barriers included bare land (56%), grassland (30%), and cropland (8%). The high-resistance values in these zones severely stopped species from migrating and affected the ecological network connectivity. The spatial distribution of barriers was closely related to land use patterns. These barriers overlapped with areas that have impervious surfaces and transportation arteries. Notably, 24% of the barriers gathered in ridgelines with complex topography. In these areas, grassland ecosystems surprisingly became barriers to connectivity because the terrain caused landscape fragmentation. The restoration of barrier zones is expected to considerably improve source connectivity.

EC(PC) and relative improvement under different optimization scenarios

optimization scenarios under four CWD thresholds. The mean EC(PC) increased with the threshold across all scenarios, indicating that allowing a larger cost-accessibility range could enhance the potential accessibility of ESs within the landscape. For the original landscape, EC(PC) increased from approximately 123,940.0 km² at CWD threshold of 150,000 to approximately 132,460.0 km² at CWD threshold of 500,000. All optimization scenarios showed higher EC(PC) than the original at each threshold, and their 95% CIs were nonoverlapping with the original estimate under high-threshold conditions. Sce3 achieved a mean EC(PC) of approximately 137,700.0 km² at CWD threshold of 500,000, a net increase of approximately 5236.0 km² over the original landscape, and performed best overall across all thresholds. Besides,

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Sce3 showed the greatest mean improvement in PC index across all thresholds (approximately 2%-4%), with statistically significant gains at higher thresholds, whereas Sce1 and Sce2 showed smaller improvements, and their CIs overlap zero at low thresholds. These results indicated that optimization yields more pronounced gains in ES functional connectivity when a larger cost-accessibility range is allowed.

Overall, increasing the cost-accessibility threshold could enhance the ES func-

tional connectivity, but the magnitude of improvement was jointly influenced by the spatial configuration of the optimization strategy and threshold settings. Multi-threshold averages and parameter sensitivity analyses demonstrated that Sce3 delivers robust improvements under most conditions, although improvements at low thresholds and under some parameter combinations may fall within model uncertainty. EC(IIC) remained stable across all thresholds, indicating that the gains primarily stem from easy transmission of service flows across the resistance surface rather than changes to network topology.

9 Ecological connectivity analysis across different CWD thresholds under different optimization scenarios. (a), EC(PC) and EC(IIC); (b), PC-based improvement rate. EC(PC) and EC(IIC) are the equivalent connectivity (EC) values for the probability of connectivity (PC) and integral index of connectivity (IIC), respectively. CWD, cost-weighted distance; Sce1, bottleneck optimization; Sce2, high-resistance corridor buffering; Sce3, barrier removal optimization.

4.9 Spatial distribution of cumulative current density and difference analysis under different optimization scenarios for the original resistance surface (baseline) and three optimization scenarios (Sce1, Sce2, and Sce3). In the original landscape, current hotspots were primarily concentrated in the northwestern, central, and southeastern coastal low-resistance ecological source areas, forming the main migration corridors and key connection nodes. Sce1 showed only minor changes compared with the original landscape, with slight expansions in hotspot areas and localized decreases in peak current density within certain bottleneck regions. The overall network flow distribution pattern remained largely unchanged. Sce2 produced more continuous hotspot belts along several high-resistance corridors and their surroundings, with markedly increased hotspot intensity, indicating that reducing the resistance of buffer zones in high-resistance corridors can effectively enhance corridor permeability, improve connectivity between core network nodes, and distribute flow evenly across multiple paths. Under Sce3, the peak current density in certain hotspot areas markedly exceeded the original landscape's hotspot values, with some regions showing increases of up to 50. The difference analysis results were consistent with the cumulative current density distribution trends: Sce2 focused on improving the performance of key corridors while maintaining network diversity, whereas Sce3 enhanced the efficiency of major corridors while yielding a high-flow concentration.

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10 Spatial distribution of cumulative current density for the original resistance surface (baseline) (a) and optimization scenarios Sce1 (b), Sce2 (c), and Sce3 (d) as well as the difference distribution between Sce2 and baseline (e) and between Sce3 and baseline (f)

Discussion

Spatial heterogeneity of ESDR

This study revealed pronounced spatial heterogeneity in the ESDR for WY, HQ, CS, and FP across the five northwestern provinces. First, overlapping high-value areas of multiple regulating services in major mountain ranges constituted the functional core of ecological sources. Results indicated that this multi-service surplus characterizes key ecological barrier zones, where ESDR values remain consistently high from Yushu Tibetan Autonomous Prefecture and Golog Tibetan

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Autonomous Prefecture in Qinghai Province (>0.980) to Gannan Tibetan Autonomous Prefecture in Gansu Province (0.980), and further to Shangluo City (0.770) and Ankang City (0.720) in Shaanxi Province. This cross-regional high supply is primarily attributed to high-elevation forest-meadow coverage and strict ecological protection policies. These findings align with previous reports on the Qilian Mountains, confirming that high-elevation regions are critical carbon sequestration and water conservation hotspots (Li et al., 2021). They also corroborate the service gradient of “high in the southeast and low in the central part” identified in Northwest China (Zhou et al., 2025). Conversely, oasis agricultural areas in Xinjiang Uygur Autonomous Region exhibited high FP efficiency but relatively fragile HQ. This is consistent with the findings that cropland expansion in Xinjiang Uygur Autonomous Region has led to grassland degradation (Liu et al., 2023b) and that oasis agricultural expansion substantially weakens critical ecological functions such as climate regulation and biodiversity conservation while enhancing provisioning services (Zhao et al., 2023). Further, WY exhibited the most drastic “source-sink” spatial differentiation. Driven by glacier meltwater (Wang et al., 2023; Li et al., 2024d), regions such as Yushu Tibetan Autonomous Prefecture and Golog Tibetan Autonomous Prefecture in Qinghai Province and Gannan Tibetan Autonomous Prefecture in Gansu Province maintained extremely high WY surpluses ($ESDR > 0.900$). However, cities such as Karamay (with ESDR of -0.997) and Hotan (-0.995) in Xinjiang Uygur Autonomous Region and Yinchuan (-0.922) in Ningxia Hui Autonomous Region experienced extreme water scarcity (Zhang et al., 2024). This vast spatial disparity validated the decisive role of water resources as the primary limiting factor for ecosystems in Northwest China.

To verify the reliability of our simulation, this study cross-referenced the results with recent regional benchmarks. The identified high-value clusters of regulating services in the Qinling and Qilian Mountains show strong spatial congruency with the ecosystem quality patterns reported by Niu et al. (2022). Further, the observed tradeoffs between FP and HQ in oasis agricultural areas corroborate the land-use impact assessments of Zhou et al. (2025). These consistencies with independent studies confirmed that the InVEST model used in this study accurately captures the complex biophysical heterogeneity of Northwest China,

establishing a robust basis for the connectivity analysis in this study.

Effectiveness and strategic tradeoffs in arid landscape restoration

The superiority of Sce3 over other scenarios highlights the potential for a shift from additive to subtractive optimization in the ecological restoration of arid regions. Although the 4% connectivity increase achieved by this strategy was modest compared with the 14% gain in the humid Haihe River Basin of China (Li et al., 2024a) or the twofold increase achieved via artificial stepping stones in Beijing of China (Na et al., 2024), this disparity largely reflects the strict hydrological tradeoffs inherent in arid regions. The additive strategies employed in previous studies often rely on extensive vegetation expansion, which poses potential risks in arid environments. As warned by Feng et al. (2016), large-scale vegetation restoration in China's arid and semi-arid areas is approaching the limits of water carrying capacity, meaning that blindly increasing vegetation patches may exacerbate soil desiccation and threaten regional water security. Consequently, this subtractive optimization approach offers a pathway that is more aligned with the ecological carrying capacity. It demonstrated that restoring connectivity by converting local high-resistance areas to low-resistance areas without largely increasing water consumption may represent a more sustainable solution adapted to the resource constraints of arid zones than the mere pursuit of numerical connectivity gains.

Beyond adapting to water constraints, the advantage of Sce3 was further reflected in its potential to circumvent land-use conflicts. A recent pan-European survey by Birk et al. (2025) indicated that traditional restoration measures, such as large-scale wetland reconstruction, can create tradeoffs with the provisioning services of intensive agriculture and lead to implementation resistance. Meanwhile, Sce3 directly converted identified high-resistance barriers into a

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low-resistance ecological matrix. This targeted replacement of specific spatial units typically avoids encroaching upon large arable lands. Therefore, it helps to mitigate the agricultural-ecological conflicts highlighted by Birk et al. (2025).

Mechanistically, unlike the flow homogenization effect caused by buffer zones, Sce3 promoted the efficient accumulation of current flow within critical corridors by eliminating high-resistance pinch points. This corroborates the finding of Yang et al. (2021) that high-resistance areas are primary factors blocking ecological processes, suggesting that improving existing key ecological corridors is more effective than expanding ecological sources for enhancing the transmission capacity of ESs in arid and semi-arid areas.

Limitations and prospects

At the implementation stage, ecological restoration in arid and semi-arid areas

remains constrained by multiple socioeconomic factors. First, high restoration and opportunity costs mean that large-scale afforestation or wetland reconstruction can conflict with food production, and such interventions may raise water withdrawals and induce soil desiccation and functional decline under stringent water constraints (Feng et al., 2016; Bryan et al., 2018; Li et al., 2020). Second, cross-jurisdictional ecological corridors often traverse heterogeneous land tenures, including state-owned, collective, and private lands, and the absence of well-designed eco-compensation and land-use coordination mechanisms can substantially increase transaction costs and delay implementation (Bryan et al., 2018; Gao et al., 2019; Zhai et al., 2021). Third, given the rigid demands of oasis agriculture and infrastructure corridors, avoidance and substitution are generally preferable to occupation and displacement, and low disturbance measures, such as micro-topography rehabilitation and road ecologization, should be prioritized to improve connectivity without materially increasing water use and minimize impacts on cropland and transport functions (Wang et al., 2021; Birk et al., 2025).

The current study also has some limitations. First, the connectivity analysis relying on static resistance surfaces did not explicitly couple future climate scenarios, including glacier retreat, variability in vegetation cover, and changes in WY, which may affect inferences about long-term network stability (Ding et al., 2022; Wang et al., 2023; He et al., 2024). Second, connectivity metrics were not explicitly integrated with cost-benefit analysis and eco-compensation mechanisms, limiting our ability to quantify the economic feasibility and distributional effects of alternative strategies. Future work can link connectivity assessment with spatial econometric models and eco-compensation scenarios (Bryan et al., 2018; Li et al., 2020; Jin et al., 2025).

Overall, we recommend developing dynamic resistance surfaces under multi-climate scenarios and multi-threshold frameworks with robustness-oriented optimization as well as integrating high-resolution, multi-source data with socioeconomic modules to enhance model generalizability and policy implementability.

Conclusions

By integrating the InVEST model, MSPA, and circuit theory, we systematically evaluated the spatiotemporal variations of ESs in Northwest China during 2000–2020 as well as different ecological corridor optimization strategies under arid region constraints. ES supply exhibited pronounced spatial heterogeneity, with high-supply areas mainly located in the southeastern and northern mountainous zones. MSPA identified 61 ecological sources, covering 8% of the study area, together with 142 ecological corridors and 237 ecological pinch points, forming the regional ecological network structure. Between 2000 and 2020, ecological resistance increased notably and demonstrated an evident spatial gradient. Among the optimization scenarios, Sce3 achieved the greatest improvement in connectivity under different CWDs, with the PC index increasing by up to 4%, while EC(IIC) remained stable, indicating that the gains in functional connectivity

may be primarily driven by improved species dispersal efficiency rather than
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changes in network structure. Theoretically, this study proposed a new perspective for constructing ESPs in arid and semi-arid areas, integrating ES supply and demand balance into connectivity optimization, and shifting restoration from simple habitat expansion to targeted removal of high-resistance barriers under water resource constraints. Methodologically, this study established a resistance weighting approach that integrated multi-source ecological and socioeconomic data, combined AHP and EHM, and incorporated multi-threshold connectivity evaluation and uncertainty analysis, forming a robust decision support workflow. Practically, this study provides strategic guidance for coordinating ecological compensation across jurisdictions and balancing ecological connectivity with agricultural production and infrastructure development.

Conflict of interest Ireneusz MALIK is an Editorial Board member of Journal of Arid Land and was not involved in the editorial review or the decision to publish this article. 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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