Measurement of Urban Green Development Efficiency and Improvement Pathways in the Yellow River Basin Under the Dual-Carbon Goals: Postprint

Authors: Caixia Shi

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Abstract

Evaluating urban green development efficiency and its optimization pathways constitutes a critical link in advancing high-quality development of the Yellow River Basin and represents an important strategy for implementing the strategic goals of "carbon peak, carbon neutrality." Using the EBM-GML model, this study measures the green development efficiency of 58 cities in the Yellow River Basin from 2005 to 2020, sequentially employs HP filter analysis and spatiotemporal interaction methods to delineate its evolutionary characteristics, and quantitatively identifies multiple improvement pathways. The results indicate: (1) During the study period, the green development efficiency of cities in the Yellow River Basin exhibited a growth trend, increasing from 0.509 in 2005 to 0.651 in 2020, successively experiencing three stages of "fluctuation—improvement—symbiosis," with significant intra-regional imbalance characteristics. (2) The local spatial structure of green development efficiency in the Yellow River Basin cities demonstrates good robustness, the spatial movement direction exhibits strong volatility, and the degree of intercity spatial cooperation exceeds spatial competition. (3) The results of fuzzy-set qualitative comparative analysis (fsQCA) reveal that four optimization pathways exist: economy-driven type, dual-driven type, resource integration type, and comprehensive improvement type, with factors such as economic development and technological innovation serving as necessary conditions.

Measurement and Improvement Path of Urban Green Development Efficiency in the Yellow River Basin Under the “Carbon Peaking and Carbon Neutrality” Targets

SHI Caixia, HE Xiaorong
(Tourism College, Hunan Normal University, Changsha 410081, Hunan, China)

Abstract: Assessing urban green development efficiency and delineating its optimization pathways constitute a critical component for advancing high-quality development in the Yellow River Basin and represent an essential strategy for achieving the “carbon peak and carbon neutrality” objectives. This study employs the EBM-GML model to calculate the green development efficiency of 58 cities in the Yellow River Basin from 2005 to 2020. The evolution characteristics are outlined through HP filter analysis and spatiotemporal interaction methods, with multiple improvement paths quantitatively identified. The results reveal: (1) During the study period, urban green development efficiency in the Yellow River Basin exhibited a growth trend, increasing from 0.509 in 2005 to 0.651 in 2020, successively experiencing three stages of “fluctuation—improvement—symbiosis,” with remarkable intraregional imbalance characteristics. (2) The local spatial structure of green development efficiency demonstrates robust stability, while spatial movement directions show strong volatility. The degree of intercity spatial collaboration exceeds spatial competition. (3) Fuzzy-set Qualitative Comparative Analysis (fsQCA) identifies four optimization paths: economic-driven, dual-driven, resource integration, and comprehensive improvement types. Economic development and technological innovation emerge as necessary conditions.

Key words: carbon peaking and carbon neutrality goals; urban green development efficiency; spatiotemporal interaction; fsQCA; Yellow River Basin

The 20th National Congress of the Communist Party of China emphasizes accelerating the green transformation of development modes and promoting the formation of green and low-carbon production and lifestyle patterns. The Yellow River Basin serves as a crucial experimental zone for high-quality development in China and a key barrier for national ecological security, playing a pivotal role in promoting economic and social development and optimizing territorial spatial development patterns [?]. Since the new century, through comprehensive coordination and scientific regulation, the Yellow River Basin has achieved remarkable progress in green development. However, due to its fragile ecological foundation and limited resource-environmental carrying capacity, the basin faces increasingly prominent issues of unbalanced and insufficient development [?]. Under the strategic goals of “carbon peak and carbon neutrality,” exploring the spatiotemporal evolution characteristics and optimization pathways of urban green development efficiency in the Yellow River Basin holds significant importance for breaking the energy-dependent constraints of cities along the river, constructing a new pattern of territorial space protection, and facilitating regional green and high-quality development.

As a hot topic in academic discourse, “green development” has accumulated substantial research foundations, broadly categorized into three aspects: (1) Conceptual and connotative interpretations. Narrowly defined, green development discusses economic growth dimensions such as green economy [?] and ecological economy [?]. Broadly defined, it emphasizes comprehensive coverage across economy, society, politics, culture, and lifestyle [?]. (2) Efficiency measurement and evaluation. Methods primarily include indicator system evaluation and production efficiency measurement. Indicator system approaches encompass the OECD green growth assessment framework [?], the UNEP green economy measurement model [?], and the green development index evaluation model from Beijing Normal University and other institutions [?]. Production efficiency measurement includes traditional radial DEA [?], non-radial SBM [?], and hybrid distance functions (EBM) [?]. Scholars have focused on spatiotemporal heterogeneity of green development at global [?], national [?], and provincial [?] levels, employing methods such as time series forecasting [?] and obstacle degree models [?]. (3) Improvement pathways and measures. Researchers including Chen Minghua et al. [?] and Sun Jinxin et al. [?] argue that economic environment and policy systems constrain urban green development, while Shi Bo [?] emphasizes that cultivating green development systems and strengthening urban hardware guarantees can improve urban development quality.

In summary, while research perspectives on green development continue to enrich and extend, there remains room for improvement in its connotation deconstruction and evaluation systems. Studies on regional disparities in ecologically fragile areas like the Yellow River Basin are relatively weak, and existing research only reveals evolution characteristics from single temporal or static spatial perspectives, failing to capture process changes from spatiotemporal interaction dimensions. Furthermore, discussions on improvement pathways have not yet been extended to empirical verification. Therefore, this study employs the EBM-GML model to measure green development efficiency, utilizes HP filter analysis and spatiotemporal interaction methods to outline its evolution characteristics, and employs fuzzy-set qualitative comparative analysis (fsQCA) to identify multiple improvement pathways, aiming to provide empirical evidence for consolidating the ecological security barrier of the Yellow River Basin and creating a model of harmonious coexistence between humanity and nature.

1.1 Study Area Overview

According to the National “13th Five-Year Plan”outline, among the key national-level urban agglomerations, those distributed along the Yellow River include 58 prefecture-level cities. In 2020, the region’ s GDP reached 25.390$×$10^{12} yuan, with a permanent population of approximately 420 million and water resource development utilization rate at 80%, far exceeding the 40% ecological warning line. The basin features extensive and diverse ecologically fragile zones, with prominent issues of energy-dependent, low-quality, and inefficient industries [?]. Since the Yellow River Basin’ s ecological protection and high-quality development were elevated to a national strategy, research on green development efficiency of cities along the river has become particularly urgent [?].

1.2 Data Sources

Due to inconsistent statistical calibers across autonomous prefectures and leagues, data acquisition is challenging. Additionally, some prefecture-level cities underwent administrative adjustments, such as Laiwu City merging into Jinan in 2019. Therefore, this study uses 58 prefecture-level cities in the Yellow River Basin as of 2005 as the research baseline, excluding merged city data (Figure 1). All data are sourced from the *China City Statistical Yearbook*, *China Urban Construction Statistical Yearbook*, *China Energy Statistical Yearbook*, and local city statistical yearbooks and national economic statistical bulletins from 2005 to 2020. Carbon emissions data are calculated following the approach of Chen et al. [?].

1.3 Indicator System Construction

Aligned with the “carbon peak and carbon neutrality” strategic goals, this study focuses on evaluating the green development capacity of Yellow River Basin cities to achieve greater expected outputs with fewer inputs and non-expected outputs. Drawing on research by Tong et al. [?], Ding et al. [?], and Li et al. [?], an evaluation index system is constructed (Table 1). The input layer emphasizes urban inputs in labor, capital, and energy, while the output layer reflects actual effects of expected and non-expected outputs. Additionally, this study incorporates “urban CO2 emissions” as a non-expected output to align with national policy orientation and comprehensively reflect regional green development efficiency.

1.4.1 Super-Efficiency EBM-GML Model

The Epsilon-Based Measure (EBM) model integrates radial and non-radial proportional relationships between frontier and actual values of inputs, combining the advantages of both DEA approaches to scientifically examine efficiency change patterns [?]. Building upon this, the Global Malmquist-Luenberger (GML) index is constructed to decompose and measure green total factor productivity (GTFP). This study employs the super-efficiency EBM-GML model to calculate urban green development efficiency in the Yellow River Basin, with the formula as follows:

$$r^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{x_{ij}\lambda_j + s_i^-}{x_{ik}} + \theta}{\frac{1}{s}\sum_{r=1}^{s}\frac{y_{rj}\lambda_j - s_r^+}{y_{rk}} + \phi}$$

Subject to:

$$\sum_{j=1}^{K} \lambda_j = 1, \quad j = 1, 2, 3, \cdots, K$$

$$\sum_{j=1}^{K} x_{ij}\lambda_j + s_i^- = \theta x_{ik}, \quad i = 1, 2, 3, \cdots, m$$

$$\sum_{j=1}^{K} y_{rj}\lambda_j - s_r^+ = \phi y_{rk}, \quad r = 1, 2, 3, \cdots, s$$

$$\sum_{j=1}^{K} z_{pj}\lambda_j + s_p^+ = \phi z_{pk}, \quad p = 1, 2, 3, \cdots, q$$

$$\lambda_j \geq 0, \quad s_i^- \geq 0, \quad s_r^+ \geq 0, \quad s_p^+ \geq 0$$

Where: r^* represents the comprehensive efficiency value; m, s, and q denote the number of input, expected output, and non-expected output indicators, respectively; K is the number of decision-making units; s_i^-, s_r^+, and s_p^+ are slack variables for inputs, expected outputs, and non-expected outputs; x_{ik}, y_{rk}, and z_{pk} represent the ith input, rth expected output, and pth non-expected output of the kth decision unit; x_{ij}, y_{rj}, and z_{pj} are the corresponding values of the evaluated unit; ε is the core parameter for the importance of the non-radial part; θ is the efficiency value under radial conditions; ϕ is the output weight; and λ_j is the weight vector.

1.4.2 HP Filter Analysis

HP filter analysis is an important method for characterizing the long-term operational patterns of systems by decomposing time series data into low-frequency trend components and high-frequency cyclical components to reveal evolutionary patterns [**?**]. This study employs HP filter analysis to decompose green development efficiency in Yellow River Basin cities, mapping their cyclical fluctuation patterns. The formula is:

$$X_t = X_t^T + X_t^C, \quad t = 1, 2, 3, \cdots, T$$

Where X_t is the economic time series; X_t^C is the cyclical component; X_t^T is the trend component in the system; $C(L)$ is the lag operator polynomial; L is the lag operator; λ is the smoothing parameter; and T is the year. The HP filter separates the X_t sequence by solving the minimization problem:

$$\min \sum_{t=1}^{T} [(X_t - X_t^T)^2 + \lambda(C(L)X_t^T)^2]$$

1.4.3 Spatiotemporal Interaction Analysis Method

The LISA time path reveals the dynamic characteristics of variables within a certain spatiotemporal scope by illustrating their movement in Moran scatterplot coordinates [?]. This study compares the migration of green development efficiency attribute values and spatial lag values for Yellow River Basin cities, interpreting their spatiotemporal interaction features. The formulas are:

$$U_i = \frac{\sum_{t=1}^{T-1} d_{i,t,t+1}}{d_{i,1,T}}$$

$$\beta_i = \frac{\sum_{t=1}^{T-1} d_{i,t,t+1}}{\sum_{t=1}^{T-1} |d_{i,t,t+1}|}$$

Where: U_i is the relative length; β_i is the curvature; N is the number of cities; $d_{i,t,t+1}$ is the movement distance of city i from year t to $t+1$; $d_{i,1,T}$ is the migration distance of city i from the first to the last year; and T is the year. If $U_i > 1$ and $\beta_i > 1$, it indicates strong dynamics in the local spatial structure and dependency direction of urban green development efficiency; conversely, it suggests relative stability.

Spatiotemporal Interaction Visualization
By calculating the covariance correlation coefficients of green development efficiency spatiotemporal movement trajectories, the competitive and cooperative relationships among cities are visualized through spatiotemporal topology networks [?]. Based on correlation coefficient magnitudes, four association types are identified: strong positive correlation (0.5–1.0), weak positive correlation (0.0–0.5), weak negative correlation (-0.5–0.0), and strong negative correlation (-1.0–-0.5). When the value exceeds 0, it indicates positive correlation, suggesting adjacent cities are in a positive synergistic state during spatiotemporal changes. When below 0, it indicates negative correlation, suggesting spatiotemporal competition. A value of 0 suggests no dynamic association between adjacent cities.

1.4.4 Fuzzy-Set Qualitative Comparative Analysis (fsQCA)

fsQCA offers advantages in explaining the interdependence of configurational phenomena and the complexity of causal relationships through multiple combinations of antecedent conditions, while further addressing partial membership and change issues [?]. This method employs coverage and consistency metrics to measure causal relationships between antecedent variables (and their combinations) and outcome variables, gradually identifying how different elements connect to produce outcomes [?]. This study uses fsQCA to effectively identify how various factors jointly influence improvement pathways for urban green development efficiency in the Yellow River Basin. The formulas are:

$$\text{Consistency}(X_i \le Y_i) = \frac{\sum_{i=1}^{N} \min(X_i, Y_i)}{\sum_{i=1}^{N} X_i}$$

$$\text{Coverage}(X_i \le Y_i) = \frac{\sum_{i=1}^{N} \min(X_i, Y_i)}{\sum_{i=1}^{N} Y_i}$$

Where: A_i is the membership degree of the ith city' s green development efficiency influencing factors to the antecedent combination; B_i is the membership degree of the ith city' s green development level to the outcome variable. If Consistency > 0.8, the antecedent variable is considered a sufficient condition for the outcome; if Consistency > 0.9, it is considered a necessary condition. Coverage indicates the explanatory power of the selected configuration for the analysis results.

2.1.1 Temporal Evolution Characteristics

As shown in Figure 2, green development efficiency in Yellow River Basin cities demonstrates an increasing trend, rising from 0.509 in 2005 to 0.651 in 2020. The Guanzhong Plain Urban Agglomeration shows the largest increase, growing by 29.024% compared to the base period. The Hubao-E-Yu and Shandong Peninsula urban agglomerations generally exceed the average level, while the Jinzhong, Zhongyuan, Ningxia Yellow River, and Lanzhou-Xining urban agglomerations lag behind.

Using Eviews 7.0 for HP filter decomposition of the study area' s green development efficiency yields its trend and cyclical components. Following the "peak-to-peak" method, the evolution cycle is divided into three stages: "fluctuation—improvement—symbiosis."

2005-2010: Fluctuating Development
The Ningxia Yellow River Urban Agglomeration suffered from persistent drought and frequent illegal water extraction. The Zhongyuan and Jinzhong urban agglomerations experienced severe gravitational erosion, with continuously increasing soil erosion area. Green development efficiency improved under multiple constraints but traditional extensive development patterns remained largely unchanged.

2010-2015: Significant Improvement
Guanzhong Plain Urban Agglomeration implemented comprehensive slope farmland management through risk elimination and reinforcement. Jinzhong Urban Agglomeration strengthened maintenance of large and medium-sized check dams, achieving information-based and scientific management. Zhongyuan Urban Agglomeration developed intensive models combining planting and breeding, constructing ecological agriculture circular industry chains. Through collaborative efforts, green development efficiency improved notably.

2015–2020: Gradual Stabilization
With successive implementation of the *National Key Ecological Function Reserve Planning Outline*, *National Ecologically Fragile Area Protection Planning Outline*, and *National Key Ecological Function Transfer Payment Measures*, collaboration among Yellow River Basin cities continuously strengthened. The Lanzhou-Baiyin Economic Zone in Gansu, Yinchuan-Shizuishan in Ningxia, and the Shanxi-Shaanxi-Henan Yellow River Golden Triangle gradually assumed their roles as industrial transfer demonstration zones. By optimizing spatial allocation of land, capital, and technology production factors, megacities achieved functional slimming, volume reduction, and efficiency enhancement.

2.1.2 Spatial Differentiation Characteristics

Following the classification method of Guo et al. [**?**], green development efficiency is categorized into four types: low efficiency (0.00–0.25), relatively low efficiency (0.25–0.50), relatively high efficiency (0.50–0.75), and high efficiency (0.75–1.00). Spatial visualization analysis using ArcGIS 10.2 reveals (Figure 3):

2005: Low and relatively low efficiency types dominated, accounting for 37.931% and 34.483% respectively. Green development efficiency weakened from the center to the periphery, showing a "high in the middle, low around" pattern.

2010: Low-efficiency cities increased to 53.448%, while relatively low-efficiency cities decreased to 24.138%. Only 4 cities achieved high efficiency (6.897%), primarily distributed in the Hubao-E-Yu and Guanzhong Plain urban agglomerations.

2015: Low-efficiency cities decreased to 20.690%, while high-efficiency cities increased to 11 (18.966%). High-efficiency cities were mainly concentrated in the Hubao-E-Yu and Guanzhong Plain urban agglomerations, showing modular agglomeration distribution.

2020: Overall green development efficiency declined slightly, with relatively low-efficiency cities increasing to 41.379% and high-efficiency cities decreasing to 14 (24.138%). Thus, while green development efficiency has improved significantly, its non-equilibrium characteristics remain prominent, with polarization effects still present and intercity collaborative capabilities requiring strengthening.

2.1.3 Spatiotemporal Interaction Characteristics

LISA Time Path Relative Length
Figure 4 shows that 47 cities have relative lengths less than 1, confirming strong robustness in the local spatial structure of green development efficiency. The ranking of sub-urban agglomerations is: Jinzhong (0.589), Hubao-E-Yu (0.612), Guanzhong Plain (0.658), Zhongyuan (0.721), Shandong Peninsula (0.745), Ningxia Yellow River (0.768), and Lanzhou-Xining (0.791). This

indicates that Shandong Peninsula, Zhongyuan, and Jinzhong urban agglomerations have relatively stable local spatial structures with certain migration inertia, while Hubao-E-Yu, Guanzhong Plain, and Ningxia Yellow River urban agglomerations show stronger spatial mobility.

LISA Time Path Curvature
During the study period, all curvature values exceed 1, indicating strong volatility in spatial movement directions. The distribution characteristics are: Jinzhong Urban Agglomeration (1.897), Hubao-E-Yu (1.745), Guanzhong Plain (1.689), Zhongyuan (1.534), Shandong Peninsula (1.423), Ningxia Yellow River (1.367), and Lanzhou-Xining (1.256). Jinzhong, Hubao-E-Yu, and Guanzhong Plain urban agglomerations exhibit greater spatial movement direction fluctuations. Cities like Tongchuan, Dezhou, and Luoyang show strong volatility, mostly located in provincial border zones and influenced by overlapping effects of high and low value areas.

Spatiotemporal Interaction Correlation Characteristics
Figure 5 reveals that the regional spatiotemporal network pattern is dominated by positive correlations, exceeding 78.261%, with 21.739% of cities showing negative correlations. This indicates deepening collaboration in green development efficiency among Yellow River Basin cities, though spatiotemporal competition persists in some areas, with spatial cooperation outweighing competition. Specifically, Tai’ an-Linyi, Linfen-Lüliang, and Yangquan-Xinzhou show strong negative correlations, as these cities differ significantly in natural resource endowments, water conservation capacity, industrial structure, development models, and governance capabilities, leading to notable green development efficiency imbalances. In contrast, Yantai-Weifang, Zhengzhou-Jiaozuo, and Yinchuan-Wuzhong demonstrate strong positive correlations, having achieved positive green development efficiency growth through deepening watershed governance systems, market-oriented reforms, and integrated application of hard engineering measures and flexible storage approaches.

2.2.1 Selection of Antecedent Variables and Variable Calibration

This study uses the average green development efficiency across different periods as the outcome variable and selects six antecedent variables: economic development (GDP per capita), urbanization level (permanent population urbanization rate), industrial structure (proportion of tertiary industry), foreign investment (proportion of foreign direct investment in GDP), technological innovation (proportion of scientific and technological innovation expenditure in GDP), and environmental regulation (comprehensive utilization rate of industrial solid waste). The quartile method is employed to set three anchor points: the upper quartile (75th percentile) as the full membership point, the median (50th percentile) as the crossover point, and the lower quartile (25th percentile) as the full non-membership point. Given that different planning periods have varying policy environments and vision goals, improvement pathways may differ. Therefore, comparative analysis is conducted separately for the "11th Five-Year," "12th Five-Year," and "13th Five-Year" periods (Table 2).

2.2.2 Necessity Analysis of Conditional Variables

Before configurational analysis, fsQCA4.0 software is used to calculate the consistency and coverage of each variable. Results (Table 3) show that all factor consistency values are below 0.9, indicating no single factor constitutes a necessary condition. Improvement pathways are formed through combinations of multiple antecedent variables. Therefore, it is essential to conduct configurational analysis by pooling all antecedent variables.

2.2.3 Sufficiency Analysis of Conditional Configurations

To reveal the influence degree of multiple pathways on urban green development efficiency in the Yellow River Basin, sufficiency analysis of conditional configurations is performed (Table 4). The consistency threshold is set at 0.8, the subset relationship consistency threshold at 0.85, and the case frequency threshold at 1. Using the intermediate solution (which is closer to theoretical reality) and referencing the parsimonious solution, four configuration pathways are identified during the study period, which are categorized into four types based on their common characteristics (Figure 6):

1) Economic-Driven Type
Represented by Configuration H1 in the "11th Five-Year" period, where economic development is the core condition and industrial structure and technological innovation are peripheral conditions. Typical cities include Hohhot, Xining, Baotou, Zibo, Pingdingshan, and Baoji. During this period, Hohhot and Xining enhanced ecological protection effects through expanded capital investment and desertification control. As resource-based cities, Baotou, Zibo, Yulin, and Baoji promoted market-based mine ecological restoration, adjusted industrial structures, and gradually improved energy utilization efficiency.

2) Dual-Driven Type
Represented by Configuration H2 in the "11th Five-Year" period and H3 in the "12th Five-Year" period, where both economic development and technological innovation exist as core conditions simultaneously. Typical cases include Weihai, Tai' an, Xuchang, Shizuishan, Jinzhong, and Changzhi. During this period, Weihai, Tai' an, and Xuchang improved market financing systems and constructed new material industry clusters, continuously enhancing green technology innovation. Shizuishan, Jinzhong, and Changzhi expanded integrated resource development channels, promoted deep processing and refined production in the energy chemical industry, extended the energy industry lifeline, and achieved notable green development efficiency improvements.

3) Resource Integration Type
Represented by Configuration H4 in the "12th Five-Year" period and H5 in the

"13th Five-Year" period, where technological innovation, industrial structure, and environmental regulation are core conditions. Typical cities include Ordos, Weinan, Yangquan, Jincheng, Liaocheng, and Yulin. During this period, Ordos continuously implemented water pollution prevention and control, improving water environment safety. Weinan introduced green and clean technologies to enhance ammonia nitrogen removal rates in urban sewage treatment plants. Yangquan, Jincheng, Liaocheng, and Yulin promoted green development of the coal industry and accelerated intelligent mine transformation, improving green production levels.

4) Comprehensive Improvement Type
Represented by Configuration H6 in the "13th Five-Year" period, where all explanatory factors are present, with economic development, urbanization level, industrial structure, technological innovation, and environmental regulation as core conditions. Typical cities include Zhengzhou, Jinan, Xi' an, Luoyang, Taiyuan, and Lanzhou. During this period, the Yellow River Basin strengthened regional economic ties in the Shanxi-Shaanxi-Henan Yellow River Golden Triangle, constructed the Zhengzhou-Luoyang-Xi'an high-quality development cooperation belt, and progressively improved urban collaborative networks. Jinzhong Urban Agglomeration and Shandong Peninsula Urban Agglomeration conducted in-depth cooperation with the Beijing-Tianjin-Hebei region in technological innovation, cross-border finance, and industrial energy, achieving "one network" coverage of environmental governance and "one line" connectivity of industrial development.

The study finds that economic development and technological innovation exist in all four improvement pathways, with urbanization level, industrial structure, foreign investment, and environmental regulation superimposed to jointly facilitate the overall transition of urban green development efficiency.

2.2.4 Robustness Test

Following Wu et al. [?], robustness tests are conducted: (1) The case frequency threshold is adjusted from 1 to 2, yielding configurations largely consistent with previous results. (2) The full non-membership and full membership anchor points are optimized by adjusting the 25th and 75th percentiles, with results containing existing configurations. (3) The crossover point anchor is adjusted by replacing the median with the 55th percentile, maintaining stability and yielding consistent results. (4) The crossover point is adjusted to the 45th percentile, with recalibrated results remaining consistent with existing configurations.

3 Discussion

This study reveals that urban green development efficiency in the Yellow River Basin exhibits phased, nonlinear, and non-equilibrium characteristics, consistent with conclusions by Chen Minghua [?] and Guo Fuyou [?]. Meanwhile, Meng Wangsheng et al. [?] only analyzed spatiotemporal evolution characteristics of green development efficiency in seven major urban agglomerations in the Yellow River Basin without quantitatively identifying improvement strategies. Compared with previous research, this study' s main contributions include: supplementing the green development efficiency evaluation system by incorporating urban CO2 emissions under the "dual carbon" goals; employing spatiotemporal interaction methods to reveal systematic spatiotemporal evolution characteristics, compensating for existing research deficiencies that only examine regional spatiotemporal evolution patterns; and advancing improvement pathway research to empirical verification through fsQCA.

Nevertheless, this study has limitations requiring further improvement: green development efficiency involves numerous dimensions, and future research should utilize multi-source data to refine the evaluation system design. Additionally, empirical research should further reveal the driving mechanisms underlying spatiotemporal differentiation of urban green development efficiency in the Yellow River Basin, providing academic support for optimizing coordinated human-land relationship regional systems and facilitating high-quality development of cities along the river.

4 Conclusion

(1) **Spatiotemporal Evolution Characteristics**: Urban green development efficiency in the Yellow River Basin shows an increasing trend, rising from 0.509 in 2005 to 0.651 in 2020. The evolution cycle is divided into three stages: "fluctuation—improvement—symbiosis." Green development efficiency weakens from central to peripheral cities, with unbalanced intercity development.

(2) **Spatiotemporal Interaction Characteristics**: The local spatial structure of green development efficiency in the study area demonstrates strong robustness, with highly volatile spatial movement directions. Although intercity collaboration continues to deepen, spatiotemporal competition persists in some regions, with spatial cooperation outweighing competition.

(3) **Optimization Pathways**: Four types of pathways emerge: economic-driven, dual-driven, resource integration, and comprehensive improvement. Economic development and technological innovation are necessary conditions. Combined with urbanization level, industrial structure, foreign investment, and environmental regulation, these factors jointly promote green and high-quality development in Yellow River Basin cities.

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