

Spatiotemporal Evolution and Influencing Factors of Ecological Security Patterns Based on Circuit Theory: A Case Study of the Northern Shaanxi Loess Plateau (Postprint)

Authors: Zhang Jie, Qu Jianjun, Chen Hai, Shi Jinxin, Ma Yuhe, Liu Di

Date: 2025-03-14T00:00:00+00:00

Abstract

Identifying point, line, and area landscape elements that are crucial for maintaining regional ecosystems, constructing dynamic ecological security patterns, and exploring their influencing factors are of great significance for safeguarding regional ecological security. To address the limitations of previous studies in investigating the dynamic evolution and influencing factors of ecological security patterns, this study employs methods such as Morphological Spatial Pattern Analysis (MSPA), landscape connectivity analysis, and circuit theory models to construct ecological security patterns for the Loess Plateau of northern Shaanxi from 2000 to 2020, analyzes their spatiotemporal evolution characteristics, and utilizes the Geographical Detector, Ordinary Least Squares (OLS), and Geographically Weighted Regression (GWR) models to explore the influencing factors of spatial heterogeneity in ecological security patterns, and proposes ecological restoration strategies. The results indicate: (1) From 2000 to 2020, ecological sources were concentrated in the southern part of the Loess Plateau of northern Shaanxi, with relatively minor area changes and stable spatial locations. (2) The mean values of the ecological resistance surface for the Loess Plateau of northern Shaanxi in 2000, 2010, and 2020 were 4.96, 4.36, and 4.40, respectively, exhibiting a spatial pattern of low values in the south and high values in the northwest. (3) The lengths of ecological corridors in the Loess Plateau of northern Shaanxi in 2000, 2010, and 2020 were 2416.25 km, 3433.61 km, and 2643.62 km, respectively. Ecological corridors were dense in the south, primarily consisting of low-resistance corridors, while they were sparse in the north, mainly comprising high-resistance corridors. (4) Ecological pinch points and ecological barrier points were mainly distributed in the northwestern part of the Loess Plateau of northern Shaanxi, with their areas continuously decreasing. (5) Vegetation coverage, landscape diversity, population density, slope, and pre-

precipitation are the main factors influencing the spatial heterogeneity of ecological security patterns in the Loess Plateau of northern Shaanxi. The research findings can provide scientifically sound references and basis for future ecological planning in the Loess Plateau of northern Shaanxi, and simultaneously facilitate the formulation and adjustment of ecological policies.

Full Text

Preamble

ARID LAND GEOGRAPHY Vol. 48 No. 3 Mar. 2025

Spatial and temporal evolution and influencing factors of ecological security pattern based on circuit theory: A case of Loess Plateau in northern Shaanxi

ZHANG Jie^{1,2}, QU Jianjun^{1,2}, CHEN Hai^{1,2}, SHI Jinxin^{1,2}, MA Yuhe^{1,2}, LIU Di³

¹ College of Urban and Environmental Science, Northwest University, Xi' an 710127, Shaanxi, China

² Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, Xi' an 710127, Shaanxi, China

³ College of Tourism, Henan Normal University, Xinxiang 453007, Henan, China

Abstract: Identifying landscape elements such as points, lines, and planes that are critical for maintaining regional ecosystems is essential for constructing dynamic ecological security patterns and understanding their influencing factors. Addressing the limitations of previous studies, this research employs morphological spatial pattern analysis (MSPA), landscape connectivity analysis, and circuit theory models to construct ecological security patterns on the Loess Plateau in northern Shaanxi Province, China, from 2000 to 2020. It investigates the temporal and spatial evolution of these patterns and uses geographical detectors, ordinary least squares (OLS), and geographically weighted regression (GWR) models to analyze the spatial heterogeneity of influencing factors, offering ecological restoration strategies. The results showed that: (1) From 2000 to 2020, ecological sources were concentrated in the southern Loess Plateau of northern Shaanxi, with minimal changes in area and stable spatial locations. (2) The mean ecological resistance surface values on the Loess Plateau in northern Shaanxi in 2000, 2010, and 2020 were 4.96, 4.36, and 4.40, respectively, showing a pattern of low resistance in the south and high resistance in the northwest. (3) Ecological corridor lengths on the Loess Plateau in northern Shaanxi were 2416.25 km, 3433.61 km, and 2643.62 km in 2000, 2010, and 2020, respectively. Southern regions exhibited dense, low-resistance corridors, while northern regions had sparse, high-resistance corridors. (4) Ecological pinch points and barriers were mainly located in the northwest of the Loess Plateau in northern Shaanxi, with their areas consistently decreasing over time. (5) Vegetation cov-

erage, landscape diversity, population density, slope, and precipitation were the primary factors influencing the spatial heterogeneity of the ecological security pattern. These findings provide a scientific basis for ecological planning on the Loess Plateau in northern Shaanxi, aiding in the development and adjustment of ecological restoration strategies.

Keywords: ecological security pattern; temporal and spatial evolution; influencing factors; circuit theory; Loess Plateau of northern Shaanxi

Since the Industrial Revolution, rapid industrialization and urbanization have greatly promoted socioeconomic prosperity, but fast urban expansion and industrial processes have increasingly disturbed ecosystems. For example, unreasonable land use patterns and high-intensity human activities have led to landscape fragmentation and declining connectivity, causing changes in ecosystem structure and function that seriously affect regional ecological security and sustainable development. Ecological security patterns, as a baseline ecosystem management approach, provide spatial solutions for regional ecological security issues and are crucial for maintaining regional ecological safety.

Ecological security patterns consist of landscape elements such as ecological sources and corridors that play important roles in regional ecological security. Research has established a paradigm of “identifying ecological sources—constructing resistance surfaces—extracting ecological corridors.” Ecological sources form the foundation of ecological security patterns, identified through methods like direct recognition, morphological spatial pattern analysis (MSPA), and landscape connectivity analysis. Ecological resistance surfaces reflect the difficulty of species and energy migration between different landscapes, constructed through indicator systems or multi-factor assignment methods, often corrected using nighttime light data. Ecological corridors serve as critical bridges for energy flow between sources, commonly identified using minimum cumulative resistance models, circuit theory models, and gravity models.

Recent studies have built and optimized ecological security patterns from perspectives like ecosystem service value and ecosystem service supply-demand balance, simulated future patterns, and identified priority restoration areas. However, most previous research has been static, constructing patterns for single years without deeply exploring dynamic evolution. Ecological security patterns change due to natural conditions, human activity intensity, and government policies, yet studies analyzing these influencing factors remain rare. Since 2000, ecological restoration measures like the Grain-for-Green program have significantly altered landscape patterns in the Loess Plateau, necessitating dynamic analysis and factor studies of ecological security patterns.

1.1 Study Area Overview

The Loess Plateau in northern Shaanxi (107°15' -111°15' E, 35°02' -39°35' N) covers 79,981.9 km² in northern Shaanxi Province, central China. The region features typical loess landforms including yuan (tablelands), liang (ridges), and mao (hills), with terrain sloping from high in the northwest to low in the southeast. It has a temperate continental monsoon climate with 350–600 mm annual precipitation concentrated in summer as heavy rain, making it a typical ecologically fragile zone with frequent landslides and debris flows. Since 1999, the government has implemented the Grain-for-Green program, causing major land use transitions from farmland to forest and grassland, significantly improving the ecological environment. The region's rich coal and petroleum resources, combined with varying intensities of urbanization and industrialization across different periods, provide an excellent platform for studying dynamic changes and influencing factors of ecological security patterns.

1.2 Data Sources

Research data 主要包括: (1) Land use data for 2000, 2010, and 2020 from the Chinese Academy of Sciences Resource and Environmental Science Data Center (30 m resolution); (2) DEM data from NASA (30 m resolution); (3) Precipitation, temperature, and evapotranspiration data from the National Earth System Science Data Center (1 km resolution); (4) Soil data from the World Soil Database (1 km resolution); (5) NDVI data from the Resource and Environmental Science Data Center (30 m resolution); (6) Population density data from the LandScan Global Population Dataset; (7) Nighttime light data from Harvard University (1 km resolution); (8) Nature reserve data from the China Nature Reserve Specimen Resource Sharing Platform; (9) Mine location data from the Shaanxi Environmental Science Research Institute; (10) Grain yield data from the *Statistical Yearbooks of Yan'an City* and *Yulin City*; (11) GDP data based on research results with 1 km resolution. All raster data were preprocessed using ArcGIS 10.2 and resampled to a unified spatial resolution.

1.3 Research Methods

The research framework is shown in [Figure 2: see original paper]. First, considering landscape patch integrity and connectivity, MSPA and landscape connectivity analysis were used to identify ecological sources. Second, the InVEST model assessed four ecosystem services (habitat quality, water conservation, soil retention, and food supply) to objectively construct ecological resistance surfaces. Third, based on biological random walk characteristics, circuit theory models identified ecological corridors, pinch points, and barrier points to build ecological security patterns for 2000, 2010, and 2020. Finally, geographical detectors, OLS, and GWR models analyzed influencing factors of spatial heterogeneity, providing ecological protection and restoration strategies.

1.3.1 MSPA Analysis and Landscape Connectivity Analysis

This study used the Guidos Toolbox to classify landscapes into seven types (core, island, bridge, loop, branch, edge, and perforation), extracting core patches larger than 10 km² as candidate sources. Patches with high connectivity were then selected as ecological sources. The probability of connectivity (PC) index evaluates landscape connectivity:

$$PC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i a_j p_{ij}}{A^2} \times 100$$

where a_i and a_j are patch areas (km²), n is patch number, A is total landscape area (km²), and p_{ij} is maximum dispersal probability between patches. The patch importance index (dPC) is:

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

where PC_{remove} is connectivity after removing a patch. Higher dPC indicates greater landscape connectivity.

1.3.2 Ecological Resistance Surface Construction

Ecosystem services connect ecological and socioeconomic systems, reflecting environmental resistance under human disturbance. Based on literature review and regional conditions, this study selected habitat quality, water conservation, soil retention, and food supply as indicators. The four services were equally weighted, superimposed, and inverted to create the resistance surface—higher service values correspond to lower resistance. Specific calculations follow Shi et al. [?].

1.3.3 Circuit Theory Model

Circuit theory models simulate biological random walk behavior. Linkage Mapper tools extracted ecological corridors, Pinchpoint Mapper identified pinch points as high current density areas, and Barrier Mapper recognized barrier points as high cumulative current recovery zones.

1.3.4 Geographical Detectors

Geographical detectors [?] detect spatial heterogeneity and driving forces. The explanatory power q is:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2}$$

where N_h and N are sample units in layer h and the entire region; σ_h^2 and σ^2 are variances; L is layer number. $q \in [0, 1]$, with higher values indicating stronger explanatory power.

1.3.5 Ordinary Least Squares (OLS)

OLS explains relationships between dependent variable y_m and independent variables x_{mk} :

$$y_m = \beta_0 + \sum_k \beta_k x_{mk} + \varepsilon_m$$

where β_0 is intercept, β_k are coefficients, and ε_m is random error.

1.3.6 Geographically Weighted Regression (GWR)

GWR extends OLS by allowing spatially varying parameters:

$$y_i = \beta_0(u_i, v_i) + \sum_j \beta_j(u_i, v_i) x_{ij} + \varepsilon_i$$

where (u_i, v_i) are geographic coordinates, $\beta_0(u_i, v_i)$ is local intercept, and $\beta_j(u_i, v_i)$ are local coefficients.

2 Results and Analysis

2.1 Spatiotemporal Evolution of Ecological Security Patterns

2.1.1 Ecological Sources From 2000 to 2020, ecological source areas were 5566.65 km², 5521.81 km², and 5813.71 km², respectively, showing initial decrease then increase but minimal overall change. Sources displayed stable spatial distribution concentrated in the south, primarily within nature reserves with good habitat quality. Eastern and northern sources were mainly water bodies, while western areas (farmland, unused land, grassland) had poor habitat quality and no sources [Figure 3: see original paper].

2.1.2 Ecological Resistance Surfaces Mean resistance values were 4.96, 4.36, and 4.40 for 2000, 2010, and 2020, respectively, indicating environmental improvement. Spatial patterns showed low resistance in the south and high resistance in the northwest, corresponding to forest-dominated southern areas versus resource-rich northwestern areas with intense human disturbance [Figure 4: see original paper].

2.1.3 Ecological Corridors Corridor numbers and lengths were 2416.25 km, 3433.61 km, and 2643.62 km for the three years, first increasing then decreasing. Spatial distribution was dense in the south and sparse in the north, dense in the east and sparse in the west. Southern corridors were predominantly low-resistance, while northern corridors were high-resistance [Figure 5: see original paper].

2.1.4 Ecological Pinch Points and Barriers Pinch points and barriers were mainly distributed in the northwest, with areas consistently decreasing [Figure 6: see original paper]. This indicates enhanced landscape connectivity benefiting biological migration and energy flow .

2.2 Influencing Factors Analysis

Ecological sources and resistance surfaces are core elements of security patterns. Sources form the foundation, while resistance surfaces simulate migration difficulty directly affecting corridor, pinch point, and barrier distributions. Analysis focused on spatial heterogeneity of these two components.

2.2.1 Factor Selection Based on literature review and regional characteristics (complex topography, severe soil erosion, low vegetation cover, varying human activity intensity), 11 potential factors were selected: elevation, slope, NDVI, precipitation, temperature, population density, GDP, nighttime light intensity, Shannon diversity index (SHDI), Shannon evenness index (SHEI), and contagion index (CONTAG).

2.2.2 Ecological Source Influencing Factors Variance inflation factor (VIF) tests removed elevation, temperature, and CONTAG due to multicollinearity. Geographical detector results showed slope and nighttime light intensity were not significant. The remaining 7 factors were significant ($P < 0.01$) with $q > 0.1$, indicating strong explanatory power. OLS results showed only NDVI was positively correlated with sources, suggesting higher vegetation coverage favors source formation. Spatial autocorrelation tests found no spatial clustering of sources, so OLS was used .

2.2.3 Ecological Resistance Surface Influencing Factors VIF tests removed elevation, temperature, GDP, nighttime light, SHDI, and SHEI. Geographical detector results showed slope, precipitation, NDVI, and population density had $q > 0.1$ and were significant. OLS results indicated all four factors were significant: slope and precipitation negatively correlated with resistance, while population density positively correlated. Population density had the strongest effect, showing a north-south decreasing gradient. Moran' s I test revealed significant spatial clustering of resistance surfaces ($I > 0$). GWR model comparison showed better fit than OLS (higher R^2 and lower AICc) [TABLE:3,

TABLE:4]. GWR results revealed spatially varying relationships [Figure 7: see original paper].

2.3 Ecological Restoration Strategies

Given limited government conservation funds, location-specific strategies are crucial. Based on results and regional conditions:

1. **Southern region:** Continue strict ecological protection policies limiting human disturbance. Implement forest closure and Grain-for-Green projects in central and northern areas to improve environment.
2. **Population density management:** Balance economic development with ecological protection. In resource-rich northern areas, comprehensively remediate abandoned mines, promote clean production, and avoid unregulated extraction.
3. **Corridor enhancement:** Add ecological sources in central and northern regions to provide resting sites for migration, improving overall connectivity.

3 Discussion

Most previous studies built static, single-year patterns, ignoring ecosystem complexity and dynamic continuity. This study's innovations include: (1) constructing dynamic patterns for 2000–2020 using circuit theory and analyzing spatiotemporal evolution; (2) identifying key influencing factors using geographical detectors, OLS, and GWR; (3) providing restoration strategies. Source areas (5566.65–5813.71 km²) were stable and concentrated in the south, consistent with previous research [?]. Using ecosystem services to build resistance surfaces improved objectivity compared to subjective scoring methods [?]. Circuit theory better simulated real migration routes than MCR models [?]. Results showing dense southern corridors and decreasing pinch/barrier areas align with provincial spatial planning and related studies [?].

4 Conclusions

1. Ecological source areas were 5566.65 km², 5521.81 km², and 5813.71 km² in 2000, 2010, and 2020, with minimal change and stable, south-dense-north-sparse distribution.
2. Mean resistance values were 4.96, 4.36, and 4.40, showing a south-low-northwest-high pattern.
3. Corridor lengths were 2416.25 km, 3433.61 km, and 2643.62 km, first increasing then decreasing. Southern corridors were dense and low-resistance; northern corridors were sparse and high-resistance.

4. Pinch points and barriers were concentrated in the northwest with decreasing areas, indicating improved connectivity.
5. Vegetation coverage, landscape diversity, population density, slope, and precipitation were primary factors influencing spatial heterogeneity of the ecological security pattern.

References

- [1] Guo M, Cong X, Zheng H, et al. Integrating the ordered weighted averaging method to establish an ecological security pattern for the Jianghuai ecological economic zone in China: Synergistic intraregional development[J]. *Ecological Indicators*, 2022, 135: 108543, doi: 10.1016/j.ecolind.2022.108543.
- [2] Chen J, Wang S S, Zou Y T. Construction of an ecological security pattern based on ecosystem sensitivity and the importance of ecological services: A case study of the Guanzhong Plain urban agglomeration, China[J]. *Ecological Indicators*, 2022, 136: 108688, doi: 10.1016/j.ecolind.2022.108688.
- [3] Peng J, Yang Y, Liu Y X, et al. Linking ecosystem services and circuit theory to identify ecological security patterns[J]. *Science of the Total Environment*, 2018, 644: 781-790.
- [4] Gao J B, Du F J, Zuo L Y, et al. Integrating ecosystem services and rocky desertification into identification of karst ecological security pattern[J]. *Landscape Ecology*, 2020, 36(7): 2113-2133.
- [5] Wei Q Q, Halike A, Yao K X, et al. Construction and optimization of ecological security pattern in Ebinur Lake Basin based on MSMCR models[J]. *Ecological Indicators*, 2022, 138: 108857, doi: 10.1016/j.ecolind.2022.108857.
- [6] Peng J, Zhao H J, Liu Y X, et al. Research progress and prospect on regional ecological security pattern construction[J]. *Geographical Research*, 2017, 36(3): 407-419.
- [7] Sun F, Zhang J H, Wang P J, et al. Construction and evaluation of urban ecological security pattern: A case study of Suzhou City[J]. *Geographical Research*, 2021, 40(9): 2476-2493.
- [8] Han J Y, Yu M Y. A multi factor integration identification method of ecological security pattern and optimization suggestions: A case of Changshan County, Quzhou City[J]. *Geographical Research*, 2021, 40(4): 1078-1095.
- [9] Huang Q S, He H. Ecological security pattern of the oasis area around the Tarim Basin based on coupled ecosystem services and landscape connectivity[J]. *Arid Land Geography*, 2024, 47(10): 1745-1754.
- [10] Wang X Y, Feng Z, Wu K N, et al. Ecological conservation and restoration of life community theory based on the construction of ecological security pattern[J]. *Acta Ecologica Sinica*, 2019, 39(23): 8725-8732.

- [11] Li H Q, Yang Y, Zhang J H. Construction of ecological security pattern in Shannan Wide Valley Basin of Yarlung Zangbo River[J]. *Arid Land Geography*, 2023, 46(9): 1503-1513.
- [12] Wang X M, Zhao P, Long Y X, et al. Identification of key areas of land space ecological protection and restoration based on the pattern of ecological security in Guangdong, Hong Kong and Macau[J]. *Acta Ecologica Sinica*, 2022, 42(2): 450-461.
- [13] Ye X, Zou C X, Liu G H, et al. Main research contents and advances in the ecological security pattern[J]. *Acta Ecologica Sinica*, 2018, 38(10): 3382-3392.
- [14] Li H K, Liu Y T, Li Q, et al. Analysis of ecological security pattern of southern rare earth mining area based on MCR model[J]. *Scientia Geographica Sinica*, 2020, 40(6): 989-998.
- [15] Yao C Y, He Y M, Cheng J X, et al. Evaluation of ecological security pattern and optimization suggestions in Minjiang River Basin based on MCR model and gravity model[J]. *Acta Ecologica Sinica*, 2023, 43(17): 7083-7096.
- [16] Pan J H, Wang Y. Ecological security evaluation and ecological pattern optimization in Taolai River Basin based on CVOR and circuit theory[J]. *Acta Ecologica Sinica*, 2021, 41(7): 2582-2595.
- [17] Cui S, Du X L, Jia Z Y, et al. Ecosystem service value estimation and ecological security pattern in Heilongjiang Province[J]. *Environmental Science*, 2024, 45(11): 6489-6500.
- [18] Shi J X, Liang X Y, Li H Q, et al. Impact of landscape pattern on ecosystem service trade-offs in the Loess Plateau of northern Shaanxi[J]. *Acta Ecologica Sinica*, 2023, 43(21): 8958-8972.
- [19] Zhao N Z, Liu Y, Cao G F, et al. Forecasting China's GDP at the pixel level using nighttime lights time series and population images[J]. *Mapping Sciences & Remote Sensing*, 2017, 54(3): 407-425.
- [20] Li Y G, Liu W, Feng Q, et al. The role of land use change in affecting ecosystem services and the ecological security pattern of the Hexi Regions, northwest China[J]. *Science of the Total Environment*, 2022, 855: 158490, doi: 10.1016/j.scitotenv.2022.158490.
- [21] Gao J, Gong J, Li Y, et al. Ecological network assessment in dynamic landscapes: Multi-scenario simulation and conservation priority analysis[J]. *Land Use Policy*, 2024, 139, 107059, doi: 10.1016/j.landusepol.2024.107059.
- [22] Zhang J, Chen H, Ma Y H, et al. Identification of priority areas for ecological restoration based on ecological security and landscape elements[J]. *Environmental Science and Pollution Research*, 2022, 30(12): 35307-35325.
- [23] Liu H L, Wang Z L, Zhang L P, et al. Construction of an ecological security network in the Fenhe River Basin and its temporal and spatial evolu-

tion characteristics[J]. *Journal of Cleaner Production*, 2023, 417: 137961, doi: 10.1016/j.jclepro.2023.137961.

[24] Qiu H L, Zhang J Y, Han H R, et al. Study on the impact of vegetation change on ecosystem services in the Loess Plateau, China[J]. *Ecological Indicators*, 2023, 154, 110812, doi: 10.1016/j.ecolind.2023.110812.

[25] Dang H, Lü Y H, Guo J Y, et al. Identifying priority conservation areas in regional ecological networks using attack scenario simulation[J]. *Global Ecology and Conservation*, 2023, 46: E02602, doi: 10.1016/j.gecco.2023.e02602.

[26] Liu L, Song W, Zhang Y J, et al. Zoning of ecological restoration in the Qilian Mountain area, China[J]. *International Journal of Environmental Research and Public Health*, 2021, 18(23): 12417, doi: 10.3390/ijerph182312417.

[27] Jiang W, Fu B J, Gao G Y, et al. Exploring spatial-temporal driving factors for changes in multiple ecosystem services and their relationships in west Liao River Basin, China[J]. *Science of the Total Environment*, 2023, 904: 166716, doi: 10.1016/j.scitotenv.2023.166716.

[28] Zhao W Z, Han Z L, Yan X L, et al. Ecological security pattern construction based on multi-scenario trade-off of ecosystem services: A case study of Wafangdian, Dalian[J]. *Journal of Natural Resources*, 2020, 35(3): 546-562.

[29] Liang K Y, Jin X B, Zhang X L, et al. Construction of ecological security patterns coupling supply and demand of ecosystem services: A case study of southern Jiangsu[J]. *Acta Ecologica Sinica*, 2024, 44(9): 3880-3896.

[30] Ni Q L, Hou H P, Ding Z Y, et al. Ecological remediation zoning of territory based on the ecological security pattern recognition: Taking Jiawang District of Xuzhou City as an example[J]. *Journal of Natural Resources*, 2020, 35(1): 204-216.

[31] Fu F J, Liu Z H, Liu H. Identifying key areas of ecosystem restoration for territorial space based on ecological security pattern: A case study in Hezhou City[J]. *Acta Ecologica Sinica*, 2021, 41(9): 3406-3414.

[32] Feng Y W, Zhen J H, Tian T Y. Optimization of land protection and restoration based on ecological security pattern: A case study of Hohhot-Baotou-Ordos region in Inner Mongolia[J]. *Journal of Natural Resources*, 2022, 37(11): 2915-2929.

[33] Wei X D, Liang G L, Feng X L, et al. Construction of ecological security pattern and quantitative diagnosis of ecological problems in Shenmu City[J]. *Acta Ecologica Sinica*, 2023, 43(1): 82-94.

[34] Li L T, Jia B Q, Liu W R, et al. Spatio-temporal dynamics and influencing factors of ecological security network elements in Yichang, Hubei Province[J]. *Acta Ecologica Sinica*, 2023, 43(15): 6154-6169.

[35] Qin B G, Lin Y L, Zhao J S, et al. Identification of key areas for the ecological restoration of territorial space in Kunming based on the InVEST model and

- circuit theory[J]. *China Environmental Science*, 2023, 43(2): 809-820.
- [36] Wang J F, Xu C D. Geodetector: Principle and prospective[J]. *Acta Geographica Sinica*, 2017, 72(1): 116-134.
- [37] Zhu B C, Li T S, Zhu X Q, et al. Importance evaluation of ecological conservation based on ecological network optimization: A case study of Shaanxi Province[J]. *Journal of Agricultural Resources and Environment*, 2023, 40(6): 1480-1493.
- [38] Zhu C M, Zhang X L, Zhou M M, et al. Impacts of urbanization and landscape pattern on habitat quality using OLS and GWR models in Hangzhou, China[J]. *Ecological Indicators*, 2020, 117: 106654, doi: 10.1016/j.ecolind.2020.106654.
- [39] Yang W Y, Ye H Y. Identification of ecological networks in the Guangdong-Hong Kong-Macao Greater Bay Area based on habitat quality assessment[J]. *Acta Ecologica Sinica*, 2023, 43(24): 10430-10442.
- [40] Peng J, Li H L, Liu Y X, et al. Identification and optimization of ecological security pattern in Xiong'an New Area[J]. *Acta Geographica Sinica*, 2018, 73(4): 701-710.
- [41] Li T, Dong Y X. Evolution of ecological security pattern and its influencing factors in the Pearl River Delta from 1986 to 2019 based on RSEI and landscape function[J]. *Journal of Shaanxi Normal University (Natural Science Edition)*, 2022, 50(4): 69-80.
- [42] Zhao J H, Yang Y C, Wang T, et al. Evolution of ecological network and identification of key restoration areas in the Loess Plateau during 2000–2020[J]. *Bulletin of Surveying and Mapping*, 2023(8): 19-23, 77.
- [43] Wu D C. Spatially and temporally varying relationships between ecological footprint and influencing factors in China's provinces using geographically weighted regression (GWR)[J]. *Journal of Cleaner Production*, 2020, 261: 121089, doi: 10.1016/j.jclepro.2020.121089.
- [44] Pan J H, Li L. Optimization of ecological security pattern in Gansu section of the Yellow River Basin using OWA and circuit model[J]. *Transactions of the Chinese Society of Agricultural Engineering*, 2021, 37(3): 259-268.
- [45] Yao C Y, He Y M, Cheng J X, et al. Evaluation of ecological security pattern and optimization suggestions in Minjiang River Basin based on MCR model and gravity model[J]. *Acta Ecologica Sinica*, 2023, 43(17): 7083-7096.
- [46] Zhu B C, Li T S, Chen X Y, et al. Research on the construction of ecological integrated network and identification of ecological security pattern in the Han River Basin[J]. *Resources and Environment in the Yangtze Basin*, 2024, 33(2): 362-373.
- [47] Li H K, Liu Y T, Li Q, et al. Analysis of ecological security pattern of southern rare earth mining area based on MCR model[J]. *Scientia Geographica*

Sinica, 2020, 40(6): 989-998.

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

Source: ChinaXiv – Machine translation. Verify with original.