Spatiotemporal Evolution of Ecological Welfare Performance and Its Influencing Factors: A Case Study of Shanxi Province Wang Houyinben

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Abstract

Ecological well-being performance integrates human social systems and natural environmental systems, holding significant importance for measuring the sustainable development capacity of resource-based cities. This study employs the super-SBM model to measure the ecological well-being performance of Shanxi Province from 2006 to 2021, analyzes its spatiotemporal evolution patterns using standard deviation ellipse and GIS spatial visualization, identifies the causes of low ecological well-being performance and the sources of regional differences through the entropy weight method and Dagum Gini coefficient, and finally explores its driving factors using geographical detector. The results reveal: (1) The mean ecological well-being performance across cities in Shanxi Province is 0.681, with significant variations existing among different cities in both performance level and improvement effectiveness. (2) During the study period, the centroid of ecological well-being performance shifted from north to south, then toward the southwest; the probability of maintaining the status quo is relatively high among different region types. (3) Regarding comprehensive index deconstruction, increased resource consumption and lower Human Development Index are the primary causes of low ecological well-being performance; inter-regional differences constitute the main source of regional disparities. (4) In terms of driving factors, urbanization level is a key driver; the synergistic effect between the degree of opening-up to the outside world and other factors represents the main driving force shaping the current state of ecological well-being performance. The findings hold important practical significance for Shanxi Province to enhance ecological well-being performance and achieve transformative leapfrog development.

Full Text

Preamble

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Research on the Spatio-Temporal Evolution and Influencing Factors of Ecological Welfare Performance: A Case Study of Shanxi Province

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Abstract: Ecological welfare performance integrates human social systems and natural environmental systems, serving as a crucial metric for evaluating the sustainable development capacity of resource-based cities. This study employs the super-SBM model to measure ecological welfare performance in Shanxi Province from 2006 to 2021, utilizes standard deviation ellipse and GIS spatial visualization to analyze spatio-temporal evolution patterns, and identifies causes of low ecological welfare performance and sources of regional disparities through the entropy weight method and Dagum Gini coefficient. Finally, geographic detectors are used to explore driving factors. Results indicate: (1) The mean ecological welfare performance across prefecture-level cities in Shanxi is 0.681, with significant variations in performance levels and improvement effects among different cities. (2) During the study period, the center of gravity of ecological welfare performance shifted from north to south, then toward the southwest; different types of regions show a high probability of maintaining their current status. (3) In terms of composite index decomposition, increased resource consumption and low human development index are primary causes of low ecological welfare performance levels, while inter-regional differences constitute the main source of regional disparities. (4) Regarding driving factors, urbanization level is a key driver, and the synergistic effect between openness to external influences and other factors primarily shapes the current state of ecological welfare performance. These findings hold important practical significance for enhancing ecological welfare performance and achieving transformative, leapfrog development in Shanxi Province.

Keywords: ecological welfare performance; super-SBM model; spatio-temporal evolution; geographic detector; Shanxi Province

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Since the reform and opening-up, China has achieved historic economic growth, accelerated new-type urbanization, and improved human welfare levels. Simultaneously enhancing resource utilization efficiency and promoting human welfare has become a new imperative of our era. However, rapid urbanization and extensive economic development patterns have imposed high resource costs on cities.

Coordinating urbanization development, resource environments, and human welfare remains fraught with obstacles, making sustainable and efficient new-type urbanization a development priority. The "Eleventh Five-Year Plan" (2006) first proposed building a resource-saving and environmentally friendly society to promote coordinated development among economy, population, resources, and environment. The 18th Party Congress incorporated ecological civilization into the "Five-in-One" overall layout, while the 20th Party Congress report emphasized green development and transformation of development modes. This series of policy directives indicates that China is pursuing high-quality development that coordinates high-quality economic growth with high-level ecological protection. Against this backdrop, how to advance urbanization while improving resource efficiency and human welfare represents a new proposition.

Ecological welfare performance unifies human production and living systems with natural ecosystems, serving as an important basis for measuring high-quality economic and social development, and a key leverage point for promoting urban sustainable development. The concept aims to achieve maximum human welfare output with minimal resource consumption and environmental pollution, involving multiple disciplines with distinct interdisciplinary characteristics. The origins of ecological welfare performance can be traced to ecological economics theory in the 1970s, though specific measurement indicators were not identified at that time. Empirical research developed after Rees proposed ecological footprint theory in 1992. Subsequently, methods such as the "Happy Planet Index" and "Gross National Happiness" have proliferated. Domestic scholar Zhu Dajian first proposed the concept of ecological welfare performance in 2009. Current domestic research primarily focuses on three aspects: (1) Measurement of ecological welfare performance, which can be categorized into ratio methods and efficiency model methods, such as stochastic frontier analysis and data envelopment analysis. The United Nations Development Programme proposed the Human Development Index (HDI) to measure economic and social development, which is widely used in academia, though specific indicator selection varies. (2) Influencing factors research, which has introduced frontier issues such as environmental regulation, digital economy, and industrial structure. (3) Spatio-temporal differentiation analysis from geographic perspectives at national, regional, provincial, and specific province scales. However, existing research predominantly focuses on large scales, with relatively few studies at the city level, particularly concerning small and medium-scale spatio-temporal evolution characteristics and influencing factors, which are essential under urbanization contexts.

Current academic achievements on ecological welfare performance are substantial, yet limitations remain: (1) Most studies concentrate on national, regional, and provincial scales, with insufficient research on city-level analysis, particularly for specific types and regions of cities. (2) Existing research often focuses on single or specific elements' linear impacts, but cities are complex giant systems where linear, single-factor analysis may be inadequate. Research on how interactions among different factors affect urban ecological welfare performance requires supplementation. (3) Studies on resource-based cities are particularly lacking. China has numerous resource-based cities serving as crucial energy resource strategic bases. Shanxi Province, as a typical resource-based economy province and the nation's first comprehensive, systematic, province-wide resource-based economic transformation pilot zone, has been tasked by the central government with pioneering new paths for high-quality transformation development. Therefore, studying urban ecological welfare performance levels and influencing factors in Shanxi is both necessary and represents the key scientific question addressed herein.

This study examines Shanxi Province from 2006 to 2021. First, the super-SBM model measures ecological welfare performance levels, with standard deviation ellipse and GIS visualization exploring spatio-temporal evolution patterns. Second, the entropy weight method and Dagum Gini coefficient decompose sources of inefficiency and regional disparities. Finally, geographic detectors analyze driving factors, providing references for improving resource-based cities' ecological welfare performance and achieving high-quality transformation development.

1.1 Data Sources and Processing

The study uses 11 prefecture-level cities in Shanxi as evaluation units. Original data on resource consumption and human development primarily come from the Shanxi Statistical Yearbook (2007–2022) and relevant city statistical yearbooks and national economic and social development statistical bulletins. Environmental pollution data are sourced from the China City Statistical Yearbook and China Environmental Statistical Yearbook. Missing data are supplemented by calculating average annual growth rates. To reduce population scale effects, all indicators use per capita values. Additionally, to satisfy data envelopment analysis requirements regarding the number of decision-making units, the entropy weight method processes raw data before inputting into the super-SBM model for ecological welfare performance calculation.

1.2.1 Ecological Welfare Performance Evaluation

The core concept of ecological welfare performance is achieving maximum welfare output with minimal resource consumption and environmental pollution. Drawing on established research and considering data availability, this study constructs an indicator system encompassing resource consumption, environmental pollution, and human development. Output indicators include undesired outputs (environmental pollution) and desired outputs (human development). Specific indicators are shown in Table 1.

Table 1 Ecological welfare performance evaluation indicator system

Category	Indicator	Unit
Resource Consumption	Per capita urban construction land area	m^2/person
	Per capita electricity consumption	kWh/person
	Per capita water consumption	m^3/person
Environmental Pollution	Per capita industrial wastewater discharge	tons/person
	Per capita industrial smoke and dust emissions	kg/person
	Per capita industrial solid waste generation	tons/person
Human Development	Per capita GDP	yuan/person
	Per capita number of college students	persons/10,000 persons
	Per capita number of urban hospital beds	beds/10,000 persons

1.2.2 Influencing Factors Indicators

Ecological welfare performance is influenced by multiple factors. Previous research highlights industrial structure, openness to external influences, and scientific-technological development levels. Considering Shanxi's characteristics as a comprehensive resource-based economic transformation pilot zone, key factors include: promoting high-quality economic development as essential for modernization; advancing new-type urbanization centered on county towns as an important support point; actively integrating into the Belt and Road Initiative and expanding high-level openness as crucial transformation drivers; and population spatial distribution for coordinated population-resource-environment development. Shanxi's ecological foundation is fragile with substantial historical environmental debts. Under the Yellow River Basin ecological protection and high-quality development strategy, Shanxi is vigorously advancing afforestation to build an ecological security barrier. These characteristics all affect ecological welfare performance. Based on previous research, regional features, data availability, and result validity, this study selects the following influencing factors: economic scale, urbanization level, openness to external influences, population density, and greening level, represented by regional GDP, urbanization rate, actual utilized foreign investment, permanent population administrative area, and per capita urban green space area.

1.3 Research Methods

1.3.1 Super-SBM Model The super-SBM model is an advanced version of the SBM model that can further evaluate decision-making units among multiple effective units and eliminates the "slack effect" of undesired outputs on efficiency. This study uses the super-SBM model to measure ecological welfare performance. The formula is as follows:

$$\rho^* = \min \frac{1 + \frac{1}{m}\sum_{r=1}^{m} \frac{s_r^-}{x_{ro}}}{1 - \frac{1}{s+t}\left(\sum_{s=1}^{s_1} \frac{s_s^g}{y_{so}^g} + \sum_{t=1}^{s_2} \frac{s_t^b}{z_{to}^b}\right)}$$

$$\text{s.t.} \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = x_{io}, \quad i = 1, 2, \dots, m$$

$$\sum_{j=1}^{n} \lambda_j y_{rj}^g - s_r^g = y_{ro}^g, \quad r = 1, 2, \dots, s_1$$

$$\sum_{j=1}^{n} \lambda_j z_{pj}^b + s_p^b = z_{po}^b, \quad p = 1, 2, \dots, s_2$$

$$\lambda_j, s_i^-, s_r^g, s_p^b \geq 0$$

where m, s_1, and s_2 represent the numbers of input, desired output, and undesired output indicators; n is the number of decision-making units; x_{ij}, y_{rj}^g, and z_{pj}^b are the ith input, rth desired output, and pth undesired output of the jth decision-making unit; s_i^-, s_r^g, and s_p^b are slack variables for inputs, desired outputs, and undesired outputs; and λ_j are weight coefficients.

1.3.2 Standard Deviation Ellipse The standard deviation ellipse reflects spatial characteristics and evolution trends through calculations of major/minor axes and center of gravity. Based on ecological welfare performance values, this study further calculates their center of gravity, axis lengths, and rotation angles. Specific calculation methods follow established literature. ArcGIS 10.8 software is used for visualization.

1.3.3 Markov Chain Model The Markov chain model reflects transition directions and probabilities between different region types by constructing transition matrices. This study builds Markov matrices to characterize ecological welfare performance transitions across types. Assuming the transition probability from state E_i to E_j is $P_{ij} = P(E_{t+1} = j|E_t = i)$, a homogeneous Markov chain's one-step transition matrix is obtained. With n possible states, the state transition probability matrix P is:

$$P = \begin{pmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{pmatrix}$$

where P_{ij} represents the probability of transitioning from current state i to state j.

1.3.4 Entropy Weight Method Information entropy, borrowed from thermodynamics, indicates that smaller entropy values correspond to greater indicator dispersion and larger influence on composite indices. This method determines evaluation indicator weights. This study uses Stata software to obtain tertiary indicator weights via the entropy method, then calculates resource consumption, environmental pollution, and human development composite indices.

1.3.5 Dagum Gini Coefficient Promoting coordinated regional development is intrinsic to Chinese modernization. The Dagum Gini coefficient measures intra-regional and inter-regional differences in ecological welfare performance and identifies difference sources. Specific calculation methods follow established literature, with Stata software performing calculations.

1.3.6 Geographic Detector Geographic detectors can detect whether explanatory variables influence the spatial differentiation of dependent variables. This study uses the factor detector and interaction detector in geographic detectors to analyze driving factors of ecological welfare performance and identify interactions among different influencing factors.

2.1 Temporal Evolution Characteristics

Based on super-SBM model calculations, ecological welfare performance values for 11 prefecture-level cities from 2006 to 2021 are obtained (Table 2). Overall, the mean ecological welfare performance is 0.681, fluctuating and showing an upward trend with a growth rate of 19.74%. At the city level, Datong, Jinzhong, Lüliang, Yuncheng, Linfen, Changzhi, and Jincheng show upward trends, while other cities exhibit varying degrees of decline. At the regional level, southeast Shanxi shows the highest mean performance (0.800), followed by north Shanxi (0.681), while south Shanxi shows the lowest (0.608) and remains far below the average, though all regions improved overall.

Table 2 Ecological welfare performance values of 11 prefecture-level cities in Shanxi Province, 2006–2021

Note: Due to space limitations, only selected years are shown.

2.2.1 Spatial Pattern Analysis

To explore spatial distribution characteristics, ecological welfare performance values are classified into four types based on magnitude and maximizing inter-group differences: low-level (0.000–0.200), relatively low-level (0.200–0.400), medium-level (0.400–0.600), relatively high-level (0.600–0.800), and high-level (0.800–1.818). Spatial distribution maps for the start and end years (Figure 1) reveal that in 2006, all cities were in low or relatively low-level zones, while by 2021, southeast Shanxi cities had entered high-level zones, whereas south Shanxi showed intensified internal imbalances with persistent low performance.

Figure 1 [Figure 1: see original paper] Spatial distribution of ecological welfare performance in Shanxi Province in 2006 and 2021

Note: Based on the standard map (GS(2019)1822) from the Ministry of Natural Resources, with no modifications to boundaries. Same below.

To further analyze spatio-temporal evolution, a standard deviation ellipse–center of gravity model is constructed (Figure 2). The center of gravity migrated from the Xinzhou–Taiyuan border to Taiyuan city, then eastward to Jinzhong, and subsequently southwestward, moving 89.87 km overall. This indicates more pronounced performance improvements in western and southern regions than in northern and eastern areas. The ellipse area fluctuated and expanded, suggesting overall upward performance trends. The flattening rate was slightly lower in 2021 than in 2006, indicating weakened directional accuracy and centripetal force.

Figure 2 [Figure 2: see original paper] Standard deviation ellipse and center of gravity of ecological welfare performance in Shanxi Province

2.2.2 Spatial Correlation Analysis

Using the Markov chain method, traditional and spatial Markov transition probability matrices are constructed (Table 3). Without considering spatial lag types, all types show maximum probabilities on the diagonal (77.27%, 61.54%, 64.29%, 85.00%), indicating weak mobility and high probabilities of maintaining original states with limited improvement capacity. Upward transitions exist between types, with probabilities of 20.45%, 15.38%, 7.14%, and 2.27% for one-level upgrades, showing that stepwise improvement is more likely than leapfrogging. Higher-level types still face downward transition risks, necessitating vigilance against "low-level lock-in."

Table 3 Markov transition probability matrix for ecological welfare performance in Shanxi Province

The spatial Markov transition probability matrix reveals that neighborhood context significantly influences urban ecological welfare performance improvement. Transition probabilities vary under different neighborhood types, indicating spatial dependency. Performance levels show synergy with neighborhood levels—cities in high-performance neighborhoods have greater upward transition probabilities. Under spatial lag conditions, "club convergence" emerges, where low-performance cities develop faster.

2.3 Comprehensive Index Decomposition

To clarify improvement pathways for different region types, entropy weighting calculates resource consumption, environmental pollution, and human development composite indices (Figure 3). Resource consumption indices declined across all cities, indicating economic development remains resource-intensive, with Jincheng showing the largest decline (97.92%). Environmental pollution indices increased variably, with Shuozhou showing the largest increase. Human development indices were lower than other indices but increased in all cities except Lüliang, with Xinzhou showing the highest mean level and Jincheng the lowest. Shuozhou showed the largest increase in human development (260.87%).

Figure 3 [Figure 3: see original paper] Composite indices from 2006 to 2021

2.4 Regional Differences and Sources

The Dagum Gini coefficient calculates ecological welfare performance differences (Table 4). Overall regional differences fluctuated and decreased by 11.48%. Inter-regional differences constitute the main source of overall disparities (47.24%), followed by intra-regional differences (30.51%) and transvariation intensity (22.25%). South Shanxi shows the largest internal differences (0.200), while southeast Shanxi shows the smallest (0.067). Inter-regional differences between south and southeast Shanxi are largest (0.246), while those between north and southeast Shanxi are smallest (0.097). All inter-regional differences fluctuated and decreased, likely because Changzhi and Jincheng accelerated industrial transformation, boosting ecological welfare performance, while Linfen faces resource shortages and pollution pressures, and Yuncheng's distance from Taiyuan limits radiational effects.

Table 4 Gini coefficient decomposition of ecological welfare performance

2.5 Driving Factor Analysis

Geographic detectors analyze driving factors (Figure 4). At the single-factor level, key drivers vary by year: greening level, openness, and urbanization (2006); population density, urbanization, and openness (2010); urbanization, greening, and openness (2015); and greening, openness, and urbanization (2021). Urbanization and openness consistently rank high, with openness's influence rising from 0.15 to 0.35. Greening's influence fluctuated but remained significant.

Figure 4 [Figure 4: see original paper] Detection map of ecological welfare performance drivers

Interaction effects show all factor pairs produce double-factor enhancement or nonlinear enhancement, where combined effects exceed individual effects or their sum. This indicates Shanxi's ecological welfare performance results from interactive enhancement among driving factors rather than single-factor direct effects. Openness shows the most pronounced synergy, with 68.75% of interactions producing double-factor enhancement, suggesting higher openness amplifies other factors' effects on performance.

3 Discussion

Regarding ecological welfare performance measurement, existing research predominantly focuses on national and provincial scales. Cities as vital socioeconomic carriers require attention. This study's contribution lies in examining resource-based cities, using Shanxi as a typical case to enrich city-level research and provide new perspectives by focusing on different city types and their disparities. Regarding influencing factors, current research often emphasizes external factors and linear impacts, while internal factor interactions receive less attention. This study decomposes composite indices to identify internal constraints and analyzes factor interactions, revealing that greening, urbanization, and openness are crucial, with openness showing the strongest synergistic effects—providing new insights and entry points for performance improvement.

However, limitations remain: (1) The study only examines Shanxi, lacking comparative analysis across different resource-based city types. Future research should explore differentiated improvement pathways for various resource-based cities. (2) Indicator system construction faces data constraints at the prefecture level, preventing use of widely accepted metrics like life expectancy. Developing more scientific welfare measurement methods at the city scale is necessary.

4 Conclusions

Based on the constructed evaluation system, this study employs super-SBM model, Markov chain, and geographic detectors to analyze Shanxi's ecological welfare performance levels, evolution trends, and influencing factors from 2006 to 2021. Main conclusions are:

1) Mean ecological welfare performance fluctuated between 0.608–0.800, remaining overall ineffective. Spatially, performance shows clear regional differences, presenting a "southeast Shanxi > north Shanxi > south Shanxi" pattern. Standard deviation ellipse–center of gravity results show performance rising with fluctuation while overall centripetal force weakened. Spatial correlation analysis indicates high probabilities of maintaining current levels without spatial lag, with upward/downward transitions possible. Neighborhood performance levels significantly influence transitions.

2) Composite index decomposition shows environmental pollution indices increased across all cities, human development indices rose (except in Lüliang), while resource consumption indices declined—constraining performance improvement. Regional difference analysis reveals overall dispar-

ities fluctuated and decreased, with inter-regional differences as the main source.

3) Geographic detector results show ecological welfare performance is comprehensively affected by urbanization, openness, and other factors, with varying driving effects and interactions. At the single-factor level, greening shows the greatest influence, followed by urbanization, with openness's importance rising. Interaction effects demonstrate significant double-factor and nonlinear enhancement, with openness showing the most pronounced synergy with other factors.

References

[1] Wang Shengyun, Luo Yuting, Han Yajie, et al. Regional difference and determinants of human well-being of the steady state[J]. *Progress in Geography*, 2018, 37(8): 1150-1158.

[2] Xu Chenglong, Zhuang Guiyang. Exploration on the connotation and differentiation of urban sustainable development under new-type urbanization[J]. *Ecological Economy*, 2021, 37(1): 77-82.

[3] Zhao Lin, Cao Naigang, Gao Xiaotong, et al. Spatio-temporal pattern of ecological well-being performance level and its influencing factors in Bohai Sea Rim Region[J]. *Economic Geography*, 2024, 44(3): 178-188.

[4] Dong Jiefang, Zhang Kaili, Qu Xueshu, et al. Measurement and influencing factors of ecological well-being performance of cities in Yellow River Basin[J]. *Arid Land Geography*, 2023, 46(5): 834-845.

[5] Daly H E. The world dynamics of economic growth: The economics of the steady state[J]. *The American Economic Review*, 1974, 64(2): 15-21.

[6] Rees W E. Ecological footprints and appropriated carrying capacity: What urban economics leaves out[J]. *Environment & Urbanization*, 1992, 4(2): 121-130.

[7] Mark N, Simms A, Thompson S, et al. The unhappy planet index: An index of human well-being and environmental impact[M]. London: New Economics Foundation, 2006.

[8] Abdallah S, Thompson S, Michaelson J, et al. The happy planet index 2.0: Why good lives don't have to cost the earth[M]. London: New Economics Foundation, 2009.

[9] Zhu Dajian. Ecological economics: Economics and management of sustainable development[J]. *Bulletin of Chinese Academy of Sciences*, 2008, 23(6): 520-530.

[10] Wang Shengyun, Duan Liancheng. Evolution of spatio-temporal patterns of ecological well-being performance in China and its driving effects[J]. *Progress in Geography*, 2023, 42(4): 617-628.

[11] Dietz T, Rosa E A, York R. Environmentally efficient well-being: Is there a Kuznets curve?[J]. *Applied Geography*, 2010, 10(11): 1-11.

[12] Long Liangjun, Wang Xia. A study on Shanghai's ecological well-being performance[J]. *China Population, Resources and Environment*, 2017, 27(2): 84-92.

[13] Wei Peng, Li Li, Li Run, et al. Local government competition, environmental regulation, and ecological welfare performance[J]. *Statistics and Decision*, 2022, 38(22): 164-169.

[14] Tan Zhongming, Kang Qin, Dong Yunyi. Research on the impact of ecological welfare performance and its spatial effect supported by green finance[J]. *Financial Theory and Practice*, 2023(5): 80-92.

[15] Zhu Jinhe, Pang Wanyu. The impact of digital economy development on ecological welfare performance[J]. *Statistics and Decision*, 2022, 38(24): 79-83.

[16] Xu Zhixiong, Xu Weixiang, Liu Chengjun. Exploring the dynamic evolution of urban ecological welfare performance and its influencing factors: Taking prefecture-level and above cities in the Yellow River Basin as an example[J]. *Urban Problems*, 2021(7): 52-60.

[17] Zhang Shanyu. *Introduction to Population Geography*[M]. Shanghai: East China Normal University Press, 2004: 265-323.

[18] Qin Zhiqin. Migration distribution and its economic factors in Shanxi Province[J]. *Areal Research and Development*, 2015, 34(1): 166-171.

[19] Tone K. A slacks-based measure of efficiency in data envelopment analysis[J]. *European Journal of Operational Research*, 2001, 130(3): 498-509.

[20] Tone K. A slacks-based measure of super-efficiency in data envelopment analysis[J]. *European Journal of Operational Research*, 2002, 143(1): 32-41.

[21] Long Liangjun, Wang Xia, Guo Bing. Evaluation of urban ecological well-being performance based on revised DEA model: A case study of 35 major cities in China[J]. *Journal of Natural Resources*, 2017, 32(4): 595-605.

[22] Ma Chao, Feng Yincheng, Zhao Kang, et al. Exploring the construction path of "waste-free city" in mineral resource-based cities in China[J]. *China Environment Science*, 2024, 44(9): 5077-5084.

[23] Ren Guixiu, Liu Kai. Spatio-temporal evolution characteristics and influencing factors of green innovation in the Yellow River Basin[J]. *Arid Land Geography*, 2024, 47(1): 158-169.

[24] Dagum C. A new approach to the decomposition of the Gini income inequality ratio[J]. *Empirical Economics*, 1997, 22(4): 515-531.

[25] Liu Xiuli, Li Wentao, Guo Pibin, et al. Can location-oriented policies promote the green transformation of resource-based cities? Taking the establish-

ment of Comprehensive Reform Zone in Shanxi as an example[J]. *Journal of Natural Resources*, 2024, 39(1): 84-103.

[26] Wang Jinfeng, Xu Chengdong. Geodetector: Principle and prospective[J]. *Acta Geographica Sinica*, 2017, 72(1): 116-134.

[27] Zang Mandan, Gao Yi, Li Jin. The influence of administrative hierarchy and urban scale on ecological well-being performance[J]. *Journal of Natural Resources*, 2022, 37(12): 3201-3216.

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