Analysis of Spatiotemporal Evolution Characteristics and Coordinated Development of Urban Ecological Resilience and Efficiency in the Yellow River Basin (Postprint)

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Abstract

Enhancing urban ecological resilience and ecological efficiency while promoting coordinated development between them constitutes an important objective for ecological governance in the Yellow River Basin. This study examines 57 cities in the Yellow River Basin as the research area, employing the weighted summation method and the SBM model to investigate the spatiotemporal evolution characteristics of ecological resilience and efficiency from 2009 to 2018, and utilizes a coupling coordination model to analyze the coordinated development relationship between urban ecological resilience and efficiency in the basin. The results demonstrate that: (1) From 2009 to 2018, urban ecological resilience in the Yellow River Basin exhibited an overall fluctuating downward trend, confronting substantial ecological threats and environmental protection pressures. The three provincial capital cities—Xi'an, Zhengzhou, and Jinan—demonstrated relatively high ecological resilience, whereas cities such as Guyuan, Dingxi, Haidong, and Lüliang exhibited lower resilience. (2) Urban ecological efficiency in the Yellow River Basin displayed a "U"-shaped evolutionary pattern characterized by initial decline followed by subsequent increase. Dingxi, Longnan, Qingyang, Ordos, Guyuan, and Luoyang represent high ecological efficiency categories, while low ecological efficiency categories are predominantly located in cities within Shanxi, Henan, and Shandong provinces in the middle and lower reaches. (3) The coordination relationship between ecological resilience and efficiency mirrors that of the ecological efficiency subsystem, transitioning from continuous decline to gradual recovery. The number of cities achieving good coordination and moderate coordination has increased, while those with barely coordination has decreased. Although the development momentum for coordinated urban ecological resilience and efficiency in the Yellow River Basin is becoming evident, contradictions between economic development and environmental protection remain pronounced in the short term. These research findings can provide theoretical references for urban ecological policy formulation and improvements in ecological resilience and efficiency in the Yellow River Basin.

Full Text

Spatiotemporal Evolutionary Characteristics and Coordinated Development Analysis of Urban Ecological Resilience and Efficiency in the Yellow River Basin

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Abstract: Enhancing urban ecological resilience and efficiency while promoting coordinated development between these two dimensions constitutes a critical objective for ecological governance in the Yellow River Basin. This study examines 57 cities in the Yellow River Basin as the research target, employing the weighted summation method and the slacks-based measurement (SBM) model to investigate the spatiotemporal evolutionary characteristics of ecological resilience and efficiency from 2009 to 2018. Furthermore, a coupling coordination model is utilized to analyze the coordinated development relationship between urban ecological resilience and efficiency across the basin. The results indicate: (1) During the study period, urban ecological resilience in the Yellow River Basin exhibited an overall fluctuating decline, with cities facing significant ecological threats and environmental pressures. Xi'an, Zhengzhou, and Jinan—three provincial capitals—demonstrated relatively high ecological resilience, whereas Guyuan, Dingxi, Haidong, and Lüliang exhibited low resilience. (2) Urban ecological efficiency displayed a "U-shaped" evolutionary pattern, characterized by an initial decline followed by a subsequent increase. Dingxi, Longnan, Qingyang, Ordos, Guyuan, and Luoyang represented high-efficiency cities, while low-efficiency cities were predominantly concentrated in Shanxi, Henan, and Shandong provinces within the middle and lower reaches. (3) The coordination relationship between ecological resilience and efficiency mirrored that of the ecological efficiency subsystem, transitioning from continuous decline to gradual recovery. The number of cities achieving good and moderate coordination increased, while those with poor coordination decreased. Although momentum for coordinated development between ecological resilience and efficiency is emerging, contradictions between economic development and environmental protection remain pronounced in the short term. These findings provide theoretical references for policy formulation aimed at enhancing urban ecological resilience and efficiency in the Yellow River Basin.

Keywords: ecological resilience; ecological efficiency; coordinated development; urban; Yellow River Basin

1 Study Area

The Yellow River flows through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong provinces from west to east, spanning approximately 5,464 km. As a massive ecological corridor connecting the Three-River Headwaters Region, Qilian Mountains, Fenwei Plain, and North China Plain, the Yellow River Basin holds significant importance in China's ecological construction. This study selected 57 prefecture-level cities listed in the *Encyclopedia of Yellow River Culture* as case targets. Several autonomous prefectures—including Aba Tibetan and Qiang, Linxia Hui, Gannan Tibetan, Haibei Tibetan, Huangnan Tibetan, Hainan Tibetan, Golog Tibetan, Yushu Tibetan, and Haixi Mongolian and Tibetan—were excluded due to substantial data gaps. Following the Yellow River Conservancy Commission's standards, the remaining cities were divided into three regions: upstream (from Xining to Hohhot), midstream (from Hohhot to Zhengzhou), and downstream (from Zhengzhou to Dongying) [Figure 1: see original paper].

2 Methodology

2.1 Data Sources

Data primarily originated from the *China City Statistical Yearbook (2010–2019)*, *China Energy Statistical Yearbook (2010–2019)*, and the *National Economic and Social Development Statistical Bulletins* of relevant cities. Missing data that could not be obtained through documentation were estimated using trend extrapolation. Certain indicators were derived through processing, including per capita green space area (ratio of urban green space area to year-end total population), energy consumption per 10,000 yuan of GDP (ratio of total energy consumption to GDP), water consumption per 10,000 yuan of GDP (ratio of total water supply to GDP), and electricity consumption per 10,000 yuan of GDP (ratio of total electricity consumption to GDP).

2.2.1 Weighted Summation Method

This study employed the weighted summation method to analyze urban ecological resilience in the Yellow River Basin. Raw data were first normalized using extreme value standardization. The entropy method was then applied to assign weights to indicators. Finally, weighted summation was used to calculate the comprehensive evaluation value of ecological resilience for each city:

$$Y_i = \sum_j \lambda_j \times X'_{ij}$$

where X'_{ij} represents the standardized value of the j-th indicator in the i-th research unit; λ_j denotes the weight of the j-th indicator; and Y_i is the ecological resilience value of the i-th research unit.

2.2.2 SBM Model

Tone (2001) proposed the slacks-based measure (SBM) model, a non-radial and non-oriented model that incorporates not only proportional improvements in input-output variables but also effectively handles undesirable outputs, thereby enhancing measurement accuracy. This study utilized the SBM model to measure urban ecological efficiency values in the Yellow River Basin:

$$\rho = \min \frac{1 - \frac{1}{N}\sum_{n=1}^{N} \frac{s_n^x}{x_{kn}^t}}{1 + \frac{1}{M+I}\left(\sum_{m=1}^{M} \frac{s_m^y}{y_{km}^t} + \sum_{i=1}^{I} \frac{s_i^b}{b_{ki}^t}\right)}$$

Subject to:

$$\begin{aligned}
&x_{kn}^t = X_n^t z_n^t + s_n^x, \quad n = 1, 2, \ldots, N \\
&y_{km}^t = Y_m^t z_m^t - s_m^y, \quad m = 1, 2, \ldots, M \\
&b_{ki}^t = B_i^t z_i^t + s_i^b, \quad i = 1, 2, \ldots, I \\
&z_k^t \geq 0, \quad s_n^x \geq 0, \quad s_m^y \geq 0, \quad s_i^b \geq 0
\end{aligned}$$

where E represents the ecological efficiency value; N, M, and I denote the numbers of input, desirable output, and undesirable output indicators, respectively; s_n^x, s_m^y, and s_i^b are slack vectors for inputs, desirable outputs, and undesirable outputs; x_{kn}^t, y_{km}^t, and b_{ki}^t represent the input, desirable output, and undesirable output values of the k-th production unit in period t; X_n^t, Y_m^t, and B_i^t are the input, desirable output, and undesirable output values of the k-th production unit in period t; and z_k^t is the weight vector. A larger E value indicates higher ecological efficiency, with $E = 1$ signifying full efficiency.

2.2.3 Coupling Coordination Model

Coupling refers to the process through which different systems influence each other via interactions, while coordination represents a benign developmental relationship characterized by mutual cooperation among systems. This study employed a coupling coordination model to analyze the coordinated relationship between the two subsystems of urban ecological resilience and efficiency in the Yellow River Basin:

$$C = \sqrt{\frac{Y_i \times E}{\left(\frac{Y_i + E}{2}\right)^2}}$$

$$D = \sqrt{C \times T}$$

$$T = \alpha Y_i + \beta E$$

where Y_i and E represent ecological resilience and efficiency values, respectively; C denotes the coupling degree between the two subsystems; D indicates the coupling coordination degree; and T represents the comprehensive development evaluation value. Given that ecological resilience and efficiency are equally important in ecological construction, both α and β were set to 0.5.

2.3 Construction of the Evaluation System for Coordinated Development of Ecological Resilience and Efficiency

Following principles of objectivity, independence, and operability, this study constructed an evaluation system comprising 2 subsystems and 18 specific indicators for coordinated development of ecological resilience and efficiency in the Yellow River Basin . The ecological resilience subsystem drew upon relevant research on economic and environmental resilience, subdividing into resistance and recovery dimensions. Resistance represents the capacity of ecosystems to actively withstand environmental disturbances without exceeding critical stability thresholds, primarily influenced by regional economic development and social infrastructure. Recovery focuses on the ability to restore stability when disturbances exceed critical thresholds, mainly affected by ecological reconstruction and pollution control.

The ecological efficiency subsystem referenced literature on energy and industrial ecological efficiency, divided into input and output dimensions. Input indicators encompass resources and energy consumed in providing socioeconomic services, including social capital and labor investment. Output indicators emphasize the value of products and services provided to meet human needs, covering both desirable and undesirable outputs.

3 Results

3.1 Spatiotemporal Evolution Characteristics of Urban Ecological Resilience

As shown in [Figure 2: see original paper], urban ecological resilience in the Yellow River Basin exhibited an overall fluctuating decline from 2009 to 2018, decreasing from 0.387 to 0.328. This trend reflects substantial ecological threats and environmental pressures confronting the basin, providing the macro context and objective rationale for the national strategy of ecological protection and high-quality development proposed in 2019. Following the 2008 global financial crisis and subsequent domestic economic impacts, numerous cities along the basin prioritized infrastructure investment and project development to pursue economic scale and growth speed, resulting in diminished ecological resilience. After 2012, the Chinese central government successively issued the *National New-type Urbanization Plan* and *Overall Plan for Ecological Civilization System*

Reform, prompting cities to incorporate ecological and environmental considerations into socioeconomic development and achieving notable progress in ecological civilization construction. Consequently, the decline in resilience slowed and showed upward trends in certain years.

From a regional perspective, ecological resilience ranked highest in the downstream region, followed by the upstream region, with the midstream region showing the lowest values. Cities in the downstream possessed sound socioeconomic foundations and strong resistance to external threats, yielding higher resilience values. Although the upstream region featured relatively fragile ecological environments, substantial environmental protection efforts and capital investment resulted in moderate resilience. The midstream region represents a typical ecologically vulnerable area, a region prone to natural disasters, and a heavy chemical industry and energy base, where prominent contradictions between socioeconomic development and ecological environment led to the lowest resilience values.

Calculating the mean ecological resilience values for Yellow River Basin cities from 2009 to 2018 and using 0.4 as the threshold, ecological resilience was classified into four categories: high, relatively high, relatively low, and low. As illustrated in [Figure 3: see original paper], high-resilience cities included Xi'an, Zhengzhou, and Jinan—three provincial capitals with robust socioeconomic foundations that have prioritized industrial transformation and ecological protection in recent years, conferring absolute advantages over other basin cities. Additionally, Dongying, Zibo, Hohhot, Baotou, Ordos, Wuhai, Yinchuan, and Shizuishan exhibited relatively high resilience, primarily due to their status as provincial capitals or surrounding cities with guaranteed ecological resistance and recovery capacity. Conversely, Yuncheng, Guyuan, Jinzhong, Haidong, Lüliang, Linfen, and Xinzhou represented low-resilience cities. Notably, Yuncheng, Jinzhong, and Lüliang in Shanxi Province—a major energy and chemical industry base—experienced severe natural environment impacts, resulting in significant resilience degradation. Guyuan, Haidong, and Dingxi suffered from arid climates with low precipitation and intense evaporation, exacerbated by unsustainable cultivation, grazing, logging, and land occupation practices that reduced ecological resilience.

3.2 Spatiotemporal Evolution Characteristics of Urban Ecological Efficiency

Urban ecological efficiency in the Yellow River Basin generally displayed a "U-shaped" evolutionary pattern, with values decreasing from 0.524 in 2009 to 0.345 in 2015 before increasing to 0.523 in 2018 [Figure 4: see original paper]. Prior to 2015, economic development in cities along the basin emphasized resource and environmental inputs, with traditional energy and chemical industries dominating industrial structures, resulting in low and declining ecological efficiency. During the 13th Five-Year Plan period (2016–2020), cities accelerated industrial transformation and upgrading, shifting from extensive, high-pollution economic models toward intensive, high-quality development, thereby continuously improving ecological efficiency.

Regionally, upstream areas exhibited the highest ecological efficiency values, followed by the midstream region, with downstream areas showing the lowest. The upstream region has long prioritized ecological maintenance and environmental governance, maintaining relatively low levels of undesirable ecological outputs. Although midstream and downstream cities possessed sound socioeconomic foundations, severe environmental degradation from earlier economic development resulted in lower efficiency values. Notably, the downstream region has actively promoted new and old kinetic energy conversion and industrial restructuring in recent years, leading to rapidly rising ecological efficiency.

Inter-city differences reveal that Dingxi, Longnan, Qingyang, Ordos, Guyuan, and Luoyang achieved high ecological efficiency, with efficiency values of 1 in multiple years, indicating fully efficient production units [Figure 5: see original paper]. Haidong, Wuwei, Zhongwei, and Tianshui represented relatively high-efficiency cities, primarily due to low undesirable ecological outputs. High and relatively high-efficiency cities were predominantly located in the upstream region, while low-efficiency cities concentrated in Shanxi, Henan, and Shandong provinces in the middle and lower reaches. Specifically, low-efficiency cities included Taiyuan, Jinzhong, Changzhi, and Jincheng in Shanxi Province; Jiaozuo, Zhengzhou, Xinxiang, and Anyang in Henan Province; and Liaocheng, Dezhou, Binzhou, Zibo, and Linyi in Shandong Province. These cities exhibited strong path dependence on resource-based economic development, characterized by high ecological inputs and low desirable outputs, necessitating transformation of economic growth patterns and strengthened environmental governance to enhance ecological efficiency.

3.3 Analysis of Coordinated Development Between Ecological Resilience and Efficiency

The coordinated development trend between ecological resilience and efficiency in Yellow River Basin cities from 2009 to 2018 mirrored that of the ecological efficiency subsystem, shifting from continuous decline to gradual recovery [Figure 6: see original paper]. The coordination index decreased from 0.445 in 2009 to 0.352 in 2015 before rebounding to 0.456 in 2018. Since 2015, cities along the basin have not only emphasized the development of technology-intensive, environmentally friendly industries but also actively implemented environmental policies and regulations to advance ecological civilization construction, substantially enhancing coordination between the two dimensions. Regionally, the coordination index ranked highest in the upstream region, followed by the downstream region, with the midstream region showing the lowest values. Although midstream and downstream coordination indices fell below the basin-wide average, they demonstrated upward trends in recent years due to ecological improvements and efficiency gains. Conversely, the upstream region's coordination index exceeded the basin average but showed a declining trend as industrialization accelerated, warranting serious attention.

To dynamically understand the evolution of coordinated development between ecological resilience and efficiency, the coupling coordination indices for the start and end years of the study period (2009 and 2018) were mapped [Figure 7: see original paper]. The number of cities with good and moderate coordination increased across the Yellow River Basin. Good coordination cities rose from 3 in 2009 to 6 in 2018, including Jinan and Zhengzhou, where significant economic structural optimization and ecological governance enhanced both resilience and efficiency, strengthening their coordination. Moderate coordination cities increased from 10 to 13, with considerable variability during the study period, reflecting the dynamic nature of moderate coordination in the basin. Poor coordination cities decreased from 31 to 24, while moderately uncoordinated cities increased from 13 to 14. Notably, Lüliang, Changzhi, Jincheng, and Yuncheng in Shanxi Province, as well as Anyang in Henan Province and Liaocheng in Shandong Province, transitioned from poor coordination in 2009 to moderate uncoordination in 2018. These cities should reduce ecological pollution and promote industrial upgrading to enhance coordination between ecological resilience and efficiency.

4 Discussion

As a crucial ecological security barrier, energy and chemical industry base, and economic development region in China, the Yellow River Basin holds a pivotal position in national ecological civilization construction and socioeconomic development. In recent years, ecological protection and high-quality development in the Yellow River Basin have been elevated to a major national strategy alongside the coordinated development of the Beijing-Tianjin-Hebei region, Yangtze River Economic Belt, Yangtze River Delta integration, and Guangdong-Hong Kong-Macao Greater Bay Area, creating significant opportunities for ecological governance and environmental protection.

Our analysis of urban ecological resilience aligns with Li et al.'s findings, indicating that cities in the basin urgently require measures such as industrial upgrading, kinetic energy conversion, and ecological protection to reverse the overall declining trend in ecological resilience. Conclusions regarding ecological efficiency differ somewhat from Chen et al., primarily due to variations in evaluation systems and measurement periods. This study's principal contribution lies in integrating ecological resilience and efficiency within a unified analytical framework, expanding current research perspectives and case applications in ecological resilience by analyzing their evolutionary characteristics and coordinated relationship.

Nevertheless, several limitations exist. First, the evaluation system emphasizes human activity impacts on ecological environments while considering fewer natural factors such as land use types, climate change, and biodiversity. Future research should incorporate additional natural environment variables to construct more comprehensive evaluation systems. Second, data availability and uniformity constraints limited the study period to 2009–2018, preceding the national strategy for ecological protection and high-quality development in the Yellow River Basin. Future studies should update data to explore evolutionary trends and internal mechanisms following the strategy's implementation.

5 Conclusion

This study investigated the spatiotemporal evolutionary characteristics and coordinated development of urban ecological resilience and efficiency in the Yellow River Basin from 2009 to 2018, yielding three primary conclusions:

(1) Urban ecological resilience in the Yellow River Basin exhibited an overall fluctuating decline, with cities facing substantial ecological threats and environmental pressures. Downstream regions demonstrated relatively good ecological protection and high resilience, upstream regions ranked second, and midstream regions showed the lowest resilience values. Among cities, Xi'an, Zhengzhou, and Jinan—three provincial capitals—possessed distinct advantages in ecological resilience, while Guyuan, Dingxi, Haidong, and Lüliang exhibited low resilience.

(2) Urban ecological efficiency displayed a "U-shaped" evolutionary pattern, decreasing initially before increasing. Dingxi, Longnan, Qingyang, Ordos, Guyuan, and Luoyang represented high-efficiency cities, predominantly located in the upstream region. Low-efficiency cities were mainly concentrated in Shanxi, Henan, and Shandong provinces within the middle and lower reaches.

(3) The coordination relationship between ecological resilience and efficiency mirrored the ecological efficiency subsystem, shifting from decline to recovery. Following 2015, cities along the basin emphasized technology-intensive, environmentally friendly industries while continuously promoting ecological civilization construction. Additionally, the number of cities with good and moderate coordination increased while poorly coordinated cities decreased, indicating emerging momentum for coordinated development. However, contradictions between economic development and environmental protection remain prominent in the short term.

References

[1] Tao Jieyi, Dong Ping, Lu Yuqi. Spatial-temporal analysis and influencing factors of ecological resilience in Yangtze River Delta[J]. Resources and Environment in the Yangtze Basin, 2022, 31(9): 1975-1987.

[2] Ren Mei, Wang Xiaomin, Liu Zhongmei, et al. Analysis on spatial-temporal change and the influencing factors of regional eco-efficiency of China[J]. East China Economic Management, 2019, 33(9): 71-79.

[3] Li Liangang, Zhang Pingyu, Cheng Yu, et al. Spatio-temporal evolution and influencing factors of economic resilience in the Yellow River Basin[J]. Scientia Geographica Sinica, 2022, 42(4): 557-567.

[4] Chen Minghua, Yue Haijun, Hao Yunfei, et al. The spatial disparity, dynamic evolution and driving factors of ecological efficiency in the Yellow River Basin[J]. Journal of Quantitative & Technological Economics, 2021, 38(9): 25-44.

[5] Li Xueming, Liu Kaiqiang, Tian Shenzhen, et al. Evaluation of urban human settlements resilience based on DPSIR model: A case study of the Yangtze River Delta Urban Systems[J]. Human Geography, 2022, 37(1): 54-62.

[6] Zhou Cheng, Zhang Xuhong, Zhang Qian, et al. The construction of "Five-in-One" comprehensive evaluation system and spatial difference in the Yellow River Basin[J]. Journal of Desert Research, 2021, 41(4): 1-11.

[7] Central Committee of Communist Party of China, the State Council of the People's Republic of China. Outline of the planning for ecological protection and high-quality development of the Yellow River Basin[N]. People's Daily, 2021-10-09(01).

[8] Lu Lan, Zhou Hongwei, Xu Qingqing. Application research on comprehensive evaluation of urban resilience from the perspective of multidimensional relational networks[J]. Urban Problems, 2020(8): 42-55.

[9] Sun Jiuwen, Sun Xiangyu. Research progress of regional economic resilience and exploration of its application in China[J]. Economic Geography, 2017, 37(10): 1-9.

[10] Holling C S. Resilience and stability of ecological systems[J]. Annual Review of Ecology & Systematics, 1973, 4(1): 1-23.

[11] Delettre O. Identity of ecological systems and the meaning of resilience[J]. Journal of Ecology, 2021, 109(9): 3147-3156.

[12] Berkes F, Jolly D. Adapting to climate change: Social-ecological resilience in a Canadian western arctic community[J]. Ecology and Society, 2000, 5(2): 213-218.

[13] Lebel L. Governance and the capacity to manage resilience in regional social-ecological systems[J]. Ecology & Society, 2006, 11(1): 230-250.

[14] Li Su, Liu Haonan. Spatio-temporal pattern evolution of coupling coordination between urbanization and ecological resilience in arid region: A case of Ningxia Hui Autonomous Region[J]. Arid Land Geography, 2022, 45(4): 1281-1290.

[15] Wang Shaojian, Cui Zitian, Lin Jingjie, et al. Coupling relationship between urbanization and ecological resilience in the Pearl River Delta[J]. Acta Geographica Sinica, 2021, 76(4): 973-991.

[16] Wang Songmao, Niu Jinlan. Dynamic evolution and obstacle factors of urban ecological resilience in Shandong Peninsula urban agglomeration[J]. Economic Geography, 2022, 42(8): 51-61.

[17] Xia Chuyu, Dong Zhaoyingzi, Chen Bin. Spatio-temporal analysis and simulation of urban ecological resilience: A case study of Hangzhou[J]. Acta Ecologica Sinica, 2022, 42(1): 116-126.

[18] Yang Xiaodong, Li Ziwei, Zhang Jiayu, et al. Spatiotemporal evaluation of urban resilience from the perspective of sustainable development[J]. Urban Problems, 2021, 40(3): 29-37.

[19] Zhu Jinhe, Sun Hongxue. Research on spatial-temporal evolution and influencing factors of urban resilience of China's three metropolitan agglomerations[J]. Soft Science, 2020, 34(2): 72-79.

[20] Zang Xinyu, Jiao Jiao, Wang Qiao. Study on the problem of ecological resilience in the existing urban areas and the strategy of spatial optimization[J]. Urbanism and Architecture, 2019, 16(15): 34-38.

[21] Shen Jie, Li Yan, Xia Chunhong, et al. Study on the measure and spatial evolution of urban ecological resilience in Yunnan[J]. China Resources Comprehensive Utilization, 2021, 39(2): 55-58.

[22] Ni Ying, Wen Chuanhao. A summary of research on ecological efficiency measurement methods and applications[J]. Journal of Guizhou University of Commerce, 2019, 32(1): 73-78.

[23] Zhao Zhe, Bai Yuping, Hu Zhaomin, et al. Evaluation of ecological efficiency and factors influencing grassland animal husbandry in the Hulunbuir region based on a super-efficiency DEA model[J]. Acta Ecologica Sinica, 2018, 38(22): 7968-7978.

[24] Fu Lina, Chen Xiaohong, Leng Zhihua. Urban agglomerations eco-efficiency analysis based on super-efficiency DEA model: Case study of Chang-Zhu-Tan "3+5" urban agglomeration[J]. China Population, Resources and Environment, 2013, 23(4): 169-175.

[25] Shi Dan, Wang Junjie. Measurement and evaluation of China's ecological pressure and ecological efficiency based on ecological footprint[J]. China Industrial Economics, 2016, 33(5): 5-21.

[26] Moutinho V, Madaleno M, Robaina M. The economic and environmental efficiency assessment in EU cross-country: Evidence from DEA and quantile regression approach[J]. Ecological Indicators, 2017, 78(7): 85-97.

[27] Moutinho V, Fuinhas J A, Marques A C, et al. Assessing eco-efficiency through the DEA analysis and decoupling index in the Latin America countries[J]. Journal of Cleaner Production, 2018, 205: 1-15.

[28] Wang X M, Ding H, Liu L. Eco-efficiency measurement of industrial sectors in China: A hybrid super-efficiency DEA analysis[J]. Journal of Cleaner

Production, 2019, 229: 53-64.

[29] Côté R, Booth A, Louis B. Eco-efficiency and SMEs in Nova Scotia, Canada[J]. Journal of Cleaner Production, 2006, 14(7): 542-550.

[30] Kharel G P, Charmondusit K. Eco-efficiency evaluation of iron rod industry in Nepal[J]. Journal of Cleaner Production, 2008, 16(13): 1379-1387.

[31] Wang S J, Cui Z T, Lin J J, et al. The coupling relationship between urbanization and ecological resilience in the Pearl River Delta[J]. Journal of Geographical Sciences, 2022, 32(1): 44-64.

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

[33] Zhang Xiaojuan, Tang Qifeng, Zhang Zhen. Spatial differentiation characteristics and its influencing factors of urban resilience in the Yellow River Basin[J]. Areal Research and Development, 2022, 41(6): 48-54.

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