Impact of collaborative innovation on green total factor productivity in Yangtze River Economic Belt: Analysis based on endogenous spatial-temporal weight matrix

lei Wu (wulei18@cug.edu.cn)
China University of Geosciences https://orcid.org/0000-0001-8761-2867
Xiaoyan Jia
China University of Geosciences School of Economics and Management
Jie Lv
China University of Geosciences School of Economics and Management
Li Gao
China University of Geosciences School of Economics and Management

Research Article

Keywords: Green total factor productivity, Spatial Durbin model, Collaborative innovation, Environmental protection

Posted Date: June 22nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-406999/v1

Impact of collaborative innovation on green total factor productivity in Yangtze River Economic Belt: Analysis based on endogenous spatial-temporal weight matrix

Lei Wu [1] • Xiaoyan Jia[1] • Jie Lv[1] • Li Gao[1]

Abstract

Technological innovation can promote high-quality economic growth. This paper discusses the promotion of green total factor productivity from the perspective of collaborative innovation in the Yangtze River Economic Belt. Firstly, the evaluation index system of collaborative innovation level is constructed from two aspects of collaborative innovation elements and collaborative innovation environment. Then the entropy method is used to measure its development level. The results show that the collaborative innovation level of provinces in the Yangtze River Economic Belt presents an increasing trend year by year. Meanwhile, there are regional differences, which is characterized by 'high in the middle reaches, middle in the downstream and low in the upstream' Secondly, the SDM model based on endogenous spatio-temporal weight matrix is constructed to analyze the influencing factors of green total factor productivity. The results show that collaborative innovation in the Yangtze River Economic Belt has significant negative impact on green total factor productivity in terms of spatial interaction and fiscal expenditure also has a negative impact. The spatial interaction between environmental protection and opening up has a significant positive impact on green total factor productivity. However, the spatial interaction between industrial structure and human capital on green total factor productivity is not obvious. Finally, this paper puts forward some policy suggestions to improve green total factor productivity.

Keywords:

Green total factor productivity; Spatial Durbin model; Collaborative innovation; Environmental protection

Highlights：

• Construct a mathematical model of collaborative innovation and green total factor productivity.

• Constructed a collaborative innovation level evaluation index system from two aspects called collaborative innovation elements and collaborative innovation environment.

• Establish an SDM model based on the endogenous time-space weight matrix to empirically analyze the factors affecting green. total factor productivity.

Corresponding author：

Lei Wu, wulei18@cug.edu.cn ; Li. Gao, gaoli@cug.edu.cn

The affiliation and address:

1 School of Economics and Management, China University of Geosciences, Wuhan, 430074, China

1 Introduction

At present, China's economy has shifted from high-speed growth stage to high-quality development stage. It is necessary to change the development mode, transform the growth momentum and accelerate the development of green economy. Therefore, Chinese government proposes to implement the innovation-driven development strategy, emphasizing that scientific and technological innovation is a strategic support for improving social productivity and comprehensive national strength. In the meantime, it is necessary to focus on promoting scientific and technological innovation. Collaborative innovation is a new paradigm of today's scientific and technological innovation(Chen and Yang 2012), which is the driving force to promote regional economic development (Liu and Chen 2020). Therefore, whether collaborative innovation promotes the improvement of green total factor productivity is crucially significant for China to accelerate green development.

The Yangtze River Economic Belt is a national strategic development area in China, covering 11 provinces and cities, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan and Guizhou. The details are shown in Figure 1 below.

Fig 1. Map of the Yangtze River Economic Belt

The belt area is about 2.052 300 square kilometers, accounting for 21.4% of the country and its population and GDP are more than 40 % of the country. It is rich in science and education resources. For example, the number of ordinary colleges and universities accounts for 43% of the country, R&D expenditure accounts for 46.7% of the country and effective invention patents account for more than 40% of the country. Otherwise, there are 2 comprehensive national science centers, 9 national independent innovation demonstration zones, 90 national high-tech zones, 161 national key laboratories and 667 enterprise technology centers along the Yangtze River. Therefore, relying on the advantages of regional talent and intelligence intensive, accelerating the cross-regional collaborative innovation of the Yangtze River Economic Belt, strengthening environmental protection and planning green development are the keys to the sustainable development of the Yangtze River Economic Belt.

However, according to the data released by 《Driving Force Index of Science and Technology Innovation in Yangtze River Economic Belt (2020)》, the average input index of scientific and technological innovation in the Yangtze River Economic Belt is 0.12 and the average driving force index of scientific and technological innovation is 0.14, which both are at a low level. So, in the context of green development concept, what is the development of collaborative innovation in the Yangtze River Economic Belt? Does it really promote regional green total factor productivity? On the basis of considering the spatial spillover effect of collaborative innovation, this paper discusses the relationship between collaborative innovation and green total factor productivity in the Yangtze River Economic Belt. The conclusion will provide scientific reference for the Yangtze River Economic Belt to promote green total factor productivity through collaborative innovation.

2 Literature review

Collaborative innovation was first proposed by Peter Gloor of the Massachusetts Institute of Technology (MIT). It refers to a network of self-motivated people who share a collective vision and achieve common goals through network communication and cooperation (Gloor 2006). Lee and Park pointed out that collaborative innovation is mainly through R&D cooperation and can enhance the agglomeration of knowledge (Lee and Park 2006). Belderbos et al. (2004) believed that the most effective way to achieve innovation is to cooperate with research institutions. Scholars further measure the degree and performance of collaborative innovation. For example, Persaud defines the evaluation index system of collaborative innovation ability from four aspects, strategic R&D, management and operation, knowledge management and innovation degree, and then promotes the measurement of collaborative innovation degree theoretically (Persaud 2005). Leydesdorff and Fritsch use information flow in innovation subsystem as a measure of collaborative innovation (Leydesdorff and Fritsch 2006).

Collaborative innovation can integrate innovation elements and make innovation resources accessible within the region, thereby enhancing the level of total factor productivity and promoting regional economic growth (Hu et al. 2019). In view of the spatial correlation of collaborative innovation, on the one hand, some scholars explore the relationship between collaborative innovation and economic growth from a spatial perspective. Using spatial econometric model, Shi et al. (2019)Shi Rong found that the synergistic effect of financial innovation and financial agglomeration significantly enhanced the positive effect of financial market on economy. Hu et al. (2019) use spatial lag model research shows that collaborative innovation in Yangtze River Delta urban agglomeration has significant spatial spillover effect, which can promote regional economic growth through direct effect, indirect effect and total effect. Hao and Yin (2019) established GMM and spatial panel Durbin model to study China's science and technology collaborative innovation and economic growth from the perspective of temporal and spatial differences. It is found that the investment in science and technology collaborative innovation has a positive impact on economic growth in the current period and local. By also using the spatial panel econometric model, Lv et al.(2017). found that the spatial linkage of innovation resource synergy has a significant promoting effect on regional economic growth. On the other hand, some scholars explored their relationship from other perspectives. For instance, Zhou and Li (2017) expounded the dynamic co-evolution of institutional innovation and technological innovation to promote economic growth through a government-enterprise game model. Liu et al. (2017) believes that intra-regional synergy and inter-regional synergy of regional innovation networks are significantly positively correlated with industrial economic growth. From the micro level, Ren and Gan (2016) believe that the collaborative innovation system formed by business model innovation will promote the quality of macroeconomic growth.

However, relevant research shows that the promoting effect of collaborative innovation on economic growth is not obvious. For example, Dai et al. (2019) analyzed the industry-university-research collaborative innovation in Liaoning coastal economic belt from the perspectives of input and output believing that it did not make outstanding contributions to the economy. Wang and Gao (2018) used the algorithm of C-D production function and Solow residual value to calculate the effect of collaborative innovation of science and technology progress on the growth of construction industry was very insignificant. Zhong and Liu (2018) used the extended Cobb-Douglas production function to empirically show that innovative entrepreneurship has no significant impact on China's economic growth. Through co-integration regression and ECM model regression analysis, Lv and Kan (2017) believed that industry-university-research collaborative innovation has little effect on promoting economic growth in Jiangxi in the short term.

Technological innovation plays a vital role not only in the development of human society but also in economic development (Adak 2015; Ganda 2019).On the one hand, some scholars believed that technological innovation helps to improve economic development and total factor productivity. Given that green technology innovation is an important part of technology innovation (Chen et al. 2019; Deng et al. 2019), so (Fan and Sun 2020) believed that green technology innovation is the main driving force for improving the development of green economy. Meanwhile, He (2015) believed that green technology innovation can effectively improve the total factor productivity of the industry. On the other hand, some scholars believed that the relationship between technological innovation and the improvement of green total factor productivity is not clear. For example, Jin et al. (2019) believe that there is no significant impact between technological innovation and the green total factor productivity of industrial water resources. Wang et al. (2020) believed that there is regional heterogeneity in the relationship between technological innovation and green total factor productivity. The improvement of technological innovation in the western region of China helps to improve the green total factor productivity, while the eastern and central regions of China have the opposite conclusion. In addition, technological innovation has a significant positive impact on the local green total factor productivity and has a significant negative impact on the green total factor productivity in the surrounding areas.

In summary, although the conclusions of the impact of collaborative innovation on economic growth in the above studies are not the same, they all verify the existence of the impact of collaborative innovation on total factor productivity. And then the impact is uncertain. At the same time, most of the previous studies only examined the relationship between collaborative innovation and economic growth without taking into account the ecological and environmental effects of economic growth. That is to say, there was no further in-depth analysis of the impact of collaborative innovation on green economic growth and little literature specifically conducts similar studies on the Yangtze River Economic Belt. The main contributions of this paper are as follows: firstly, a mathematical model is established to analyze the impact mechanism of regional collaborative innovation on green total factor productivity. Secondly, this paper constructs an index system to measure regional collaborative innovation, specifically analyzing the level of collaborative innovation in the Yangtze River Economic Belt and further exploring its spatial dynamic evolution characteristics. Thirdly, the spatial economic matrix is established to explore the impact of collaborative innovation on green total factor productivity in the Yangtze River Economic Belt from the perspective of spatial spillover effect. Therefore, this study has important guiding significance for accelerating the high-quality development of China's green economy.

3 Theoretical model analysis

Based on the production function, this paper constructs a spatial expansion model of collaborative innovation and analyzes how collaborative innovation affects regional green total factor productivity growth through provincial spatial spillover mechanism. Total factor productivity refers to the ratio of the total output of a system to the input of various production factors. Green total factor productivity is the efficiency of resource development and utilization based on total factor productivity, which takes energy consumption and environmental costs into account. Referring to Zhu Wentao' s research on green total factor productivity calculation (Zhu et al. 2019), the green total factor productivity corresponding to the province i is expressed as :

$$GTFP_{i,t} = \frac{Y_{i,t}}{{L_{i,t}}^{\alpha}{K_{i,t}}^{\beta}} \tag{1}$$

Among them, $GTFP_{i,t}$ is the corresponding green total factor productivity of provinces i in years t; $Y_{i,t}$ is the corresponding total output; $L_{i,t}$ is the corresponding labor input, $K_{i,t}$ is the corresponding capital input; α and β are the share of labor and capital in the input respectively.

In a fully competitive market, it is believed that the total output is realized by the combination of labor force L and other production factors. Referring to the research of Broda et al., the total output can be specifically expressed as (Broda et al. 2006) :

$$Y_{i,t} = (A_{i,t}L_{i,t})^{\alpha}[\int_{0}^{Q_{i,t}} P_{i,t}(\tau)^{\tau}dv]^{\beta/\tau} \tag{2}$$

Among them, τ is the elasticity of substitution of other production factors. The greater the value is, the more alternatives are. $P_{i,t}$ is other production factors. At the same time, this paper considers that other production factors have the same price and proportion of inputs, the total output can be further expressed as :

$$Y_{i,t} = (A_{i,t}L_{i,t})^{\alpha}{Q_{i,t}}^{\beta/\tau}{P_{i,t}}^{\beta} \tag{3}$$

Under the condition of equal proportion of input production factors, according to the production technology conditions, the i capital stock of the province can be expressed as :

$$K_{i,t} = Q_{i,t}P_{i,t} \tag{4}$$

The total output of province i can ultimately be expressed as :

$$Y_{i,t} = (A_{i,t}L_{i,t})^{\alpha}{Q_{i,t}}^{((1-\tau/\tau)\beta)}{K_{i,t}}^{\beta} \tag{5}$$

Then the corresponding Eq. (1) can be transformed into :

$$GTFP_{i,t} = {A_{i,t}}^{\alpha}{Q_{i,t}}^{((1-\tau/\tau)\beta)} \tag{6}$$

This formula shows that green total factor productivity can be decomposed into two parts, including technological innovation of other production factor combinations represented by ${A_{i,t}}^{\alpha}$ and diversification of other production factors represented by ${Q_{i,t}}^{((1-\tau/\tau)\beta)}$.

For its technological innovation part, this paper adopts.(Ertur and Koch 2011), which is specifically expressed as :

$$ {A_{i,t}}^{\alpha} = \xi \prod_{j=1}^{n} (\frac{T_{j,t}}{GTFP_{i,t}})^{\gamma\omega_{i,j}} \tag{7} $$

Where $T_{j,t}$ represents the geometric average of technical level of all provinces; γ is defined as the absolute value of the level of technological gap valued in [0, + ∞], which indicates the technological gap between province j and province i. If γ tends to 0, it indicates that the technological gap is small; $\omega_{i,j}$ represents the economic matrix. When $i = j$, $\omega_{i,j}$ = 0; when $i = j$, $\sum_{j\neq i}^{n} \omega_{i,j} = 1$.

Since technological innovation results need to be transformed into production technology to improve the actual production efficiency. However, the transformation ability of innovation achievements will be affected by the technological level gap in different regions. If the technological level of the region is higher, the ability to transform innovative achievements is stronger. Assuming that the technological level of province i is higher than that of province j, the corresponding transformation of innovation achievements of each province is specifically expressed as :

$$ AT_{i,t} = \rho_i {CI_{i,t}}^{\gamma} \tag{8} $$

$$ AT_{j,t} = \rho_j {CI_{j,t}}^{-\gamma} \tag{9} $$

Among them, $CI_{i,t}$ and $CI_{j,t}$ denote the level of collaborative innovation corresponding to the t-year of i and j provinces respectively; AT denotes the level of transformation of collaborative innovation achievements. ρ_i and ρ_j represent other influencing factors.

For the diversification of its production factors, it is expressed as follows, where ζ is the positive conversion elastic coefficient of innovation results. :

$$Q_{i,t}{}^{((1-\tau/\tau)\beta)} = AT_{i.t}^{\zeta}\prod_{j=1}^{n}(AT_{j.t}^{\zeta})^{\gamma\omega_{i,j}} \tag{10}$$

Substituting Eq. (7) (8)(9)(10) into Eq. (6), we can get :

$$GTFP_{i,t} = \xi\prod_{j=1}^{n}\left(\frac{T_{j,t}}{GTFP_{i,t}}\right)^{\gamma\omega_{i,j}} AT_{i.t}^{\zeta}\prod_{j=1}^{n}(AT_{j.t}^{\zeta})^{\gamma\omega_{i,j}} \tag{11}$$

Taking logarithms on both sides of Eq. (11), we can get :

$$\begin{aligned} ln(GTFP_{i,t}) = ln\xi + \gamma\sum_{j=1}^{n}\omega_{i,j}ln\left(T_{i,t}\right) - \gamma ln\left(GTFP_{i,t}\right)\sum_{j=1}^{n}\omega_{i,j} + \zeta ln(AT_{i,t}) \\ + \zeta\gamma\sum_{j=1}^{n}\omega_{i,j}ln(AT_{j,t}) \end{aligned} \tag{12}$$

$$ln(GTFP_{i,t}) = \frac{ln\xi}{1+\gamma} + \frac{\gamma}{1+\gamma}\sum_{j=1}^{n}\omega_{i,j}ln\left(T_{i,t}\right) + \frac{\zeta}{1+\gamma}ln(AT_{i,t}) + \frac{\zeta\gamma}{1+\gamma}\sum_{j=1}^{n}\omega_{i,j}ln(AT_{j,t}) \tag{13}$$

$$\begin{aligned} ln(GTFP_{i,t}) = \frac{ln\xi}{1+\gamma} + \frac{\gamma}{1+\gamma}\sum_{j=1}^{n}\omega_{i,j}ln\left(T_{i,t}\right) + \frac{\zeta}{1+\gamma}ln\rho_i + \frac{\zeta\gamma}{1+\gamma}ln\left(CI_{i,t}\right) + \frac{\zeta\gamma}{1+\gamma}ln\rho_j \\ - \frac{\zeta\gamma^2}{1+\gamma}\sum_{j=1}^{n}\omega_{i,j}\,ln(CI_{j,t}) \end{aligned} \tag{14}$$

The Eq. (14) shows that the average technical level of each region has a positive effect on green total factor productivity. The level of local collaborative innovation has a positive effect on the local green total factor productivity. While the level of collaborative innovation in surrounding regions has negative effect on the local green total factor productivity. When the technical level of the region is higher than that of the surrounding area, the level of local collaborative innovation has a greater positive effect on local green total factor productivity. When the technical level of the region is lower than that of the surrounding area, the level of collaborative innovation in the surrounding area has a greater negative effect on local green total factor productivity. In comparison, when $0 < \gamma < 1$, the regional collaborative innovation has a positive effect on the regional green total factor productivity and the effect is larger. When $\gamma > 1$, due to spatial interaction, local collaborative innovation has a negative effect on green total factor productivity in the surrounding areas and the effect is larger. Overall, when the regional technology gap is small, collaborative innovation has a positive impact on local green total factor productivity. When the regional technology gap is too large, collaborative innovation has a negative impact on green total factor productivity in surrounding areas.

4 Calculation and analysis of collaborative innovation level in Yangtze River Economic Belt

4.1 Measurement index of collaborative innovation

At present, collaborative innovation plays an increasingly important role in economic development and has become an important way and core driving force to realize the coordinated development of a country or region's economy (Li and Wu 2019). Researchers have given different connotations of collaborative innovation and interpreted collaborative innovation from the perspectives of innovation subject collaboration, innovation factor flow, collaborative innovation organization model and collaborative innovation content. For example, Chen and Yang (2012) believed that collaborative innovation is a large-span integrated innovation organization model for enterprises, governments, knowledge production institutions (universities, research institutions), intermediaries and users to achieve major scientific and technological innovation. Bai and Jiang (2015) believed that collaborative innovation includes not only the innovation achievements obtained by the integration of resources through collaborative cooperation among innovation subjects but also the collaborative innovation effect formed by the flow of regional innovation elements among regions. Wang and Wei (2016) think collaborative innovation includes knowledge innovation and technology innovation.

This paper believes that collaborative innovation is a technological innovation process based on the collaborative integration of innovation resources among different innovation subjects under the support of collaborative innovation environment. To a certain extent, the collaborative innovation process is the technological innovation process (He and Qiao 2015). Therefore, the collaborative innovation process is composed of two aspects of innovation factor collaboration and innovation environment collaboration. The synergy of innovation elements refers to the process that collaborative innovation subjects invest certain innovation resources to achieve scientific and technological output and transform technological achievements to achieve economic benefits. It reflects the research and development of innovation achievements and its application in the production stage, mainly including the synergy of funds, personnel and knowledge. Innovation environment synergy refers to the integration of external supporting environment for collaborative innovation, mainly including the synergy of external environment such as government policies, finance and human resources. Research shows that collaborative innovation is inseparable from the support of innovation environment, which provides survival support for innovation subjects (Fei and Ling 2019). According to Albert's research (Albert et al. 2013), the number and impact of collaborative innovation research results have been greatly improved with government funding. According to King and Levine's (1993) research, financial institutions have a great probability to promote the innovation process. Therefore, based on the collaborative innovation process, this paper constructs the evaluation index system of collaborative innovation level from two aspects of innovation element synergy and innovation environment synergy. The specific indicator system is shown in Table 1.

Table.1 Collaborative innovation evaluation index

	Indictors	Specific indictors	Unit
Synergy of innovation elements	Fund synergy	External R&D expenditure of industrial enterprises above designated size	Million yuan
		External expenditure on R&D funds in institutions of higher learning	Million yuan
		R&D external expenditure of research and development institutions	Million yuan
		Internal Expenditure of R&D Funds for Universities and Research Institutions from Enterprises	Million yuan
	Staff coordination	Authors' scientific papers from the same province and different units	%
		Author 's Sci - tech Papers	%
		Author of Foreign Scientific Papers	%
	Knowledge synergy	Technology market turnover	Million yuan
		Ten thousand science and technology intermediary service personnel	People
Innovation environment synergy	Policy coordination	Government funds in regional R&D funds	Million yuan
	Financial coordination	Financial Institution Funds in Regional R&D Funds	Million yuan
	Social	Ten thousand Internet users	People/Million

	coordination	Number of employees in producer services	Million people

4.2 Calculation method of collaborative innovation

The measured methods of collaborative innovation include factor analysis, principal component analysis and evaluation index system. For example, Yang and Li (2019) use factor analysis to extract the common factors between innovation subjects as a measure of collaborative innovation and calculate the corresponding score to measure collaborative innovation. Wu et al. (2016). used principal component analysis to measure collaborative innovation capability. Huang and Xie (2016) used principal component-correlation coefficient method to construct collaborative innovation measurement method. In addition to the above methods, Li and Liu (2020) used the extended DEA method to measure the level of collaborative innovation. Based on the above literature research, this paper selects entropy method to calculate collaborative innovation according to Zheng et al 's (2010) research. Entropy method is an effective method for multi-index comprehensive evaluation of regional development. In this paper, the weight of each index in each province of the Yangtze River Economic Belt is calculated and then the comprehensive index of collaborative innovation is obtained by multiplying each index and its weight. The process is as follows :

(1) Dimensionless treatment of indicators. The indicators selected in this paper are positive indicators, so dimensionless processing formula :

$$X_{ij} = \frac{x_{ij} - min(x_j)}{max(x_j) - min(x_j)} \tag{15}$$

(2) Coordinate translation and normalization of dimensionless data. Where A is the translation distance, the value is selected as 1.

$$Y_{ij} = X_{ij} + A\text{；}\ P_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{m} Y_{ij}} \tag{16}$$

(3) Calculation of index information entropy and difference coefficient. K = 1/lnn, n is the number of samples.

$$e_j = -K \sum_{i=1}^{m} P_{ij} lnP_{ij}\,;\, d_j = 1 - e_j \tag{17}$$

(4) Calculation of index weight.

$$\omega_j = \frac{d_j}{\sum_{i=1}^{n} d_j} \tag{18}$$

4.3 Analysis of collaborative innovation calculation results of Yangtze River Economic Belt

This paper calculates the overall level of collaborative innovation in the Yangtze River Economic Belt from 2009 to 2017, as well as the sub-data of financial synergy, personnel synergy, knowledge synergy and environmental synergy, and converts the level of collaborative innovation into graphic representation (limited to length, this paper does not list the results of relevant calculations, which can be obtained from the author if necessary).

From A and B in Figure 2, it can be seen that since 2009, the level of collaborative innovation in each province of the Yangtze River Economic Belt has been increasing year by year. Further subregionally, the collaborative innovation level of the Yangtze River Economic Belt shows the characteristics of 'high in the middle reaches, middle in the downstream and low in the upstream'. However, the level of downstream collaborative innovation grew rapidly, from near upstream provinces in 2009 to near midstream provinces. From the perspective of a single province, there are Shanghai, Yunnan, Anhui and Hubei provinces above the average level of overall collaborative innovation. However, there are Zhejiang, Jiangxi, Hunan, Sichuan, Jiangsu, Chongqing and Guizhou provinces below the average level of overall collaborative innovation. It not only further explains the regional differences in the level of collaborative innovation in the Yangtze River Economic Belt but also shows that there is a significant deviation between the level of regional collaborative innovation and the level of economic development, which is consistent with Zhao Zhe 's conclusion that the performance of collaborative innovation and its contribution to economic growth are not significant (Zhao 2020).

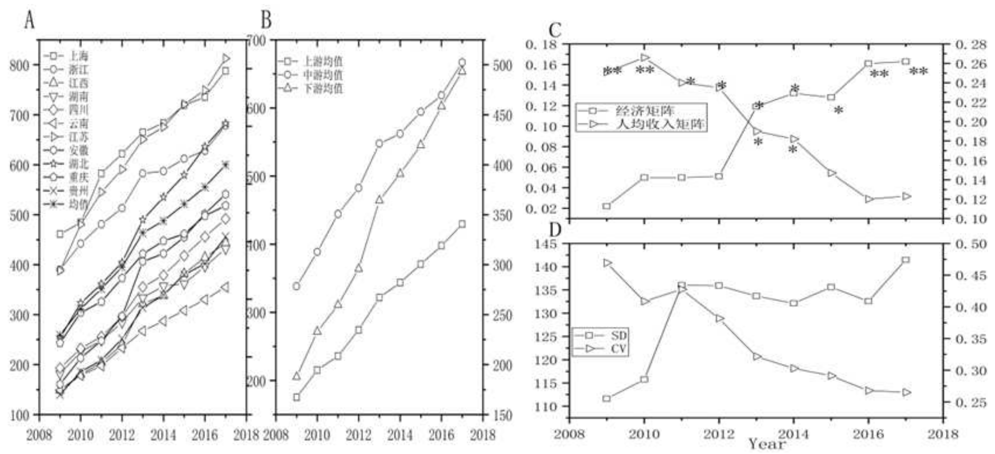

Fig 2. Changes in the level of collaborative innovation of provinces in the Yangtze River Economic Belt

Note: A. The level and mean change of collaborative innovation in the provinces of the Yangtze River Economic Belt B. The mean change of regional collaborative innovation C. Moran 's I value of collaborative innovation corresponding to different matrices D. Standard deviation and coefficient of variation of collaborative innovation

Figure C in Figure 2 shows the self-correlation coefficient of collaborative innovation space under different spatial weight matrices. The economic matrix uses the reciprocal of GDP gap as the weight to measure the 'adjacent' degree between provinces and the per capita income matrix uses the reciprocal of per capita income gap as the weight to measure the 'adjacent' degree between provinces. The map shows that the Moran's I value of the spatial autocorrelation coefficient of collaborative innovation calculated under the economic matrix is positive and passed the test from 2013 to 2019 at different significant levels. The Moran's I value of the spatial autocorrelation coefficient of collaborative innovation calculated under the per capita income matrix is positive and passed the test from 2009 to 2013 at different significant levels. The corresponding Moran's I values under different matrices show that collaborative innovation is positively correlated in space and the global Moran's I value changes little, indicating that the spatial distribution pattern of collaborative innovation is relatively stable and there is no large change. It can be seen from Figure D in Figure 2 that the standard difference corresponding to collaborative innovation changes greatly before 2011, tending to be stable from 2011 to 2017. The corresponding coefficient of variation tends to increase between 2010 and 2011 and the coefficient of variation at other time stages decreases year by year. It is believed that there is σ convergence in collaborative innovation, which is mainly due to the agglomeration of high-tech innovation bases. Under the effect of agglomeration-diffusion effect, regions with high level of scientific and technological innovation can promote the development of regions with low level of scientific and technological innovation.

5. Empirical design

5.1 Indicator selection

(1) Explained variable: green total factor productivity. Green total factor productivity is an input-output efficiency that considers energy and resource consumption. It is an important guarantee for transforming mode of economic development and achieving sustainable economic growth.

There are many methods to measure green total factor productivity. The traditional DEA model was proposed by Chsrnes, Cooper and Rhodes (Charnes et al. 1979). Since it is unnecessary to determine the specific form and estimated parameters of the model, it has been widely used. However, because it is a radial and angle measurement method, it will lead to overestimation of efficiency value and inaccurate results. Therefore, this paper selects Tone's SSBM model(Tone 2001;2002) based on the undesirable output SBM model and the idea of super-efficiency model :

$$min\,\rho = \frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}}{x_{ik}}\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{\bar{y}^g}{y_{sk}^g}+\sum_{q=1}^{s_2}\frac{\bar{y}^b}{y_{qk}^b}\right) \tag{19}$$

$$\begin{cases} \bar{x} \geq \sum_{j=1,\neq k}^{n} x_{ij}\lambda_j\,;\bar{y}^g \leq \sum_{j=1,\neq k}^{n} y_{sj}^g\lambda_j\,;\bar{y}^g \geq \sum_{j=1,\neq k}^{n} y_{qj}^g\lambda_j\,; \\ \bar{x} \geq x_k;\bar{y}^g \leq y_k^g;;\bar{y}^b \geq y_k^b; \\ \lambda_j \geq 0, i = 1,2,\cdots,m; j = 1,2,\cdots,n; \\ j \neq 0; s = 1,2,\cdots,s_1; q = 1,2,\cdots,s_2 \end{cases}$$

ρ is the efficiency evaluation value; x, y^g y^b respectively represent input indicators, expected output indicators, unexpected output indicators; n is the number of DMUs; m is the number of input indicators; s_1 is the number of expected output indicators; s_2 is the number of unexpected output indicators.

In this paper, the input indicators used to calculate green total factor productivity are labor, energy and capital. On labor input, referring to the study of most scholars in total factor productivity research, this paper select the provinces over the years of employment as a substitute indicator. With regard to energy input, taking into account the regional differences in energy consumption types, the total regional energy consumption equivalent to standard coal is selected as a substitute indicator. Regarding the capital stock index, we choose the total amount of fixed capital formation to measure and use the perpetual inventory method for conversion. The investment price index is replaced by the fixed asset investment price index of each province. And the depreciation rate is determined to be 10.96 % based on the existing research (Zhang et al. 2004).

The expected output indicators in output are replaced by regional GDP and are reduced to constant price levels based on 2000. In terms of undesirable output, using Chen Shiyi's (Chen 2009) method to calculate the total CO_2 emissions of each province or city as the undesirable output index of the region. The specific indicators are shown in Table 2.

Table 2 Green Total Factor Productivity Indicators

Indictors	Specific indictors	Unit
Labour	Employees at the end of the year	Million people
Energy source	Total energy consumption	Ten thousand tons of standard coal
Capital	Stock of capital	Billion yuan
Expected output	Gross domestic product	Billion yuan
Undesirable output	CO_2 emissions	Ton

(2) Explanatory variables: collaborative innovation level. This paper uses the measurement data of the overall level of collaborative innovation of provinces and cities in the Yangtze River Economic Belt calculated above.

(3) Other control variables. Based on the research of other scholars, this paper selects five types of control indicators, including environmental protection (*EP*), human capital (*HC*), industrial structure (*IS*), fiscal expenditure (*MF*) and openness (*OP*). Considering the attributes of public goods and positive externalities of environmental resources, this paper uses environmental protection expenditure to measure government investment in environmental protection and then measures the specific relationship between environmental protection and economic development. Human capital is calculated and characterized by the formula of the proportion of primary school students * 6 + the proportion of junior high school students * 9 + the proportion of high school students * 12 + the proportion of college students and above * 16. The industrial structure of this paper selects the tertiary industry output value and GDP ratio to measure. Fiscal expenditure is characterized by the ratio of regional fiscal expenditure to regional GDP. The degree of opening to the outside world is measured by the ratio of regional import and export volume to regional GDP; meanwhile, the RMB is converted according to the exchange rate of the year. Before the model regression, the data are dimensionless to eliminate the impact of dimension.

5.2 Model construction

In order to reveal the influence mechanism of spatial factors on green total factor productivity, this paper uses spatial econometric model analysis. This model is mainly divided into spatial lag model and spatial error model. Because different regional subjects in the innovation network can share the knowledge spillover effect of the network (Gao and Zhang 2019), the spatial correlation between regions is considered in the classical regression model, namely the SDM model :

$$GTFP = \beta_0 t_0 + \rho TWGTFP + XB_1 + TWXB_2 + U_1 \quad (20)$$

GTFP is the explained variable matrix of $NT \times 1$ order, which represents the pool accumulation sequence of green total factor productivity in the Yangtze River Economic Belt. N is the number of provinces in the Yangtze River Economic Belt, T is the time span.and t_0 is a matrix with $NT \times 1$ elements and its value is 1. β_0 is an empirical constant and ρ is the spatial correlation coefficient, which is between -1 and 1. X is the explanatory variable matrix of $NT \times K_1$, which represents the pool accumulation sequence of possible influencing factors affecting the green total factor productivity of the Yangtze River Economic Belt, where K_1 is the number of explanatory variables. TW is a space-time weight matrix of $NT \times NT$ order and its construction method is based on the research of Fan Qiao (Fan and Hudson 2018). The spatial weight matrix uses the economic matrix to represent the spatial spillover effect between different regions. The time weight matrix is based on the ratio of global Moran index in different years to reflect the transfer and conduction effects of spatial spillover effects with time. B_1 and B_2 are the parameter matrices of order $K_1 \times 1$ respectively, representing the parameters of explanatory variables. U_1 is a random perturbation matrix of order $NT \times 1$, obeying the multidimensional normal distribution of mean 0 and variance $\sigma^2 I_{NT}$, where σ^2 is a constant and I_{NT} is a unit matrix of order NT.

5.3 Data sources and descriptive statistics

The specific indicators involved in this paper come from 《*China Statistical Yearbook*》, 《*China Energy Statistics Yearbook*》, 《*China Statistical Yearbook of Science and Technology*》, 《*China Torch Statistical Yearbook*》, 《*China Urban Statistical Yearbook*》, 《*China Regional Innovation Capacity Report*》, National Bureau of Statistics and 《*China Environmental Yearbook*》. The data in this paper is provincial panel data and the time span is 2009-2017. The missing values are added by interpolation method. Data units and descriptive statistical results are shown in Table 3.

Table 3 Definitions of indicators and descriptive statistics

Variable	Abbreviation	Min	Max	Mean	Std.Dev
Green total factor productivity	*GTFP*	0.558 9	1.079 7	0.877 2	0.127 0
Collaborative innovation	*CI*	134.715 6	787.820 8	393.311 5	157.418 5
Environmental protection	*EP*	33.856 5	370.580 0	114.096 4	63.217 9
Human capital	*HC*	707.640 0	125 8	926.313 8	109.120 7
Industrial structure	*IS*	32.500 0	69.780 0	43.908 5	7.999 1
Financial expenditure	*MF*	15.210 6	77.046 5	34.415 9	14.839 5
Opening to the outside world	*OP*	6.116 1	198.314 6	43.068 0	48.308 2

5.4 Impact of collaborative innovation on green total factor productivity

5.4.1 Regression results and analysis

This paper first tests the panel data. ADF method is used to test the panel data stability and the conclusion is that the data is stable. Through Kao, Pedroni, Westerlund and other test variables cointegration relationship, this paper found that there is a cointegration relationship between the variables, the results show that it can carry out the next measurement operation. The specific test results are shown in Tables 4 and Table 5.

Table 4 Stability Test of Panel Data

Variable	ADF
GTFP	247.098 1***
CI	57.351 2***
EP	393.300 0***

Variable	ADF
HC	42.130 5***
IS	63.609 6***
MF	160.048 2***
OP	66.095 9***

Note : * 、 * * 、 * * * are significant at the level of 10 % 、 5 % 、 1 % respectively.

Table 5 Cointegration Test of Variables

Cointegration test	Results of inspection
Kao	-1.521 9*
Pedroni	5.822 3***
Westerlund	1.599 3*

Note : * 、 * * 、 * * * are significant at the level of 10 % 、 5 % 、 1 % respectively.

Secondly, the endogenous space-time weight matrix based on economic space weight matrix and time weight matrix is calculated, which is transformed into a visual graph, as shown in Figure 3 below.

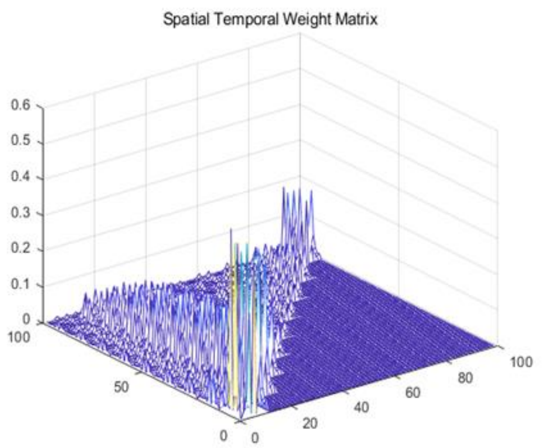

Fig 3. Endogenous space-time weight matrix based on economic matrix

Then, MATLABR2020b software is used to calculate the SDM model of mixed effect and the calculation results are shown in Table 6. From the regression results, without considering the spatial interaction effect, it is found that the regression coefficients of environmental protection, human capital and industrial structure are all positive and pass the test at the significance level of 1 %, indicating that the three have a positive role in promoting the green total factor productivity of the Yangtze River Economic Belt. However, collaborative innovation, fiscal expenditure and opening up did not pass the significant test, indicating that the impact of the three on green total factor productivity is uncertain.

In the case of introducing space-time interaction effect, the regression coefficient of collaborative innovation is negative and the test is passed at 1% significance level, indicating that the level of collaborative innovation in the surrounding areas has a significant negative effect on the green total factor productivity of the region. Collaborative innovation is based on the flow of knowledge and technology. The improvement of collaborative innovation level in surrounding areas means that innovative resources and achievements will flow out, which has a negative impact on technological innovation and green economic development. The regression coefficient of environmental protection and opening up is significantly positive, indicating that the improvement of the two in the surrounding areas has obvious spatial interaction effect on the improvement of local green total factor productivity. As public goods, when the environmental protection level in the surrounding areas is high, the environmental protection in the region also has a promoting effect, which will further improve the development of green economy. The opening up can promote the economic growth and technological progress of the region and the spillover effect affects the surrounding areas. The regression coefficient of fiscal expenditure is significantly negative, indicating that fiscal expenditure in surrounding areas inhibits the improvement of local green total factor productivity. The reason is that fiscal expenditure in each region is mostly used around the region and aims at economic growth. Economic growth in surrounding areas will form a siphon effect on local resources and inhibit the development of local green economy. The human capital and industrial structure did not pass the significant test, indicating that the spatial spillover effect of human capital and industrial structure changes in surrounding areas on local green total factor productivity is uncertain.

Table 6 SDM regression estimation results of endogenous spatio-temporal weight matrix based on economic matrix

Variable	SDM	t-value	p-value
CI	0.017 5	0.0800	0.936 2

Variable	SDM	t-value	p-value
EP	0.747 5***	5.93	0.000 0
HC	0.383 2***	2.69	0.007 1
IS	0.661 1***	4.61	0.000 0
MF	0.033 1	0.31	0.754 9
OP	-0.110 6	-0.65	0.514 7
TW×CI	-2.558 5***	-6.21	0.000 0
TW×EP	1.390 3*	1.87	0.061 2
TW×HC	-0.303 9	-0.96	0.336 9
TW×IS	-0.650 2	-1.57	0.116 4
TW× MF	-1.643 0***	-6.29	0.000 0
TW×OP	0.995 5**	2.30	0.021 7
rho	-0.183 0	-0.98	0.327 6
Sigma2_e	0.012 6		
Log-likelihood	110.090 0		
R^2	0.788 1		

Note : * 、 * * 、 * * * are significant at the level of 10 % 、 5 % 、 1 % respectively.

5.4.2 Effect decomposition

Since regions are interrelated, the spatial interaction of some economic variables does not affect the local economy but affect the economy of neighboring regions. That is to say, there is an external effect. Therefore, this paper decomposes the effect of mixed effect SDM model based on endogenous space-time weight matrix to obtain direct effect and indirect effect. Generally speaking, direct effects represent the impact of explanatory variables on the region and indirect effects represent the impact of explanatory variables on other regions. The decomposition results are shown in Table 7.

Table 7 Direct effect, indirect effect and total effect decomposition of mixed effect SDM model based on endogenous time-space weight matrix of economic matrix

Variable	Direct effect	Indirect effect	Total effect
CI	0.057 7	-2.218 7***	-2.161 0***

Variable	Direct effect	Indirect effect	Total effect
	(0.27)	(-5.44)	(-4.42)
EP	0.730 2***	1.131 2	1.861 4**
	(5.84)	(1.46)	(2.18)
HC	0.384 8**	-0.347 9	0.036 9
	(2.62)	(-1.25)	(0.13)
IS	0.667 1***	-0.677 0*	-0.009 9
	(4.45)	(-1.78)	(-0.03)
MF	0.053 3	-1.435 6***	-1.382 3**
	(0.50)	(-5.41)	(-5.92)
OP	-0.125 7	0.869 4**	0.743 8**
	(-0.73)	(2.23)	(2.21)

Note: The number in brackets is the t-statistics of the coefficient, and *, * *, * * * represent the significance at the levels of 10 %, 5 % and 1 %, respectively.

The results of Table 7 show that the direct effect of collaborative innovation is not significant but the indirect effect is very significant and the coefficient is large, which has a significant inhibitory effect on the green total factor productivity in the surrounding areas. The results are consistent with the regression results of spatial effect in SDM model. Overall, the total effect reflects that the level of collaborative innovation in various regions has a significant impact on the growth of green total factor productivity in terms of spatial interaction. Since the inhibitory effect of collaborative innovation in the region on green total factor productivity in surrounding areas is too strong, it is not conducive to improving the green total factor productivity level in the Yangtze River Economic Belt. On the one hand, it shows that collaborative innovation does not necessarily aim at green efficiency but may be at the cost of high consumption and high output, thereby inhibiting the growth of green total factor productivity (Zhao and Chen 2020). On the other hand, it shows that the effect of collaborative innovation in backward areas may not be obvious when the technical level gap is too large.

The direct effect of environmental protection and human capital is very significant, which can greatly promote the growth of local green total factor productivity. However, its indirect effect is not significant, indicating that its spatial spillover effect is insufficient. Under the impact of this indirect effect, the total effect is differentiated. That is to say, environmental protection has significantly promoted the growth of regional green total factor productivity, while human capital has little effect on the growth of regional green total factor productivity. In general, the growth of human capital will promote the growth of total factor productivity

(Benhabib and Spiegel 1994). And if human capital is mismatched or under-matched, it will also lead to the reduction of green total factor productivity (Lai and Ji 2015).

The direct effect of industrial structure upgrading is very significant, which greatly promotes the growth of green total factor productivity in the region. However, its indirect effect shows that it has a significant inhibitory effect on the green total factor productivity in the surrounding areas. The reason is that the rational allocation of factors and dynamic equilibrium effect caused by industrial structure optimization can promote the growth of green total factor productivity in the region and inhibit the growth of green total factor productivity in the surrounding areas through the radiation effect caused by the correlation between industrial chains and industrial agglomeration.

The direct effect of fiscal expenditure index is not significant, while its indirect effect is very significant. The results show that the growth of green total factor productivity in the surrounding areas is greatly inhibited and its total effect also reflects a significant inhibitory effect, which is consistent with the regression results in the SDM model. This may be due to the negative impact of fiscal policies aimed at promoting economic growth on the environment, resulting in no significant contribution to productivity growth (Zhu and Li 2019). This shows that the implementation of the current 'green finance' strategy needs to adopt diversified means other than green special funds and green government procurement to promote the sustainable growth of green economy.

The direct effect of openness index is not significant, while its indirect effect is very significant. The results show that it greatly promotes the growth of green total factor productivity in surrounding areas and its total effect also reflects a significant promotion effect, which is consistent with the regression results of spatial effect in the SDM model. The reason is that, as mentioned above, it is caused by the spatial spillover effect of economy and technology.

5.4.3 Robustness test

Considering the need for robustness test of spatial measurement, this paper selects alternative indicators to recalculate the endogenous spatio-temporal weight matrix. Because there are many alternative indicators that can be used to calculate the economic matrix, this paper selects per capita income as an alternative indicator to calculate the economic matrix to recalculate the endogenous space-time weight matrix. Figure 4 below shows.

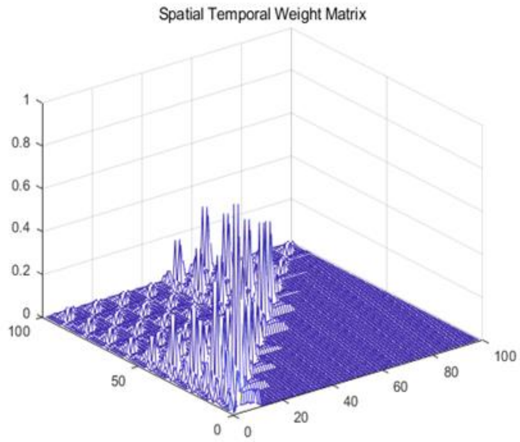

Fig 4. Endogenous time-space weight matrix based on per capita income matrix

Then, the effect of SDM model based on the mixed effect of endogenous time-space weight matrix based on per capita income matrix is decomposed. And the direct effect and indirect effect are obtained to do stability test, comparing with the previous calculation results. The specific results are shown in Table 8.

Table 8 Direct effect, indirect effect and total effect decomposition of mixed effect SDM model based on endogenous time-space weight matrix of per capita income matrix

Variable	Direct effect	Indirect effect	Total effect
CI	0.058 8	-2.208 6***	-2.149 9***
	(0.28)	(-5.63)	(-4.47)
EP	0.728 2***	1.082 4	1.810 6**
	(6.07)	(1.47)	(2.24)
HC	0.383 6***	-0.325 6	0.058 0
	(2.78)	(-1.15)	(0.20)
IS	0.671 5***	-0.672 7*	-0.001 3
	(4.44)	(-1.85)	(-0.004)
MF	0.058 8	-1.440 0***	-1.381 3**
	(0.54)	(-5.74)	(-6.39)
OP	-0.131 4	0.896 0**	0.764 6**
	(-0.77)	(2.35)	(2.32)

Note: The number in brackets is the t-statistics of the coefficient, and *, * *, * * * represent the significance at the levels of 10 %, 5 % and 1 %, respectively.

It can be seen from Table 8 that no matter the total effect of the SDM model and the direct and indirect effects obtained by decomposition, the sign and significance of the collaborative innovation variable are completely consistent with the empirical results above, indicating that the transformation of the endogenous spatio-temporal weight matrix does not change the previous conclusion. Furthermore, the symbols and significance of the other five control variables are consistent with the previous empirical calculation results. All these conclusions prove that the empirical results are still robust and the conclusions are also convincing even considering the differences in the endogenous spatio-temporal weight matrix.

6 Conclusion, discussion and policy implications

6.1 Conclusion and discussion

In this paper, the mathematical model is used to analyze the way that collaborative innovation affects regional green total factor productivity. Meanwhile, the evaluation index system of regional collaborative innovation level is constructed. The entropy method is used to calculate the collaborative innovation level of the Yangtze River Economic Belt and its evolution is analyzed. On this basis, the spatial Durbin model based on endogenous spatial-temporal weight matrix of economic matrix is used to explore the specific relationship between collaborative innovation and green total factor productivity in the Yangtze River Economic Belt.

And then the following conclusions are obtained: firstly, the level of collaborative innovation in each province of the Yangtze River Economic Belt shows an upward trend year by year, which is characterized by 'high in the middle reaches, middle in the downstream and low in the upstream'. The level of collaborative innovation in the Yangtze River Economic Belt has a positive spatial correlation and σ convergence. Secondly, collaborative innovation in the Yangtze River Economic Belt has a significant negative impact on green total factor productivity in terms of spatial interaction. And its impact on local green total factor productivity is not significant. Oppositely, the inhibitory effect on green total factor productivity in surrounding areas is very strong. Thirdly, environmental protection and opening up in the Yangtze River Economic Belt have significant positive impact on green total factor productivity in terms of spatial interaction. However, the former mainly affects local green total factor productivity, while the latter mainly affects green total factor productivity in surrounding areas. Fiscal expenditure has significant negative spatial effect on green total factor productivity, mainly inhibiting the growth of green total factor productivity in surrounding areas. The spatial interaction between industrial structure and human capital on green total factor productivity is not obvious.

6.2 Policy implications

According to above conclusions, following suggestions are proposed to improve green total factor productivity and collaborative innovation:

Firstly, it is necessary to further strengthen regional collaborative innovation. Through the coordination of science and technology innovation policy, it provides a good policy environment for collaborative innovation, gives full play to the role of intermediary service institutions, improves the supporting environment of collaborative innovation, promotes the flow and sharing of innovation personnel, funds and knowledge resources and maximizes the enthusiasm of innovation subjects. It is also indispensable to strengthen the transformation of collaborative innovation results in order to accelerate the reduction of regional technical level differences and promote the transformation, promotion and application of collaborative innovation achievements. Speed up the improvement of technology market and relevant laws and regulations, establish incentive and supervision mechanism for the transformation of innovation achievements and improve the positive feedback level of collaborative innovation.

Secondly, it is necessary to further strengthen environmental protection. Give full play to the spatial spillover effect of environmental protection, strengthen the coordination of regional environmental policies and accelerate the rational use of ecological environmental protection big data in environmental quality improvement and regional cooperation will improve the efficiency of green economy. By optimizing the industrial structure and layout, improve the energy consumption structure and actively develop energy saving and environmental protection technology will contribute to promoting the development of green economy. Through diversified industrial development, expanding the industrial chain and increasing the radiation effect of environmental protection industry for economic development will contribute to promoting the development of green economy.

Thirdly, it is necessary to accelerate the transition to green finance. Further optimize the fiscal expenditure of local governments, increase the 'green expenditure' in fiscal expenditure and guide the flow of funds to green industries will promote the transformation of economy to green. Continue to adhere to opening up. Pay special attention to the development of foreign trade green industry and increase the export of green goods. Pay attention to the quality of foreign investment and give full play to its spatial spillover effect will help to promote the balanced development of regional green economy.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

Not applicable

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research was jointly supported by the Open Funds of Regional Innovation Capabilities Monitoring and Analysis Soft Science Research Base of Hubei Province (Grant No. HBQY2021z05) and the Soft Science Research Projects of Hubei Science and Technology Support Plan (Grant No. 2017ADC138).

Authors' contributions

Lei Wu: Conceptualization, Formal analysis, Writing - review & editing. **Xiaoyan Jia:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Jie Lv:** Writing - review & editing. **Li Gao:** Conceptualization, Writing - review & editing.

Ackowledgements

Not applicable

References

Adak, M., 2015. Technological Progress, Innovation and Economic Growth; the Case of Turkey. Procedia - Soc. Behav. Sci. 195, 776–782. https://doi.org/10.1016/j.sbspro.2015.06.478

Albert, B.-E., Macho-Stadler, I., Pérez-Castrillo, D., 2013. Research Output From University–Industry Collaborative Projects. Econ. Dev. Q. 27, 71–81. https://doi.org/10.1177/0891242412472535

Bai, J. h, Jiang, F.X., 2015. Collaborative innovation, spatial correlation and regional innovation performance. J. Econ. Res. 50, 174–187. https://doi.org/CNKI:SUN:JJYJ.0.2015-07-014

Belderbos, R., Carree, M., Diederen, B., Lokshin, B., Veugelers, R., 2004. Heterogeneity in R&D cooperation strategies. Int. J. Ind. Organ. 22, 1237–1263. https://doi.org/10.1016/j.ijindorg.2004.08.001

Benhabib, J., Spiegel, M.M., 1994. The role of human capital in economic development evidence from aggregate cross-country data. J. Monet. Econ. 34, 143–173. https://doi.org/10.1016/0304-3932(94)90047-7

Broda, C., Greenfield, J., Weinstein, D., 2006. From Groundnuts to Globalization: A Structural Estimate of Trade and Growth. NBER Work. Pap. https://doi.org/10.1016/j.rie.2017.10.001

Charnes, A., Cooper, W.W., Rhodes, E., 1979. Measuring the efficiency of decision making units. Eur. J. Oper. Res. 2, 429–444. https://doi.org/10.1016/0377-2217(78)90138-8

Chen, J., Yang, Y.J., 2012. The theoretical basis and connotation of collaborative innovation. J. Stud. Sci. Sci. 30, 161–164. https://doi.org/10.16192/j.cnki.1003-2053.2012.02.001

Chen, S.Y., 2009. Energy consumption, carbon dioxide emissions and the sustainable development of China's industry. J. Econ. Res. 44, 41–55. https://doi.org/CNKI:SUN:JJYJ.0.2009-04-006

Chen, X., Wang, X., Zhou, M., 2019. Firms' green R&D cooperation behaviour in a supply chain: Technological spillover, power and coordination. Int. J. Prod. Econ. 218, 118–134. https://doi.org/10.1016/j.ijpe.2019.04.033

Dai, W.L., Li, D.Q., Li, Q.M., 2019. Analysis on the Contribution of Liaoning Coastal Economic Belt to the Collaborative Innovation of Industry, University and Research in Liaoning Province. J. Econ. Res. Guid. :47-50+97. https://doi.org/CNKI:SUN:JJYD.0.2019-07-021

Deng, Y., You, D., Wang, J., 2019. Optimal strategy for enterprises' green technology innovation from the perspective of political competition. J. Clean. Prod. 235, 930–942. https://doi.org/10.1016/j.jclepro.2019.06.248

Ertur, C., Koch, W., 2011. A contribution to the theory and empirics of Schumpeterian growth with worldwide interactions, Journal of Economic Growth. https://doi.org/10.1007/s10887-011-9067-0

Fan, D., Sun, X.T., 2020. Environmental regulation, green technology innovation and green economic growth. J. China Popul. Environ. 30, 105–115. https://doi.org/10.12062/cpre.20200123

Fan, Q., Hudson, D., 2018. A new endogenous space-time weight matrix construction method including variable time effects. J. Quant. Tech. Econ. 35, 131–149. https://doi.org/10.13653/j.cnki.jqte.20171228.007

Fei, Y.Y., Ling, L., 2019. Build an efficient national innovation ecosystem. J. People's Forum 000, 62–63. https://doi.org/CNKI:SUN:RMLT.0.2019-18-025

Ganda, F., 2019. The impact of innovation and technology investments on carbon emissions in selected organisation for economic Co-operation and development countries. J. Clean. Prod. 217, 469–483. https://doi.org/10.1016/j.jclepro.2019.01.235

Gao, A.G., Zhang, L., 2019. The theoretical framework of inter-industry collaborative innovation across spaces from the perspective of knowledge heterogeneity: conditions, motivations and paths. J. Sci. Technol. Manag. Res. 39, 168–175. https://doi.org/10.3969/j.issn.1000-7695.2019.11.023

Gloor, P., 2006. Swarm Creativity: Competative Advantage Through Collaborative. Jounarl Innov. Manag. Policy Prat. 8, 413–414. https://doi.org/10.5172/impp.2006.8.4.413

Hao, J.L., Yin, M., 2019. Collaborative innovation of science and technology and economic growth in my country from the perspective of time and space differences. J. Econ. Manag. Rev. 35, 146–158. https://doi.org/10.13962/j.cnki.37-1486/f.2019.06.014

He, X.G., 2015. Energy constraints, green technological innovation and sustainable growth — Theoretical models and empirical evidence. J. Zhongnan Univ. Econ. Law 30–38. https://doi.org/CNKI:SUN:ZLCJ.0.2015-04-004

He, Y.Q., Qiao, X.N., 2015. Collaborative innovation, collaborative innovation network and technological innovation. J. Beifang Univ. Natl. 133–136. https://doi.org/CNKI:SUN:XBDR.0.2015-02-027

Hu, Y., Pan, T., Zhang, W., 2019. Research on the Economic Growth Effect of Collaborative Innovation in the Yangtze River Delta City Group under the Integrated National Strategy. J. East China Norm. Univ. (Philosophy Soc. Sci. Ed. 51, 99-106+239. https://doi.org/10.16382/j.cnki.1000-5579.2019.05.011

Huang, X.R., Xie, R.H., 2016. Research on the Agglomeration of Scientific and Technological Resources and Regional Collaborative Innovation in the Yangtze River Economic Zone. J. Sci. Manag. Res. 53–56. https://doi.org/10.19445/j.cnki.15-1103/g3.2016.04.014

Jin, W., Zhang, Heng quan, Liu, S. shuang, Zhang, Hong bo, 2019. Technological innovation, environmental regulation, and green total factor efficiency of industrial water resources. J. Clean. Prod. 211, 61–69. https://doi.org/10.1016/j.jclepro.2018.11.172

Lai, D.S., Ji, W.W., 2015. Human capital allocation and innovation. J. Econ. Perspect. 22–30. https://doi.org/CNKI:SUN:JJXD.0.2015-03-004

Lee, J., Park, C., 2006. Research and development linkages in a national innovation system: Factors affecting success and failure in Korea. Technovation 26, 1045–1054. https://doi.org/10.1016/j.technovation.2005.09.004

Leydesdorff, L., Fritsch, M., 2006. Measuring the knowledge base of regional innovation systems in Germany in terms of a Triple Helix dynamics. Res. Policy 35, 1538–1553. https://doi.org/10.1016/j.respol.2006.09.027

Li, L., Liu, R., 2020. The impact of the flow of innovative elements on the collaborative innovation of urban agglomerations ———Based on the empirical study of the Yangtze River Delta urban agglomeration and the Yangtze River midstream. J. Sci. Technol. Manag. Res. 37, 56–63. https://doi.org/10.6049/kjjbydc.2019090842

Li, Y.H., Wu, J.M., 2019. Collaborative innovation literature review. J. Xidian Univ. (Social Sci. Ed. 29, 1–7. https://doi.org/10.16348/j.cnki.cn61-1336/c.2019.04.001

Liu, G.W., Zhang, T.T., Yu, J., 2017. Research on the Relationship between Regional Synergy System of Innovation Network and Industrial Economic Growth. J. China Sci. Technol. Forum 123–132. https://doi.org/10.13580/j.cnki.fstc.2017.11.015

Liu, H.D., Chen, L., 2020. The Measurement of Regional Collaborative Innovation Efficiency and Its Key Influencing Factors——Based on Empirical Analysis of Static and Dynamic Spatial Panels. J. Sci. Technol. Manag. Res. 40, 55–63. https://doi.org/10.3969/j.issn.1000-7695.2020.12.008

Lv, H.P., Chi, R.Y., Hua, X.Y., 2017. Collaborative spatial linkages of innovative resources and regional economic growth: an empirical analysis based on China's provincial data. J. Geog. 37, 1649–1658. https://doi.org/10.13249/j.cnki.sgs.2017.11.006

Lv, L.J., Kan, D.X., 2017. An Empirical Study on the Impact of Industry-University-Research Collaborative Innovation on Economic Growth ——Take Jiangxi Province as an example. J. Sci. Technol. Manag. Res. 37, 130–135. https://doi.org/10.3969/j.issn.1000-7695.2017.23.019

Persaud, A., 2005. Enhancing Synergistic Innovative Capability in Multinational Corporations: An Empirical Investigation. J. Prod. Innov. Manag. 22. https://doi.org/10.1111/j.1540-5885.2005.00138.x

Ren, B.P., Gan, H.X., 2016. The Construction of the Micro Mechanism for the Improvement of China's Economic Growth Quality. J. Guizhou Soc. Sci. 111–118. https://doi.org/10.13713/j.cnki.cssci.2016.05.019

Wang, H., Cui, H., Zhao, Q., 2020. Effect of green technology innovation on green total factor productivity in China: Evidence from spatial durbin model analysis. J. Clean. Prod. 288, 125624. https://doi.org/10.1016/j.jclepro.2020.125624

Wang, W.J., Wei, H.A., 2016. Construction of the Evaluation Index System of Collaborative Innovation Capability ———Based on the Empirical Research of the State Key Laboratory. J. Stud. Sci. Sci. 34, 471–480. https://doi.org/10.16192/j.cnki.1003-2053.2016.03.018

Wang, X., Gao, S., 2018. Contribution rate of collaborative innovation and technological progress to the economic growth of the construction industry in the three eastern provinces. J. Technol. Ind. 18, 44–47. https://doi.org/CNKI:SUN:CYYK.0.2018-05-008

Wu, W.H., Li, N.N., Zhang, A.M., Liu, A.G., Wang, J.Y., 2016. The impact of the similarity, coupling and multi-dimensional proximity of innovation capabilities between Beijing-Tianjin-Hebei provinces and cities on collaborative innovation. J. Technol. Prog. Countermeas. 33, 24–29. https://doi.org/10.6049/kjjbydc.2015100448

Yang, Y.Z., Li, S., 2019. Research on the Evaluation of Cooperative Innovation of Industry-University-Research Institute Based on Factor Analysis. J. Math. Pract. Knowl. 49, 23–30. https://doi.org/CNKI:SUN:SSJS.0.2019-03-003

Zhang, J., Wu, G.Y., Zhang, J.P., 2004. China's inter-provincial material capital stock estimation: 1952-2000. J. Econ. Res. 35–44. https://doi.org/CNKI:SUN:JJYJ.0.2004-10-004

Zhao, Y.L., Chen, H.Z., 2020. Heterogeneous technological innovation and green total factor productivity improvement. J. Financ. Account. Mon. 145–152. https://doi.org/10.19641/j.cnki.42-1290/f.2020.18.023

Zhao, Z., 2020. Connotation interpretation, interactive relationship and motivation mechanism of the coordinated development of universities and strategic emerging industries. J. High. Educ. Manag. 14, 9–18. https://doi.org/10.13316/j.cnki.jhem.20200507.002

Zhong, H.B., Liu, X., 2018. Arbitrage Entrepreneurship, Innovative Entrepreneurship and China's Economic Growth — Empirical Research Based on the Synergy of Marketization. J. Technol. Prog. Countermeas. 35, 74–81. https://doi.org/10.6049/kjjbydc.2017110354

Zhou, X.L., Li, T., 2017. Research on the Conditions of Promoting Economic Growth under the Co-evolution of Technological Innovation and Institutional Innovation. J. Southeast Acad. 189-197+248. https://doi.org/10.13658/j.cnki.sar.2017.01.021

Zhu, P.H., Li, J.L., 2019. How Fiscal Policy Affects Total Factor Productivity: A Perspective of Heterogeneity and Marketization. J. Shandong Univ. Soc. Sci. 85–95. https://doi.org/10.3969/j.issn.1001-9839.2019.01.010

Zhu, W.T., Lv, C.R., Gu, N.H., 2019. Research on the Impact of OFDI and Reverse Technology Spillover on Green Total Factor Productivity. J. China Popul. Environ. 29, 63–73. https://doi.org/10.12062/cpre.20181106

Figures

Figure 1

Map of the Yangtze River Economic Belt. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area o bbnhjr of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

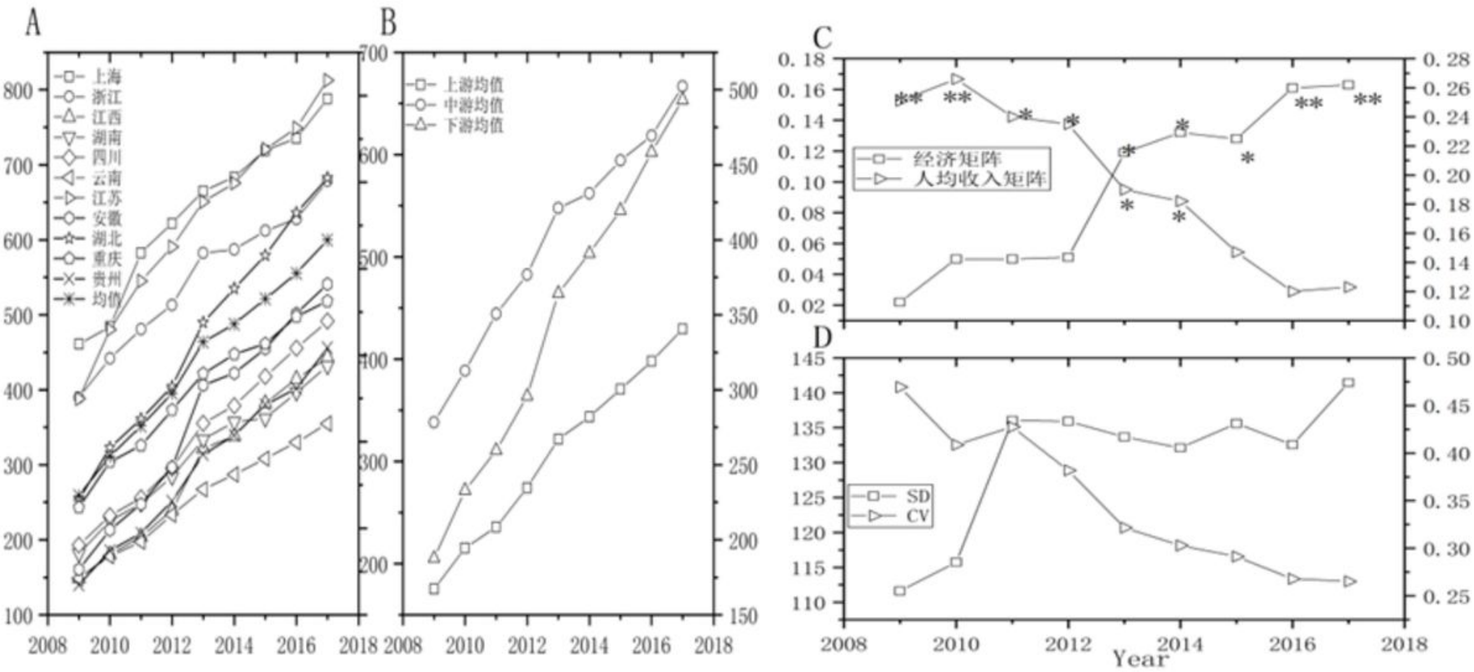

Figure 2

Changes in the level of collaborative innovation of provinces in the Yangtze River Economic Belt Note: A. The level and mean change of collaborative innovation in the provinces of the Yangtze River Economic Belt B. The mean change of regional collaborative innovation C. Moran 's I value of collaborative innovation corresponding to different matrices D. Standard deviation and coefficient of variation of collaborative innovation

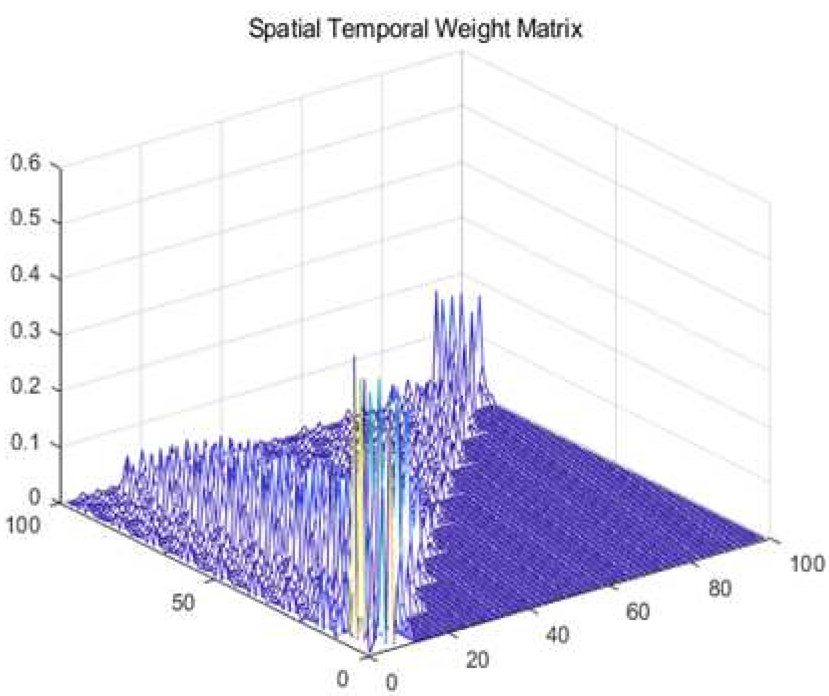

Figure 3

Endogenous space-time weight matrix based on economic matrix

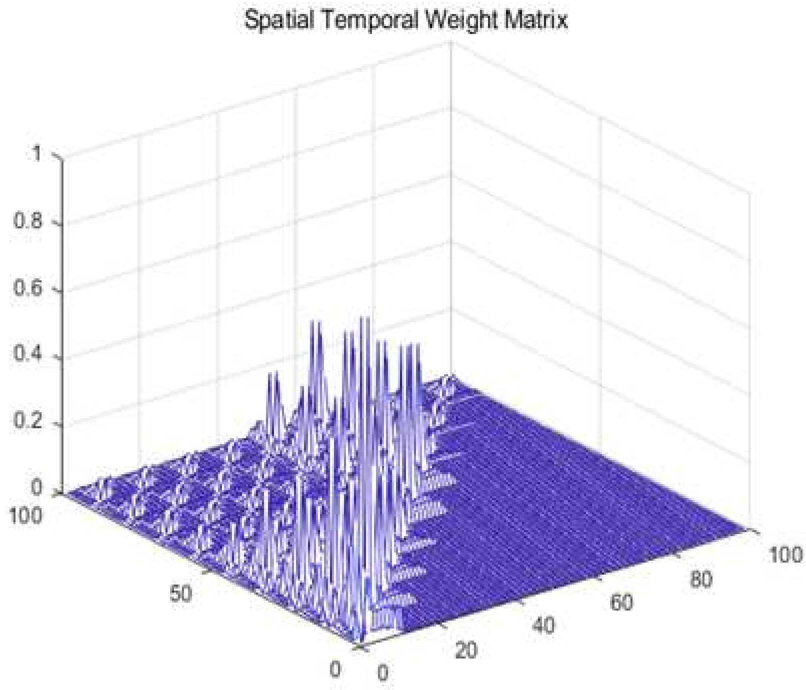

Figure 4

Endogenous time-space weight matrix based on per capita income matrix

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformation.docx