Ecological Security Pattern in the Shaanxi-Gansu-Ningxia Region from the Perspective of Ecosystem Service Supply-Demand Matching (Postprint)

Authors: Ye Fanni, Fang Xinzhuo, Gong Bikai

Date: 2026-01-30T16:53:17+00:00

Abstract

Ecological security patterns are an important foundation for enhancing human well-being and maintaining regional sustainable development. Focusing on the Shaanxi-Gansu-Ningxia region, which encompasses ecologically sensitive areas and ecological transition zones, this study constructs a research framework of "supply-demand matching-pattern analysis-optimization and reorganization." Using the InVEST model and integrated supply-demand parameters, it evaluates the dynamic changes in the supply-demand relationships of ecosystem services, and, combined with circuit theory, analyzes the characteristics of the ecological security pattern to propose optimization and reorganization strategies. The results show that: (1) The ecosystem service supply-demand relationships in the Shaanxi-Gansu-Ningxia region exhibit significant spatiotemporal differentiation. Overall, supply exceeds demand, presenting a pattern of "supply in the south and demand in the north, with localized imbalances." (2) From 2000 to 2020, ecological source areas followed a pattern of contiguous, concentrated distribution "from north to south" ; both ecological corridors and ecological pinch points exhibited the characteristic of "first decreasing and then increasing in number, with continuous contraction in length and area" ; the number of ecological barrier points increased by 49, and their area increased by 588.66 km^2. (3) Based on the spatiotemporal characteristics of ecosystem service supply-demand relationships and ecological security patterns in the Shaanxi-Gansu-Ningxia region, the study proposes an ecological security pattern construction and optimization strategy of "one axis and one point" and "two shields and multiple zones," providing a scientific basis and methodological reference for formulating regional ecological conservation planning and promoting future sustainable development.

Full Text

Ecological Security Patterns in the Shaanxi-Gansu-Ningxia Region from the Perspective of Matching Ecosystem Service Supply and Demand

YE Fanni, FANG Xinzhuo, GONG Bikai

(School of Management, Southwest Minzu University, Chengdu 610041, Sichuan, China)

Abstract

Ecological security patterns constitute a critical foundation for enhancing human well-being and maintaining sustainable regional development. This study examines the Shaanxi-Gansu-Ningxia region, a typical ecologically sensitive area and ecological transition zone, by constructing a research framework of "supply-demand matching—pattern analysis—optimization and restructuring." Using the InVEST model and comprehensive supply-demand parameters, we assessed the dynamic changes in ecosystem service supply-demand relationships and analyzed ecological security pattern characteristics through circuit theory to propose optimization strategies. The results demonstrate that: (1) The supply-demand relationship of ecosystem services in the Shaanxi-Gansu-Ningxia region exhibits significant spatiotemporal heterogeneity, with overall supply exceeding demand and a characteristic pattern of "southern supply, northern demand, and local imbalances." (2) From 2000 to 2020, ecological source areas followed a concentrated and continuous distribution pattern from north to south. Both ecological corridors and pinch points showed a trend of "decreasing then increasing in number, with continuous contraction in length and area." The number of ecological barrier points increased by 49, with a total area increase of 588.66 km^2. (3) Based on the spatiotemporal characteristics of ecosystem service supply-demand relationships and ecological security patterns, we propose an ecological security pattern construction and optimization strategy of "one axis and one point" and "two screens and multiple zones," providing scientific basis and methodological reference for regional ecological protection planning and sustainable development.

Keywords: ecosystem services; Shaanxi-Gansu-Ningxia region; supply-demand matching; circuit theory; ecological security pattern

Introduction

Accelerated urbanization and rapid economic development have increasingly highlighted environmental pollution, ecosystem degradation, and resource overconsumption. These interconnected issues create complex ecological dilemmas that not only damage ecosystem stability and service functions but also severely constrain socioeconomic development and threaten the very foundation of human survival. The Shaanxi-Gansu-Ningxia region, as a typical ecologically sensitive area and ecological transition zone in China, faces severe constraints on coordinated development between natural environments and socioeconomic systems due to fragile ecosystems, degraded service functions, and intensifying ecological risks. Therefore, constructing scientifically sound ecological security patterns is essential for ensuring ecosystem service capacity and achieving sustainable human-nature coexistence.

Ecological security patterns are intimately linked to ecosystem services, which serve as the bridge connecting natural and socioeconomic systems and form the foundation for building ecological security patterns. Defined as the direct or indirect contributions of ecosystems to human well-being and welfare, ecosystem services encompass both the provision of services by ecosystems and human consumption of these services. Current research on ecosystem services has integrated with regional ecological resilience, ecological security, ecological function zoning, and ecological risk prediction. Evaluating supply potential, clarifying demand structures, and revealing supply-demand differences are necessary pathways for understanding ecosystem functions and values, as well as essential tools for constructing ecological security patterns.

Ecological security patterns originated from landscape ecological planning, initially focusing on actual habitats as ecological sources and species migration paths as corridors, without identifying potential sources, corridors, and critical points. However, with the refinement of ecosystem service theory, a basic paradigm centered on "source identification—resistance surface construction—corridor extraction" has gradually formed, shifting research from single themes to multi-objective coordination of natural-social interaction mechanisms. Scholars have developed integrated multi-model, multi-method frameworks such as the Minimum Resistance Model (MCR), Grain Inverse Analysis, Morphological Spatial Pattern Analysis (MSPA), and Circuit Theory. Nevertheless, most current ecological security pattern studies rely solely on natural conditions without incorporating human activities and demands, resulting in patterns that lack dynamic adaptability and may fail to effectively guarantee regional ecological security and human well-being.

The Shaanxi-Gansu-Ningxia region serves as a critical corridor connecting the Northwest Arid Zone, the middle-upper reaches of the Yellow River Basin, and the Loess Plateau, bearing multiple ecological functions including windbreak and sand fixation, soil and water conservation, and water source conservation. Climate change 叠加 high-intensity human activities have exacerbated ecosystem service supply-demand imbalances and highlighted ecological degradation risks. Scientifically identifying supply-demand matching characteristics to construct ecological security patterns has become an urgent issue for ecological protection and high-quality development in this region. This study establishes an integrated framework of "supply-demand matching—optimization and restructuring," combining ecosystem service supply-demand relationships with the spatial topology of ecological "sources—corridors—pinch points—barrier points" to systematically reveal the evolution patterns of ecological service supply-demand

and construct cross-regional ecological security pattern optimization schemes.

1.1 Study Area Overview

The Shaanxi-Gansu-Ningxia region is located in the middle and upper reaches of the Yellow River Basin, encompassing 10 prefecture-level cities in Shaanxi Province, 12 prefecture-level cities and two autonomous prefectures in Gansu Province, and 5 prefecture-level cities in Ningxia Hui Autonomous Region. The total area is approximately 69.78$×10^{4}$ km^2, representing a critical transition zone between the Yellow River Basin and Northwest inland areas [Figure 1: see original paper]. The region features complex and diverse topography, including plateaus, mountains, basins, plains, deserts, and Gobi. Significant elevation gradients create distinct climate variations, transitioning from subtropical monsoon climate in the south to plateau alpine climate, with annual precipitation ranging from 36–1240 mm and temperatures from -9 to 16°C. The area has dense river networks and abundant water resources, with the main Yellow River channel crossing the Ningxia Plain, its largest tributary Wei River flowing through Tianshui City in Gansu and the Guanzhong Plain in Shaanxi, and inland rivers Heihe and Shule supporting oasis economies in the Northwest Arid Zone.

1.2 Data Sources

This study utilized data from 2000, 2010, and 2020, including Digital Elevation Model (DEM) data, land use data, annual precipitation and average temperature, soil data, evapotranspiration data, plant-available water content data, population density, and Normalized Difference Vegetation Index (NDVI). Statistical data were obtained from corresponding statistical yearbooks .

1.3 Research Methods

Ecosystem service supply and demand jointly constitute the dynamic flow from natural ecosystems to human society. This study first assessed the supply, demand, and importance of four ecosystem services—carbon sequestration, food provision, water conservation, and soil retention—to identify ecological sources. Second, we constructed a comprehensive ecological resistance surface and applied circuit theory to extract ecological corridors, pinch points, and barrier points. Finally, we analyzed ecological element characteristics to propose ecological security pattern construction strategies.

1.3.1 Ecosystem Service Supply-Demand Assessment **Supply Assessment:** Carbon sequestration, water conservation, and soil retention were calculated using the InVEST model (Carbon Storage and Sequestration, Water Yield, Sediment Delivery Ratio). Food provision was calculated using the ratio of NDVI values. For carbon sequestration assessment, carbon density was corrected based on its positive correlation with annual precipitation and weak correlation with average temperature .

Demand Assessment: Ecosystem service demand is primarily determined by regional population density and socioeconomic development. Carbon sequestration demand was calculated using carbon emissions, food demand using per capita grain consumption, water conservation demand using water resource consumption, and soil retention demand using actual soil erosion .

Supply-Demand Relationship Assessment: The relationship between supply and demand can be expressed using the ecosystem service supply-demand ratio. The comprehensive supply-demand ratio reflects the overall status of multiple ecosystem service functions:

$$ESDR_i = \frac{S_i - D_i}{S_i + D_i}$$

$$CESDR_i = \frac{1}{m}\sum_{i=1}^{m} ESDR_i$$

where $ESDR_i$ is the supply-demand ratio for grid cell i, S_i and D_i are supply and demand quantities, $CESDR_i$ is the comprehensive supply-demand ratio (ranging from -1 to 1, where >0 indicates surplus and <0 indicates deficit), and m is the number of ecosystem services studied.

1.3.2 Ecological Resistance Surface Construction The ecological resistance surface characterizes the resistance encountered by organisms moving through the study area. Based on previous research and regional conditions, we selected elevation, slope, population density, distance to rivers, and land use as positive indicators, and distance to roads and NDVI as negative indicators. We used the Analytic Hierarchy Process to calculate weights and constructed the resistance surface through weighted summation.

1.3.3 Extraction of Ecological Corridors, Pinch Points, and Barrier Points Ecological corridors are linear or strip spatial structures that facilitate species migration, energy flow, and ecosystem function continuity between ecological sources. Pinch points are narrow areas or critical nodes that determine connectivity and require priority protection. Barrier points are areas or elements that block species migration, energy flow, or ecological function continuity. Circuit theory, based on Ohm' s law and random walk theory, effectively identifies these elements by analogizing ecological flow to electrical current. We used Linkage Mapper to identify corridors, Pinch Point Mapper to extract high-value areas as pinch points, and Barrier Mapper with an 800 m search radius threshold to identify barrier points.

2 Results and Analysis

2.1 Spatiotemporal Characteristics of Ecosystem Service Supply and Demand 2.1.1 Supply-Demand Characteristics: The Shaanxi-Gansu-

Ningxia region showed overall supply exceeding demand with a "southern supply, northern demand, local imbalance" pattern [Figure 2: see original paper]. Carbon sequestration surplus areas had the highest proportion, concentrated in forest-covered regions like Jiuquan, Gannan, and the Qinling Mountains in southern Shaanxi, while deficit areas were mainly in the densely populated Guanzhong Plain with expanding proportions. Food provision deficit areas had the highest proportion, decreasing from 62.76% to 58.32%, with persistent deficits in the Loess Plateau hilly region of northern Shaanxi and Northwest Arid Zone due to soil erosion and desertification. Water conservation surplus areas were stable (74.2% to 72.46%), concentrated in the southern region, while deficit areas were in the low-precipitation, high-evaporation Northwest Arid Zone. Soil retention surplus areas decreased from 83.85% to 80.91%, with improved balance in the Northwest Arid Zone and Hexi Corridor due to ecological restoration projects .

2.1.2 Supply-Demand Importance: Based on the "Ecological Protection Redline Delimitation Guide," we classified importance into five levels using the quantile method. The most important level represents areas with the best ecological resource endowment. From 2000 to 2020, the most important comprehensive supply areas decreased then increased, accounting for 21.93% of the total area, concentrated in Gannan, southern Shaanxi, and the Hexi Corridor. The most important comprehensive demand areas were in the densely populated Guanzhong Plain, expanding from 0.45% to 1.03%. The most important comprehensive supply-demand areas showed similar spatial distribution to supply areas [Figure 3: see original paper] .

2.2 Spatiotemporal Changes in Ecological Sources and Resistance Surfaces Ecological sources are patches providing important ecosystem services or radiation functions. We identified sources by overlaying the highest-level intersections of comprehensive supply and supply-demand layers with areas >100 km^2. From 2000 to 2020, ecological sources followed a "north-to-south" concentrated distribution pattern, with area first increasing then decreasing while numbers first decreased then increased, showing an overall increasing trend . Sources were concentrated in the Hexi Corridor from Jiuquan to Wuwei, Gannan, and the Qinling Mountains in southern Shaanxi, with a small portion in Yan' an, Shaanxi. The smallest area occurred in 2010 (8.91$\times 10^{3}$ km^2), increasing to 14.96$\times 10^{3}$ km^2 in 2020, with growth mainly in Jiuquan, Longnan (Gansu), and the Qinling Mountains. However, sources shrank in 2020 due to economic development and urbanization encroachment.

The ecological resistance surface showed high resistance in the Northwest Arid Zone with severe desertification and in parts of Xi' an. Overall resistance decreased with environmental improvement, but continued rising in densely populated Xi' an [Figure 4: see original paper] [Figure 5: see original paper].

2.3 Spatiotemporal Changes in Ecological Corridors, Pinch Points, and Barrier Points From 2000 to 2010, ecological corridors expanded under natural dominance, with Baiyin and Xianyang as convergence areas providing stable continuity for species migration [Figure 6: see original paper]. From 2010 to 2020, corridor numbers decreased by 10 to 136, total length shortened by 1367.27 km, showing contraction toward the east. In 2020, numbers slightly increased to 138, but degradation of sources in the Ningxia Plain and southern Shaanxi further reduced total length by 169.36 km.

Pinch points decreased from 2000 to 2010 (reduced by 231, area decreased by 169.36 km^2), concentrated in northwestern and central regions. From 2010 to 2020, central region pinch points drastically decreased due to corridor reduction, while northwestern areas partially reconstructed. Pinch points in Baiyin and Xianyang remained prominent but with weakened cross-regional flow functions.

Barrier points increased from 111 in 2000 to 160 in 2020, with area growing from 111.46 km^2 to 588.66 km^2, showing "scale expansion and spatial aggregation" . They were concentrated in the southern region in 2000, but by 2020 they aggregated in the Guanzhong Plain, Ningxia Plain, and Lanzhou-Baiyin metropolitan areas—ecological deficit zones where urbanization, agricultural intensification, and human activities fragmented corridors and blocked ecological flows [Figure 6: see original paper].

2.4 Ecological Security Pattern Construction Based on ecological function zoning and the spatial distribution characteristics of ecological elements, we propose an optimization scheme of "one axis and one point" and "two screens and multiple zones" [Figure 7: see original paper].

"One Axis and One Point" : The core axis runs through the entire study area, connecting ecological barriers, protection zones, construction zones, and core zones, forming a complete ecological network that maintains functional integrity. The "point" is located at the "throat" of the Hexi Corridor, surrounded by numerous pinch points and corridor intersections, serving as a critical connectivity node.

"Two Screens and Multiple Zones" : The Northwest Ecological Barrier Zone and the Northern Shaanxi Loess Plateau Ecological Barrier Zone. The Northwest Oasis, adjacent to the Qaidam Basin with scattered sources and strong supply capacity, reduces desertification and serves as an ecological barrier. The Loess Plateau in northern Shaanxi, with concentrated sources, functions as a soil and water conservation barrier. "Multiple zones" include the Hexi Corridor Ecological Protection Zone, Longdong-Ningxia Plain Ecological Construction Zone, Northwest Ecological Construction Zone, Gannan Ecological Core Zone, and Southern Shaanxi Ecological Core Zone.

3 Discussion

This study introduces an ecosystem service supply-demand matching perspective, incorporating human well-being needs into a dynamic interaction framework and expanding traditional single-perspective paradigms. The analysis reveals the unique "southern supply, northern demand" gradient pattern, rooted in the region' s special location at the intersection of three geographic units, requiring integrated approaches to address Loess Plateau erosion, Northwest Arid Zone desertification, and Yellow River water source conservation.

The proposed "one axis and one point" and "two screens and multiple zones" strategy offers cross-regional solutions: strictly limiting development in surplus areas (Gannan, Longnan, southern Shaanxi) to protect water conservation and biodiversity; rationally planning urban layouts in deficit metropolitan cores (Guanzhong Plain, Lanzhou-Baiyin, Yinchuan) to increase green and wetland spaces; and intensifying restoration efforts in vulnerable, imbalanced high-risk areas (Yan' an, Yulin, northern Jiuquan) through measures like returning farmland to forest, sand fixation, and soil conservation.

However, limitations remain. The study does not deeply analyze the complexity, dynamics, and uncertainty of ecosystem services or demand heterogeneity driven by socioeconomic development. Cross-regional optimization strategies are also subject to social, economic, and technical constraints. Future research should focus on endogenous ecosystem mechanisms and deeply couple natural processes with socioeconomic development needs to provide stronger support for dynamic optimization of ecological security patterns.

4 Conclusions

From 2000 to 2020, ecosystem services in the Shaanxi-Gansu-Ningxia region showed a "southern supply, northern demand" gradient pattern. Gannan, southern Shaanxi, and the Hexi Corridor were supply-dominated areas of high importance, while urbanized areas like the Guanzhong Plain showed prominent contradictions between human activity intensity and ecological resource consumption. The Northwest Arid Zone faced high critical risk due to water shortage and desertification.

Ecological sources followed a north-to-south concentrated distribution, with total corridor length decreasing by 2236.6 km and pinch point area decreasing by 169.36 km^2, indicating weakened ecosystem service flow functions. Barrier points increased by 49 in number and 588.66 km^2 in area, showing "scale expansion and spatial aggregation."

Based on supply-demand characteristics and ecological element distribution, the "one axis and one point" and "two screens and multiple zones" pattern provides a scientific foundation for regional ecological protection planning and sustainable development.

References

[1] Dai Wenyuan, Ma Jiucao, Chen Yichen, et al. Analysis of driving forces and dynamic evolution of water ecological security in the Gansu section of the Yellow River Basin[J]. Arid Zone Research, 2024, 41(10): 1662-1671.

[2] Fu Bojie, Zhang Liwei. Land use change and ecosystem services: Concepts, methods and progress[J]. Progress in Geography, 2014, 33(4): 441-446.

[3] Yan Shuiyu, Wang Xiangrong. Advances of research on ecosystem service[J]. Chinese Journal of Ecology, 2002, 21(5): 61-68.

[4] Ma Lin, Liu Hao, Peng Jian, et al. A review of ecosystem services supply and demand[J]. Acta Geographica Sinica, 2017, 72(7): 1277-1289.

[5] Ouyang Zhiyun, Wang Xiaoke, Miao Hong. A primary study on Chinese terrestrial ecosystem services and their ecological economic values[J]. Acta Ecologica Sinica, 1999, 19(5): 19-25.

[6] Xie Gaodi, Lu Chunxia, Leng Yunfa, et al. Ecological assets valuation of the Tibetan Plateau[J]. Journal of Natural Resources, 2003, 18(2): 189-196.

[7] Chu Wenxi, Yang Xinjun, Li Runyang. Coupling coordination relationship and influencing factors between urban resilience and ecosystem services in the Guanzhong Plain urban agglomeration[J]. Arid Land Geography, 2025, 48(3): 1-14.

[8] Li Zhongfeng, Gao Jie, Zhong Yi. Assessment on grassland ecological security in Xizang based on ecological footprint model improved by ecosystem services value[J]. Journal of Arid Land Resources and Environment, 2023, 37(4): 9-19.

[9] Zhang Xin, Zhang Dan, Zhang Guangsen, et al. Spatiotemporal characteristics of ecosystem services and ecological function areas in Guanzhong Plain urban agglomeration[J]. Arid Land Geography, 2024, 47(9): 1587-1595.

[10] Cao Qiwen, Zhang Xiwen, Ma Hongkun, et al. Review of landscape ecological risk and an assessment framework based on ecological services: ESRISK[J]. Acta Geographica Sinica, 2018, 73(5): 843-855.

[11] Peng Jian, Zhao Huijuan, Liu Yanxu, et al. Research progress and prospect on regional ecological security pattern construction[J]. Geography Research, 2017, 36(3): 407-419.

[12] Tao Dekai, Zhang Zijian, Zhou Wenli, et al. Construction of ecological security pattern based on demand supply coordination of ecosystem service: A case study of Anhui Province[J]. Planners, 2024, 40(10): 16-24.

[13] Yu Kongjian. Landscape ecological security patterns in biological conservation[J]. Acta Ecological Sinica, 1999, 19(1): 10-17.

[14] Qiao E, Reheman R, Zhou Z, et al. Evaluation of landscape ecological security pattern via the pattern function stability framework in the Guanzhong Plain

Urban Agglomeration of China[J]. Ecological Indicators, 2024, 166: 112325.

[15] Peng Jie, Cai Haisheng, Zhang Xueling, et al. Spatial pattern analysis of ecological security in Fuhe River Basin based on dominant ecological function[J]. Acta Ecologica Sinica, 2022, 42(18): 7430-7444.

[16] Zhou Jing, Wang Hongwei, Tan Bo, et al. Construction of ecological security pattern and identification of ecological rehabilitation zones in Kaidu River Basin[J]. Acta Ecologica Sinica, 2022, 42(24): 10127-10137.

[17] Xu Jing, Liao Xingkai, Gan Qixu, et al. Construction of ecological security pattern based on MSPA and circuit theory in Gansu Section of the Yellow River Basin[J]. Ecology and Environmental Sciences, 2023, 32(4): 805-813.

[18] Han Qunzhu, Zhu Lingyi, E Yuting, et al. Empirical analysis of spatiotemporal evolution of urban land use efficiency in the Shaanxi Gansu Ningxia region in 2004-2020 based on DEA model[J]. Journal of Desert Research, 2024, 44(5): 245-253.

[19] Wan Xing, Ji Guangxing, Chen Weiqiang, et al. Simulation and prediction of spatio temporal evolution of ecosystem carbon storage in the Yangtze River Basin based on the InVEST model[J]. Journal of Agricultural Resources and Environment, 2025, 42(2): 1-17.

[20] Sun Menghua, Niu Wenhao, Zhang Bangbang, et al. Spatial temporal evolution and responses of ecosystem service value under land use change in the Yellow River Basin: A case study of Shaanxi Gansu Ningxia region, Northwest China[J]. Chinese Journal of Applied Ecology, 2021, 32(11): 3913-3922.

[21] Sun Baodi, Zhong Chenghao, Cui Dongxu, et al. Constructing ecological security patterns through regional cooperation in the Yellow River Basin[J]. Acta Ecologica Sinica, 2024, 44(11): 4624-4636.

[22] Cong Zhongxiao, Liu Jinhua, Sun Zengyu, et al. Analysis of carbon stock changes in nine provinces (regions) of the Yellow River Basin based on PLUS and InVEST models[J]. Yellow River, 2024, 46(12): 24-30.

[23] Chen Zhuan, Kuang Da, Wei Xiaojian, et al. Developing ecological networks based on MSPA and MCR: A case study in Yujiang county[J]. Resources and Environment in the Yangtze Basin, 2017, 26(8): 1199-1207.

[24] Pan Tao, Wu Shaohong, Dai Erfu, et al. Spatiotemporal variation of water source supply service in Three Rivers source area of China based on InVEST model[J]. Chinese Journal of Applied Ecology, 2013, 24(1): 183-189.

[25] Bao Yubin, Wang Yaozong, Lu Feng, et al. Construction of an ecological security pattern and zoning optimization for territorial space in the Liupan Mountain Area[J]. Arid Zone Research, 2023, 40(7): 1172-1183.

[26] Chen Tongyao, Jia Yanfeng, Wang Jianan, et al. Current situation and function of soil conservation in national nature reserves in the Qilian Mountains based on InVEST model[J]. Arid Zone Research, 2020, 37(1): 150-159.

[27] Yan Yujiang, Li Jiangui, Li Junli, et al. Construction of ecological security patterns in the Kaidu Kongque River Basin based on the supply and demand of ecosystem services[J]. Arid Zone Research, 2023, 40(5): 829-839.

[28] Zhao Xueyan, Ma Wenqi, Liu Yaqun, et al. Spatiotemporal changes of supply and demand relationships of ecosystem services in the Loess Plateau[J]. Acta Geographica Sinica, 2021, 76(11): 2780-2796.

[29] Sun Maosen, Wang Ranghui, Ning Husen. Construction of the ecological network in the Aksu River Basin[J]. Arid Zone Research, 2023, 40(9): 1509-1516.

Note: Figure translations are in progress. See original paper for figures.