

SPATIOTEMPORAL EVOLUTION AND TREND PREDICTION ANALYSIS OF INCLUSIVE GREEN EFFICIENCY IN CITIES ALONG THE YELLOW RIVER BASIN IN CHINA

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ABSTRACT. *This paper conducts a study based on the mechanism of coordinated “economy-society-environment” development in the Yellow River Basin. It defines the concept of inclusive green efficiency, measures efficiency levels using the SBM-GML model, and analyzes its spatiotemporal evolution characteristics and future development trends. Kernel density estimation and exploratory spatial data analysis are used to examine its spatiotemporal evolution features. The GM(1,1) model is applied to predicting future development trends. The results show that 1) The inclusive green efficiency of the Yellow River Basin presents a “U” shaped development trend, and the development pattern of backward upstream, rising midstream and developed downstream is manifested in the basin; 2) The overall change of agglomeration level showed a trend of “first decreasing, then rising and then decreasing”; 3) From the perspective of development trend prediction and analysis, the pattern of “high in the east and low in the west” is becoming more and more prominent, and the proportion of high-efficiency areas in the middle reaches of the Yellow River has increased significantly.*

Keywords: Inclusive green efficiency, The Yellow River Basin, Spatiotemporal evolution, Trend prediction

1. **Introduction.** Ensuring that the cities along the Yellow River Basin achieve ‘inclusiveness’ and ‘greenness’ during the process of economic development is of great significance for promoting coordinated and sustainable development in China. Currently, academic research on inclusive green development primarily focuses on conceptual definition and level measurement. Regarding conceptual definition, scholars concentrate on two dimensions. On the one hand, drawing from development economics, this perspective holds that social development requires economic growth while simultaneously necessitating the protection of the environment that underpins development [1,2]. Thus, inclusive green development demands support from three major systems – social, economic, and environmental [3-5]. The principles of inclusiveness, equity, and sustainable development collectively advance the realization of inclusive green development objectives [6,7]. Economic agglomeration and technological innovation serve as crucial pathways for driving inclusive green development [8]. The three systems – social, economic, and environmental – are closely interconnected and mutually reinforcing. Research indicates that ecosystem restoration can generate employment opportunities, enhancing economic efficiency while promoting social equity [9]. On the other hand, from a welfare economics perspective, sustainable economic development is viewed as the fundamental pathway and material

foundation for enhancing social welfare. This approach requires pursuing high-quality, efficient growth within ecological carrying capacity boundaries [10]. The ultimate goal of inclusive green development is to achieve sustainable economic growth [11], thereby elevating social welfare [12]. Regarding horizontal measurement, representative evaluation studies primarily fall into two categories. The first involves constructing evaluation indicator systems, with existing research predominantly employing multidimensional comprehensive evaluation methods such as subjective weighting [13], principal component analysis [14], and entropy weighting [15-17]. These methods assign differentiated weights to different indicators to reflect their relative importance within the overall objective. The second approach analyzes inclusive green efficiency from an input-output perspective. This methodology transcends the limitations of traditional efficiency evaluations that focus solely on economic benefits by incorporating undesirable outputs such as resource consumption and environmental pollution into the analytical framework. Consequently, it provides a more accurate portrayal of comprehensive efficiency levels under sustainable development constraints. Representative approaches include the SBM-DDF (Slack-Based Measure – Directional Distance Function) model [18], the Super-EBM model (Super Efficiency Epsilon-Based Measure) [19,20], and the SBM-GML (Slack-Based Measure – Global Malmquist-Luenberger Index) model [21].

Academic research on inclusive green development has been relatively systematic; however, several shortcomings remain. First, in terms of research subjects, existing studies predominantly focus on inclusive growth and green development, with the construction of measurement indicators for inclusive green development levels still requiring refinement. Second, in terms of spatial scale, existing studies predominantly operate at the provincial level. While recent research has begun to address key strategic regions such as the Yangtze River Economic Belt and the Bohai Rim, studies on cities along China's Yellow River basin remain relatively scarce. Third, regarding research content, literature analyzing spatiotemporal evolution characteristics primarily explores historical development trajectories, with limited analysis of future trends from a spatiotemporal visualization perspective. Given these limitations, this study examines 56 prefecture-level cities in China's Yellow River Basin. It constructs an input indicator system encompassing labor, capital, land, and technology, and develops an output indicator system for both desired and undesired outcomes across economic, social, and environmental dimensions. The SBM-GML model and GM(1,1) model are employed to measure and forecast inclusive green efficiency, supplemented by visualization analysis. This study delves into the spatiotemporal evolution characteristics of inclusive green development efficiency in the Yellow River Basin, aiming to provide theoretical support, empirical insights, and strategic references for achieving high-quality development in the region.

The structure of this article is arranged as follows. The second part analyzes the mechanism of coordinated development of the economy, society, and ecology in the Yellow River Basin. The third part clarifies the research area and data sources. The fourth part introduces the research methods used. The fifth part is an analysis of the research results. The sixth part summarizes the research conclusions and outlook.

2. Mechanism Analysis. In the traditional input-output system, economic growth relies on inputs such as land, labor, and capital, but this often comes at the expense of declining environmental quality [22]. Environmental degradation erodes the resource base for economic development, leading to the decline of industries that depend on resource inputs and constraining overall economic growth [23]. The transfer of urban industry and consumer waste to rural areas undermines livelihoods based on natural resources, damages farmers' sources of income, and exacerbates the urban-rural income gap.

Figure 1 shows under the guidance of the high-quality development strategy [24], economic development will take account of ecological and environmental protection. The optimization of the ecological environment provides resources and landscapes for industries such as agriculture, forestry, and tourism, offering stable employment opportunities for society [25]. This, in turn, achieves an optimization of the industrial structure, forming a virtuous cycle where the economic system empowers the ecological system, the ecological system empowers the social system, and the social system again empowers the economic system. At the same time, the optimization of the ecological environment can ensure the continuous supply of production factors, guarantee a steady improvement in economic levels, provide public service support to society, enhance the overall quality of residents, and subsequently provide a foundation for the protection of the ecological environment [26], thus forming a virtuous cycle in which the ecological system empowers the economic system, the economic system empowers the social system, and the social system again empowers the ecological system.

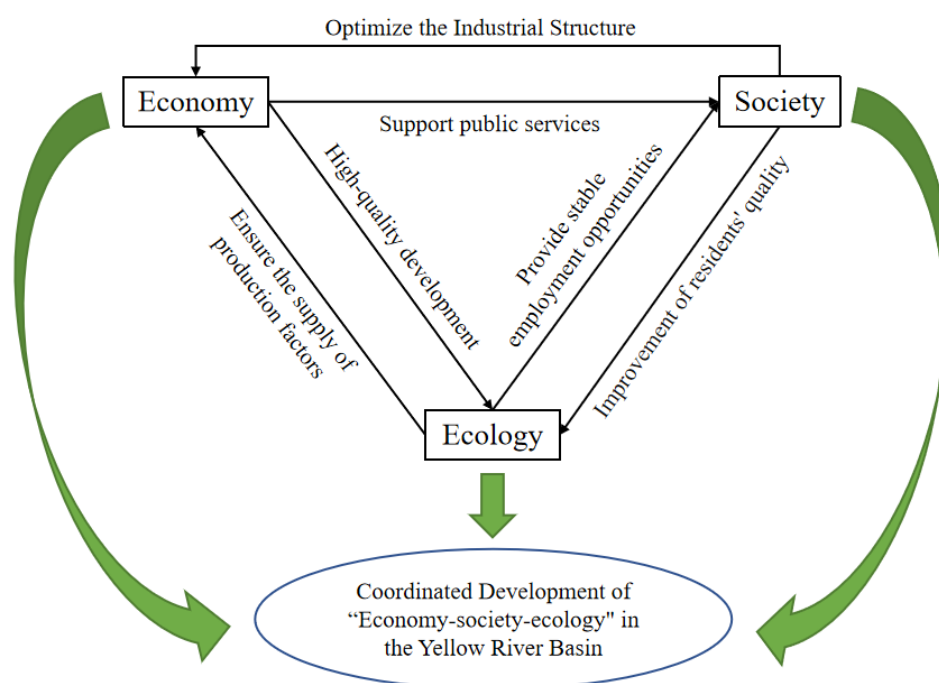


FIGURE 1. Analysis diagram of the mechanism for coordinated economic, social, and ecological development in the Yellow River Basin

It is evident that the coordinated development of the economic, social, and ecological systems plays a vital role in the nation's sustainable economic growth. Inclusive green development, which encompasses all three systems, serves as the key pathway to transition from quantitative expansion to high-quality development. This concept accurately captures the profound interdependence among economic, social, and ecological systems, clearly defining the ultimate goal of development as benefiting all people while rejecting the outdated logic of polluting first and cleaning up later. This philosophy is committed to ensuring that the economic opportunities and ecological benefits generated by the green transition are shared by all members of society, particularly those in marginalized regions and vulnerable groups. This encompasses both broadening income sources through the creation of green jobs and safeguarding the health rights of all by improving environmental quality. Consequently, it effectively narrows disparities between urban and rural areas, regions, and groups during the green development process, thereby strengthening

the foundation for social harmony. Integrating ecological conservation into the economic development process means not only enhancing resource efficiency through technological innovation but also transforming ecosystems into natural capital that underpins emerging industries like eco-tourism and green agriculture. This reshapes regional core competitiveness, injecting sustainable, high-quality green momentum into economic growth.

Guided by the concept of inclusive green development, the three systems have moved beyond zero-sum competition toward a positive-feedback virtuous cycle, representing a crucial and viable pathway to sustainable development.

3. Overview of the Study Area and Data Sources.

3.1. Research area division. Considering the significant differences in natural geographical characteristics, stages of economic development, and ecological functions among cities along the Yellow River Basin, this study categorizes the 56 prefecture-level cities in the basin into three types: upper, middle, and lower reaches. This classification aims to precisely reveal the regional heterogeneity of inclusive green efficiency and its underlying drivers. The specific categorization is shown in Figure 2 and Table 1.

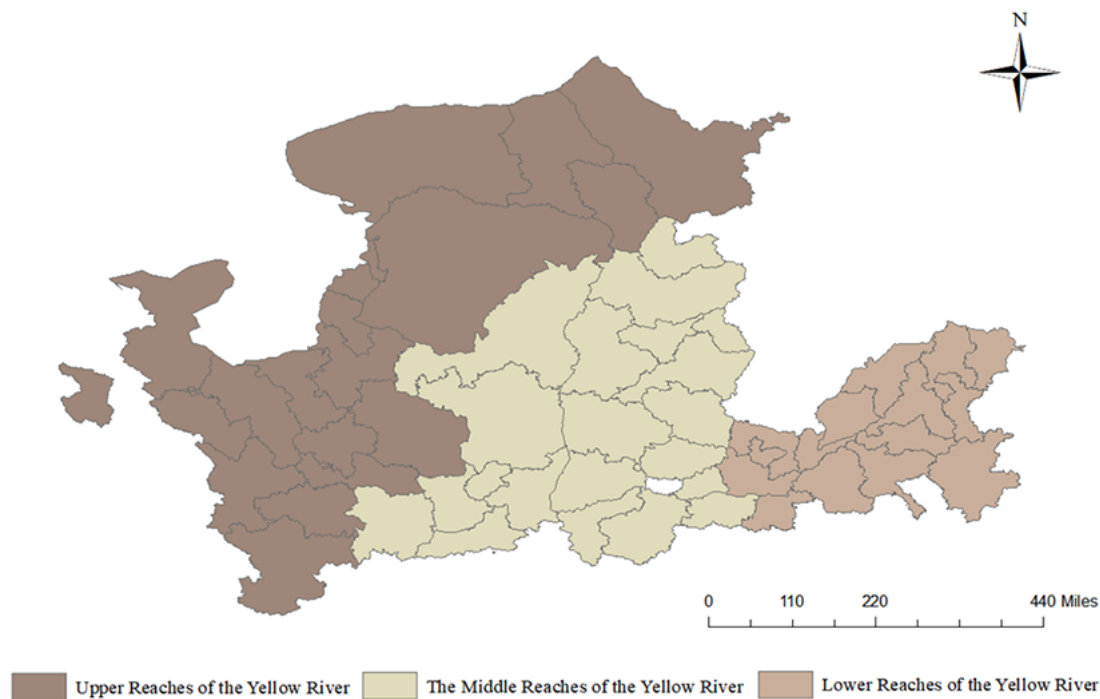


FIGURE 2. Schematic diagram of the research area

3.2. Data processing. This study primarily selected data samples from 56 prefecture-level cities in the Yellow River Basin covering the period from 2003 to 2022. The data mainly originated from the Statistical Yearbook of Chinese Cities, the Statistical Yearbook of Chinese Urban Construction, and statistical yearbooks and bulletins publicly released by the statistical departments of each prefecture-level city.

Inclusive green development represents a new category synthesizing inclusive growth and green development, emphasizing that economic growth must prioritize both “equitable sharing” and “resource and environmental sustainability”. Within this framework, inclusive efficiency excludes consideration of undesirable environmental outputs, while green efficiency disregards undesirable social outputs. Therefore, in selecting indicators,

TABLE 1. Sample division of the research area

Region	Province (Autonomous Region)	Prefecture-level city
The upper reaches of the Yellow River	Qinghai Province	Xining
	Ningxia Hui Autonomous Region	Yinchuan, Shizuishan, Wuzhong, Zhongwei, Guyuan
	Gansu Province	Lanzhou, Baiyin, Tianshui, Wuwei, Pingliang, Qingyang, Dingxi, Longnan
	Inner Mongolia Autonomous Region	Hohhot, Baotou, Wuhai, Ordos, Bayannur, Ulanqab
The middle reaches of the Yellow River	Shaanxi Province	Xi'an, Tongchuan, Baoji, Xianyang, Weinan, Yan'an, Yulin
	Shanxi Province	Taiyuan, Yangquan, Changzhi, Jincheng, Shuozhou, Jinzhong, Yuncheng, Xinzhou, Linfen, Lvliang
	Henan Province	Zhengzhou, Luoyang, Jiaozuo, Sanmenxia
The lower reaches of the Yellow River	Henan Province	Kaifeng, Anyang, Hebi, Xinxiang, Puyang
	Shandong Province	Jinan, Zibo, Dongying, Jining, Tai'an, Linyi, Dezhou, Liaocheng, Binzhou, Heze

this paper incorporates measures of social inclusiveness alongside traditional environmental output metrics, represented by the year-end registered urban unemployment rate (ten thousand persons), the urban-rural disposable income ratio (%), and the urban-rural per capita consumption expenditure ratio (%). Regarding input indicators, this paper adds scientific and technological investment metrics to the traditional labor, capital, and land inputs, represented by scientific and technological expenditure (billion yuan). All economic data are converted to constant 2003 prices using price indices. Descriptive statistical analysis of the relevant variables is shown in Table 2.

4. Research Methods.

4.1. **SBM-GML (Slack-Based Measure – Global Malmquist-Luenberger Index) model.** In this paper, an SBM-GML model is constructed to measure inclusive green efficiency, and the global SBM directional distance function is expressed as

$$\begin{aligned}
 S_V^G(x^{t,k'}, y^{t,k'}, b^{t,k'}, g^x, g^y, g^b) &= \max_{s^x, s^y, s^b} \frac{\frac{1}{N} \sum_{n=1}^N \frac{s_n^x}{g_n^x} + \frac{1}{M+I} \left(\sum_{m=1}^M \frac{s_m^y}{g_m^y} + \sum_{i=1}^I \frac{s_i^b}{g_i^b} \right)}{2} \\
 s.t. \quad &\sum_{t=1}^T \sum_{k=1}^K z_k^t x_{kn}^t + s_n^x = x_{k'n}^t, \quad \forall n; \quad \sum_{t=1}^T \sum_{k=1}^K z_k^t y_{km}^t - s_m^y = y_{k'm}^t, \quad \forall m; \\
 &\sum_{t=1}^T \sum_{k=1}^K z_k^t b_{ki}^t + s_i^b = b_{k'i}^t, \quad \forall i; \quad \sum_{k=1}^K z_k^t = 1, \quad z_k^t \geq 0, \quad \forall k; \quad s_n^x \geq 0, \quad \forall n; \\
 &s_m^y \geq 0, \quad \forall m; \quad s_i^b \geq 0, \quad \forall i
 \end{aligned} \tag{1}$$

$x^{t,k'}$, $y^{t,k'}$ and $b^{t,k'}$ represent the vectors of input, expected output, and non-expected output in region k at time t , respectively. g^x , g^y and g^b represent the direction vectors of reduced input, increased expected output, and reduced non-expected output, respectively.

TABLE 2. Construction and descriptive statistics of input-output indicators for the efficiency of inclusive green development in the Yellow River Basin

Standard layer	Element layer	Indicator layer	Unit	Observation number	Mean value	Standard deviation	Minimum value	Maximum value
Input metrics	Labor input	The number of employees in the unit at the end of the year	Ten Thousand People	1120	39.27	34.18	4.84	219.82
	Capital input	Investment in fixed assets	Billion Yuan	1120	1130.25	1349.06	21.24	9296.47
	Land input	Urban construction land area	Square Kilometer	1120	99.41	105.94	4.99	786.35
		The total annual water supply	Ten Thousand Cubic Meters	1120	9300.37	11059.76	105.00	89259.52
	Investment in science and technology	Expenditure on science and technology	Ten Thousand Yuan	1120	33489.25	72437.63	66.00	854910.00
Output metrics	Economic expected output	Regional gross domestic product	Billion Yuan	1120	1545.75	1727.58	35.23	12935.00
		Local general fiscal budget revenue	Billion Yuan	1120	117.67	162.43	1.22	1259.21
	Social undesirable outputs	The number of registered unemployed people in urban areas at the end of the year	People	1120	19510.84	18081.48	409.00	126515.00
		The ratio of per capita disposable income between urban and rural areas	%	1120	2.80	1.22	1.60	23.17
		The ratio of per capita consumption expenditure between urban and rural areas	%	1120	2.50	0.71	0.74	6.20
	Environmental undesired outputs	Discharge volume of industrial wastewater	Ten Thousand Tons	1120	4841.26	4599.62	18.61	22522.00
		Industrial sulfur dioxide emissions	Ten Thousand Tons	1120	6.05	5.80	0.01	33.72
		Industrial smoke (dust) emissions	Ten Thousand Tons	1120	4.05	18.50	0.01	516.88

s_n^x , s_m^y and s_i^b are slack variables, with s_n^x , s_m^y and s_i^b being positive indicating that actual input is greater than boundary input, actual expected output is less than boundary output, and actual non-expected output is greater than boundary output.

Based on the global SBM directivity function, the GML index can be expressed as

$$GML_t^{t+1} = \frac{1 + S_V^G(x^t, y^t, b^t; g)}{1 + S_V^G(x^{t+1}, y^{t+1}, b^{t+1}; g)} \quad (2)$$

The GML index represents the inclusive green efficiency index, which can be decomposed into two components: inclusive green technological efficiency change (GEC) and inclusive green technological change (GTC). This paper employs a cumulative GML index approach to measure inclusive green efficiency levels. Labor, capital, land, and technology are treated as input variables, while economic expected output, social non-expected output, and environmental non-expected output serve as output variables. This constructs an input-output system aligned with the essence of inclusive green development.

4.2. Kernel density estimation. Nuclear density analysis is primarily employed to study spatially non-uniform distributions. By utilizing continuous density curves to describe the distribution dynamics of variables, it reveals their spatial location, morphological characteristics, and extent. This paper employs continuous density curves to characterize the distribution patterns of inclusive green efficiency across the Yellow River Basin and its upper, middle, and lower reaches. The specific formula is as follows:

$$f_j(y) = \frac{1}{n_j h} \sum_{i=1}^{n_j} K\left(\frac{y_{ji} - y}{h}\right) \tag{3}$$

$n_j h$ denotes the number of observations; h represents the bandwidth; y_{ji} is the observed value; y is the mean; $K(\cdot)$ is the kernel function.

4.3. Exploratory spatial data analysis. The exploratory spatial analysis method typically visualizes the spatial distribution patterns of research subjects, measuring the degree of spatial association through global and local spatial autocorrelation metrics. This study employs global spatial autocorrelation to identify whether inclusive green efficiency values exhibit spatial clustering across the entire Yellow River Basin. Local spatial autocorrelation is used to examine the clustering relationships and evolutionary characteristics of inclusive green efficiency values among adjacent prefecture-level cities. The specific formulas are as follows:

$$I = \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^n \sum_{j=1}^n w_{ij}} \tag{4}$$

Among them, x_i and x_j represent the attribute values of geographic units in regions i and j , respectively. \bar{x} is the average of the attribute values of all regions. w_{ij} is the spatial weight matrix, indicating the adjacency relationship between regions i and j . n is the number of measured regions. S^2 is the sample variance.

Local Moran Index Formula:

$$I_i = \frac{(x_i - \bar{x})}{S^2} \sum_{j=1}^n w_{ij} (x_j - \bar{x}) \tag{5}$$

4.4. GM(1,1) (Grey Model First Order One Variable) model. The GM(1,1) model based on grey forecasting theory is widely applied in dynamic prediction research. This model processes raw data to identify patterns in system fluctuations and generates highly regular data sequences. It then establishes corresponding differential equation models to predict future trends. The prediction principle and steps are as follows.

Establish the original non-negative time data sequence: $X^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)\}$. Perform cumulative summation on the original sequence to obtain the cumulative sequence: $X^{(1)} = \{x^{(1)}(1), x^{(1)}(2), \dots, x^{(1)}(n)\}$. Perform adjacent averaging on $X^{(1)}$ to obtain the sequence: $Z^{(1)} = \{z^{(1)}(1), z^{(1)}(2), \dots, z^{(1)}(n)\}$, where $z^{(1)}(k) = \frac{1}{2}[x^{(1)}(k) + x^{(1)}(k - 1)]$.

Construct the GM(1,1) (Gray Differential Equation Model):

$$x^{(0)}(k) + az^{(1)}(k) = b \tag{6}$$

Among them: a is the developing gray number, b is the endogenous control gray number, and the corresponding whitening differential equation is as follows:

$$\frac{dx^{(1)}(t)}{dt} = -\hat{a}^{(1)}(t) + \hat{b} \tag{7}$$

Solve for

$$\hat{x}^{(1)}(k+1) = \left[x^{(0)}(1) - \frac{\hat{b}}{\hat{a}} \right] e^{\hat{a}k} + \frac{\hat{b}}{\hat{a}} \quad (8)$$

Perform a single iterative reduction to generate the predicted value:

$$\hat{x}^{(0)}(k+1) = x^{(1)}(k+1) - x^{(1)}(k) \quad (9)$$

Subsequently obtain the predicted sequence:

$$\hat{X}^{(0)} = \{ \hat{x}^{(0)}(1), \hat{x}^{(0)}(2), \dots, \hat{x}^{(0)}(n) \} \quad (10)$$

The GM(1,1) model is particularly well-suited for forecasting data sequences with small sample sizes but exhibiting overall trends. As an emerging complex indicator, inclusive green efficiency typically has limited historical observational data, making it an ideal candidate for gray forecasting models. These models can uncover intrinsic evolutionary patterns within the limited efficiency data available.

5. Results and Analysis.

5.1. Temporal evolution analysis of inclusive green efficiency in the Yellow River Basin. Based on input-output data from the Yellow River Basin, Matlab software was used to calculate the inclusive green efficiency of 56 prefecture-level cities in the basin from 2003 to 2022. The trend is illustrated in Figure 3. Overall, the basin exhibits a U-shaped trajectory of fluctuating declines followed by fluctuations in growth. This pattern reflects the region's transition from extensive development to sustainable green growth, alongside a shift in resource allocation from partial concentration to equitable distribution. The Yellow River Basin is progressively exploring a low-consumption, high-efficiency economic development model. Notably, in 2016, the 13th Five-Year Plan Outline adopted by the National People's Congress explicitly called for "establishing a green financial system, developing green credit and green bonds, and setting up green development funds". In the same year, seven ministries and commissions including the People's Bank of China and the Ministry of Finance jointly issued the "Guiding Opinions

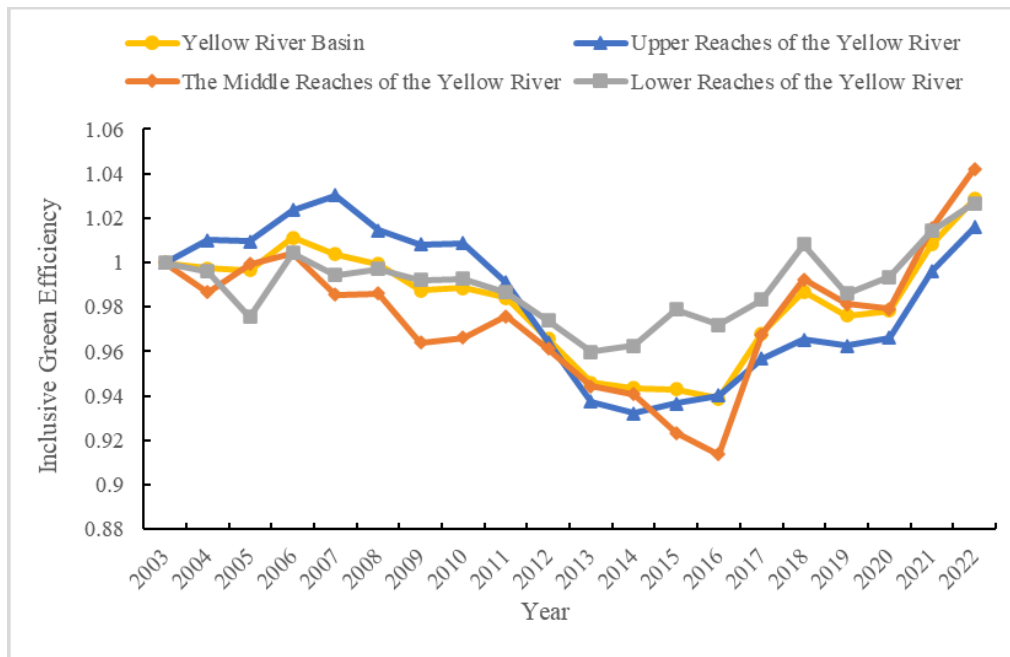


FIGURE 3. Temporal evolution trend of inclusive green efficiency in the Yellow River Basin from 2003 to 2022

on Establishing a Green Financial System”. The establishment of this policy framework injected momentum into inclusive, green, and efficient growth, leading to an upward trend in inclusive green efficiency within the Yellow River Basin after 2016.

Within the basin, the level of inclusive green efficiency has gradually shifted from “upstream > downstream > midstream” to “downstream > midstream > upstream”, revealing an overall development pattern where the upstream lags behind, the midstream rises, and the downstream thrives. This pattern arises because the Yellow River’s downstream region possesses relatively abundant water, soil, and population resources. Its rapid development across primary, secondary, and tertiary industries, coupled with diverse economic activities, has fostered high economic growth, ample employment opportunities, and favorable conditions for equitable resource distribution. Although environmental costs have been incurred during this development, the region’s rich foundational resources have enabled continuous transformation and optimization of traditional industries, sustaining high efficiency levels. As a vital energy production base for China, the middle reaches of the Yellow River Basin have experienced significant ecological pollution in its cities due to traditional, extensive economic growth patterns. Consequently, its level of inclusive green development lags behind that of the downstream region. The upper reaches of the Yellow River Basin, characterized by sparse population and fragile natural ecosystems, exhibit pronounced regional economic imbalances. This results in slower transformation of old and new growth drivers across cities, poorer sharing of development outcomes, and ultimately, low development efficiency.

Figure 4 illustrates the temporal trends of inclusive green efficiency, inclusive green technological progress, and inclusive green technological efficiency in the Yellow River Basin. The trend chart reveals that inclusive green technological progress follows a trajectory similar to that of inclusive green efficiency, while inclusive green technological efficiency exhibits a relatively stable development pattern. It can be seen that inclusive green technological progress is a key factor affecting efficiency values. Technological progress and technological efficiency respectively reflect a region’s adoption of advanced technologies

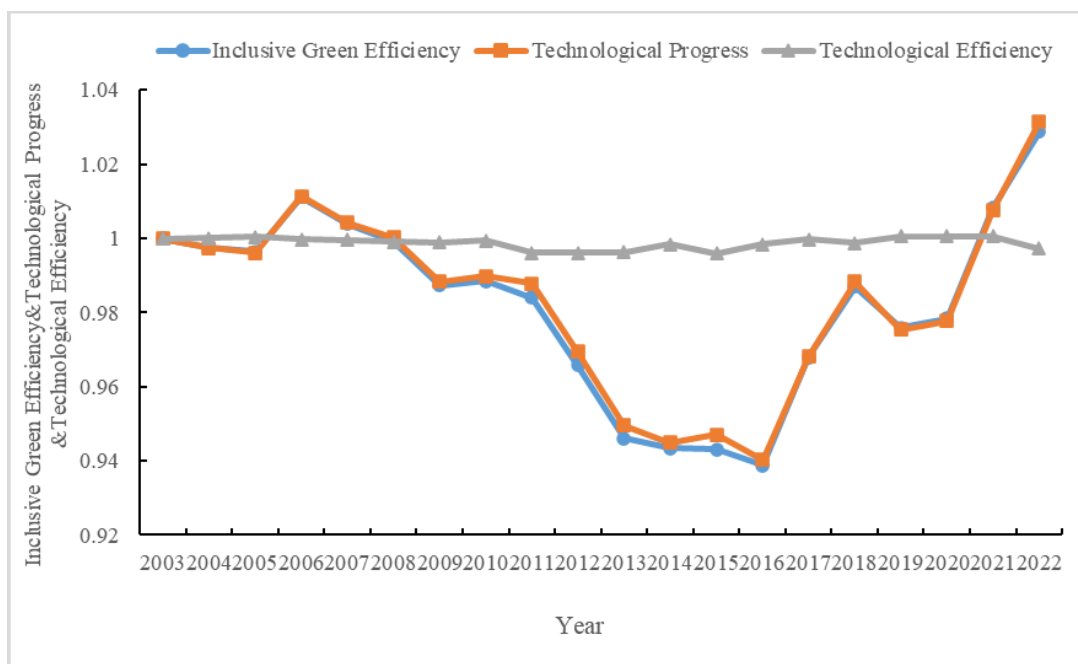


FIGURE 4. Temporal evolution trend of inclusive green efficiency, technological progress, and technological efficiency in the Yellow River Basin

and its resource allocation capabilities. As shown in the figure, the capacity for allocating technological resources and their utilization efficiency have remained relatively stable. The inclusive green efficiency development level in the Yellow River Basin exhibits a U-shaped trend – initially declining before increasing – primarily due to the following factors: During the early phase of advanced technology adoption, the region experienced rapid economic growth characterized by extensive production technologies dominating the landscape. As the economy entered a phase of steady growth, technological adoption increasingly considered the environmental and social impacts of production activities. This led to a gradual shift from a pattern characterized by “high energy consumption and pollution, coupled with high social distribution disparities” to one marked by “low energy consumption and pollution, alongside low social distribution disparities”. Therefore, to enhance inclusive green efficiency in the future, efforts should focus on two key areas: On the one hand, further introducing and promoting advanced green technologies with strong capabilities to balance environmental pollution control and equitable social development; On the other hand, strengthening regional resource integration capabilities to improve technological efficiency and establish a scale-driven economic growth model.

Figure 5 presents kernel density estimates of inclusive green efficiency for the Yellow River Basin as a whole, its upper reaches, middle reaches, and lower reaches. Across the entire basin, the center of gravity of the curve exhibits a trend of “shifting leftward first, then rightward” over time, indicating that the overall level of inclusive green efficiency first declined and then improved – a pattern consistent with the objective facts discussed earlier. The peak height gradually transforms from a sharp, towering shape to

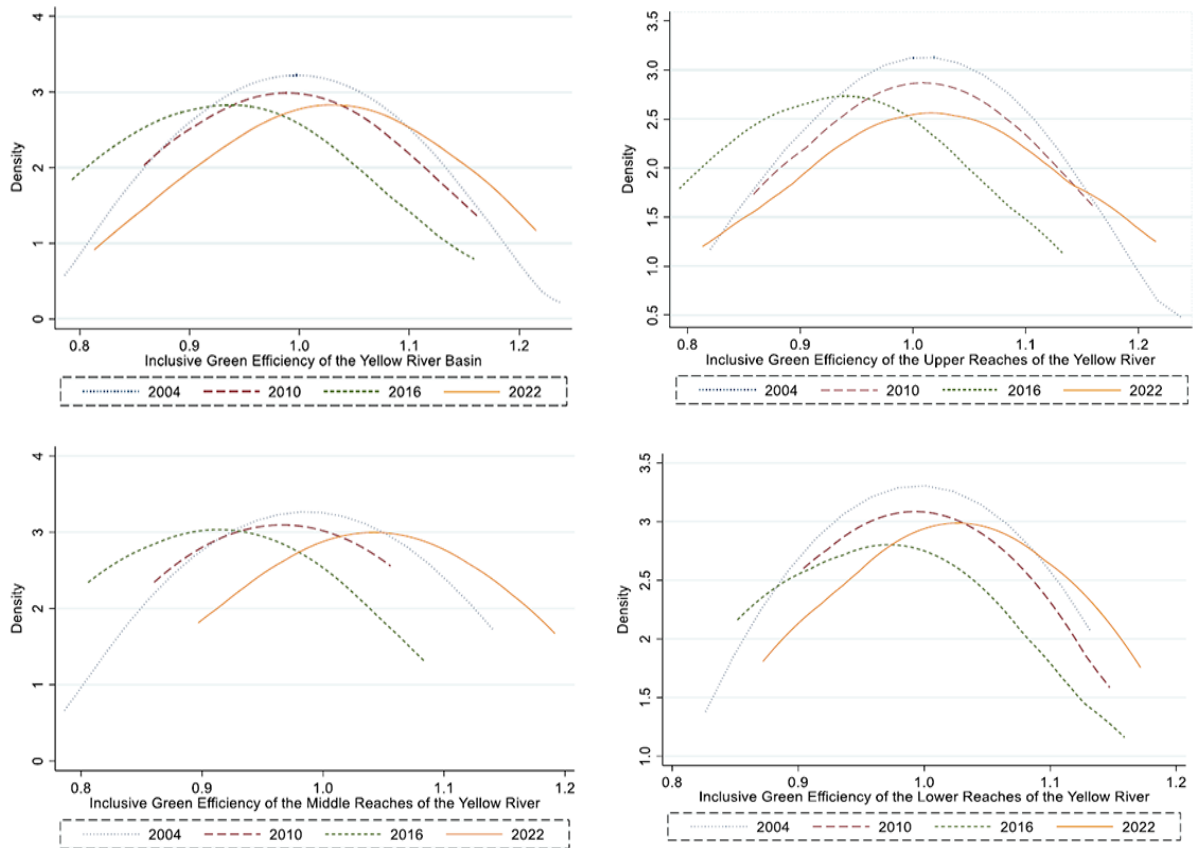


FIGURE 5. Kernel density curves of inclusive green efficiency in the Yellow River Basin

a broad, low-lying form, indicating that regional disparities in inclusive green efficiency are widening. The nuclear density curve exhibits a right-tailing pattern, characterized by an extended and elevated trend on the right side. This indicates an increasing proportion of high-value zones with inclusive green efficiency.

When analyzed by sub-basin, the center of gravity of the kernel density curve in the three major basins of the Yellow River exhibits an evolutionary trend of “shifting left first, then shifting right”, with regional variations in the migration span. This indicates that the overall level of inclusive green efficiency shows an evolutionary trend of declining first and then improving, but the magnitude of change varies across basins. The peak height of the kernel density curve exhibits a declining trend in the upper and middle reaches of the Yellow River Basin, indicating that regional disparities in inclusive green efficiency are widening. Conversely, the peak height in the lower reaches first decreases and then increases, suggesting that these regional differences first expand and then narrow.

5.2. Spatial evolution analysis of inclusive green efficiency in the Yellow River Basin. Figure 6 presents the spatial distribution pattern of inclusive green efficiency in the Yellow River Basin, mapped using the natural breakpoint classification method. Spatially, high-efficiency zones are primarily concentrated in the upper and lower reaches of the Yellow River, while low-efficiency zones are predominantly distributed in the middle reaches. Efficiency values in the middle and lower reaches exhibit relatively uniform distribution, with overall efficiency levels being comparable. Regarding spatial evolution trends, over time, efficiency values in the upper reaches exhibit increasingly pronounced polarization. Meanwhile, the proportion of high-efficiency areas in the middle and lower reaches

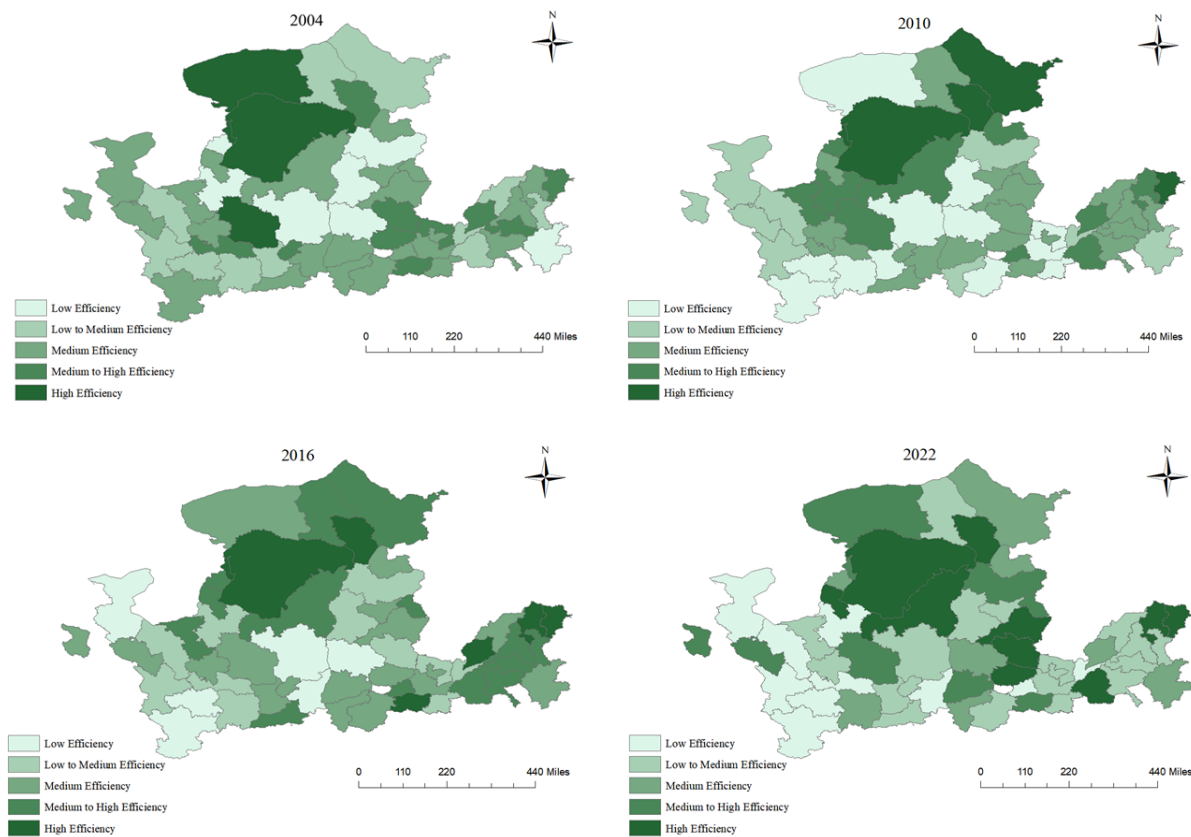


FIGURE 6. Characteristics of the realistic pattern of inclusive green efficiency in the Yellow River Basin

gradually increases, with efficiency values consistently maintaining a relatively uniform distribution pattern. Across the entire Yellow River Basin, a spatial distribution pattern of “higher in the east, lower in the west” has gradually emerged. High-efficiency zones typically possess superior ecological endowments and advanced industrial structures, enabling them to support increased desired outputs while reducing undesired outputs. This results in relatively high inclusive green efficiency.

Table 3 presents the global autocorrelation statistics for inclusive green efficiency in the Yellow River Basin. Regarding spatial correlation characteristics, the global Moran’s I index for efficiency values during the study period passed significance tests in most years, indicating a pronounced spatial dependency. The calculation results show that all significant global Moran’s I values are positive, indicating that cities with high inclusive green efficiency in the Yellow River Basin tend to be spatially proximate to other high-efficiency cities, thus exhibiting spatial clustering effects. The overall trend of Moran’s I changes follows a pattern of “initial decline, subsequent increase, and final decline”: Between 2004 and 2015, the Moran’s I fluctuated downward. From 2016 to 2017, the index values showed an increasing trend, peaking in 2016 and 2017. Subsequently, from 2018 to 2022, it exhibited a fluctuating downward trend. This indicates that regional disparities in inclusive green efficiency within the Yellow River Basin first narrowed, then widened, before narrowing again.

TABLE 3. Global autocorrelation statistical analysis of inclusive green efficiency in the Yellow River Basin

Year	Moran’s I	Z	P	Year	Moran’s I	Z	P
2004	−0.07	−0.66	0.51	2014	0.09	1.46	0.14
2005	−0.11	0.09	0.92	2015	0.18	2.68	0.01
2006	0.04	0.75	0.45	2016	0.24	3.46	0.00
2007	0.17	2.19	0.03	2017	0.24	3.46	0.00
2008	0.12	1.88	0.06	2018	0.13	1.97	0.05
2009	0.15	2.25	0.02	2019	0.10	1.61	0.10
2010	0.15	2.24	0.03	2020	0.10	1.57	0.12
2011	0.15	2.24	0.03	2021	0.11	1.71	0.09
2012	0.10	1.50	0.13	2022	0.11	1.68	0.09
2013	0.05	0.96	0.33				

To investigate local spatial correlations, this paper presents a geographic visualization of spatial association patterns (Figure 7), illustrating the distribution of cities exhibiting “high-high, high-low, low-high, and low-low” agglomeration characteristics. Among these four spatial agglomeration types, the “high-high” agglomeration exhibits a high-level spatial clustering pattern, where inclusive green efficiency is mutually high in both local and neighboring areas. This pattern is primarily concentrated in the upper reaches of the Yellow River Basin and shows a trend of spreading toward the middle and lower reaches. During the study period, regions such as Ordos City and Hohhot City in the upper reaches of the Yellow River, as well as Jinan City and Binzhou City in the lower reaches, demonstrated strong spatial continuity and agglomeration characteristics. This is closely linked to the region’s abundant natural resources and the national top-down orientation toward green development. To investigate local spatial correlations, this paper presents a geographic visualization of spatial association patterns (Figure 7), illustrating the distribution of cities exhibiting “high-high, high-low, low-high, and low-low” agglomeration

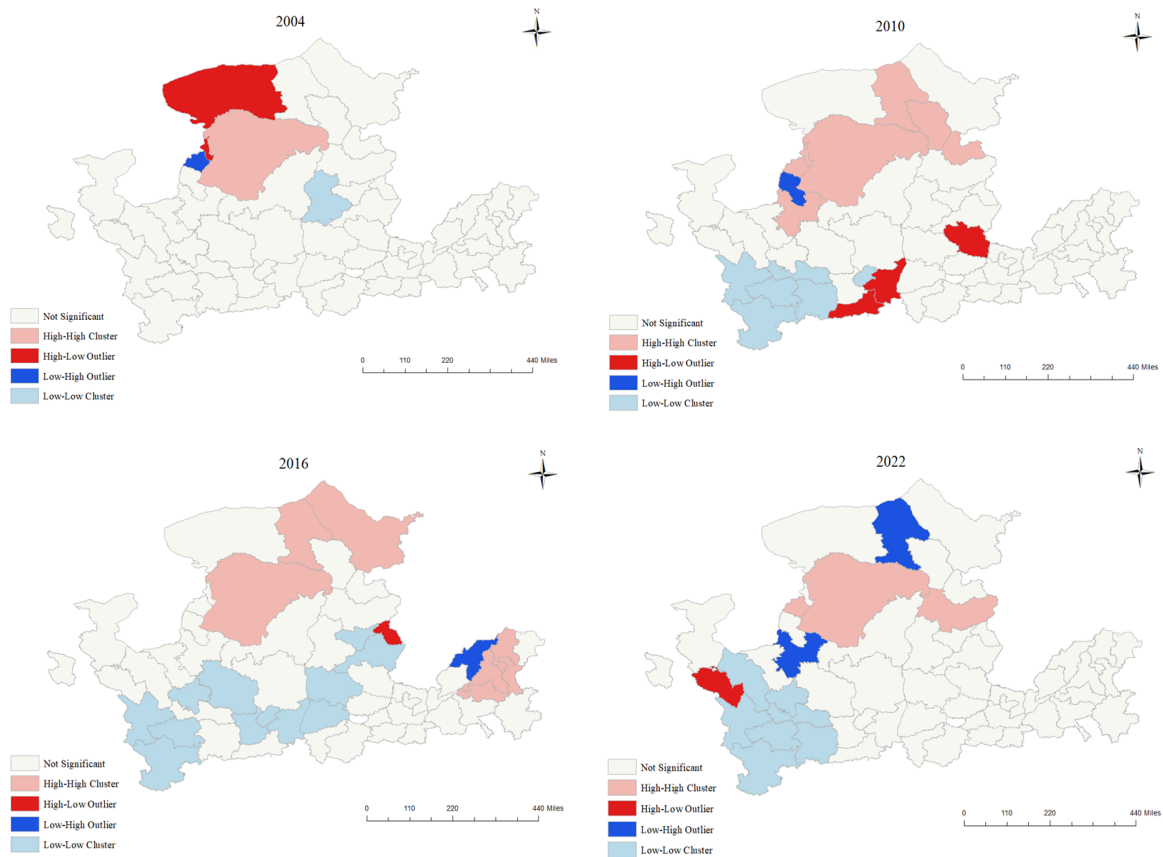


FIGURE 7. Spatial correlation pattern characteristics of inclusive green efficiency in the Yellow River Basin

characteristics. Among these four spatial agglomeration types, the “high-high” agglomeration exhibits a high-level spatial clustering pattern, where inclusive green efficiency is mutually high in both local and neighboring areas. This pattern is primarily concentrated in the upper reaches of the Yellow River Basin and shows a trend of spreading toward the middle and lower reaches. During the study period, regions such as Ordos City and Hohhot City in the upper reaches of the Yellow River, as well as Jinan City and Binzhou City in the lower reaches, demonstrated strong spatial continuity and agglomeration characteristics. This is closely linked to the region’s abundant natural resources and the national top-down orientation toward green development. As regional hubs, Ordos and Hohhot drive surrounding areas toward higher efficiency levels through industrial synergy and linkage. Jinan and Binzhou, traditional resource-based and industrial cities, initially relied on low-factor-cost traditional drivers to accelerate industrialization, stimulating urban economic growth and laying a solid foundation for industrial transformation and upgrading. Facing resource depletion and stricter environmental regulations, they continuously explore new models for transitioning between old and new drivers, promoting green sustainable development while exerting radiating influence to form a “high-high” agglomeration pattern. The “low-high” agglomeration pattern exhibits spatial heterogeneity characterized by “low local, high neighboring areas”, primarily distributed in the upper and lower reaches of the Yellow River Basin. The “high-low” agglomeration pattern displays spatial heterogeneity marked by “high local, low neighboring areas”, also concentrated in the upper and lower reaches of the Yellow River Basin. The “low-low” agglomeration pattern exhibits low-level spatial clustering, with both local and neighboring

areas sharing low inclusive green efficiency values. This pattern is primarily distributed in the middle reaches of the Yellow River and gradually extends upstream. The main reason lies in the region's inefficient resource allocation, which hinders the realization of complementary advantages and synergistic effects between areas. It is evident that during the study period, major provincial capitals failed to exert the inclusive green driving role expected of leading cities, indicating that endogenous development mechanisms promoting mutual reinforcement between society and the environment remain underdeveloped.

5.3. Prediction and analysis of the development trend of inclusive green efficiency in the Yellow River Basin. Using the GM(1,1) model to forecast the future 10-year development trends of inclusive green efficiency in the Yellow River Basin, a spatial pattern map is generated based on the prediction results, as shown in Figure 8. Since official data is updated to 2022, this study's projections encompass the development trends of inclusive green efficiency from 2023 to 2032.

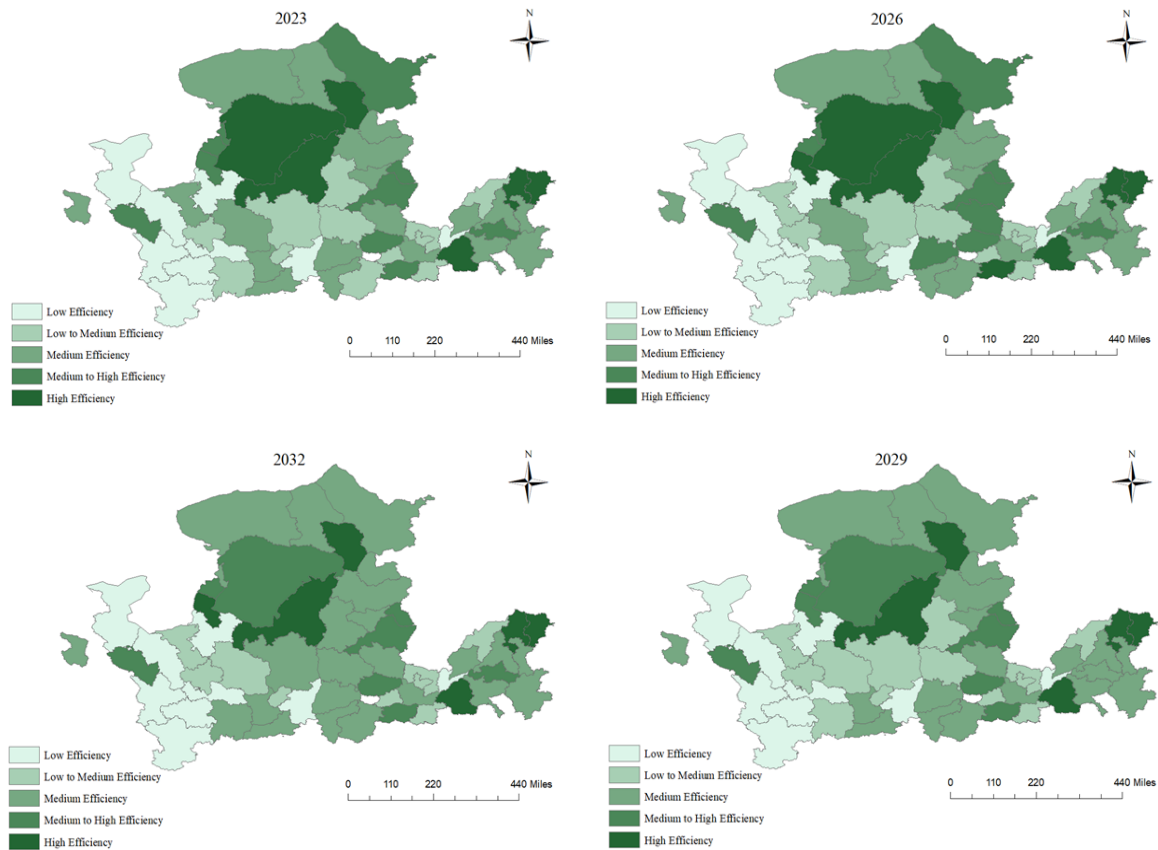


FIGURE 8. Prediction of the development trend of inclusive green efficiency in the Yellow River Basin

As shown in the figure, the inclusive green efficiency of the Yellow River Basin continues to exhibit a pronounced disparity in efficiency levels between the upper reaches and the middle and lower reaches, with the latter two regions showing similar efficiency values. The pattern of “higher efficiency in the east and lower in the west” is becoming increasingly pronounced. Projections indicate that the proportion of high-efficiency areas in the middle reaches will significantly increase over time. This is attributed to the effective implementation of regional coordination mechanisms in this zone. The three provinces of Shanxi, Shaanxi, and Inner Mongolia have signed a horizontal ecological compensation

agreement for the Yellow River Basin (Shanxi-Shaanxi-Inner Mongolia section). Through financial transfers and industrial collaboration, this agreement balances ecological conservation and economic development needs between upstream and downstream regions, driving green development in cities like Yan'an, Lvliang, and Linfen in the middle reaches. Shanxi Province's implementation of the Three-Year Action Plan for Quality Improvement and Efficiency Enhancement along the Three No. 1 Tourist Highways will promote regional transportation connectivity, narrow urban-rural development gaps, and achieve inclusive development.

Notably, the inclusive green efficiency level in the western region of the upper Yellow River Basin remains relatively low, with no clear upward trend over time. This stems from constraints imposed by extreme water scarcity and fragile ecological carrying capacity, which limit the region's momentum for green transformation. Additionally, the high proportion of traditional industries in this area means that industrial restructuring may adversely affect social welfare, leading to significant unintended environmental and social consequences. Furthermore, the region's relatively weak economic foundation and the difficulty in transforming traditional industries make it challenging to achieve the desired output improvements. Collectively, these factors create a dilemma where enhancing inclusive green efficiency in this area proves particularly difficult.

6. Conclusions. First, from the perspective of the temporal change trend, the inclusive green efficiency of the Yellow River Basin presents a "U" shaped development trend, and the development pattern of backward upstream, rising midstream and developed downstream in the basin is present, in which technological progress is the key influencing factor. Second, from the perspective of spatial evolution trend, the polarization of regional efficiency values in the upper reaches of the Yellow River is becoming increasingly prominent, showing a pattern of high in the east and low in the west, and the proportion of high efficiency values in the middle and lower reaches of the Yellow River is gradually increasing. The agglomeration level showed a trend of "first declining, then rising and then decreasing". The local agglomeration characteristics are as follows: the "high-high" agglomeration area is concentrated in the upstream and spreads to the middle and lower reaches, while the "low-low" agglomeration area is mainly distributed in the middle reaches and gradually extends to the upstream. Thirdly, from the perspective of development trend prediction and analysis, the inclusive green efficiency of the Yellow River Basin continues to have the characteristics of obvious gap between high and low efficiency in the upper reaches and similar efficiency values in the middle and lower reaches, and the pattern of "high in the east and low in the west" is becoming more and more prominent.

Future research can further delve into more microscopic levels, building econometric models to quantify the direct and indirect effects of various factors such as technological innovation, industrial structure upgrading, and the intensity of environmental regulations on inclusive green efficiency. It will focus on answering questions like "What are the key driving factors?", "What are the mechanisms and transmission pathways?", and "Which policy interventions are more effective?", providing more precise targeting for policy formulation.

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