

Research on the Spatiotemporal Evolution Characteristics and Influencing Factors of Green Total Factor Productivity in Industrial Cities in the Yellow River Basin

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Abstract

The contradiction between the resource-environment and industrial development in the Yellow River Basin has become increasingly prominent. Improving the Green Total Factor Productivity (GTFP) of industries is crucial for achieving high-quality development in the Yellow River Basin. This study utilizes the Supe-EBM model, standard deviation ellipse, Theil index, and other methods to measure and characterize the spatiotemporal evolution and regional differences of industrial GTFP in the Yellow River Basin from 2006 to 2020. Additionally, the spatial Durbin model is employed to explore the influencing mechanisms and spatial spillover effects. The research findings are as follows: (1) From 2006 to 2020, the industrial GTFP in the Yellow River Basin exhibited an overall "N"-shaped upward trend, increasing from 0.42 in 2006 to 0.76 in 2020. (2) The industrial GTFP in the Yellow River Basin demonstrated a pattern of central cities acting as the core, characterized by agglomeration and contiguous development. The centroid was located within the territory of Shanxi Province, with the centroid moving distance and speed gradually increasing. The standard deviation ellipse was mainly concentrated in the middle and lower reaches of the Yellow River Basin, exhibiting a trend of "initial expansion and subsequent contraction." The spatial distribution showed a tendency towards polarization in the east-west direction and equilibrium in the north-south direction. (3) The Theil index of GTFP in the Yellow River Basin fluctuated but showed no significant overall change. At both the basin and city cluster scales, the internal differences were significantly greater than the inter-regional differences. The development in the middle reaches and the Guanzhong city cluster exhibited the most significant imbalance. (4) In terms of influencing factors, the level of industrial structure and economic development demonstrated significant positive direct effects and negative spillover effects. Industrial agglomeration and infrastructure construction exhibited significant positive effects, while labor quality showed a significant positive direct effect. Environmental regulations hindered the high-quality development of industries.

Keywords

Industrial Green Total Factor Productivity; Super-EBM Model; Temporal and Spatial Evolution; Spatial Spillover Effects; Yellow River Basin.

1. Introduction

China was the only country in the world with a fully industrialized system. As a core component of the modern economic system, industry plays a pivotal role in promoting the country's economic development. Since the reform and opening up, China's industrial economy has realized rapid development, but it has also had a non-negligible impact on the ecological

environment. This phenomenon is particularly significant in the Yellow River Basin, where the industrial development model is mainly characterized by high pollution, high energy consumption and high emissions, which in turn has led to increasingly significant problems in terms of resources, environment and ecology^[1]. The China Ecological and Environmental Statistics Annual Report 2021 points out that the Yellow River Basin is at the forefront of the country in terms of industrial waste and other pollutant emissions. In order to promote the green development and transformation of industries in the Yellow River Basin, the Ministry of Industry and Information Technology (MIIT) and the Development and Reform Commission (DRC) issued the "Guiding Opinions on Deeply Promoting the Green Development of Industries in the Yellow River Basin" in 2022, aiming to enhance the vitality of the green development of industries. Green Total Factor Productivity (GTFP) is a productivity indicator that comprehensively considers input factors such as capital and labor while focusing on environmental pollution indicators, which can scientifically assess the combination of resource and environmental benefits and economic development benefits in economic activities, and therefore is important for measuring economic green development^[2]. Therefore, adopting industrial green total factor productivity to assess the level of green development of industries in the Yellow River Basin and analyzing its changing law is of guiding significance for realizing high-quality development of industries in the Yellow River Basin.

At present, the research on green total factor productivity at home and abroad is quite rich. Firstly, in terms of measurement methods, Solow residual method^[3,4], stochastic frontier analysis^[5], semiparametric method^[6], DEA (Data Envelopment Analysis) model and other methods are usually used for measurement^[7]. Among them, the DEA model can deal with the advantages of multiple inputs, multiple outputs and is not limited by the data outline, so scholars at home and abroad have widely used the DEA model to measure GTFP^[8,9], and the measurement process usually adopts the capital and labor factors as the input factors, in which some scholars will take the lead in setting the energy consumption^[10], land resources^[11], and the innovation factors^[12] as the input indexes, and so on. This has enriched the research system of green total factor productivity. However, water resources are still an indispensable input factor for industrial development, especially for the Yellow River Basin where water resources are scarce, which restricts its industrial development, so it is difficult to reflect the actual level of green total factor productivity in the Yellow River Basin industry without water resources factor measurement. Secondly, the research mainly focuses on the economically more developed areas such as Chinese cities, the Yangtze River Economic Belt, and major urban agglomerations, and the objects of the research are cities, manufacturing industry and agriculture, but there is not much research on the economically more backward areas, and on the industry, which is regarded as the "pillar industry of the national economy". The Yellow River Basin is one of the few economically backward regions in China with a good foundation for industrial development, and there are also internal differences, which is very representative and can make up for the vacancies in related research. When exploring the influencing factors, scholars at home and abroad are more inclined to focus on single factors such as digital economy^[13], industrial transformation^[14], environmental regulation^[15], foreign direct investment^[16], resource allocation^[17], green innovation^[18], etc., but the overall impact of factors and spatial effects of factors are less analyzed, so it is necessary to use spatial measurement models to explore the role of influencing factors and spatial effects of factors. There is an urgent need to use spatial econometric modeling to explore the mechanisms and spatial effects of the factors.

To summarize, this paper takes the Yellow River Basin as the research object, uses the super-efficient EBM model to measure the green total factor productivity of industry in each prefecture-level city, which is different from the previous research in that the water resource factor is included as an input indicator, expanding the research paradigm of green total factor

productivity; adopts the standard deviation ellipse and the Terre coefficient method to explore the spatial and temporal evolution characteristics and regional differences of the industrial green total factor productivity in the Yellow River Basin in the period of 2006-2020, and uses the spatial Durbin model to explore the influencing factors and their spatial effects. The standard deviation ellipse and Terrell coefficient methods are used to explore the spatial and temporal evolution characteristics and regional differences of industrial green total factor productivity in the Yellow River Basin from 2006 to 2020, and the spatial Durbin model is used to explore the influencing factors and their spatial effects. The results of the study enrich the research on industrial green total factor productivity in less developed regions, and provide reference basis for the green transformation of industries in the Yellow River Basin and the realization of high-quality development in the Yellow River Basin.

2. Overview of the Study Area and Research Methodology

2.1. Scope of the Study Area

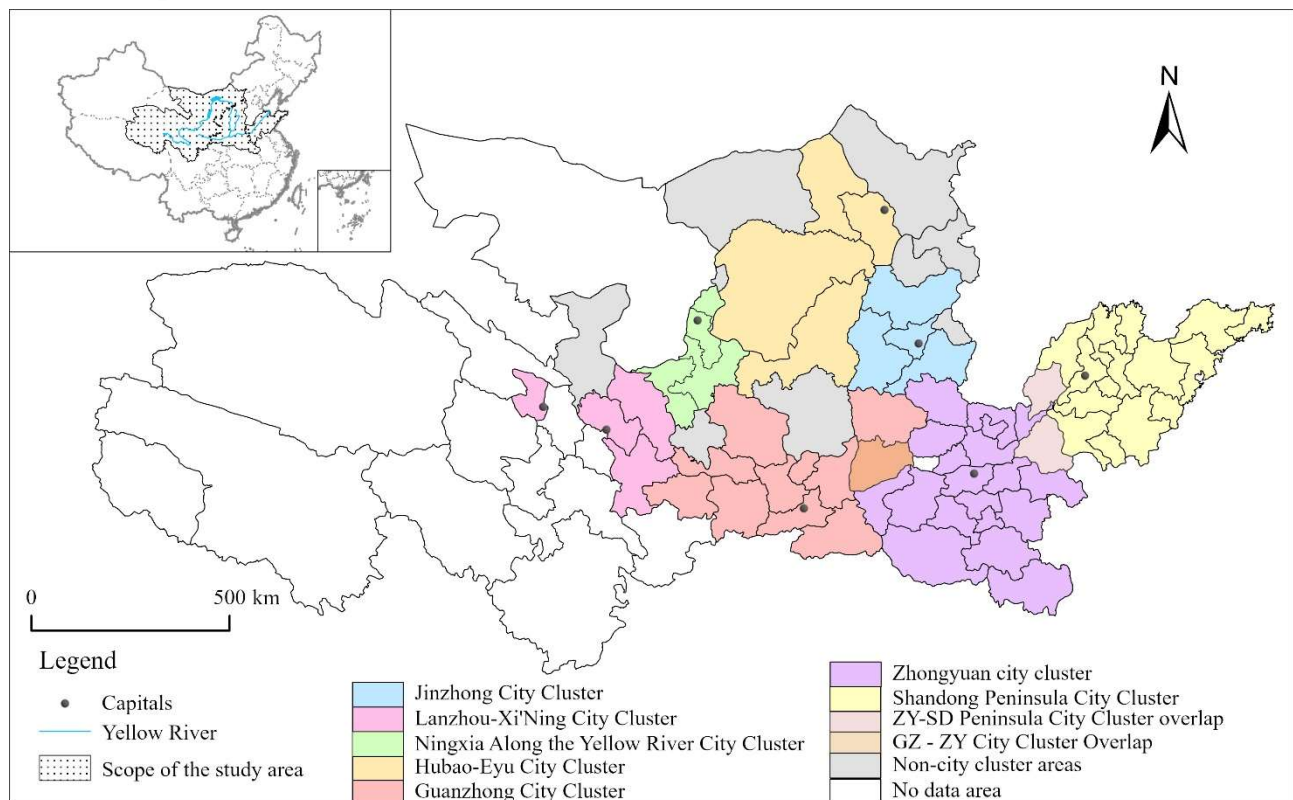


Figure 1. Overview of the Study Area

Note: The map is based on the standard map with review number GS(2020)4619 downloaded from the standard map service website of the Technical Review Center of the Ministry of Natural Resources, with no modification to the base map.

The Yellow River Basin is the second longest river in China, due to the fact that most of it is located in arid and semi-arid areas, the ecological environment is fragile and the supply of water resources is limited, in addition to the fact that it is the largest energy and raw material industrial base in China, and its industrial development is extremely dependent on energy and resources, and its rough industrial development has led to more and more ecological and environmental problems, therefore, the study of the natural environmental background and industrial "three highs" development characteristics of the Yellow River Basin makes it more urgent to study the green total factor productivity of industry. Therefore, the natural environment background of the Yellow River Basin and the industrial "three highs"

development characteristics make the research on the green total factor productivity of the Yellow River Basin industries more urgent. Therefore, based on the natural endowment of the watershed, and taking into account the administrative divisions and the closeness of urban economic ties, this paper defines the study area as the nine provinces and regions through which the Yellow River flows, with a total of 85 municipalities (or states and leagues)^[19]. Due to the limited access to data, 73 prefecture-level cities were finally identified (Figure 1), and due to the change of administrative division, Laiwu City has been merged into Jinan City since 2019, so it has been merged into Jinan City as the object of study since 2019. In addition the study area includes seven city clusters^[20], of which Liaocheng City, Heze City and Yuncheng City are overlapping city clusters.

2.2. Research Methodology

2.2.1. The Super-EBM Model

The SBM model is commonly used in measuring green total factor productivity. However, this model deals with zero and positive values with the situation of increased contrast between input and output optimal slacks, which can lead to bias in the measurement. To solve this problem, Tone et al^[21] proposed the EBM model (Epsilon-Based Measure). This model can effectively avoid measurement bias and improve the accuracy of the model. Therefore, this paper combines the EBM model with the super-efficiency DEA model^[22], i.e., adopts the Super-EBM model,, in order to more accurately measure the green total factor productivity. Its model formula is as follows:

$$GTFP^* = \min \frac{\theta - \varepsilon_x \sum_{i=1}^m \frac{w_i^- s_i^-}{x_{i0}}}{\varphi + \varepsilon_y \sum_{r=1}^s \frac{w_r^+ s_r^+}{y_{r0}} + \varepsilon_z \sum_{p=1}^q \frac{w_p^- s_p^-}{z_{p0}}} \quad \text{s.t.} \quad \begin{cases} \sum_{j=1}^n x_{ij} \lambda_j + s_i^- = \theta x_{i0} & (i = 1, 2, \dots, m) \\ \sum_{j=1}^n y_{rj} \lambda_j - s_r^+ = \varphi y_{r0} & (r = 1, 2, \dots, s) \\ \sum_{j=1}^n z_{pj} \lambda_j + s_p^- = \varphi z_{p0} & (p = 1, 2, \dots, q) \\ \lambda_j \geq 0, & s_i^-, s_r^+, s_p^- \geq 0 \end{cases} \quad (1)$$

where: n is the number of decision units; x, m, and w_i⁻ represent the weights of input elements, input quantities, and input indicators, respectively; z, q, s_p⁻, and w_p⁻ denote the weights of non-desired output elements, non-desired output quantities, non-desired output slack, and non-desired output indicators, respectively; y, s, s_r⁺, and w_r⁺ denote the weights of desired output elements, desired output quantities, desired output slack, and weights of desired output indicators; and λ denotes the relative importance of the reference cell.

2.2.2. Standard Deviation Ellipse

The spatial characteristics of the natural environment, socio-economic and other elements are revealed by measuring the basic parameters such as the area, center of gravity, long and short axes, and angle of rotation of the standard deviation ellipse^[23,24].

2.2.3. Theil Index

Theil's index (Theil) can be used to measure the degree of regional differences by measuring intra-regional differences and inter-regional differences combined^[25]. Its formula is as follows:

$$\begin{aligned}
 Theil &= Theil_w + Theil_B \\
 Theil_w &= \sum_{i=1}^m \left(\frac{n_i}{n} \frac{\bar{X}_i}{\bar{X}} \right) Theil_i \\
 Theil_B &= \sum_{i=1}^m \frac{n_i}{n} \left(\frac{\bar{X}_i}{\bar{X}} \right) \ln \left(\frac{\bar{X}_i}{\bar{X}} \right)
 \end{aligned}
 \tag{2}$$

Where: m denotes the number of regional classifications; n_i/n denotes the proportion of cities within different regional clusters; \bar{x}_i/\bar{x} denotes the ratio of the mean value of each city to the mean value of the watershed; $Theil_i$ denotes the Terre index of industrial green total factor productivity for city i ; $Theil_w$ and $Theil_B$ denote the intra-region and inter-region differences in industrial green total factor productivity, respectively.

2.2.4. Spatial Measurement Models

This paper explores the spatial effect of industrial green total factor productivity in the Yellow River Basin by constructing a spatial Durbin model, in order to test the spatial correlation characteristics of industrial green total factor productivity in the Yellow River Basin, and sets the model as follows:

$$GTFP_{it} = \rho \sum_{j=1}^n W_{ij} GTFP_{jt} + \beta x_{it} + \sum_{j=1}^n \phi W_{ij} x_{jt} + \mu_i + \nu_t + \varepsilon_{it}
 \tag{3}$$

Where: $GTFP_{it}$ denotes the industrial green total factor productivity in region t in year i ; x_{it} is the influencing factor of industrial GTFP; w_{ij} is the spatial adjacency matrix; $W_{ij}GTFP_{jt}$ and $W_{ij}x_{jt}$ are the lag terms of industrial GTFP and the influencing factors, respectively; β , ρ and ϕ are the coefficients to be estimated for the independent variables and the spatial lag coefficients; μ_i , ν_t , and ε_{it} are the spatial and temporal effects and the error terms, respectively. and are the spatial and temporal effects and error terms, respectively.

2.3. Construction of the Indicator System and Data Sources

Table 1. Indicators and Data Sources for Calculation of GTFP in the Industrial Sector

	standardized layer	indicator layer	Data sources
Input indicators	Capital input	Investment in industrial fixed assets	“Statistical Yearbook of the Provinces”
	Labor input	Number of persons employed in industry	“China Urban Statistical Yearbook”
	Energy input	Industrial energy consumption	DMSP/OLS with NPP/VIIRS Nighttime Lighting Data Simulation
	Land input	Industrial land area	“China Urban Statistical Yearbook”
	Water input	Total industrial water use	“Provincial water resources bulletins”
Output indicators	Economic output	value added by industry	China Economic and Social Big Data Research Platform
	Environmental outputs	Industrial SO ₂ emissions	“China Urban Statistical Yearbook”
		Industrial wastewater discharge	“China Urban Statistical Yearbook”
		Industrial fume (dust) emissions	“China Urban Statistical Yearbook”

Note: Data relating to values in this paper are obtained by deflating through price indices using 2006 as the base period.

Studying industrial GTFP in the Yellow River Basin based on the city scale is more advantageous for exploring industrial high-quality development. This paper adopts the input-output perspective and measures industrial GTFP based on the super-efficient EBM model, and the measurement process and results have strong objectivity^[26]. According to the analysis of related literature, the GTFP measurement index system is constructed (Table 1).

Among them, the capital input was calculated using the perpetual inventory method, using the fixed asset investment in 2006 divided by 10% as the base period capital stock of the city^[27]; the amount of new industrial fixed asset investment in each city was calculated through the method of decomposition of the proportion of the city's industrial added value in the provincial (regional) industrial added value^[10]; and the depreciation rate of fixed asset investment was taken as 9.6%^[28]. Energy input was simulated using nighttime lighting data, and industrial energy consumption in cities was simulated by linear regression without intercept ($R_2=0.952$, $P<0.01$) through two nighttime lighting relative radiation corrections, DMSP/OLS and NPP/VIIRS, as well as inter-annual series correction^[29,30]. Land input was measured using industrial land area. In addition, the missing parts of industrial three-waste data were supplemented by linear interpolation.

3. Analysis of Results

3.1. Characteristics of Spatio-temporal Evolution of Industrial Green Total Factor Productivity in the Yellow River Basin

3.1.1. Time-series Evolution of Green Total Factor Productivity in the Yellow River Basin Industry

Based on the super-efficient EBM model, the industrial GTFP of 73 prefecture-level cities in the Yellow River Basin was measured from 2006 to 2020 (Figure 2). The results show that the average value of industrial GTFP in the Yellow River Basin from 2006 to 2020 generally exhibits an 'N'-shaped fluctuation trend of "rapid growth-slow decline-steady increase", i.e., the first stage (2006-2012) is in the stage of rapid growth, from 2006 to 2020, industrial GTFP is in the stage of rapid growth. That is, in the first stage (2006-2012), the industrial GTFP is in the stage of rapid growth, increasing from 0.423 in 2006 to 0.644 in 2012, an increase of 52%, with an average annual increase of 3.6%. In this stage, after the implementation of the strategy of developing the west and rising central China, the efficiency of resource allocation has been improved, and the rapid growth of industrial green total factor productivity has been realized. Facing the severe impact of the economic crisis in 2008, the growth rate of industrial GTFP in the Yellow River Basin slowed down. In the second stage (2012-2014), industrial GTFP was in a slow decline stage, decreasing by 3% from 0.644 in 2012 to 0.623 in 2014. In this stage, due to the technology and production enhancement brought about by the intensification of environmental pollution problems and the non-conservative use of resources, which triggered serious ecological and environmental problems, industrial pollution and environmental pollution and other non-desired outputs continue to increase, resulting in a continuous reduction of GTFP. In the third stage (2014-2020), industrial GTFP is in a period of steady increase. During this stage, due to the enhancement of technological innovation and awareness of environmental protection, as well as the increased emphasis on resource allocation efficiency in various regions, the non-desired output of industrial pollution and environment is constantly reduced, and resource inputs in various regions are more reasonable, thus realizing the steady growth of industrial GTFP.

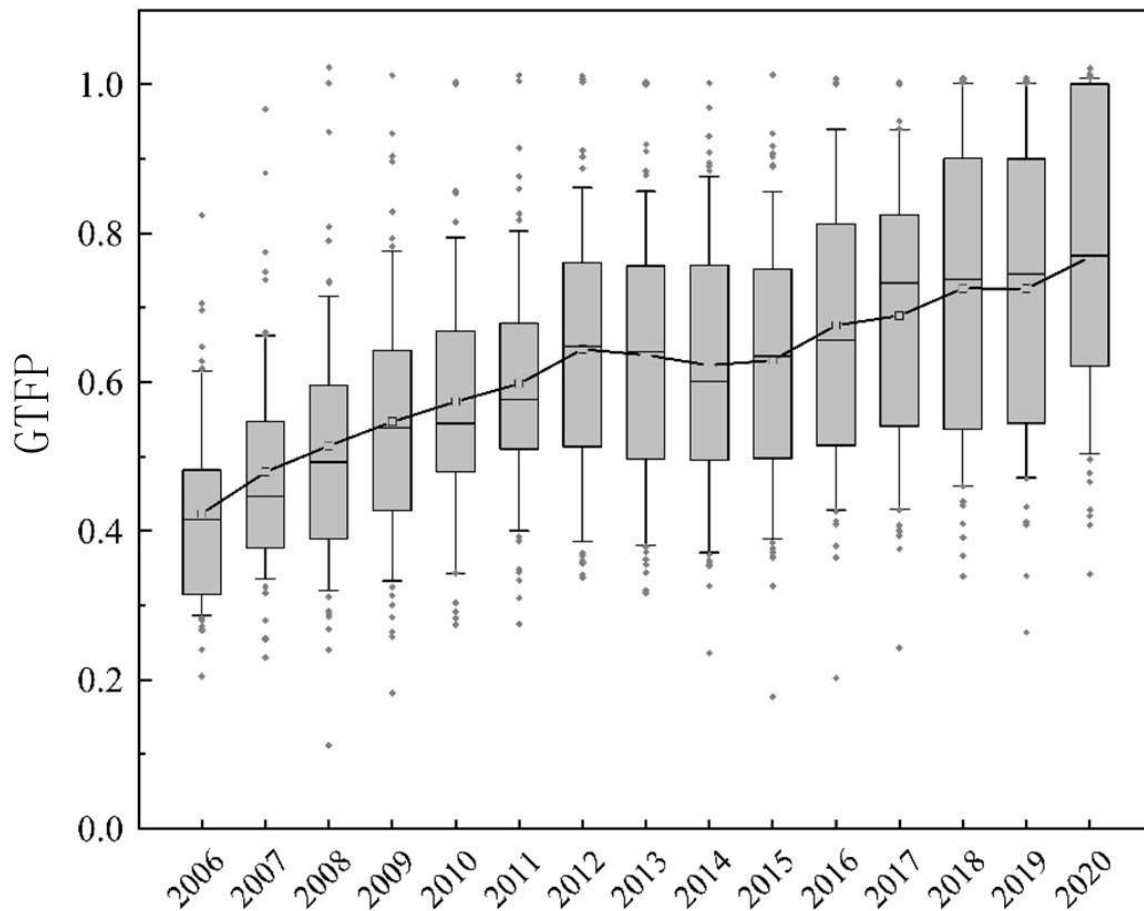


Figure 2. Temporal Changes in GTFP in the Industrial Sector of the YRB from 2006 to 2020

From the box part, the upper quartile to lower quartile distribution is gradually discrete, indicating that the cities with medium industrial GTFP in the Yellow River Basin show the trend of increasing regional differences, i.e., some of the cities achieve rapid growth in industrial GTFP and the gap between them and the cities with higher industrial GTFP narrows, while some of the cities with slow growth in industrial GTFP show a pattern of polarization of the cities with medium industrial GTFP.

3.1.2. Spatial Evolution of Green Total Factor Productivity in the Yellow River Basin Industry

Based on the calculation results of industrial GTFP in the Yellow River Basin from 2005 to 2020, the mean values were classified into three categories by the natural breakpoint method, which were low green total factor productivity ($GTFP \geq 0.5233$), medium total factor productivity ($0.5233 < GTFP < 0.7000$), and high total factor productivity ($GTFP \leq 0.7000$), and spatial visualization and mapping were carried out, which reflected the The spatial distribution characteristics of industrial GTFP in the Yellow River Basin (Figure 3). The industrial GTFP of the Yellow River Basin is characterized by the development of agglomeration with the regional central city as the core, and in 2006, the medium and high industrial GTFP of the Yellow River Basin were concentrated in the core areas of city clusters, i.e., the core areas of the Central Plains City Cluster, the Shandong Peninsula City Cluster, as well as the intersection areas of the Hubao, Ou-Yu City Cluster and the Central Plains City Cluster, which showed a pattern of multi-point agglomeration. 2010, there were only two city clusters: Jinzhong City Cluster and Ningxia City Cluster. In 2010, only Jinzhong City Cluster and Ningxia Along the Yellow River City Cluster

showed no medium- or high-industry GTFP, showing a spatial pattern of "upstream and central collapse". In 2015, the industrial GTFP of the Yellow River Basin further increased, and the spatial pattern basically remained unchanged, but Jinzhong City Cluster showed sporadic medium- or high-industry GTFP cities. In 2020, except for the Lanxi city cluster, a spatial pattern of medium- and high-green industrial GTFP clusters will be formed in all major city clusters.

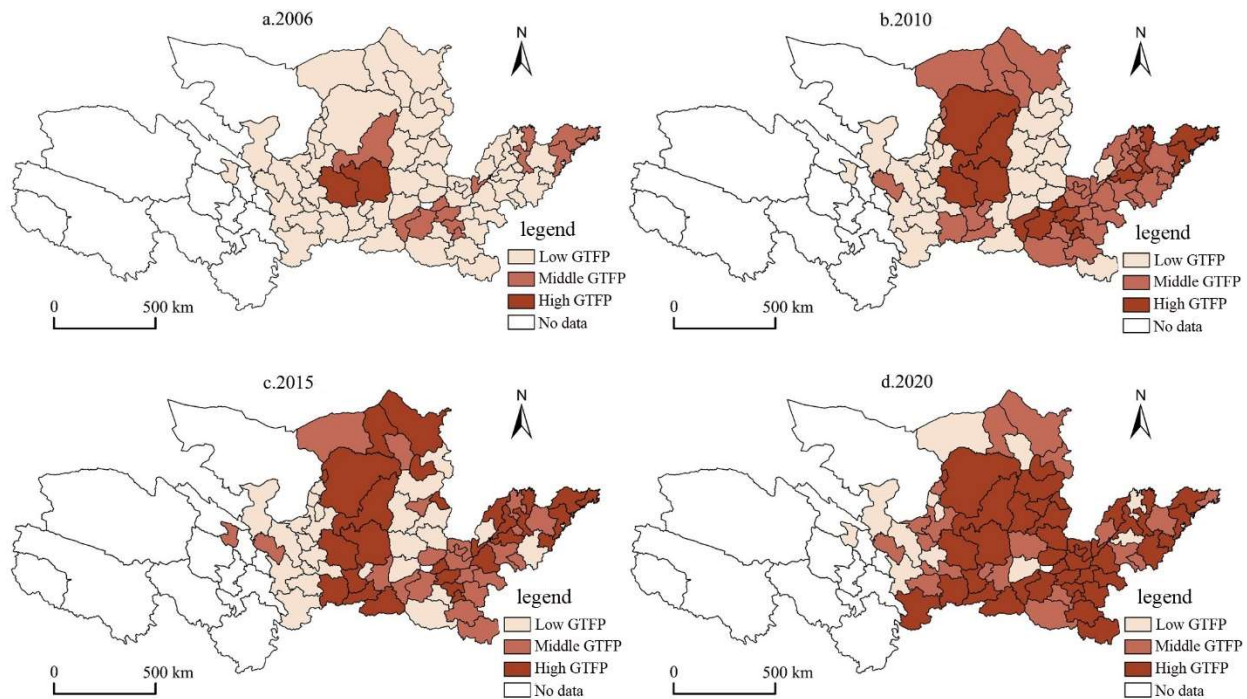


Figure 3. Spatial Distribution of Industrial GTFP in the YRB from 2006 to 2020.

In order to explore its spatial evolution pattern, the spatial center of gravity and standard deviation ellipse of the industrial GTFP in the Yellow River Basin were analyzed using ArcGIS 10.8 software, and the following relevant attributes were obtained (Tables 2 and 3), and the distribution of the standard deviation ellipse of the industrial GTFP in the Yellow River Basin and the trajectory of the center of gravity were mapped at the four selected time points of 2006, 2010, 2015 and 2020 (Figure 4).

During the period from 2006 to 2020, the center of gravity of industrial GTFP in the Yellow River Basin is in Shanxi Province, which shows a moving trend of "northeast-northwest-southwest" within the ranges of $36.19^{\circ}\text{N}\sim 36.44^{\circ}\text{N}$ and $112.42^{\circ}\text{E}\sim 112.68^{\circ}\text{E}$, and the trend is "northeast-northwest-southwest". The center of gravity moves in a "northeast-northwest-southwest" trend, and the distance and speed of the center of gravity gradually increase (Figure 4 and Table 2). Specifically, during the period from 2006 to 2010, the center of gravity moved with the smallest distance and speed of 3.72 km and 0.93 km/a, respectively, in which the center of gravity moved northward with a speed greater than that of eastward. During this period, cities in Shandong Peninsula Urban Agglomeration, Central Plains Urban Agglomeration, Hubao-Eyu Urban Agglomeration and Guanzhong Urban Agglomeration in the north of the basin achieved faster improvement in industrial green total factor productivity, while Jinzhong Urban Agglomeration, Ningxia Along the Yellow River Urban Agglomeration and Lanxi-Urban Agglomeration faced many difficulties in the areas of structural transformation and technological upgrading, which resulted in the center of gravity of the basin's industrial GTFP shifted to the northeast. During the period from 2010 to 2015, the distance and speed of the

center of gravity movement increased, which were 14.93km and 2.99km/a, respectively, and mainly showed that the center of gravity shifted westward and northward at roughly equal speeds. The industrial GTFP of the northern Shandong Peninsula City Cluster, Hubao-Eyu City Cluster and the central Guanzhong City Cluster showed a faster growth trend, while the industrial GTFP of Jinzhong, Central Plains and Lanxi City Clusters grew slowly, resulting in the center of gravity shifting to the northwest, which further highlights the effectiveness achieved by the western development strategy. From 2015 to 2020, the distance and speed of movement of the center of gravity further increased to 29.17km and 5.83km/a, respectively, which is mainly manifested by the center of gravity moving southward and in a southwesterly direction. During this period, pollutants such as industrial waste emissions in the upstream region decreased significantly, while taking over the technology spillover effect from the middle and downstream regions, especially the rapid increase in industrial GTFP in the Lanxi urban agglomeration and the Ningxia Along the Yellow Urban Agglomeration, which resulted in the center of gravity of industrial GTFP moving to the southwest.

Table 2. Direction and Distance Parameters of the Center of Gravity Shift in GTFP in the Industrial Sector of the Yellow River Basin from 2006 to 2020

Year	Center of Gravity Coordinate	Direction of Travel	Distance traveled (km)	Speed of movement (km/a)
2006	36.30°N, 112.66°E			
2010	36.33°N, 112.68°E	northeastern	3.72	0.93
2015	36.44°N, 112.56°E	northwestern	14.93	2.99
2020	36.19°N, 112.42°E	southwestern	29.17	5.834

The standard deviation ellipse of industrial GTFP in the Yellow River Basin is mainly located in the middle and downstream areas of the basin, and the coverage first expands and then narrows, indicating that the spatial distribution of industrial green GTFP in the basin shows the phenomenon of dispersion and then agglomeration (Figure 4). From the perspective of the corner, the corner shows a trend of "increasing first and then narrowing", with little change in general, and has a more stable spatial distribution pattern.

Table 3. Parameters of Standard Deviation Ellipse for the Spatial Distribution of GTFP in the Industrial Sector of the YRB from 2006 to 2020

Parameters	2006	2010	2015	2020
Turning angle (°)	87.63	88.99	89.75	88.23
Standard deviation along y-axis (km)	304.48	313.86	324.43	308.95
Standard deviation along x-axis (km)	577.33	566.68	574.18	541.27

From 2006 to 2010, the turning angle increased from 87.63° to 88.99°, indicating that the spatial distribution pattern of industrial GTFP in the basin shifted by 1.36° from the "northeast-southwest" to the "east-west" direction. From 2010 to 2015, the angle of rotation further increased, again shifting 0.76° to the east-west direction, making the spatial distribution pattern east-west; from 2015 to 2020, the angle of rotation showed a decreasing trend, once again presenting a northeastern-southwestern spatial pattern. -Southwest spatial pattern. In terms of the length of the main axis and short axis, the main axis has experienced the process of "shortening-extending-re-shortening", shortening from 577.33 km in 2006 to 541.27 km in 2020; the short axis has experienced the process of "extending-shortening"; the short axis has experienced the process of "extending-shortening"; the short axis has experienced the process

of "extending-shortening". extension-shortening" process, from 304.48km in 2006 to 308.95km in 2020, indicating that the spatial distribution of industrial GTFP in the Yellow River Basin tends to be polarized in the east-west direction (in the direction of the main axis) and balanced in the south-north direction (in the direction of the short axis). (short-axis direction) tends to be balanced.

3.2. Regional Differences in Green Total Factor Productivity in the Yellow River Basin Industry

In order to explore the regional differences in industrial green total factor productivity within the basin at different scales. According to the natural nature and socio-economic development of the basin, the Yellow River Basin is divided into the upper, middle and lower reaches, and seven urban agglomerations and non-urban agglomerations are explored for their intra- and inter-regional differences.

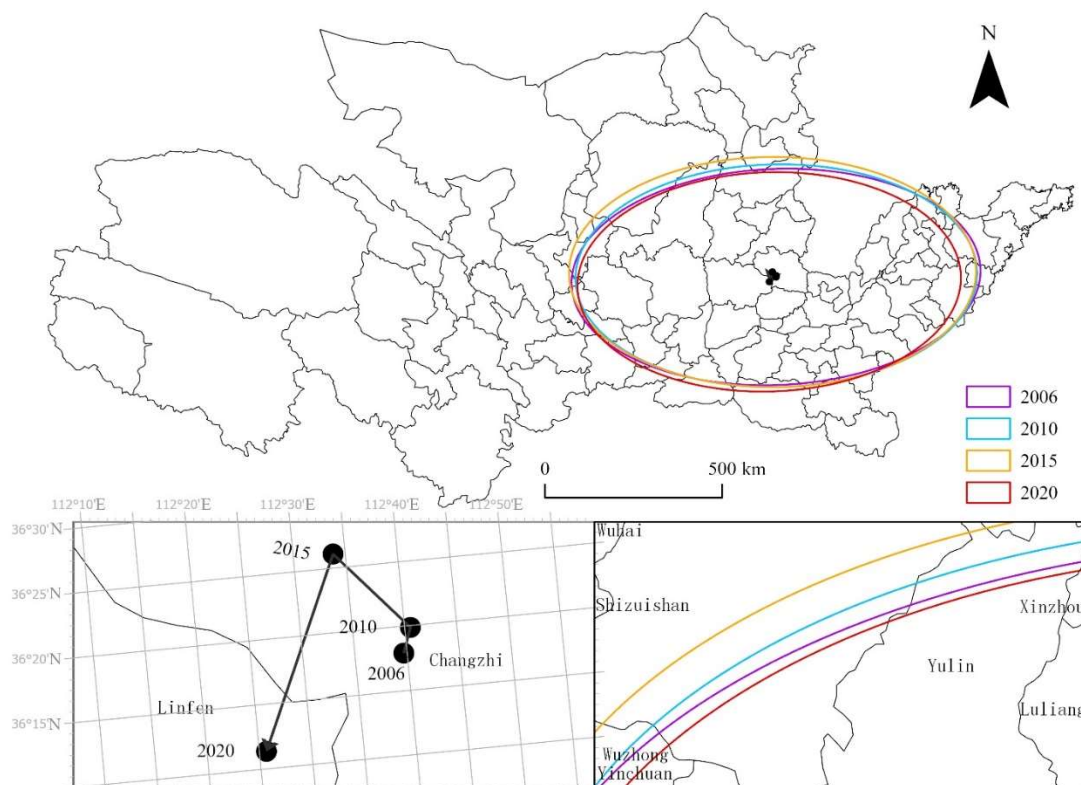


Figure 4. Analysis of Standard Deviation Ellipse and Trajectory of Centroid Movement for GTFP in the Industrial Sector of the YRB

As can be seen in Figure 5, the mean value of the intra-regional difference contribution rate at the basin scale is 83.67%, which is significantly larger than the inter-regional contribution rate, so the uneven development within the Yellow River Basin region is the key constraint to the improvement of industrial GTFP. In terms of intra-regional differences, the contribution of intra-regional differences in the midstream region is the largest at 35.01%, followed by the contribution of regional differences in the upstream region at 33.46%, and the contribution of the downstream region at 15.20%, which shows that regional coordination between the midstream and the upstream regions is facing a greater challenge. However, the internal difference of the downstream region has gradually become larger, and the proportion of the Thiel index has increased from 11.20% to 22.30% since 2012. Relying on its resource endowment conditions and the reduced pressure on the resources and environment with the scientific and technological innovation and opening up to the outside world, the downstream

region has been the zone with the highest industrial GTFP for many years. Differences within the midstream and upstream regions are gradually decreasing, with the gradual promulgation of policies for the protection of resources and the environment in recent years, the intensity of development in the midstream and upstream regions is decreasing, so that the overall regional coordination of regional development is more balanced, so the differences between regions are gradually becoming bigger, and the industrial GTFP of downstream regions is further increasing.

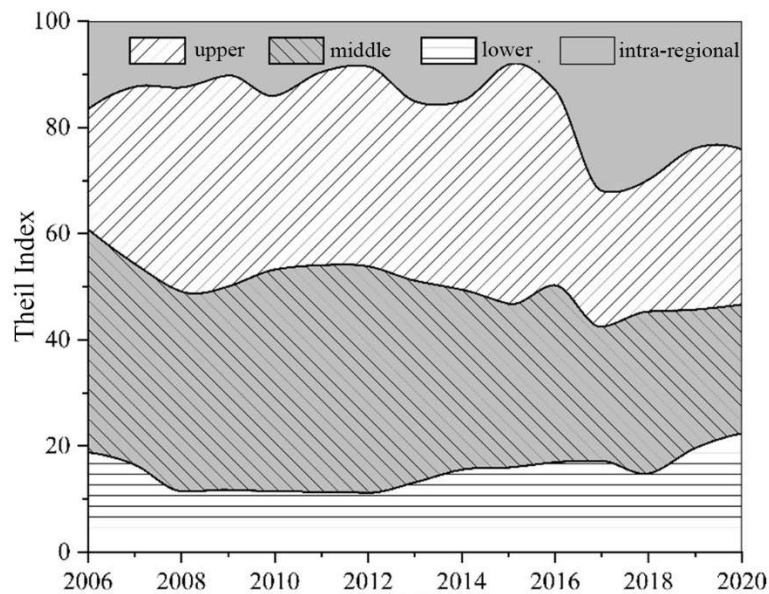


Figure 5. Contribution and Decomposition of Theil Index for GTFP in the Industrial Sector of the Yellow River Basin

As can be seen from Fig. 6, the main contributor to regional differences at the city cluster scale is still the differences within the city clusters, with an annual average contribution rate of 71.93%, which is significantly larger than the inter-regional contribution rate (28.07%), and according to the above, the regional differences within the upper and middle reaches of the watersheds are smaller than the regional differences between the city clusters. Specifically, the highest contribution rate of Thiel coefficient is Guanzhong urban agglomeration (17.80%), followed by Central Plains urban agglomeration (16.08%). That is to say, there is a big difference in industrial GTFP within Guanzhong City Cluster and Central Plains City Cluster, which is due to the fact that the cities of Xi'an, Baoji, Qingyang, Zhengzhou, Luohe, Xuchang and other cities within the city cluster have a large industrial GTFP, while Pingliang, Yuncheng, Liaocheng, Nanyang and other places have a small industrial GTFP, which leads to a big difference within the region. The lowest Tel coefficient contribution is in Ningxia along the yellow city cluster (0.54%), Jinzhong city cluster (1.55%). The reason behind this is that the industrial base of Ningxia Along the Yellow City Cluster is weak and small, and the overall industrial green total factor productivity is low, and Jinzhong City Cluster is dependent on the path of industrial development, which leads to its industrial three-waste emissions have remained high, and ultimately, the industrial GTFP presents an overall low situation. It is worth noting that the contribution rate of the Thiel coefficient of non-urban agglomeration areas is 15.86%, which confirms the previous part that non-urban agglomeration areas are dispersed in the periphery of each urban agglomeration, but because of the spatial spillover effect of the geographic environment in which they are situated, the overall mean value is higher, but the internal differences are significant. In terms of the evolution trend of the differences, the inter-

regional differences have shown a gradual increase in the past five years, and except for the Guanzhong City Cluster, which has shown a gradual decrease in the internal differences, the rest of the city clusters (regions) have shown a relatively stable trend. The reason is that many provinces have issued relevant industrial development policies in the past five years, and the advantages of integrated development within the city clusters have gradually come to the fore, but due to the different industrial bases and resource status of the city clusters, a balanced development within the city clusters and a polarized development between the city clusters have been shown.

3.3. Analysis of the Influencing Factors of Green Total Factor Productivity in the Yellow River Basin Industry

3.3.1. Variable Selection and Model Test Results

In order to investigate the spatial and temporal evolution of industrial GTFP in the Yellow River Basin and the reasons for the formation of regional differences, this paper will use a spatial econometric model to explore the influencing factors of industrial GTFP in the Yellow River Basin. Referring to related studies^[31-33], this paper selects the industrial structure (proportion of GDP in the secondary industry), the level of economic development (logarithmic of the per capita GDP), the development of infrastructure (density of highways), the quality of labor force (proportion of the population with a college education), the level of openness to the outside world (the proportion of foreign direct investment), the level of innovation (the proportion of science and education expenditures to fiscal expenditures), environmental regulation (the proportion of environmental vocabulary in the government's work report), and industrial agglomeration (industrial density) are modeled and analyzed.

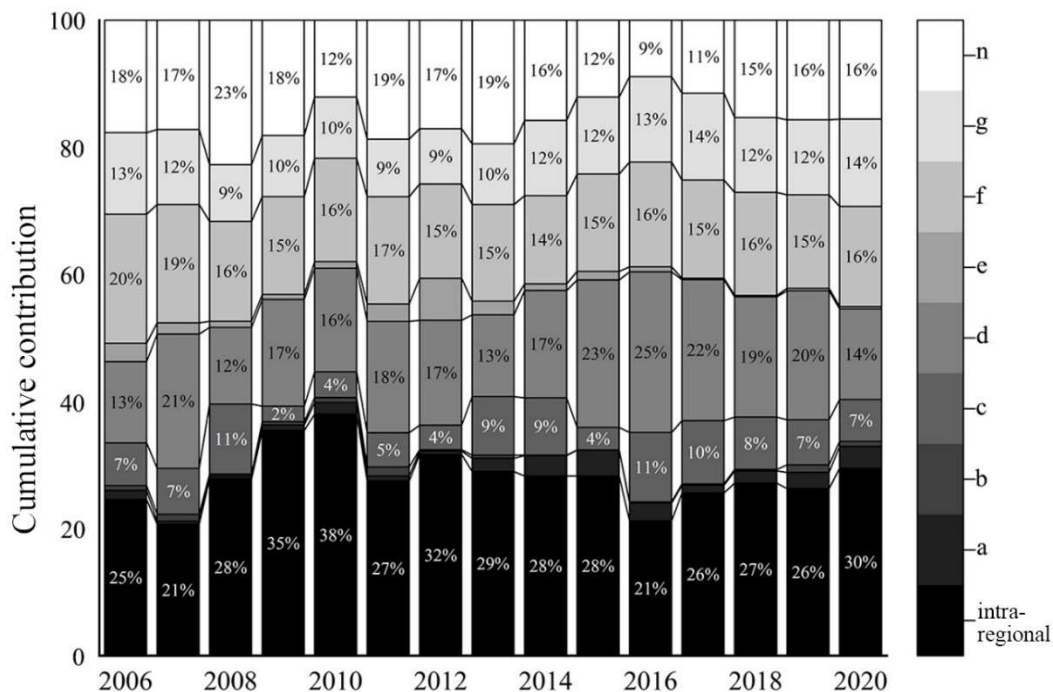


Figure 6. Cumulative Contribution of Theil Index for GTFP in Different City Clusters of the Yellow River Basin

Note: a.Lanxi city cluster, b.Ningxia along the yellow city cluster, c.Hubao-Eyu city cluster, d.Guanzhong city cluster, e.Jinzhong city cluster, f.Zhongyuan city cluster, g.Shandong Peninsula city cluster, n.Non-city cluster areas

Firstly, the mean and maximum VIF values of each influence factor were calculated, and all of them were less than 10, and there was no multicollinearity. Secondly, the geographic adjacency matrix is constructed to calculate the annual average Moran'I=0.191 (p<0.01) of industrial GTFP in the Yellow River Basin, indicating that industrial GTFP in the Yellow River Basin has spatial agglomeration. This paper draws on the tests of Elhorst [34] and Han Feng [35], and conducts the LM test, LR test, Wald test, and Hausman test (Table 4) in turn, and finally determines the spatial and temporal double fixed-effects spatial Durbin model for regression estimation.

Table 4. Model test results

Test Methods	Eigenvalue	Test Methods	Eigenvalue
Moran'I	0.191***	LR-Lag test	72.71***
LM-Lag test	75.537***	Wald-Lag test	74.79***
Robust LM-Lag test	46.525***	LR-Error test	77.51***
LM-Error test	41.865***	Wald-Error test	79.88***

Note: *** denotes significant at the 1 percent level.

3.3.2. Decomposition of Industrial GTFP Influencing Factors and Their Spatial Effects in the Yellow River Basin

From the regression results of the spatial Durbin model (Table 5), it can be seen that the influencing factors of industrial structure, economic development level, infrastructure construction, environmental regulation and industrial agglomeration not only have a significant effect on the development of GTFP of its own urban industry, but also have a significant spillover effect on the neighboring areas; the quality of labor force has a significant positive effect on the development of its own industrial high quality; and the level of openness to the outside world and the level of innovation have passed the test.

Table 5. Regression Results of Spatial Durbin Model and Decomposition of Spatial Effects

	Regression Coefficient	Lag term Coefficient	Direct Effect	Indirect Effect	Aggregate Effect
Industrial structure	0.0071***	-0.0051***	0.0069***	-0.0044***	0.0026
Level of economic development	0.0889***	-0.1070***	0.0841***	-0.1060**	-0.0216
Infrastructure development	0.0410**	0.0999**	0.0475**	0.1250***	0.1720***
Quality of labor	0.0087*	0.0037	0.0088*	0.0069	0.0157
open to the outside world	0.3500	-0.2260	0.3460	-0.2150	0.1300
Innovation level	-0.0656	0.2710	-0.0471	0.3190	0.2720
Environmental regulation	-4.0100*	-10.17**	-4.455**	-13.04***	-17.50***
Industrial agglomeration	0.1780***	0.1950***	0.1870***	0.267***	0.4550***
Spatial rho	0.1750***	(4.39)	Variance sigma ²	0.00567**	(23.33)
r ₂	0.530		N	1095	

Note: *p<0.10,**p<0.05,***p<0.01.

In this paper, the spatial effects of each explanatory variable are further decomposed into direct, indirect and total effects through the partial differentiation method (Table 5), which can more intuitively explain the marginal effects generated by random shocks. Among them, the direct effect is reflected in the impact on the city's own industrial GTFP, and the indirect effect reflects the impact on the neighboring city's industrial green total factor productivity, i.e., the spatial spillover effect. The sum of direct and indirect effects is the total effect. Therefore, this paper obtains the following related research results through decomposition:

(1) industrial structure and economic development level on industrial GTFP both show a significantly positive direct effect, significantly negative indirect effect, but the overall effect is positive and negative effect, and did not pass the test; that is, the industrial structure of the city to enhance the industrial GTFP by 1% to enhance the city's industrial GTFP by 0.0069% and the surrounding cities to decline by 0.0044%, and the level of economic development of every 1% lead to the city's industrial GTFP to enhance by 0.0841%, and the level of economic development of each enhancement to lead to the city's industrial GTFP to enhance by 0.0841%. GTFP by 0.0841% as well as suppressing the surrounding cities by 0.1060%.

(2) Infrastructure development and labor quality show positive direct, indirect and total effects on industrial GTFP, but labor quality does not pass the significance test of spillover effect and total effect. Among them, the overall effect of road density shows a significant positive effect, the reason is that the road is one of the most important infrastructures for industrial development, and its degree of perfection has a decisive significance on the transfer of industrial products and semi-finished products by industrial enterprises. The better the infrastructure, the more favorable the exchange of material information between industrial enterprises, and promote the improvement of efficiency. Every 1% increase in infrastructure level will bring 0.0475%, 0.1250% and 0.1720% increase in industrial GTFP for the city, neighboring cities and the overall city distribution. The quality of labor force is a positive spillover effect, indicating that the improvement of the quality of labor force has an uplifting effect on the high quality development of industry in this city and the surrounding cities.

(3) The impact of openness level on industrial GTFP is not tested, and the correlation coefficient is positive for the city and negative for the neighboring cities, which indicates that the "pollution paradise hypothesis" has not been generated in the Yellow River Basin in the study period, and it may be related to the fact that cities have screened the investment of foreign enterprises in high energy-consuming and high-polluting industries.

(4) The influence of innovation level on industrial GTFP is not tested, the reason why the innovation level is not significant may be related to the fact that the Yellow River Basin is not a "scientific research town" in the country at the present stage, and there are fewer scientific research and innovation results in industrial development and the scientific research results have a certain time lag, and it takes time for the accumulation from the theory to the application.

(5) Environmental regulation shows significant negative direct, indirect and total effects on industrial GTFP, i.e., every 1% increase in government documents related to environmental regulation will lead to a 4.46% and 13.04% decrease in industrial GTFP in this city and neighboring cities; the reason for this may be that most of the industries in the cities in the Yellow River Basin are related to energy and resource-based industries, and there are relatively few high-tech industries, which have a negative impact on the region. The environmental protection policies formulated have led to enterprises having to use production reduction or even partial shutdown to achieve the goal of environmental regulation, thus leading to a decline in industrial GTFP.

(6) Industrial concentration has a significant positive effect on industrial green total factor productivity, which has a better promotion effect on this city as well as the neighboring cities,

which further supports that the integrated development of industrial parks, metropolitan areas and urban agglomerations is of great practical significance.

4. Conclusion and Discussion

4.1. Conclusion

Industrial green development is the cornerstone of high-quality development in the Yellow River Basin and an important way for China to carry out industrial transformation. According to the current situation of water and natural resources in the Yellow River Basin, this paper innovatively incorporates industrial water into the input-output indexes, explores the spatial and temporal characteristics of industrial GTFP in the Yellow River Basin from 2006 to 2020 as well as the regional differences by using the super-efficient EBM model, standard deviation ellipse, and the Terre coefficient, and finally uses a spatial econometric model to explore the influencing factors and their spatial spillover effects, and arrives at the following conclusions:

(1) From 2006 to 2020, the green total factor productivity of industries in the Yellow River Basin shows a three-stage trend of "rapid growth-slow decline-steady improvement". Among them, 2006-2012 shows a trend of rapid increase, with an average annual growth of 3.7%; 2012-2014 shows a trend of slow decline, with an average annual decline of 1.1%; 2014-2020 shows a trend of steady increase, with an average annual increase of 2.4%;

(2) The industrial GTFP in the Yellow River Basin presents the characteristics of clustering and continuous development with the regional central city as the core. The analysis of center of gravity trajectory and standard deviation ellipse reveals that the center of gravity of industrial GTFP in the Yellow River Basin from 2006 to 2020 shows a moving trend of "Northeast-Northwest-Southwest" in the range of $36.19^{\circ}\text{N}\sim 36.44^{\circ}\text{N}$ and $112.42^{\circ}\text{E}\sim 112.68^{\circ}\text{E}$, and the center of gravity of industry in the Yellow River Basin shows a trend of "Northeast-Northwest-Southwest". " moving trend, the center of gravity moving distance, speed gradually increase; standard deviation ellipse is mainly located in the middle and lower reaches of the Yellow River Basin, the corner change is not big, with a more stable spatial distribution pattern, and the spatial distribution shows the characteristics of east-west tends to be polarized, and south-north tends to be balanced.

(3) The Terre coefficient of the Yellow River Basin is fluctuating, but the overall change is not big. Multi-scale view, intra-regional differences are all major contributors to the differences. Specifically, the intra-regional difference is the largest in the middle reaches, and the difference between the middle reaches and the upper reaches has been decreasing in recent years; the Guanzhong City Cluster has the largest intra-regional difference at the city cluster scale, but in the past five years, the Guanzhong City Cluster has shown a trend of gradual decrease in the internal difference, and the regional difference of the city clusters along the Yellow River in Ningxia has the lowest contribution rate. The industrial GTFP in the Yellow River Basin finally shows the development trend of equilibrium within city clusters - polarization between city clusters.

(4) The analysis of influencing factors finds that the level of industrial structure and the level of economic development show significant positive direct effect and negative spillover effect, highlighting the siphoning effect of cities with better industrial foundation; the quality of labor force shows a significant direct effect; the environmental regulation shows a negative effect on the high-quality development of industry; the level of opening up and the level of innovation do not pass the test; the industrial agglomeration and infrastructure construction show a significant positive effect, further supporting the positive effect of industrial agglomeration and infrastructure construction, further supporting the positive effect of industrial agglomeration. The positive effect of industrial agglomeration and infrastructure construction further confirms

that the integrated development of industrial parks, metropolitan areas and city clusters is of great practical significance.

4.2. Discussion

This paper analyzes the spatial and temporal evolution, regional differences and influencing factors of the green total factor productivity of industries in the Yellow River Basin, and through the analysis of the industrial development of the Yellow River Basin, it provides reference bases for the green transformation of industries in the Yellow River Basin and the realization of high-quality development of the Yellow River Basin, and at the same time, it provides theoretical references for the study of high-quality development of industries in less developed regions. While the research achieved results, there are still some things worth exploring. From the results of the spatial Durbin model, the influence of industrial structure on industrial green total factor productivity is positive direct effect, because the specific index selected in this paper is the proportion of the secondary industry, the higher the proportion of the secondary industry is the more unfavorable for the transformation of the green development of the city, resulting in the decline of the sustainability of the city's industrial development, especially for the heavy industry cities in the Yellow River Basin, so in the future, the proportion of the secondary industry may be negative direct effect on the industrial GTFP. GTFP transformation into a negative direct impact^[36]. The impact of environmental regulation on.

The impact of environmental regulation on industrial GTFP in the Yellow River Basin is a significant negative effect^[37], which is consistent with the research results of other scholars that "the relationship between environmental regulation and GTFP shows an inverted "U"-shaped relationship"^[38], and at present, the "inflection point" has been reached. The "inflection point" has not yet appeared.

This paper adopts prefecture-level cities as the research scale, limited by the availability and accuracy of data, and does not explore the characteristics of the development of green total factor productivity in the Yellow River Basin industry in specific industrial sectors; therefore, the next step of the research focuses on the refinement of industrial total factor productivity and the simulation of the forecast of development trends in the municipal level of specific industrial sectors.

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