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Original Research

Temporal-Spatial Characteristics and Driving Factors of Total Factor Carbon Productivity in the Yangtze River Economic Belt

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Abstract

Under the policy background of carbon neutralization and carbon peaking, how to promote total factor carbon productivity (TFCP) has become an important part of promoting green and low-carbon development of the Yangtze River Economic Belt. This paper uses SBM model to measure the TFCP of the Yangtze River Economic Belt, and uses empirical analysis methods such as Dagum Gini coefficient and geographical detector to measure the spatio-temporal evolution characteristics and driving factors of the TFCP of the Yangtze River Economic Belt. The research finds that: First, the development trend of TFCP in the Yangtze River Economic Belt shows a downward trend no matter from the overall regional or subregional level. There are differences in the number and spatial agglomeration patterns of different levels of cities. Second, the overall difference of TFCP in the Yangtze River Economic Belt is gradually decreasing, and the regional difference has become the main factor of spatial difference. The dispersion of TFCP has decreased, and the regional gap has gradually narrowed. TFCP is characterized by non -normal distribution, with local agglomeration development trend, and its focus gradually shifted to the southwest. Third, technological innovation, infrastructure construction and economic growth are the key drivers of the Yangtze River Economic Belt TFCP. The dominant driving factors of TFCP are different in different regions.

Keywords: Yangtze river economic belt, total factor carbon productivity, temporal and spatial evolution, driving factors

Introduction

Climate change is a global environmental problem. The continuous increase of carbon dioxide emissions in various countries poses a threat to life systems [1-2]. As the largest developing country and carbon emitter in the world, China needs to achieve rapid emission reduction while promoting development, and the task is arduous. According to the Global Energy Review: 2021 Carbon Emissions released by the International Energy Agency, China's carbon emissions exceed 11.9 billion tons, accounting for 33% of the global total. In order to cope with climate change, China has made solemn commitments such as

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"striving to reach the peak of carbon dioxide emissions by 2030 and strive to achieve carbon neutrality by 2060" [3]. As a leading demonstration belt of national ecological civilization construction, the Yangtze River Economic Belt shoulders the major mission of taking the lead in achieving "carbon peak" and "carbon neutrality". In recent years, the ecological environment protection of the Yangtze River Economic Belt has made a turning point. However, the green low-carbon transformation is a broad and profound economic and social systematic change, which is characterized by periodicity and complexity. Therefore, the green and low-carbon transformation of the Yangtze River Economic Belt still faces many challenges. How to realize the green and low-carbon transformation of the Yangtze River Economic Belt? The improvement of carbon productivity should be the fundamental way to coordinate economic growth and solve the problem of climate change [4]. However, there is still little literature research on the carbon productivity of the Yangtze River Economic Belt in academia. Therefore, this paper scientifically evaluates the carbon productivity of the Yangtze River Economic Belt, explores its spatio-temporal evolution and explores the internal mechanism of influencing factors, which has important theoretical and practical significance for realizing its green low-carbon transformation.

Productivity refers to the ratio between output and required input in the production process. Under the goal of green and low-carbon development, how to improve carbon productivity has become a hot issue in recent years. At present, the academic research on carbon productivity mainly includes the following three aspects: First, indicator measurement. The measurement of carbon efficiency can be divided into single factor productivity or multi factor productivity according to the number of input factors. The single indicator method uses the ratio of GDP to CO2 emissions to measure carbon productivity [5]. Although carbon productivity emphasizes the direct relationship between carbon emissions and economic growth, it separates the internal organic links between carbon emissions and capital, labor, energy, and technological factors, which is difficult to reflect the comprehensive effect of more input and more output. Therefore, many scholars use Data Envelopment Analysis (DEA) or Stochastic Frontier Analysis (SFA) to comprehensively consider the relationship between input and output of multiple factors and overcome the shortcomings of single factor measurement [6-7].

Second, the analysis of spatio-temporal evolution characteristics. The tools commonly used to measure the characteristics of spatio-temporal evolution are: Dagum Gini coefficient, Markov chain, Kernel density estimation, Theil index, standard deviation ellipse, Moran index and other methods. Xiao et al., (2022) [8] used Dagum Gini coefficient decomposition method to study the regional difference of industrial green total factor productivity from 2003 to 2018. Liu & Zhu (2022) [9] used Kernel density estimation and spatial Markov chain to explore the spatio-temporal evolution characteristics of green total factor productivity in 53 coastal cities from 2003 to 2017. Zhou et al. (2020) [10] used Thiel index, spatial Markov chain and other methods to measure the spatio-temporal evolution characteristics of urban green low-carbon from 2005 to 2015. Zhao et al., (2019) [11] used Moran index, Markov chain and other methods to explore the spatial characteristics and dynamic evolution trend of low-carbon economic development. Yang et al., (2022) [12] studied the temporal and spatial distribution pattern of carbon emissions in China's prefecture level cities from 2005 to 2020 by using the methods of standard deviation ellipse and Moran index.

Third, the study of influencing factors. The formation of regional carbon efficiency differences often stems from many complex factors. Many scholars discuss the influencing factors of carbon efficiency gaps from the perspectives of green technology innovation and environmental regulation. Du and Li (2019) [13] believed that green technology innovation had a positive impact on total factor carbon productivity (TFCP) of high-income economies; Due to the lack of relevant innovation subsidy support, it is difficult for underdeveloped economies to use green technology innovation to improve TFCP. Zhou and Tang (2021) [14] used DID method to investigate the impact of environmental regulation on industrial TFCP. They believed that the implementation of environmental policies was conducive to the growth of TFCP in air pollution intensive industries. In addition, there are also some documents that further include infrastructure construction [15], digital economy [16], financial development [17], industrial structure [18], foreign investment [19] and other factors into the analysis framework, discussing the impact of different factors on regional carbon efficiency differences and their mechanisms.

This paper uses SmartArt chart to draw the research status of literature review, as shown in Fig. 1.

The existing literature lays the foundation for this study, but the following aspects still need to be further discussed. First, the research object. Most literature studies on TFCP mainly focus on the overall region, but lack of discussion on key regions. Second, the analysis of space-time characteristics. Scholars generally study carbon emissions, total factor productivity, green total factor productivity and other aspects, but the temporal and spatial evolution characteristics of TFCP still need to be further explored. Third, the analysis of driving factors. Which drivers play a greater role in TFCP? Is there heterogeneity? At present, there are few references. Based on this, this paper first uses the SBM super efficiency model to measure the TFCP of the Yangtze River Economic Belt. Secondly, by using Dagum Gini coefficient, Kernel density estimation, standard deviation ellipse and other analysis methods, this paper examines the temporal and

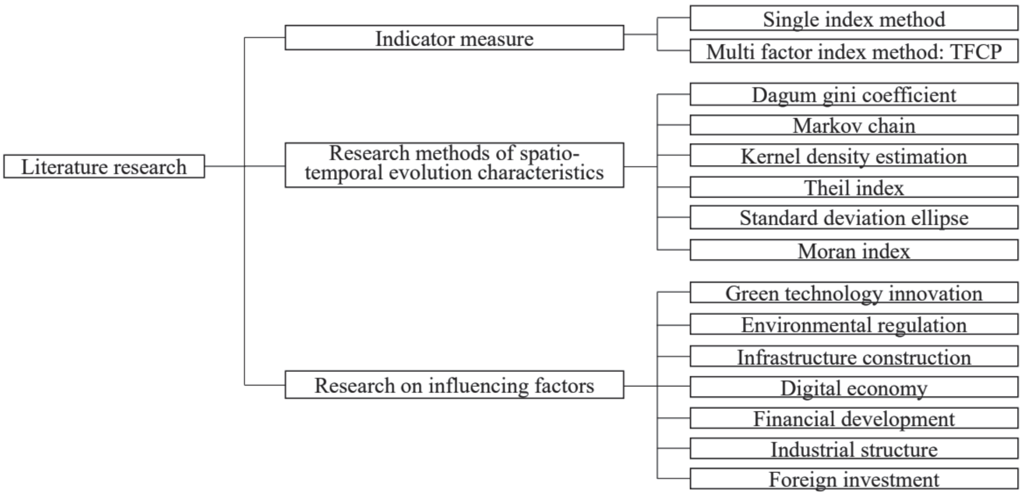

Fig. 1. Framework of literature review.

spatial evolution characteristics of TFCP in the Yangtze River Economic Belt. Finally, this paper attempts to measure the driving factors of TFCP in the Yangtze River Economic Belt by using geographical detectors, and further discusses the driving factors of TFCP in different regions of the Yangtze River Economic Belt.

Materials and Methods

Study Area

The Yangtze River Economic Belt spans China's east and west, covering 11 provinces and cities, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou. It is the most comprehensive economic belt, resource belt, and industrial belt in China. According to the official data of the National Bureau of Statistics in 2021, 11 provinces and cities in the Yangtze River Economic Belt account for 21.5% of the country's land area, carry 43.0% of the country's permanent population, and create 46.4% of the country's GDP. In September 2016, the Outline of the Yangtze River Economic Belt Development Plan was officially issued, establishing a new development pattern of "one axis, two wings, three poles and multiple points" of the Yangtze River Economic Belt. Relying on the golden waterway of the Yangtze River, the Yangtze River Economic Belt is an important "growth pole" for China's regional economic development. The remarkable development advantages of the Yangtze River Economic Belt determine that it is of great significance in promoting regional balanced development, building ecological civilization and realizing the Chinese Dream of national rejuvenation. In the context of the "dual carbon" goal, improving TFCP has become the key and breakthrough point for the Yangtze River Economic Belt to achieve green and low-carbon transformation. Fig. 2 shows the spatial

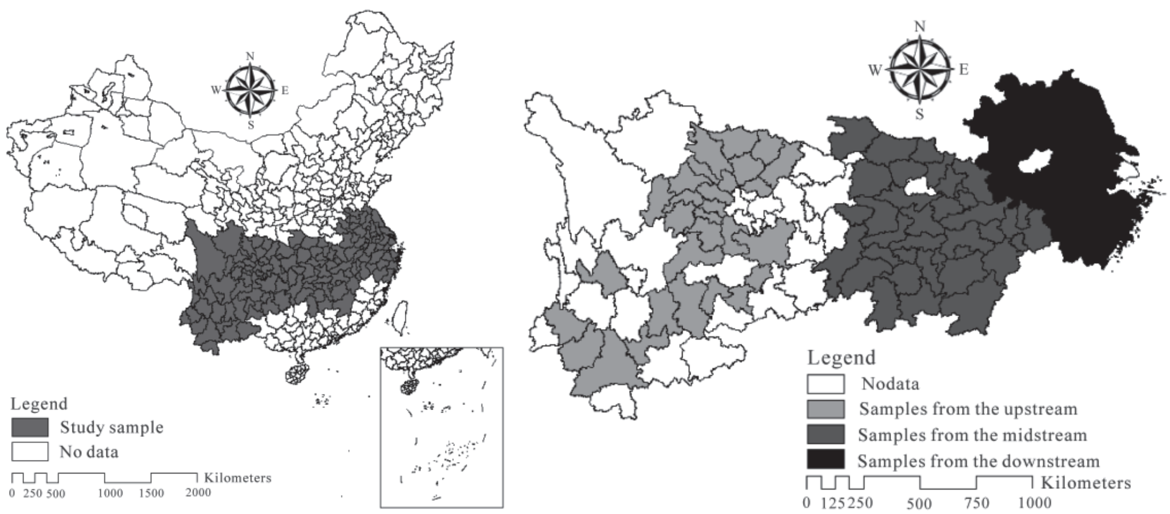

Fig. 2. Spatial distribution of the study area.

distribution range of the study area in this paper, and divides the Yangtze River Economic Belt into the upper, middle and lower reaches.

Method

SBM Model

Super efficiency SBM model is a model that combines super efficiency and SBM model. Compared with the traditional BBC and CCR models, the SBM model directly incorporates the slack variables into the objective function, which makes the economic objective of the SBM model realize profit maximization. Meanwhile, the super-efficiency SBM can solve the evaluation unit problem with efficiency value of 1. This paper adopts this model to measure TFCP in the Yangtze River Economic Belt, and the specific formula can be obtained from Jiang et al. (2021) [20].

Dagum Gini Coefficient Method

In this paper, the Dagum Gini coefficient is used to measure the composition and source of spatial differences of TFCP in the Yangtze River Economic Belt. The calculation method is shown in Equation (1) :

$$G=\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{c_j}\sum_{r=1}^{c_h}\left|y_{ji}-y_{hr}\right|/2c^2\overline{y} \tag{1}$$

In formula (1), $y_{ji}(y_{hr})$ represents TFCP in region $j(h)$; c is the number of samples; $\bar{y}$ is the mean value of TFCP of the research unit; k is the number of areas; $c_j(c_h)$ is the number of samples in area $j(h)$. Dagum Gini coefficient can be decomposed into intra regional difference contribution G_w, inter regional contribution G_{cb} and hypervariable density G_t (Liang et al., 2022) [21].

Kernel Core Density Curve Method

Kernel density is widely used as a non-parametric estimation method for spatial disequilibrium analysis, which describes the distribution change pattern of random variables through Kernel density curve [22]. The density function of random variable x is $f(x)$, and Equation (2) is the point density function. Equation (3) is a Gaussian Kernel function, which can estimate the spatial evolution pattern of TFCP in the Yangtze River Economic Belt. Where, N is the number of observations, x is the independent and identically distributed observations, h is the bandwidth, and $K(x)$ is the Kernel function.

$$f(x)=(1/Nh)\sum_{i=1}^{N}K\left[\left(X_i-\overline{X}\right)/h\right] \tag{2}$$

$$K(x)=\left(1/\sqrt{2\pi}\right)\exp\left(-x^2/2\right) \tag{3}$$

Standard Deviation Ellipse Method

The standard deviation ellipse method measures the direction and distribution of data, the output result is an ellipse, and the spatial evolution characteristics such as the central trend, discrete and directional trend of geographical elements are summarized. The long semi axis of the ellipse represents the data distribution direction, and the short semi axis represents the data distribution range. The greater the difference between the long and short semi axes, that is, the greater the flatness, the more obvious the directivity of the data; On the contrary, the smaller the difference between the long axis and the short axis, the less obvious the directivity. The shorter the short semi axis is, the more obvious the centripetal force is; On the contrary, the longer the short semi axis is, the greater the dispersion of data is. This paper uses this model to measure the spatial evolution characteristics of TFCP in the Yangtze River Economic Belt. The specific formula can refer to Yang et al. (2022) [23].

Geographic Detector Method

Geographic detector model can overcome the problem of excessive assumptions in traditional measurement methods, and is widely used to measure the driving factors and mechanisms related to economic society and physical geography [24]. This paper analyzes the driving factors of TFCP spatial differentiation pattern in the Yangtze River Economic Belt by using geographic detector. Factor detection analyzes the degree of driving factors affecting the spatial differentiation of dependent variables, which is measured by q value. The specific formula is as follows:

$$q=1-(1/N\delta^2)\sum_{h=1}^{L}N_h\delta_h^2=1-(SSW/SST) \tag{4}$$

$$SSW=\sum_{h=1}^{L}N_h\delta^2 \tag{5}$$

$$SST=N\delta^2 \tag{6}$$

Where, N and N_h are the sample sizes in the overall and sub regions respectively. The detection factors are divided into L levels. δ^2 and δ_h^2 are the discrete variances of samples in the population and sub regions respectively. SSW and SST are the sum of the variance of the secondary region and the sum of the population variance, respectively. $q\in[0,1]$, the larger the q value, the stronger the explanatory power of this driving factor to the TFCP of the Yangtze River Economic Belt.

To sum up, the empirical research method of this paper is shown in Fig. 3.

Data Source

This paper selects 108 prefecture-level and above cities in 11 provinces and cities in the Yangtze River

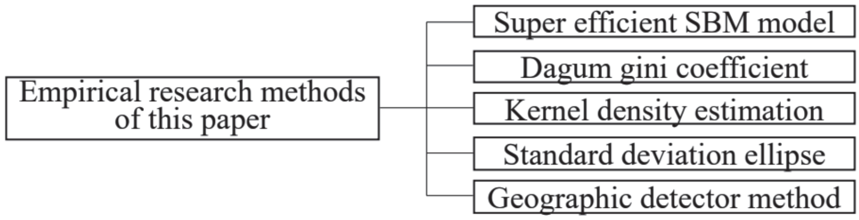

Fig. 3. Empirical Research Methods.

Economic Belt from 2005 to 2020 as the research objects. Relevant data are obtained from China Urban Statistical Yearbook, China Urban Construction Statistical Yearbook, EPS database, DMSP and VIIRS satellite raster data, State Intellectual Property Office and local government work reports, etc. The missing data of individual years are completed by trend interpolation method and moving average method.

Dependent Variable

Measurement of total factor carbon productivity (TFCP). With reference to the existing literature, this paper measures the TFCP of the Yangtze River Economic Belt using the super efficient SBM model from the perspective of input-output. TFCP is the result of the comprehensive effect of capital, labor, energy and other input factors. With reference to the perpetual inventory method of Zhang et al. (2004) [25], the capital stock is regarded as productive capital input. The fixed asset investment price index is selected as the original value of the capital stock, and the year 2003 is taken as the base period for reduction. The number of urban employees as labor input is measured by the number of urban unit employees at the end of the period. Energy consumption input is measured by electricity consumption of the whole society. Output indicators are divided into unexpected output and expected output. Among them, the unexpected output is urban carbon emissions, which can be measured from the perspective of direct and indirect carbon emission sources with reference to Wang and Zhang (2022) [26]. Direct carbon emission sources include natural gas and liquefied petroleum gas, while indirect carbon emission sources include carbon emissions generated by consumption of electric energy and heat energy. Expected output is measured by real GDP.

Indicator Selection of Driving Factors

Urban TFCP is the result of multiple factors, and it is of great significance to evaluate the driving factors of urban TFCP for the whole society. Driving factors refer to the internal or external forces that affect the development of things. On the premise of resource constraints, limited resources and energy need to be invested in key driving factors to effectively improve the TFCP of the Yangtze River Economic Belt.

Based on the research results of existing literature, the following factors affecting TFCP are selected for analysis. Industrial upgrading (Ind): drawing lessons from Zou and Xiong (2022) [27], we use the included Angle cosine to construct the high-level index of industrial structure. Market: measured by Fan Gang index. Infrastructure construction (Instra): measured by highway mileage. Government intervention (Gov): measured by the proportion of fiscal expenditure in GDP. Financial development (Fin): measured by the proportion of deposit and loan balance in GDP. Foreign investment (Fdi): measured by the proportion of foreign direct investment in GDP. Environmental regulation (Reg): learn from Zou and Pan (2022) [28], and measure environmental regulation by using the frequency of environmental words in the government work report. Economic growth (Light): measured by night light data. Technological innovation (Innov): measured by the number of patent applications. Urbanization level (Pop): measured by population density. Human capital (Hum): measured by the number of college students per 10000. Because the geographic detector needs to discretize the independent variables into type variables, this paper uses the equal division method to divide the independent variables into five equal type variables.

Results and Discussion

Time Distribution Characteristics of Total Factor Productivity of Carbon

The super efficiency SBM model is used to measure the TFCP of the Yangtze River Economic Belt from 2005 to 2020. Due to the comparability of efficiency values between different years, the trend characteristics of the measurement results are described in order to find the development trend characteristics of TFCP in the Yangtze River Economic Belt [29]. This paper draws a line chart to show the time development trend of TFCP in the Yangtze River Economic Belt and its upper, middle and lower reaches, as shown in Fig. 4.

The results show that from 2005 to 2020, the average TFCP of the Yangtze River Economic Belt decreased from 0.529 to 0.233, with a decrease of 56.003%, showing a steady downward trend. The possible reason is that the growth rate of energy consumption and carbon emissions exceeded the expected output in the

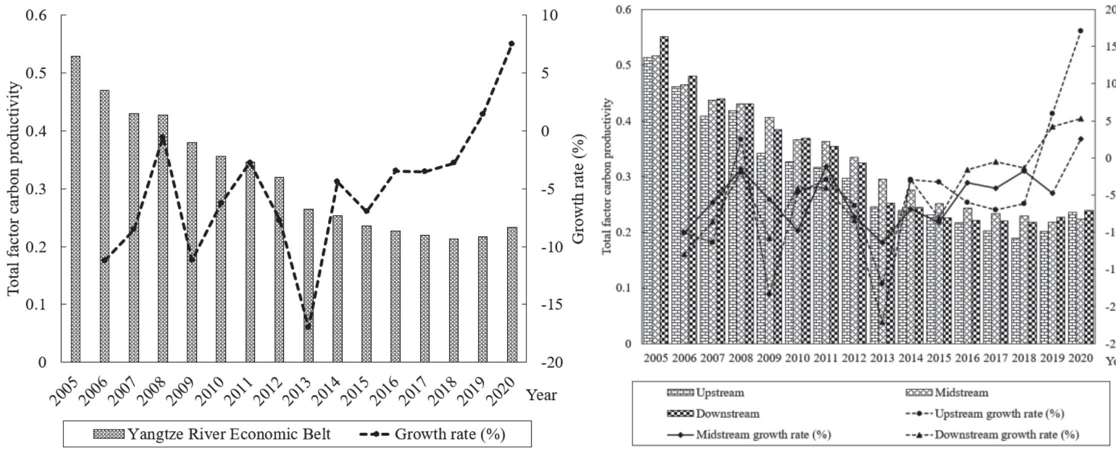

Fig. 4. Temporal trend characteristics of TFCP in the Yangtze River Economic Belt and various regions.

same period, leading to the decline of TFCP. At the same time, TFCP in the upper, middle and lower reaches of the Yangtze River Economic Belt has shown a steady downward trend, which is the same as the overall development trend. From the perspective of the annual mean of TFCP, the middle reaches > the downstream > the upstream, and the annual mean values are 0.331, 0.324 and 0.303, respectively. In terms of the decline rate of TFCP, the midstream region has the fastest decline, followed by the downstream region, and finally the upstream region, with an average annual decline of 5.358%, 5.183%, and 4.700%. From 2013 to 2020, the decline rate of TFCP in the Yangtze River Economic Belt slowed down and showed positive growth in 2019 to 2020. This shows that the Yangtze River Economic Belt has achieved remarkable results in green and low-carbon work, and TFCP has improved. In particular, the lower and upper reaches of the Yangtze River have gradually surpassed the middle reaches.

Spatial Distribution Characteristics of Total Factor Productivity of Carbon

In order to reflect the spatial distribution characteristics more intuitively, this paper draws the spatial distribution map of TFCP in the Yangtze River Economic Belt [30-31]. According to the natural fracture method of Arcgis10.5 software, TFCP is divided into five echelons from high to low: the first echelon, the second echelon, the third echelon, the fourth echelon and the fifth echelon. The analysis of the characteristics of spatial distribution pattern is conducive to understanding the regional development differences of TFCP in the Yangtze River Economic Belt as a whole. Due to space problem, this paper selects 2005, 2010, 2015 and 2020 as representative years to draw the spatial distribution map of TFCP in the Yangtze River Economic Belt (Fig. 5).

The results show that the spatial distribution of TFCP in the Yangtze River Economic Belt has changed significantly. From the quantity characteristics of each echelon, the number of cities in the first tier of TFCP has decreased, showing a decentralized distribution. Representative cities include Lincang, Chuzhou, Suizhou, etc. The number of cities in the second and third echelons of TFCP continues to increase, showing a continuous block like spatial distribution. Representative cities, such as Yueyang, Changsha, Yichun and Zhuzhou in the middle reaches of the Yangtze River, are clustered in the second tier of TFCP; Lianyungang, Xuzhou, Suzhou, Suqian and other eight cities in the lower reaches of the Yangtze River are clustered. The number of cities in the fourth and fifth echelons of TFCP has generally decreased. The cities in the fourth echelon of TFCP are relatively clustered, and representative cities such as Guangyuan, Nanchong, Dazhou and Chongqing are clustered. The cities in the fifth echelon of TFCP are relatively scattered, and the representative cities such as Bazhong, Shiyan, Lu'an, Nanchang, etc. are scattered.

Decomposition of Temporal and Spatial Differences in TFCP

Dagum Gini Coefficient

This paper uses Dagum Gini coefficient and its decomposition method to calculate the overall difference, intra regional difference, inter regional difference and contribution of TFCP in the Yangtze River Economic Belt from 2005 to 2020, which aims to reveal the size and source of spatial difference of TFCP in the Yangtze River Economic Belt. The calculation results are shown in Fig. 6 and Fig. 7.

The results show that, from the perspective of the overall trend of change, the total Gini coefficient G is declining on the whole, and the overall difference is gradually decreasing. It decreased from 0.219 in 2005 to 0.145 in 2020, with a decrease of 33.569% during the study period. From 2005 to 2013, the overall Gini coefficient G fluctuated downward. From 2014 to 2020, the overall Gini coefficient G fluctuated around

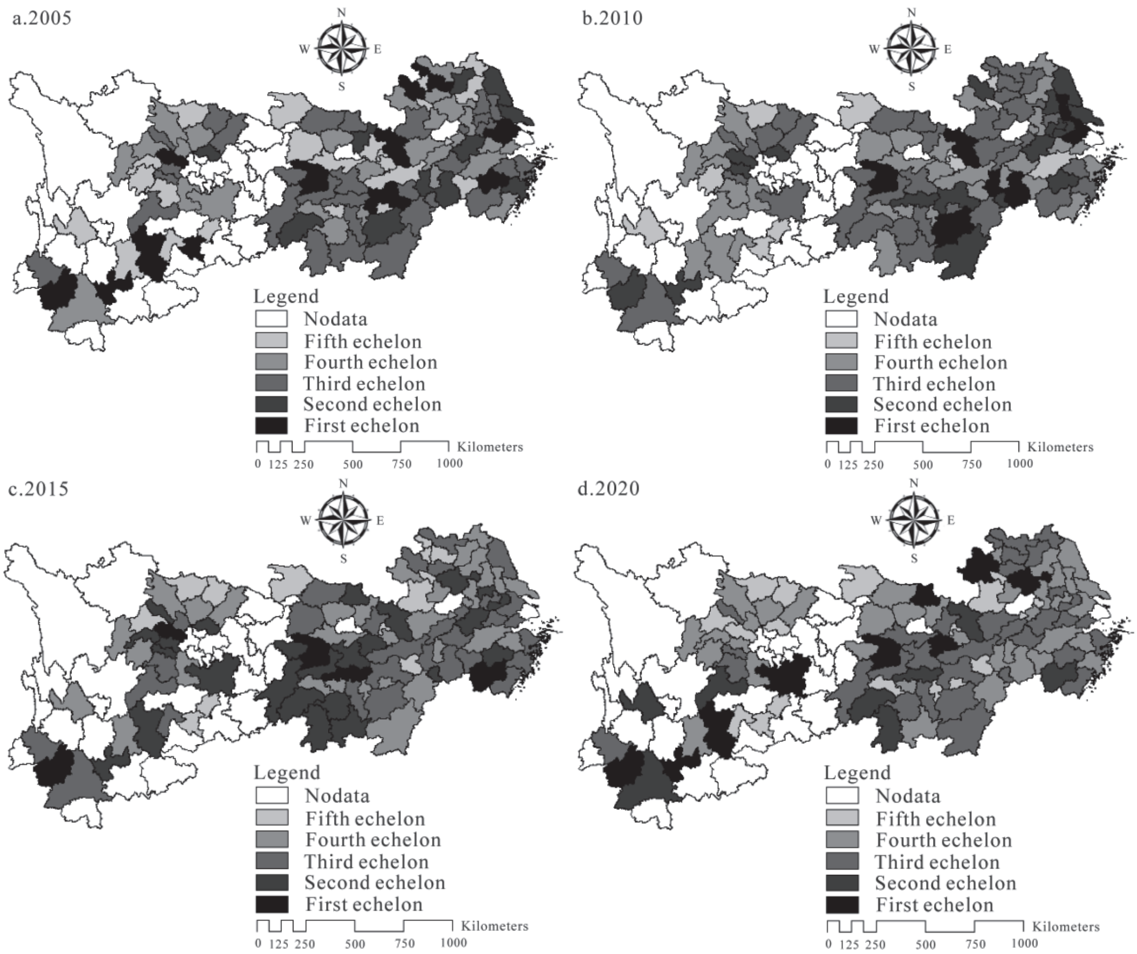

Fig. 5. Spatial distribution characteristics of TFCP in the Yangtze River Economic Belt.

0.145. During the investigation period, the differences between regions constitute the main source of TFCP differences in the Yangtze River Economic Belt. From the perspective of the mean contribution rate, the average contribution rate of the supervariable density Gt and the inter-regional difference Gw are 51.050% and 16.522%, and the contribution rate of the inter-regional difference is 67.571%. The mean contribution rate of regional difference Gcb is 32.429%.

From the perspective of the intra region, the average Gini coefficient in the region is ranked as: downstream>midstream>upstream, with the average values of 0.184, 0.157 and 0.136 respectively. On the whole, the difference of Gini coefficient in the lower, middle and upper reaches of the Yangtze River Economic Belt is fluctuating and declining. During the investigation period, the largest decrease in Gini coefficient in the region was in the upstream, which was 43.822% lower than that at the beginning of the period. The second is the middle reaches, and the last is the downstream, with a decrease of 33.572% and 27.477% respectively.

From the perspective of the inter region, the mean value of Gini coefficient among regions is ranked as follows: midstream-downstream > upstream-downstream > upstream-midstream, with the mean value of 0.179, 0.168 and 0.151, respectively. On the whole, the Gini coefficient between regions shows a trend of fluctuation and decline, which means that the difference between regions has been narrowed. During the investigation period, the biggest decrease of Gini coefficient among regions was from the difference between the upstream and midstream, which was 37.832% compared with the beginning of the period, followed by the difference between the upstream and downstream, and finally the difference between the midstream and downstream, which was 30.395% and 26.861% respectively.

Kernel Density Estimation

Through Dagum Gini coefficient, the regional differences and their sources of TFCP in the Yangtze River Economic Belt are analyzed in detail, but only the relative differences are reflected. Kernel density estimation method is helpful to describe the overall shape and dynamic evolution law of absolute difference distribution of economic factors. Therefore, this paper uses the Kernel density method for further analysis and draws a three-dimensional TFCP nuclear density map of the Yangtze River Economic Belt.

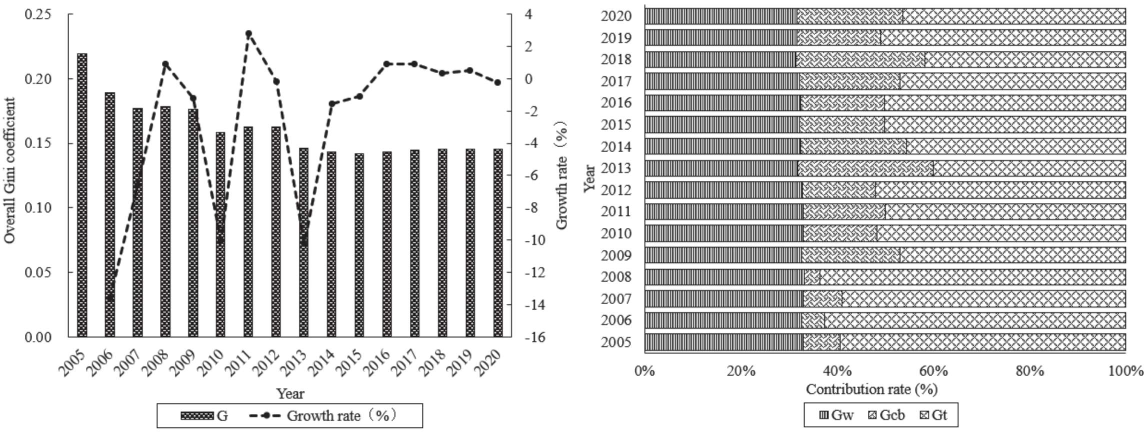

Fig. 6. Time trend characteristics of total TFCP Gini coefficient and contribution rate of regional differences in the Yangtze River Economic Belt.

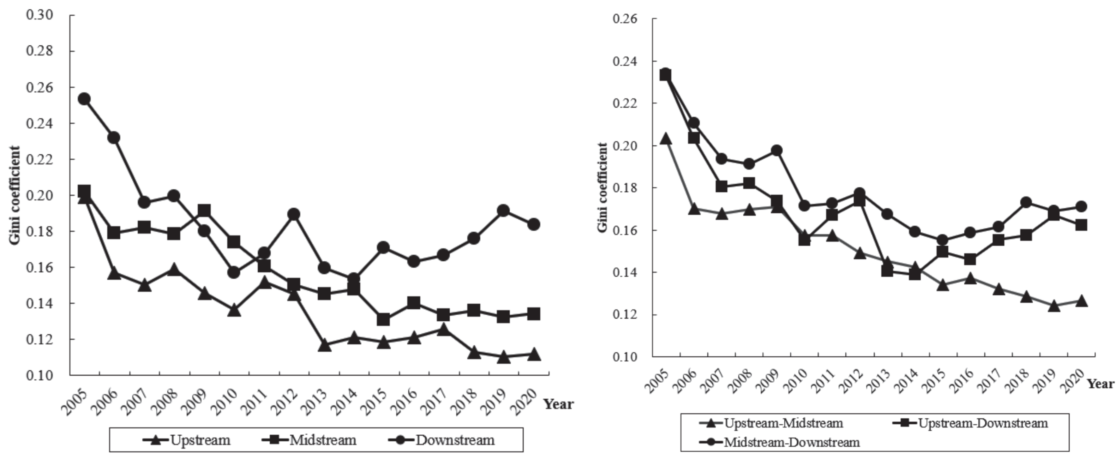

Fig. 7. Time trend characteristics of intra-regional differences and inter-regional differences of TFCP in the Yangtze River Economic Belt.

Fig. 8 reports the nuclear density maps of TFCPs in the Yangtze River Economic Belt (Fig. 8a) and its upstream (Fig. 8b), midstream (Fig. 8c) and downstream (Fig. 8d), respectively.

It can be seen from Fig. 8a) that the TFCP of the Yangtze River Economic Belt was mainly distributed in 0.18~1.10 in 2000 and 0.10~0.50 in 2020. From the perspective of distribution position, the density curve of TFCP in each year was shifted to the left as a whole, reflecting a downward trend of TFCP. From the perspective of distribution pattern, the height of the main peak of the nuclear density curve showed an “up-down” fluctuation trend during the investigation period, which means that the gap of TFCP was narrowed. The distribution of Kernel density curve gradually changed from “one main peak with multiple side peaks” to “single peak”, reflecting the gradual narrowing of the gap in most regions. From the perspective of distribution ductility, the Kernel density curve does not have right trailing, indicating that the internal development is relatively balanced.

It can be seen from Fig. 8(b-d) that the nuclear density curves of the upstream, midstream and downstream are similar to those of the whole region. From the perspective of distribution position, the Kernel density curve generally shifted to the left, reflecting the decreasing trend of TFCP in each region. In terms of distribution morphology, the height of the main peak was slightly different in each region. The main peaks of the upstream and downstream nuclear density curves rise first and then fall, and the overall trend is a slight decline. The Kernel density curve of the main peak in the midstream is a development trend of "up-down-up", and it is also a slight decline development trend in general. The distribution of the Kernel density curve gradually changed from "one main peak with multiple side peaks" to "single peak", which means that the gap within the TFCP of each region was reduced. From the perspective of distribution extensibility, there is no right trailing phenomenon in each region, indicating that TFCP in each region has the characteristics of balanced development.

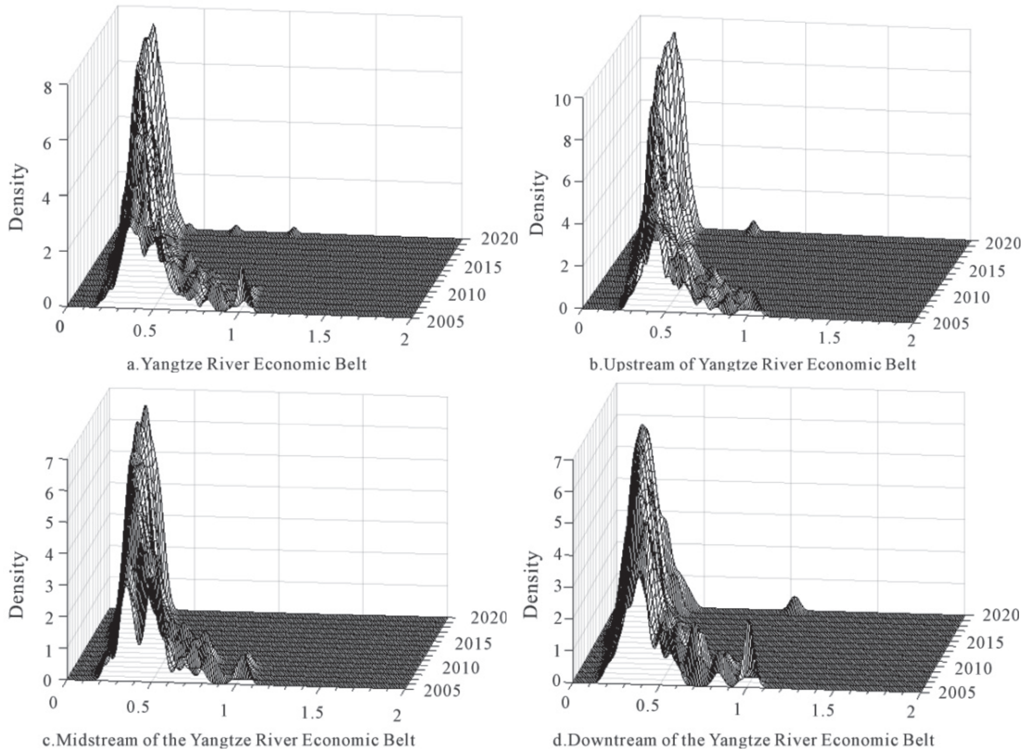

Fig. 8. Kernel density map of TFCP in the Yangtze River Economic Belt and various regions.

Spatial Evolution Characteristics of Total Factor Productivity of Carbon

The standard deviation ellipse method can quantitatively explain the centrality, directivity, centralization and other integrity characteristics of the spatial pattern from a global and spatial perspective. In order to further explore the temporal and spatial distribution and evolution of TFCP in the Yangtze River Economic Belt in representative years, this paper uses the first standard deviation of the standard deviation ellipse method to cover about 68% of the total element centroids, uses ArcGIS10.5 software to calculate the standard deviation ellipse parameters (Table 2), and draws the center of gravity migration trajectory of TFCP in the Yangtze River Economic Belt (Fig. 9).

The results show that the average geometric center of gravity is (113°41‘37“E, 29°40’83”N), which is located in Jingzhou city. However, the region of high value of TFCP is not located here, so TFCP shows a non-normal distribution. The orientation Angle varies from 75°55'41" to 77°51'22", and the spatial distribution of TFCP is from northeast to southwest, indicating that the spatial distribution pattern of TFCP is from northeast to southwest. The coverage area of the ellipse decreases first and then increases, indicating that TFCP presents a development trend of agglomeration. According to the characteristics of spatial agglomeration distribution map, it is a low level of spatial agglomeration of TFCP. In general, the major half axis becomes longer and the minor half axis becomes shorter, and the shape index first increases and then decreases, showing a flattening trend. The reason is that the development of TFCP in the direction of "Northeast to southwest" is more powerful. From the migration trajectory, the center of gravity gradually shifted to the southwest. The development of TFCP in the midstream and upstream is gradually improved, which has a certain pulling effect.

Table 2. Elliptic parameters of TFCP standard deviation in the Yangtze River Economic Belt from 2005 to 2020.

Year	Barycentric coordinates	Long half shaft/km	Short half shaft/km	Azimuth/(°)	Area/ten thousand km²	Shape index
2005	(113°12′07″E, 29°41′02″N)	9.187	2.942	76°27′22″	84.879	0.320
2010	(113°25′59″E, 29°48′18″N)	8.953	2.907	77°51′22″	81.750	0.325
2015	(112°57′07″E, 29°35′56″N)	9.061	2.894	77°40′59″	82.350	0.319
2020	(113°01′16″E, 29°38′56″N)	9.228	2.857	75°55′41″	83.280	0.310

Note: The data are calculated by ArcGIS10.5 software; Excluding Hong Kong, Macao and Taiwan data.

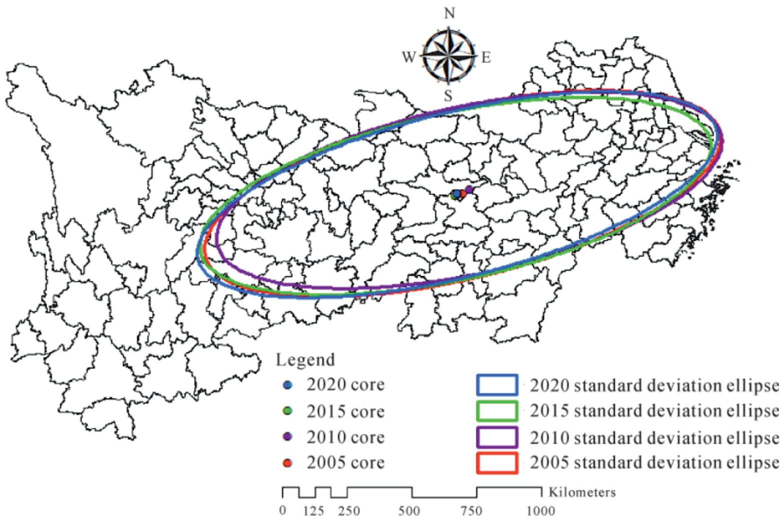

Fig. 9. Standard deviation ellipse and spatial migration trajectory of TFCP in the Yangtze River Economic Belt.

Analysis on Driving Factors of Total Factor Productivity of Carbon

Analysis of Driving Factors

TFCP is affected by many factors, such as economy, society, education and culture, but which driving factors play a greater role in promoting TFCP in the Yangtze River Economic Belt? This paper selects 11 indicators as explanatory variables, namely, industrial upgrading, marketization level, infrastructure construction, government intervention, financial development, foreign investment, environmental regulation, economic growth, technological innovation, urbanization level and human capital. In order to find the key factors conducive to improving the TFCP of the Yangtze River Economic Belt, this paper uses the GeoDetector software to calculate the q value of each driving factor, and draws a radar chart to show the force of each driving factor (Fig. 10).

The results show that the top three driving factors affecting the spatial differentiation pattern of TFCP in the Yangtze River Economic Belt are: Innov, Instra and Light. q values are 0.020, 0.017 and 0.013, respectively, indicating that technological innovation, infrastructure construction and economic growth have a greater role in promoting TFCP in the Yangtze River Economic Belt. Technological innovation can realize low-carbon, economical and efficient production, and promote the low-carbon transformation of production mode. Infrastructure construction is the foundation for promoting ecological and environmental protection and high-quality economic development. In particular, strengthening the construction of ecological and environmental infrastructure is conducive to promoting the implementation of ecological projects and improving the ability of ecological and environmental protection and pollution prevention and control. With the continuous improvement of economic level, people's awareness of environmental protection has been enhanced, which is conducive to environmental pollution control. The last three TFCP rankings are Pop, Reg and Fdi, with q values of 0.007, 0.005 and 0.004, respectively. Urbanization level, environmental regulation and foreign investment have relatively little driving effect on TFCP.

From the perspective of different regions, the leading driving factors of TFCP are different. From the upstream perspective, the top three drivers are Innov, Fin and Reg, and the q values are 0.083, 0.074 and 0.072 respectively. That is, technological innovation, financial development and environmental regulation are important driving factors to promote TFCP in the upper reaches of the Yangtze River Economic Belt. The upstream regions of the Yangtze River Economic Belt are Sichuan, Yunnan and Guizhou provinces, which are endowed with superior natural resources but fragile ecological environment. Technological innovation is conducive to improving clean production technology, saving energy and reducing emissions while improving production efficiency. Financial development is conducive to the transformation of local economic development mode, reduce the dependence on natural resources. Since the ecological environment is relatively fragile, the government's environmental regulation can well "force" enterprises to carry out green innovation and promote the output of green products.

In the middle reaches, the top three driving factors are Market, Innov and Instra, with q values of 0.098, 0.081 and 0.077 respectively. That is, the level of marketization, technological innovation and infrastructure construction are important driving factors to promote TFCP in the middle reaches of the Yangtze River Economic Belt. The middle reaches of the Yangtze River Economic Belt are the economic hinterland connecting the east to the west and the south to the north. The overall urbanization rate of Hubei, Hunan and Jiangxi provinces has reached about 60%. In the middle reaches, through the combination of the paid use of resources and the arrangement of property rights system, the market mechanism of “who repairs who gains” is built. And promote environmental governance by means of marketization. Green, low-carbon and clean technology production processes are conducive to improving production efficiency and reducing environmental pollution emissions. Building green infrastructure and promoting the greening of infrastructure will provide the basic guarantee for long-term and high-quality economic development.

In terms of downstream regions, the top three driving factors are Light, Instra and Ind. The q values are 0.031, 0.019 and 0.019 respectively. That is, economic growth, infrastructure construction and industrial upgrading are more conducive to promoting the improvement of TFCP in the lower reaches of the Yangtze River Economic Belt. The provinces and cities in the lower reaches of the Yangtze River Economic Belt are Anhui, Jiangsu, Zhejiang and Shanghai, respectively. The GDP accounts for more than 50% of the Yangtze River Economic Belt. As environmental problems are not conducive to economic development, people’s living standards are constantly improving, and their awareness of environmental protection is also growing. The concept of green consumption guides green production and increases green supply. The downstream area attaches importance to infrastructure construction to create a good business environment for the local area. At the same time, downstream regions focus on improving the core competitiveness and cleaner production level of traditional manufacturing, and accelerate the transformation and upgrading of traditional manufacturing in the Yangtze River Economic Belt.

This paper uses SBM super efficiency model to measure the TFCP of the Yangtze River Economic Belt. Using Dagum Gini coefficient, Kernel density estimation, standard deviation ellipse and other analysis methods, this paper discusses the temporal and spatial evolution characteristics of TFCP in the Yangtze River Economic Belt. The driving factors of TFCP in the Yangtze River Economic Belt are further measured by using geographical detectors. Drawing on Nawaz et al. (2021) [32], this paper further draws a graphical demonstration of empirical results, as shown in Fig. 11.

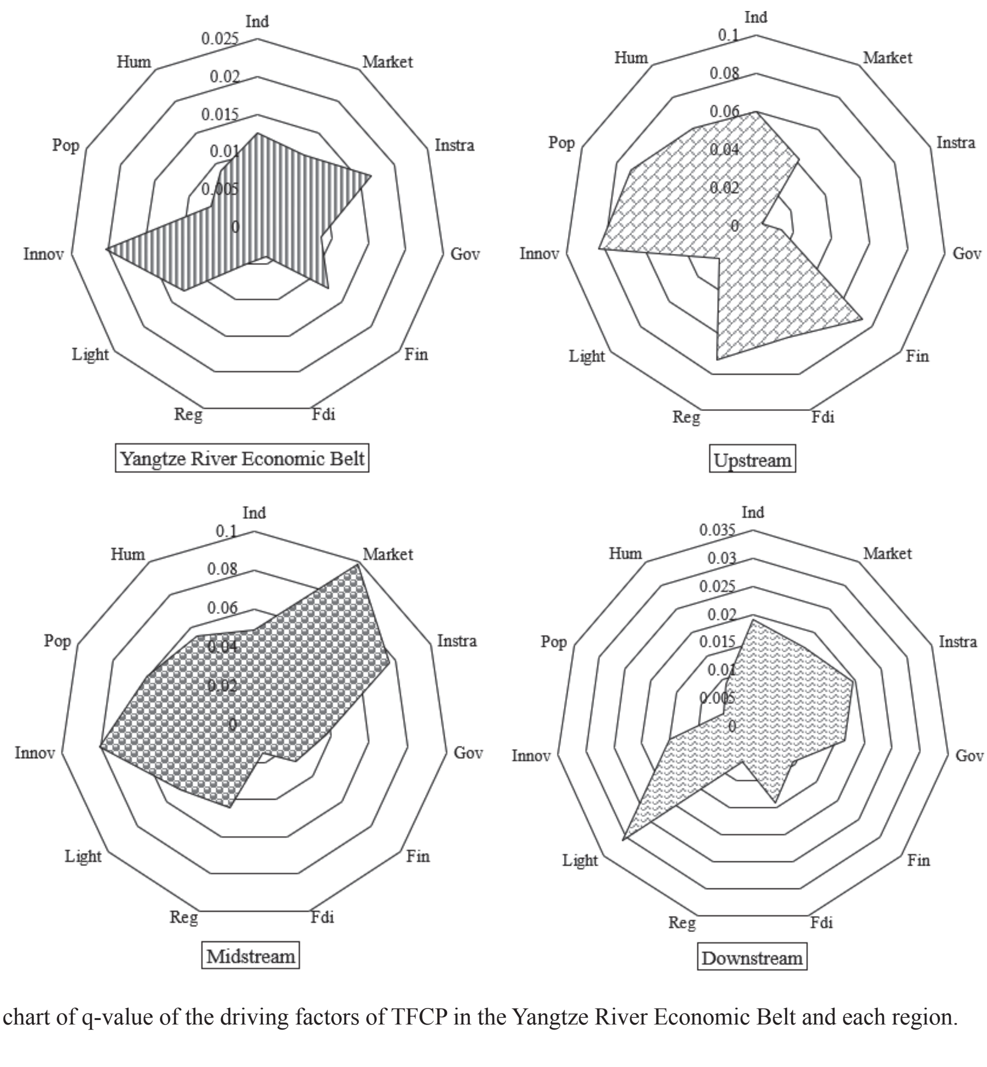

Fig. 10. Radar chart of q-value of the driving factors of TFCP in the Yangtze River Economic Belt and each region.

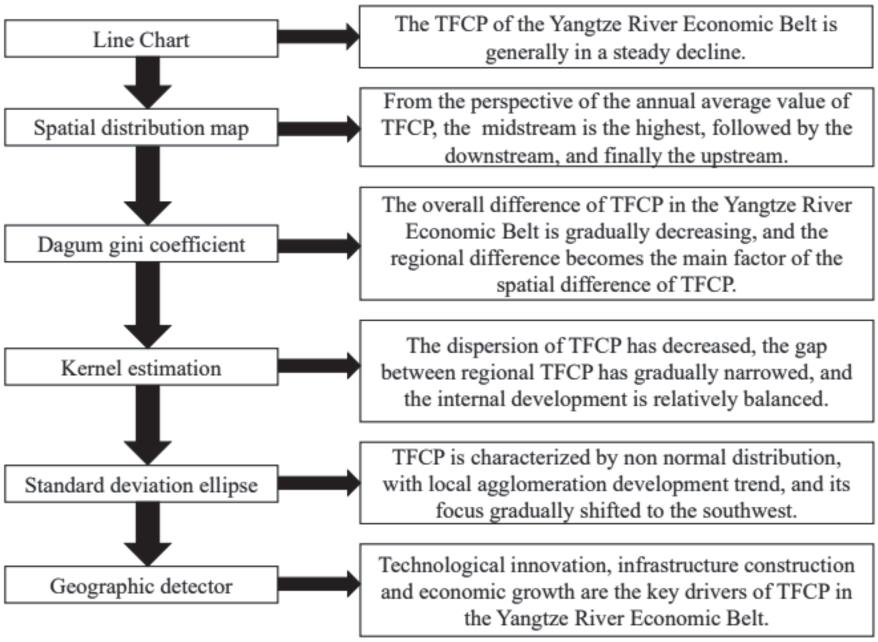

Fig. 11. Graphic demonstration of empirical results.

Government Policy Suggestion

The research results reveal the temporal and spatial distribution characteristics and evolution laws of TFCP in the Yangtze River Economic Belt. Due to the imbalance of regional development and the difference of regional driving factors, in order to better promote the development of TFCP in the Yangtze River Economic Belt, this paper puts forward the following targeted policy recommendations.

Implement Carbon Emission Reduction Plan According to Local Conditions

The planning and deployment of carbon emission reduction in various regions of the Yangtze River Economic Belt need to adapt to local conditions. We could build a carbon reduction spatial pattern that matches the development orientation and regional synergy and complementarity. Specifically, a differentiated target decomposition mechanism for carbon reduction responsibility should be established by comprehensively considering the development stages and resource endowments of the upper, middle and lower reaches of the Yangtze River Economic Belt.

Focus on Technological Innovation and Industrial Structure Upgrading

Focus on technological innovation and promote the upgrading of industrial structure. Organize key technology research and accelerate the construction of scientific and technological innovation capacity. A number of provincial key laboratories, technology innovation centers, enterprise technology centers and other innovation platforms should be arranged around carbon capture, utilization, storage and other fields. All regions should comprehensively implement the industrial green transformation and upgrading project, and cultivate and expand green emerging industries. Create a green factory and develop a green supply chain.

Promote the Development of Pilot Cities and Demonstration Areas

Accelerate the construction of pilot projects and promote successful experience nationwide. The government should promote the construction of “double carbon” pilot cities and demonstration areas in the Yangtze River Economic Belt, and strive to build a green and low-carbon model city. Each region needs to build a green and low-carbon science and technology innovation platform, and coordinate the implementation of major green technology research and development and demonstration projects. At the same time, we can build an ecological security technology innovation center in the Yangtze River Economic Belt, and create a “double carbon” high-end talent joint introduction mechanism.

Conclusions

Enhancing TFCP is the key to achieving the dual carbon target and high-quality development of the Yangtze River Economic Belt. This paper discusses the spatio-temporal evolution characteristics of TFCP and its driving factors in the Yangtze River Economic Belt from 2005 to 2020, and provides empirical enlightenment for the green and low-carbon development of the Yangtze River Economic Belt. The conclusions are as follows:

(1) The TFCP of the Yangtze River Economic Belt shows a steady decline on the whole. At the same time, the upstream, middle and downstream regions also show a steady downward trend, which is the same as the overall development trend. According to the annual mean value of TFCP, the midstream region > the downstream region > the upstream region. The natural fracture method is used to divide the levels. The results show that the number of cities in the first echelon has decreased, showing a decentralized distribution. The number of cities in the second and third echelons continues to rise, showing a continuous block distribution. The number of cities in the fourth echelon and the fifth echelon has generally decreased. The cities in the fourth echelon are relatively concentrated, while the cities in the fifth echelon are relatively dispersed.

(2) The overall Gini coefficient G shows a downward trend, and the overall difference is gradually decreasing. According to the mean contribution rate, regional differences become the main factor of TFCP spatial differences, accounting for about 70%. The Kernel density estimation shows that the dispersion degree of TFCP is decreasing, the gap of most regions is narrowing gradually, and the internal development is relatively balanced. The Kernel density curves of the upstream, middle and downstream are generally similar to the shape of the Kernel density curves of the overall region. The average geometric center of gravity of TFCP in the Yangtze River Economic Belt is located in Jingzhou, showing a non-normal distribution. The coverage area of the ellipse decreases first and then increases, indicating that TFCP presents a development trend of agglomeration. The shape index increases first and then decreases, showing a flattening trend, and the development force of "northeast to southwest" direction is greater. From the migration trajectory, the center of gravity gradually shifted to the southwest.

(3) Technological innovation, infrastructure construction and economic growth play a greater role in promoting TFCP in the Yangtze River Economic Belt. From the perspective of different regions, the leading driving factors of TFCP are different. Technological innovation, financial development and environmental regulation are important driving factors to promote TFCP in the upstream of the Yangtze River Economic Belt. Marketization, technological innovation and infrastructure construction are important driving factors for promoting TFCP in the midstream of the Yangtze River Economic Belt. Economic growth, infrastructure construction and industrial upgrading are more conducive to the improvement of TFCP in the downstream of the Yangtze River Economic Belt.

The existing research lays a logical framework and research foundation for this paper, but there are still some limitations. Based on this, this paper makes further discussion.

First of all, in terms of research objects, the existing research only focuses on the overall region, and lacks of discussion on key regions. The Yangtze River Economic Belt is the first demonstration belt of ecological civilization construction in China, and it is of great significance to take the lead in realizing green low-carbon in the Yangtze River Economic Belt. Therefore, this paper selects the Yangtze River Economic Belt as the key area for research, which has important practical significance for promoting China's green and low-carbon development.

Secondly, in the analysis of the characteristics of spatio-temporal evolution, few sources mention TFCP. Most studies focus on carbon emissions, total factor productivity and green total factor productivity, but few scholars pay attention to the temporal and spatial distribution characteristics and evolution laws of TFCP. In this paper, TFCP is calculated by super efficient SBM model to reduce the measurement error of traditional DEA model. In addition to using broken line charts and spatial distribution maps to show the spatio-temporal distribution characteristics, this paper also uses a series of spatial analysis tools to further explore the spatio-temporal evolution characteristics of TFCP in the Yangtze River Economic Belt. The Dagum Gini coefficient is used to measure the composition and source of spatial difference of TFCP in the Yangtze River Economic Belt. The Kernel density estimation method is used to describe the overall shape and dynamic evolution law of the absolute difference distribution of economic factors. The spatial and temporal distribution and evolution of TFCP in the Yangtze River Economic Belt are further discussed by using the standard deviation ellipse method.

Finally, what are the drivers of TFCP? Are the drivers different in different regions? Obviously, the existing research has not explored this in depth. In this paper, we use GeoDetector software to calculate the q value of each driving factor, and reveal the key driving factors of TFCP in the Yangtze River Economic Belt. The discussion on the driving factors will provide targeted policy recommendations for promoting TFCP in the Yangtze River Economic Belt.

Research prospect. Further prospects for future research work. First of all, this paper only conducts empirical analysis on possible driving factors, but other economic variables that have not been paid attention to still need to be explored. Because there may be endogenous problems among explanatory variables, too many parameters may lead to biased and inconsistent parameter estimates. In the future, we can focus on analyzing the impact of digital economy, financial technology, fiscal decentralization and other variables on the whole elements of the Yangtze River Economic Belt. In discussing the key driving factors, we can use the spatial econometric model to explore the spatial spillover effect of economic variables. At the same time, GMM model can also be used to further alleviate the endogenous problem of the model. Secondly, the research object of this paper is limited to the Yangtze River Economic Belt, and other important development strategic regions need to be further explored. Due to the heterogeneity, there are differences in the advantages of different geographical locations. Therefore, in order to better study TFCP, the scope of future research can be expanded to other important strategic areas. For example, Beijing-Tianjin-Hebei Urban Agglomeration, the Yellow River Economic Belt, Guangdong-Hong Kong-Macao Greater Bay Area and other important development strategic locations. At the same time, in order to eliminate the unilateralism of single region research, the research object can be expanded to multiple urban agglomerations for comparative analysis to find more heterogeneous characteristics of TFCP.

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Conflict of Interest

The authors declare no conflict of interest.

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