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Carbon constraints, industrial structure upgrading, and green total factor productivity: an empirical study based on the Yangtze River Economic Belt

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ABSTRACT

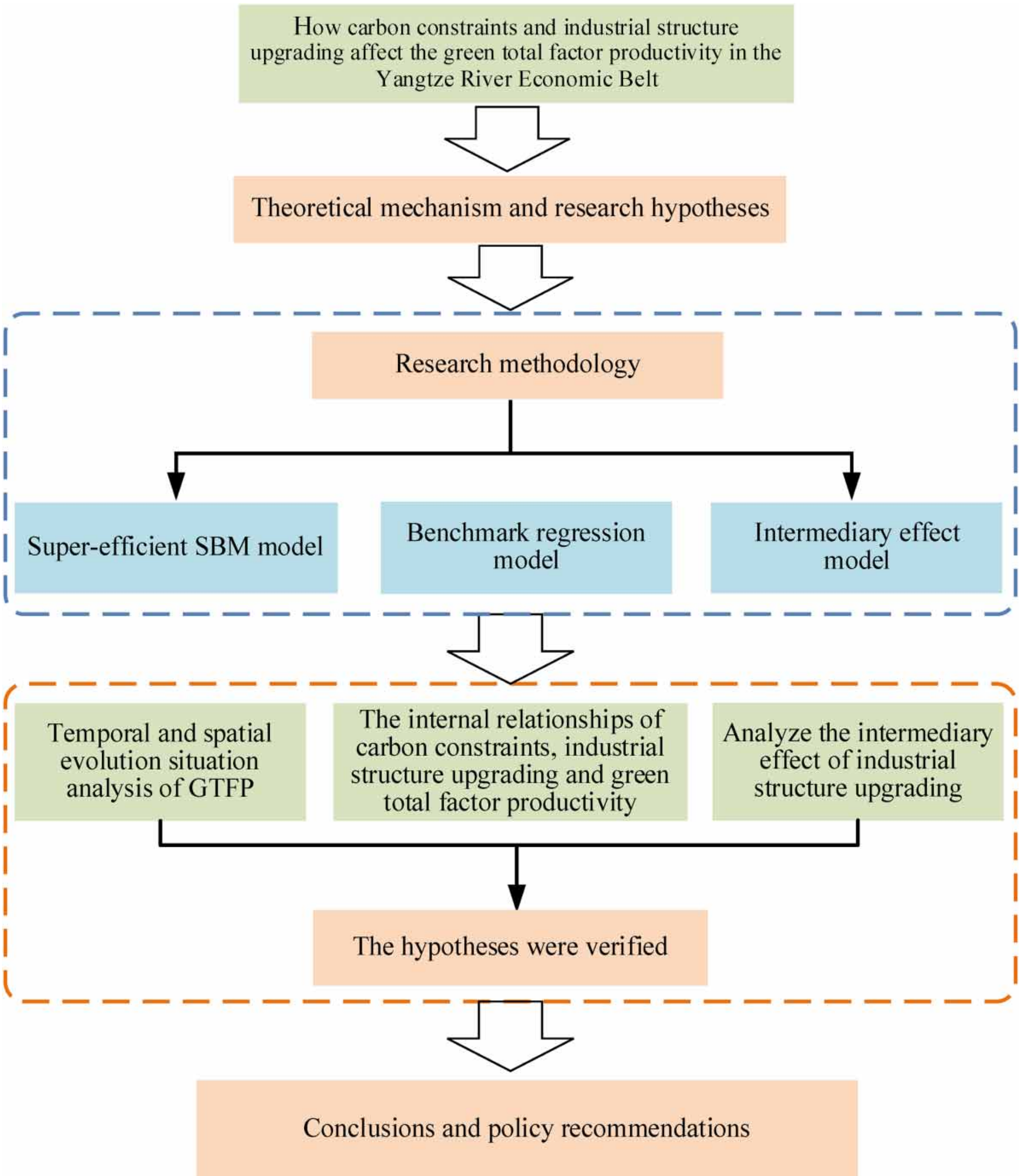
Reducing carbon emissions, upgrading industrial structure, and promoting green total factor productivity are important ways to tackle global climate change. The Yangtze River Economic Belt is an important economic region and industrial corridor in China. Using the panel data of 11 provinces in the Yangtze River Economic Belt from 2006 to 2020, this study calculates industrial green total factor productivity using the super-efficient SBM model, and analyzes its evolution trends in time and space. This study discusses how carbon constraints and industrial structure upgrading affect green total factor productivity by using benchmark regression and the intermediary effect model. The results show that green total factor productivity is fluctuating and rising over time, and is in a gradient decreasing spatial distribution from the Yangtze River Delta to Urban Agglomeration in the Middle Reaches to Chengdu–Chongqing Economic Zone; carbon constraints, industrial structure upgrading, and their synergy have a positive effect on the industrial green total factor productivity; industrial structure upgrading has partial intermediary effects, and can help carbon constraints positively impact on industrial green development. Based on the above results, reducing carbon emission and accelerating industrial structure upgrading are important for achieving economic and ecological sustainability.

Key words: carbon constraints, green total factor productivity, industrial structure upgrading, intermediary effect model, synergistic effect, Yangtze River Economic Belt

HIGHLIGHTS

- Calculate green total factor productivity and analyze trends.
- Carbon constraints (ER) are measured by the weighted sum of energy consumption and CO_2 emission.
- Use different models to analyze the relationship among carbon constraints, industrial structure, and green total factor productivity.
- Provide an effective tool for developing carbon emission and green industry management strategies in other regions of the world.

GRAPHICAL ABSTRACT



1. INTRODUCTION

As industrialization and urbanization continue to increase, carbon constraints have gained a prominent place in the discourse on global climate change. Carbon constraints are essentially environmental rules. Because of the close relationship between industrial energy saving and carbon emission reduction, the concept of carbon constraints includes energy saving and emission reduction. Industries are the lifeblood of economic development, but they are also the largest producers of carbon emissions. The traditional production mode characterized by high inputs, high energy consumption, and high emissions cannot support sustainable and high-quality economic development. This production mode has also set back the low-carbon green development of China's economy. In September 2020, China's central government pledged to ensure that CO_2 emissions peak by 2030 and achieve carbon neutrality by 2060, at the 75th United Nations General Assembly, which means that China's economy will have to carry out rapid and comprehensive decarbonization reforms in the next 40 years. The Yangtze River Economic Belt is one of the densest and critical economic regions and one of China's most important industrial corridors. Many of the modern industries, such as steel, automobiles, electronics, and petrochemicals, are concentrated here, which are high-energy-consuming, high-emissions, and large-scale enterprises. Industrial activities are closely related to water, and water is an essential resource in industrial development. However, the utilization of water resources in industries in the past was rough, and water resources were greatly wasted due to unreasonable structure and low-efficiency recycling, which hindered the green development of industry. Therefore, it is of great significance for China to study the green development of industry in the Yangtze River Economic Belt and put forward corresponding suggestions.

In this study, green total factor productivity (GTFP) is used to measure the level of industrial green development. Taking environmental factors into account, green total factor productivity is the ratio of total input to total output in a country or a region. It considers input factors including capital, labor, and energy consumption, as well as output factors including expected output and unexpected output, which is an important indicator to measure the coordinated development of resources, environment, and economy in a country or region.

How we effectively control industrial carbon emissions and improve green total factor productivity is an important concern in promoting the green development of industry. Wang & Xiang (2014) proposed that industrial structure upgrading could reduce carbon emissions. Industrial carbon constraints play a vital role in the upgrading of industrial structure. Although many scholars have studied the relationship between carbon constraints, industrial structure upgrading, and green total factor productivity using different methods, few have combined the three concepts into the same research framework. In order to broaden the research in this field, this study explored how carbon constraints and industrial structure upgrading affect green total factor productivity in the Yangtze River Economic Belt.

2. THEORETICAL MECHANISM AND RESEARCH HYPOTHESES

2.1. Influence of carbon constraints on industrial green development

In order to promote the green development of industry, many scholars have discussed carbon emissions from different perspectives, mainly focusing on how carbon constraints affect industrial development. Xu *et al.* (2014) adopted the Logarithmic Mean Divisia Index model to analyze the influence factors of the emission intensity of industrial energy consumption. Ouyang & Lin (2015) studied the determinants of industrial emissions in China by using the co-integration method. Dong *et al.* (2017) analyzed carbon emissions and implied carbon transfer in the copper industry. Dong *et al.* (2016) and Guo *et al.* (2021) studied the relationship between carbon emissions and economic development from a provincial perspective. Yu *et al.* (2015) and Liu *et al.* (2022) studied the impact of carbon emissions on industrial low-carbon transformation at the urban level. Wang & Jiang (2019), Wang & Zhang (2020), and Apeaning (2021) used the decoupling principle to explore the relationship between industrial carbon emissions and economic growth. Wu & Zhang (2021) found that the Yangtze River Economic Belt has strategic importance in China's regional development and discussed the internal relationship between carbon emissions and regional economic development. Sanguinet *et al.* (2022) applied the cross-regional input–output model to determine the interaction between CO_2 emissions embedded in the commodities of resource-based industries and other industries. Based on the above analysis, this study proposes the following Hypothesis 1:

Hypothesis 1 Carbon constraints have a positive effect on green total factor productivity.

2.2. Influence of industrial structure upgrading on industrial green development

Industrial structure upgrading can directly promote industrial green development and be an essential driver for changing the mode of regional industrial development. New technologies emerge with the upgrading of industrial structure, for example, the integration of industrial technology and intelligent technology and Industry 4.0. Industry 4.0 uses information technology to promote industrial transformation – the era of intelligence, which will promote the green development of industry (Ghobakhloo 2018, 2020; Wichmann *et al.* 2019). Industrial structure upgrading mainly affects industrial green development through the replacement of production factors and change in industrial structure, more efficiency in industrial factor replacement, exploring the characteristics of industrial structure adjustment, and discussing the upgrading path to be taken (Zhu *et al.* 2019; Zeng *et al.* 2020). Industrial structure upgrading also affects industrial green development by coordinating the operations of various industrial sectors, promoting a more effective resource allocation in various industrial sectors, improving green total factor productivity, and achieving high-quality development of the industrial economy (Yang & Wang 2020). Based on the above analysis, this study proposes the following Hypothesis 2:

Hypothesis 2 The upgrading of industrial structure is conducive to improving green total factor productivity.

2.3. Influence of carbon constraints on industrial structure upgrading

Carbon constraints have profoundly changed the development mode of China's economy and are significant in optimizing and upgrading China's industry. Carbon constraints are important for strategic industrial entrepreneurship and forming the basis of economic development (Boudreaux 2020). With carbon constraints, industrial structure can be optimized and upgraded through technological innovations and improvements in energy efficiency (Wu *et al.* 2019). Technological innovation not only promotes the adjustment of industrial structure, but also improves sharing of resources and benefits, promotes the flow of innovation resources, and improves energy and environmental efficiency, thus effectively promoting further upgrading of the industrial structure (Li & Zeng 2020). However, as industrial development is tilted toward the traditional production mode, economic and industrial development structure show *three highs* – high pollution, high emissions, and high energy consumption. Under the new carbon emissions constraint policy, upgrading industrial structure and achieving sustainable economic development are important (Dong *et al.* 2020). Transforming industrial low-carbon energy is an effective way to achieve energy conservation and emission reduction (He *et al.* 2022). Han & Zhao (2022) explained that the upgrading of industrial intelligence can narrow the gap in the regional economy. Based on the above analyses, this study proposes the following hypotheses:

Hypothesis 3 Carbon constraints are conducive to promoting the upgrading of industrial structure.

Hypothesis 4 The upgrading of industrial structure has played an intermediary role in the process of carbon constraints promoting industrial green development.

3. VARIABLES AND METHODS

3.1. Description of variables and data sources

3.1.1. Explained variable

The GTFP of 11 provinces in the Yangtze River Economic Belt is selected as the explained variable. According to the definition of GTFP, the input–output system refers to Yan *et al.* (2020) and Huang & Wu (2021), and the input index variables are industrial capital inputs, labor inputs, and energy consumption. The output is divided into expected and unexpected output. The expected output index variable is industrial added value and the unexpected output index variables are three kinds of major industrial pollutants, which are industrial wastewater discharge, industrial waste gas discharge, and industrial solid waste production. The super-efficient SBM model is used to calculate the green total factor productivity of 11 provinces in the Yangtze River Economic Belt, and the descriptive statistics of the input–output indicators are shown in Table 1. The data mainly come from the *China Statistical Yearbooks* from 2006 to 2020.

3.1.2. Explanatory variables

Carbon constraints and industrial structure upgrading are the explanatory variables, and the measurement method of carbon constraints refers to Mao & Wang (2022). Carbon constraints (ER) are measured by energy savings and the carbon emission

Table 1 | Descriptive statistics of the input–output indicators

Index category	Index variable	Unit	Average value	Maximum
Input element	Assets of industrial enterprises above the designated size	100 million yuan	30,467.6	133,267.4
	Annual average number of employees in industrial enterprises above the designated size	10,000 people	876.3	2,045.5
	Industrial energy consumption	10,000 tons of coal	9,184.9	23,498.5
Expected output	Industrial added value	100 million yuan	8,983.7	38,198.1
Unexpected output	Industrial wastewater discharge	10,000 tons	80,516.9	287,181
	Industrial sulfur dioxide emissions	Tons	471,532.6	1,241,000
	Industrial solid waste	10,000 tons	8,003.3	18,721.8

intensity index, as is shown in Equation (1):

$$ER_{it} = 0.5 \times \left[\frac{\text{Energy(S)}_{it}}{\text{GDP(S)}_{it}} / \frac{\text{Energy(S)}_{it-1}}{\text{GDP(S)}_{it-1}}\right] + 0.5 \times \left[\frac{\text{CO}_2\text{(S)}_{it}}{\text{GDP(S)}_{it}} / \frac{\text{CO}_2\text{(S)}_{it-1}}{\text{GDP(S)}_{it-1}}\right], \quad (1)$$

where i represents the province, t represents the year, and $t-1$ represents the year variable lagged by one period; Energy (S) represents total industrial energy consumption, GDP (S) represents industrial added value, and CO_2 (S) represents industrial CO_2 emissions. As shown in Equation (1), energy savings and the carbon emission intensity index refer to the weighted sum of the energy consumption intensity index per unit of industrial added value and the CO_2 emission intensity index per unit of industrial added value, with a respective weight of 0.5. If the value of the carbon constraints (ER) is less than 1, then the carbon constraint intensity in the current period is greater than it was in the previous period. In order not to contradict the basic concept of carbon constraints, and considering the data characteristics of the variables, the relationship between the carbon constraints (ER) and the carbon constraint intensity is reversed; the lower the carbon constraints (ER), the greater the carbon constraint intensity. This point is critical to correctly interpreting the following empirical results. Combined with the current state of economic development and the industrial structure, industrial structure upgrading (IND) is measured as the ratio of the tertiary industry's output value to the secondary industry's output value. The data come from the *China Statistical Yearbooks* from 2006 to 2020.

3.1.3. Control variables

There are other factors that affect green total factor productivity in reality, so control variables are added to this study: the level of economic development (GDP) measured by the regional gross product; the level of science and technological achievement (STL) expressed by the investment intensity of R&D funds; human resources (HR) expressed as the number of colleges and universities; government intervention ability (GOV), which measures government intervention as the proportion of fiscal expenditure in each province to GDP; industrial scale (IES) expressed as the number of industrial enterprises; and foreign investment (FI) expressed as total foreign investment. To accurately measure the impact of carbon constraints and industrial structure upgrading on green total factor productivity, based on the existing studies in the literature, different control variables are added to the benchmark regression model and the intermediary effect model. The data come from the Wind database and the Yangtze River Economic Belt Big Data Platform.

3.1.4. Descriptive statistic

In order to eliminate the influence of dimensions between variables, the logarithm of the above individual variables is first taken. In Table 2, the descriptive statistics of each variable are given.

Table 2 | Descriptive statistics of variables

Variable	Maximum	Minimum	Average	Standard deviation
GTFP	2.0152	0.670 0	1.0206	0.1428
ER	1.1219	0.9172	1.0137	0.0356
IND	2.7481	0.5863	1.0462	0.3673
LnGDP	11.53975	7.75747	10.09651	9.83104
STL	4.1600	0.4765	1.6406	0.8104
LnHR	5.117994	3.583519	4.546513	3.454613
GOV	0.402160	0.065526	0.211834	0.072204
LnIES	11.089730	7.738924	9.729990	9.654696
LnFI	9.524932	3.258097	7.544092	7.872134

3.2. Model

3.2.1. Super-efficient SBM model

The super-efficient SBM model overcomes the defects of the DEA model, combining the super-efficient DEA model with the SBM model, which can not only effectively deal with an unexpected output, but also effectively evaluate the cutting-edge DMU. The model is as follows:

$$\min \rho = \frac{\frac{1}{m}\sum_{i=1}^{m}(\overline{x}/x_{ik})}{\frac{1}{h_1+h_2}\left(\sum_{p=1}^{h_1}\overline{y^{d}}/y_{pk}^{d}+\sum_{q=1}^{h_2}\overline{y^{u}}/y_{qk}^{u}\right)},$$
$$\begin{cases} \overline{x} \geq \sum\limits_{j=1,\neq k}^{n} x_{ij}\lambda_j;\ \overline{y^{d}} \leq \sum\limits_{j=1,\neq k}^{n} y_{pj}^{d}\lambda_j;\ \overline{y^{u}} \geq \sum\limits_{j=1,\neq k}^{n} y_{qj}^{u}\lambda_j \\ \overline{x} \geq x_k;\ \overline{y^{d}} \leq y_k^{d};\ \overline{y^{u}} \leq y_k^{u} \\ \lambda_j \geq 0,\ i=1,2,\ \ldots,m;\ j=1,2,\ \ldots,n,\ j\neq 0 \\ p=1,2,\ \ldots,h_1;\ q=1,2,\ \ldots,h_2. \end{cases} \tag{2}$$

Equation (2) assumes that there are n decision-making units, that is, 11 provinces in the Yangtze River Economic Belt, each of which contains m input indicators, h_1 expected output indicators, and h_2 unexpected output indicators; x, y^{d}, and y^{u}, respectively, represent the corresponding elements in the input matrix, expected output matrix, and unexpected output matrix, and ρ represents the value of GTFP.

3.2.2. Benchmark regression model

Because the benchmark regression model has good anti-environment noise ability, it can solve the pseudo-difference of the model and provide good calculation precision and data precision. Therefore, this study uses the benchmark regression model to test the related hypotheses. According to the literature discussed above, carbon constraints and industrial structure upgrading affect green total factor productivity independently. Therefore, this study focuses on the impact of carbon constraints, industrial structure upgrading, and their synergy on green total factor productivity, and uses longitude panel data to analyze the internal relationship among carbon constraints, industrial structure upgrading, and green total factor productivity. This has the advantage of increasing the number of samples, and the R^2 of the regression result is closer to 1. In order to eliminate the influence of dimensions between variables, this study takes the logarithm of individual variables. The synergistic effect model of carbon constraint and industrial structure upgrading is shown in Equation (3), which is Model 3. When the IND is not included in Equation (3), it represents the independent influence of carbon constraint on green total factor productivity, which is Model 1. Also, when the ER is not included in Equation (3), it represents the independent influence of industrial structure upgrading on green total factor productivity, which is Model 2.

$$\mathrm{GTFP}_{it} = \alpha_0 + \alpha_1\mathrm{ER}_{it} + \alpha_2\mathrm{IND}_{it} + \alpha_3\mathrm{LnGDP}_{it} + \alpha_4\mathrm{STL}_{it} + \alpha_5\mathrm{GOV}_{it} + \alpha_6\mathrm{LnIES}_{it} + \alpha_7\mathrm{LnFI}_{it} + \mu_{it}, \tag{3}$$

where i and t, respectively, represent the province and year, α_0 represents the cross-section effect, α_1, α_2, α_3, α_4, α_5, α_6, and α_7 are, respectively, the estimation coefficients of each variable, and μ represents the random error term.

3.2.3. Intermediary effect model

To further examine the relationship among carbon constraints, industrial structure upgrading, and green total factor productivity, this study uses the intermediary effect model to explore how carbon constraints influence green total factor productivity when industrial structure upgrading is an intermediary variable. Based on our above theoretical mechanism analysis and hypotheses, a transmission path model of carbon constraints–industrial structure upgrading–green total factor productivity is constructed in Equations (4)–(6), which are Model 4, Model 5, and Model 6, respectively:

$$\mathrm{GTFP}_{it} = \beta_0 + \beta_1\mathrm{ER}_{it} + \beta_2\mathrm{Lncontrols}_{it} + \varepsilon_{it}, \tag{4}$$

$$\mathrm{IND}_{it} = \gamma_0 + \gamma_1\mathrm{ER}_{it} + \gamma_2\mathrm{Lncontrols}_{it} + \theta_{it}, \tag{5}$$

$$\mathrm{GTFP}_{it} = \delta_0 + \delta_1\mathrm{ER}_{it} + \delta_2\mathrm{IND}_{it} + \delta_3\mathrm{Lncontrols}_{it} + \sigma_{it}. \tag{6}$$

Equation (4) is the total effect model of carbon constraints on green total factor productivity, Equation (5) is the direct effect model of carbon constraints on industrial structure upgrading, and Equation (6) is the direct effect model of carbon constraints on green total factor productivity. In these models, i and t represent the province and year, respectively, the explained variable $GTFP_{it}$ is green total factor productivity, the explanatory variable ER_{it} is the carbon constraints intensity index, IND_{it} is the level of industrial structure upgrading, and $controls_{it}$ is the control variable groups that include economic development level GDP_{it}, human capital HR_{it}, and foreign investment FI_{it}. In addition, β_1 is the total effect of carbon constraints on green total factor productivity, γ_1 is the direct effect of carbon constraints on industrial structure upgrading, δ_1 is the direct effect of carbon constraints on green total factor productivity, δ_2 is the direct effect of industrial structure upgrading on green total factor productivity, and $\gamma_1\delta_2$ is the intermediary effect, which satisfies $\beta_1 = \delta_1 + \gamma_1\delta_2$.

For the intermediary effect test, the stepwise regression method is adopted following Wen & Ye (2014). First, we check whether the total effect coefficient β_1 is significant, and if so, whether there is a tentative intermediary effect. If it is not significant, the test is complete, and we can conclude that the intermediary variable has a masking effect in the entire process.

Second, if β_1 is significant, δ_1, γ_1, and δ_2 are tested. There can be four possible situations here: (1) γ_1 and δ_2 are significant but δ_1 is not significant, then there is no direct effect, only indirect effect. It can be considered that there is a total intermediary effect; the influence of carbon constraints on green total factor productivity is achieved entirely by upgrading the industrial structure. (2) δ_1, γ_1, and δ_2 are all significant, and $\gamma_1\delta_2$ has the same sign as δ_1, then it can be considered that there is a partial intermediary effect; the influence of carbon constraints on green total factor productivity is achieved partly by upgrading the industrial structure. (3) At least one of γ_1 and δ_2 is not significant, but the bootstrap test shows that $\gamma_1\delta_2$ is significantly different from 0 and has the same sign as δ_1, then it can be considered that there is a partial mediating effect. (4) $\gamma_1\delta_2$ and δ_1 have different signs in cases (2) and (3), then it can be considered that industrial structure upgrading has a masking effect in the influence path; there is a substitution effect between carbon constraints and industrial structure upgrading. In order to observe the inspection process of the intermediary effect more intuitively, the specific inspection process is shown in Figure 1.

When conducting an empirical test, the panel model must be chosen according to the problem being solved. If the measurement model is not appropriate, there will be large deviations in the results and the results will not be authentic. There are three models for analyzing panel data: the fixed effect model, the random effect model, and the mixed effect model. The model is chosen by the Hausman test. In this study, the explanatory variables of carbon constraints, industrial structure upgrading, and green total factor productivity are tested with the Hausman test. As shown in Table 3, the results show

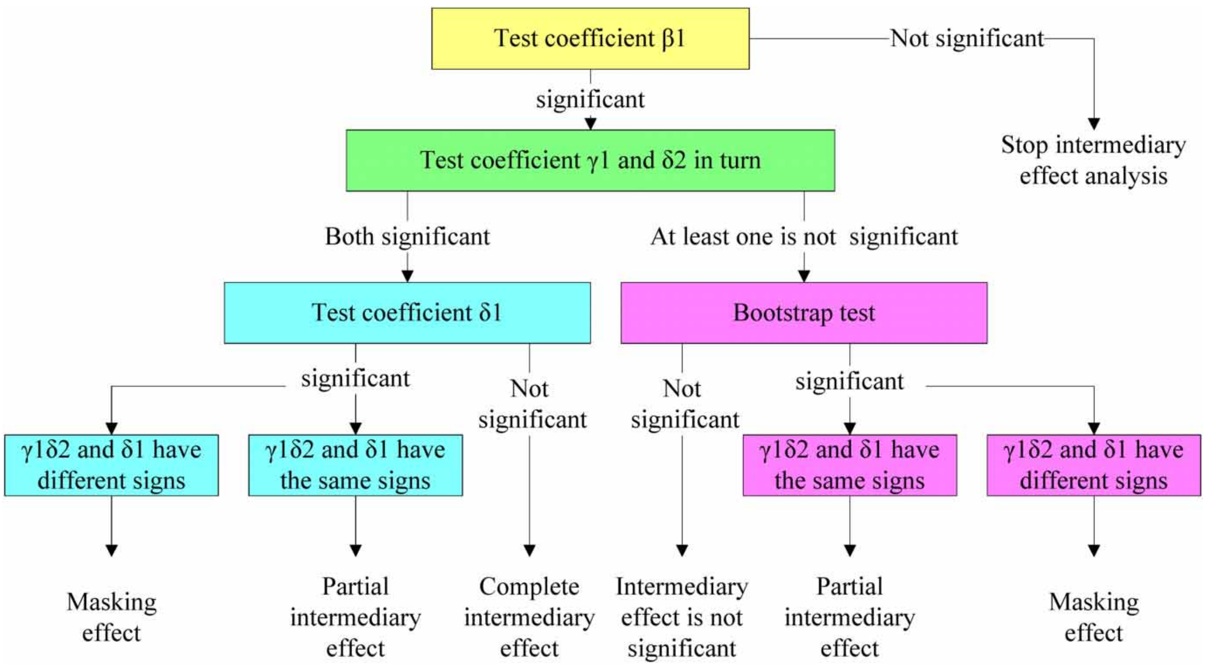


Figure 1 | Intermediary effect inspection process.

Table 3 | Hausman test results

Hausman statistics	*p*-value
3.89	0.7924

that the *p*-value is 0.7924, which is greater than 0.01. The original hypothesis cannot be rejected at the 1% significance level, so this study uses the random effect model.

4. ANALYSIS OF RESULTS

4.1. Temporal and spatial evolution situation analysis of GTFP

The Yangtze River Economic Belt was divided into three regions: the Yangtze River Delta, the Urban Agglomeration in the Middle Reaches, and the Chengdu–Chongqing Economic Zone. The overview of the Yangtze River Economic Belt is shown in Figure 2. Most of the previous findings were qualitative analyses of the level of green development, but this study made a quantitative analysis of the level of green development, which more truly reflected the industrial development of the Yangtze River Economic Belt. The values of green total factor productivity of the 11 provinces in the Yangtze River Economic Belt from 2006 to 2020 were calculated according to Equation (2). Figure 3 is the result of the temporal and spatial evolution analysis on green total factor productivity of the three regions. As can be seen from Figure 3, the overall green total factor productivity of the Yangtze River Economic Belt showed a fluctuating upward trend from 2006 to 2020. In this, the green total factor productivity in the Chengdu-Chongqing Economic Zone has an obvious upward trend, the green total factor

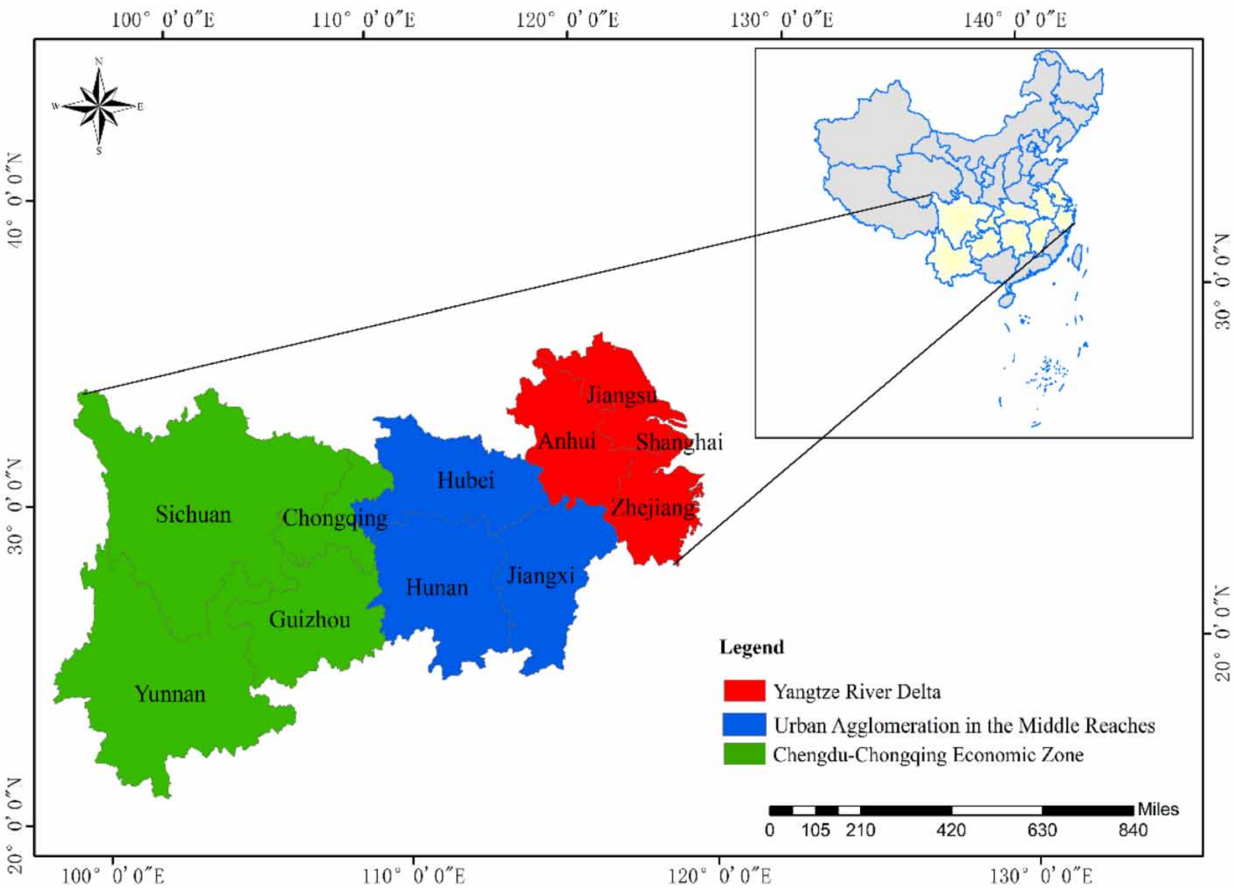


Figure 2 | Overview of the Yangtze River Economic Belt.

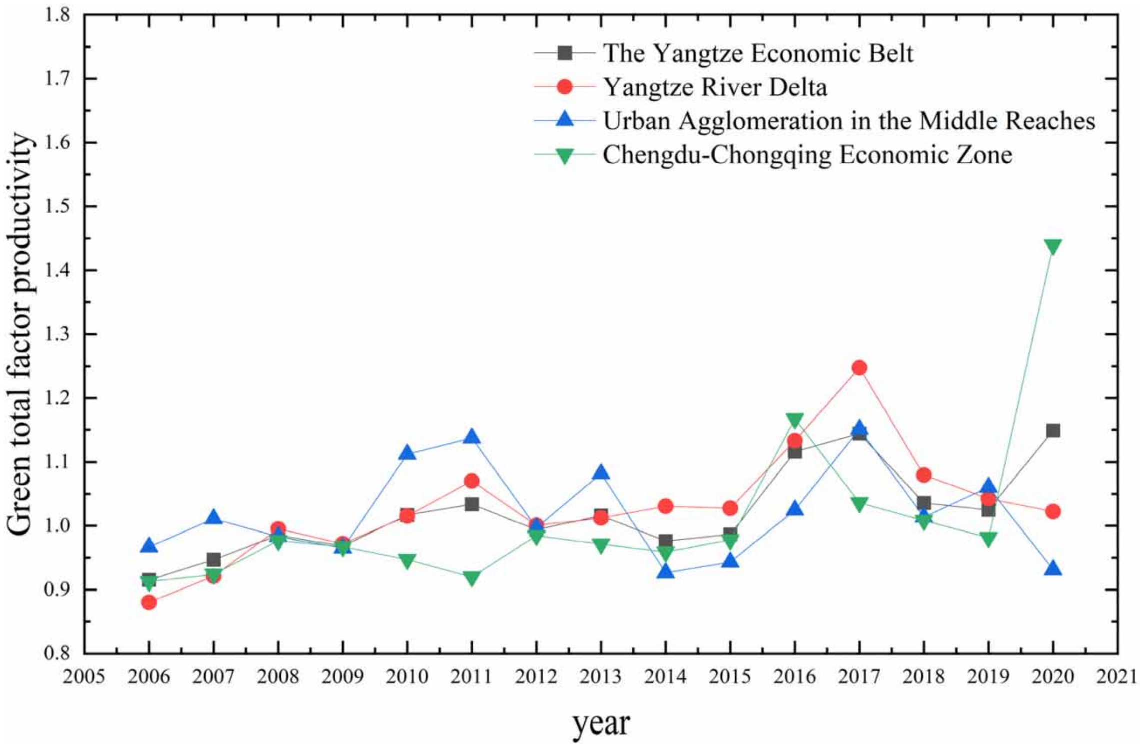


Figure 3 | Green total factor productivity in the Yangtze River Economic Belt.

productivity in the Yangtze River Delta is in the leading position, and the fluctuation in the Urban Agglomeration in the Middle Reaches is obvious. To sum up, the Chengdu-Chongqing Economic Zone should continue to maintain this trend. The Yangtze River Delta should give consideration to the development of ecology, while developing the economy to form a situation of coordinated development of economy and ecology. The Urban Agglomeration in the Middle Reaches should improve the corresponding industrial green development policies and promote industrial green total factor productivity.

In order to show the temporal and spatial evolution characteristics of green total factor productivity in the Yangtze River Economic Belt more vividly, the spatial distribution maps of green total factor productivity in the Yangtze River Economic Belt in 2006, 2013, and 2020 were obtained by visualizing green total factor productivity in 11 provinces with ArcGIS10.8 software, as shown in Figures 4–6.

The green total factor productivity in the Yangtze River Economic Belt shows a fluctuating upward trend. From 2006 to 2013, the overall increase in green total factor productivity was not obvious. From 2013 to 2020, the green total factor productivity of the 11 provinces increased significantly, showing obvious spatial characteristics. In 2020, the spatial pattern of green total factor productivity of the 11 provinces in the Yangtze River Economic Belt was characterized by 'a gradient decreasing spatial distribution from the Yangtze River Delta to Urban Agglomeration in the Middle Reaches to the Chengdu–Chongqing Economic Zone.' That is to say, green total factor productivity in the Urban Agglomeration in the Middle Reaches and the Yangtze River Delta is generally higher than that of the Chengdu–Chongqing Economic Zone. There are two main reasons: on the one hand, the economic development strength of the Chengdu–Chongqing Economic Zone is not as good as that of the Yangtze River Delta, and the capital, talents, and other factors that promote industrial green development technology are lacking. On the other hand, the industrial fields of the provinces in the Urban Agglomeration in the Middle Reaches insist on promoting industrial energy conservation and emission reduction as a breakthrough and an important starting point for structural transformation. However, the overall level of industrial green development in the Chengdu–Chongqing Economic Zone has improved significantly in recent years. From the above results, it can be found that regions should play a linkage role, strengthen regional cooperation, promote the formation of a new pattern of regional development, and improve the industrial green total factor productivity of each region. The results are also applicable to areas similar to the development of the Yangtze River Economic Belt.

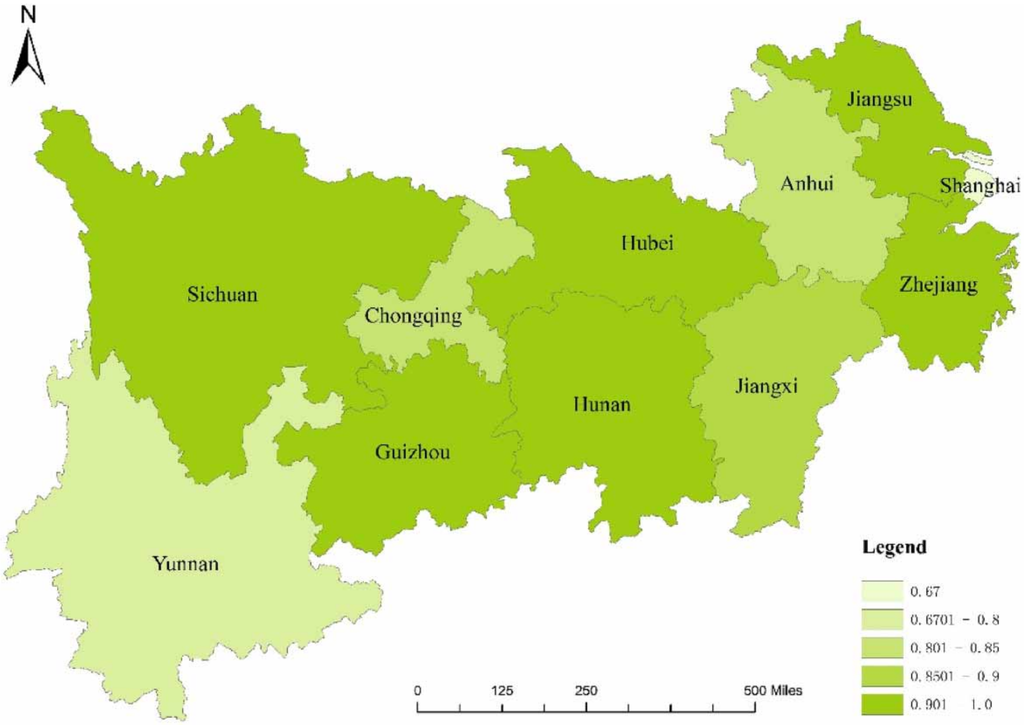


Figure 4 | Green total factor productivity in the Yangtze River Economic Belt (2006).

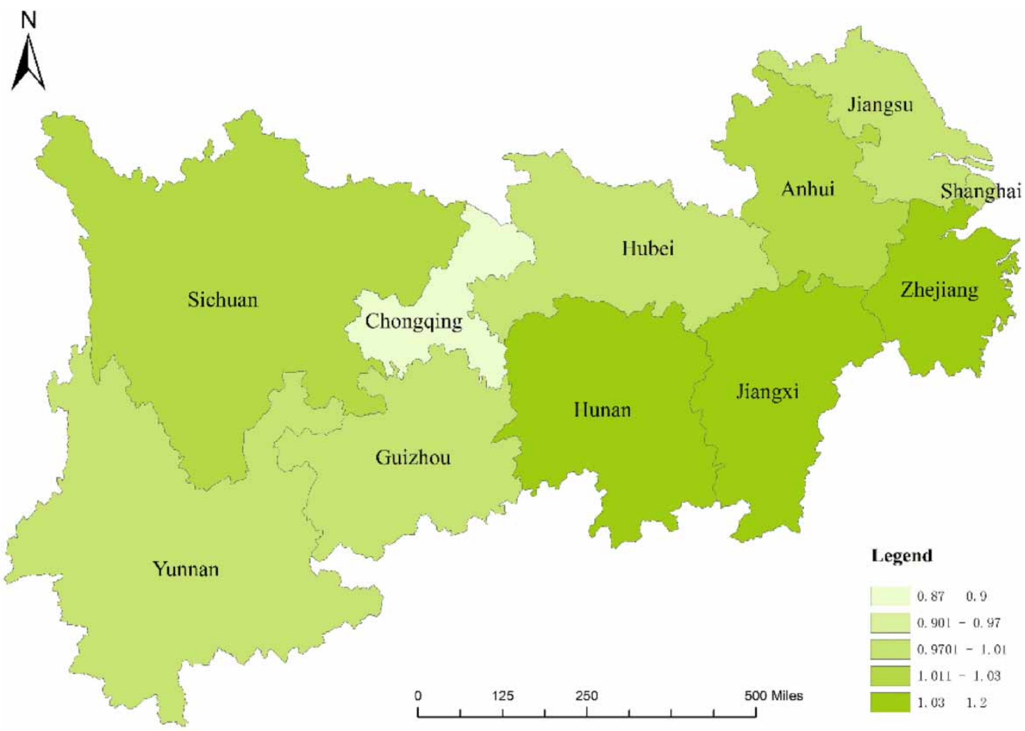


Figure 5 | Green total factor productivity in the Yangtze River Economic Belt (2013).

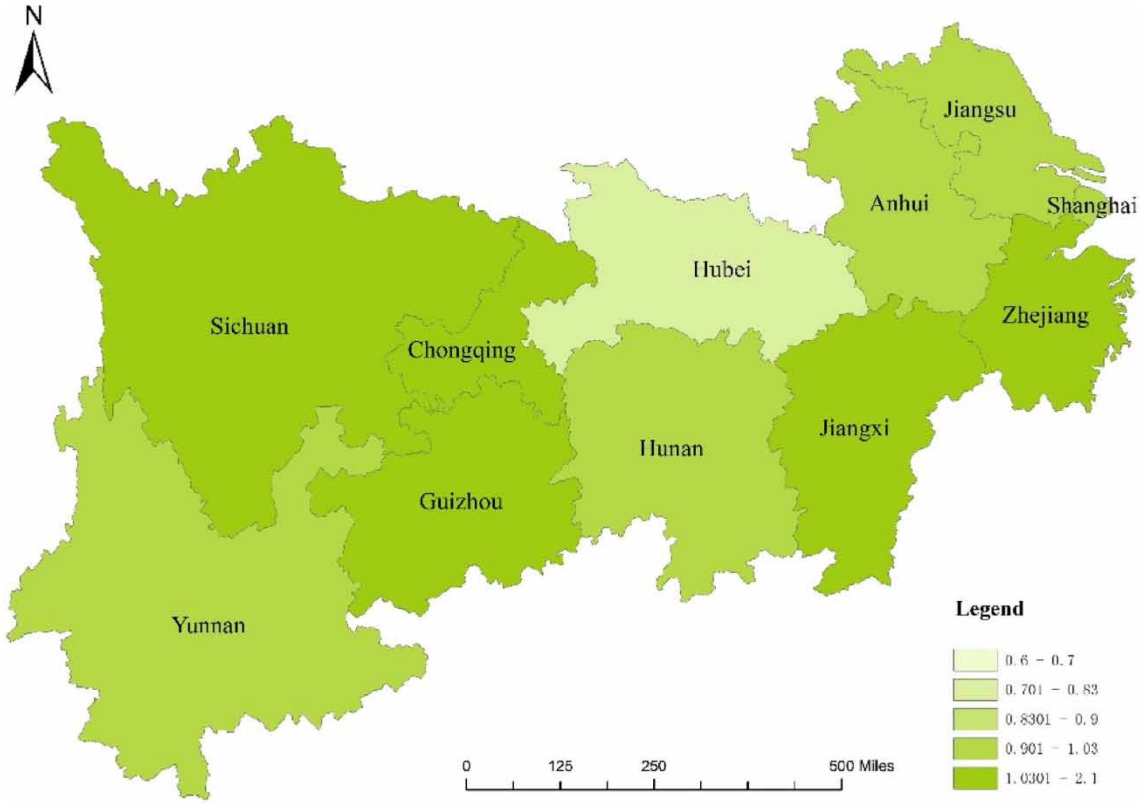


Figure 6 | Green total factor productivity in the Yangtze River Economic Belt (2020).

4.2. Benchmark regression analysis

First, 11 provinces in the Yangtze River Economic Belt are used in the study sample to empirically analyze the internal relationship and impact of carbon constraints, industrial structure upgrading, and green total factor productivity. Model 1 is the effect of carbon constraints on green total factor productivity, Model 2 is the effect of industrial structure upgrading on green total factor productivity, and Model 3 is the effect of synergy between carbon constraint and industrial structure upgrading on green total factor productivity. This study discussed the relationship among carbon constraints, industrial structure upgrading, and green total factor productivity from multiple models, but the previous findings did not consider the synergistic effect of carbon constraints and industrial structure upgrading. Therefore, this study could broaden the research in related fields. Combining the results of Model 1, Model 2, and Model 3, the study can test the overall synergistic effect of carbon constraints and industrial structure upgrading on green total factor productivity. Also, the regression results are shown in Table 4.

Table 4 shows that the regression results of Model 1–Model 3 are all significant. The coefficient of carbon constraints intensity index is negative, indicating that the higher the intensity of carbon constraints, the higher the green total factor productivity. The coefficient of industrial structure upgrading is positive, indicating that industrial structure upgrading has a positive role in promoting green total factor productivity. However, careful perusal shows that the results of Model 1 and Model 2 are different from those of Model 3. In Model 3, when both carbon constraints and industrial structure upgrading are included in the model, the absolute value of the coefficient of carbon constraints intensity index and the coefficient of industrial structure upgrading variable all increase, which shows that the synergistic effect of carbon constraints and industrial structure upgrading is stronger for improving green total factor productivity.

Specifically, carbon constraints have a positive effect on green total factor productivity. Both Model 1 and Model 3 are significant at 5% and 1% levels, respectively, which verifies Hypothesis 1. Currently, under China's *double carbon* strategy, strengthening carbon constraints has become an important goal to improve the quality of industrial development and move away from the traditional industrial growth model of high pollution, high emissions, and high energy consumption

Table 4 | Benchmark regression results of green total factor productivity from 2006 to 2020

Variable	Model 1 GTFP	Model 2 GTFP	Model 3 GTFP
ER	−0.2517** (0.003)		−0.3155*** (0.000)
IND		0.0653** (0.006)	0.0714** (0.003)
LnGDP	0.1265*** (0.000)	0.1205*** (0.000)	0.1181*** (0.000)
STL	0.0266** (0.022)	0.0045 (0.703)	0.0036 (0.786)
GOV	−0.1649 (0.157)	−0.2439** (0.049)	−0.2351** (0.037)
LnIES	−0.0382*** (0.000)	−0.0168 (0.198)	−0.0138 (0.300)
LnFI	−0.0307** (0.004)	−0.0356*** (0.000)	−0.0364** (0.001)
Constant term	0.5850*** (0.000)	0.2029* (0.084)	0.5203*** (0.000)

Note: ***, **, and * show significance at 1%, 5%, and 10% levels, respectively, and *p* values are in parentheses.

in the Yangtze River Economic Belt. According to the above analyses, the development of green industry and the transformation of green and low carbon can be accelerated by reducing CO_2 emissions, reducing the intensity of energy consumption, and increasing the use of clean energy, which can lead to an improvement in green total factor productivity. In Model 1, the control variables, economic development level (GDP), and scientific and technological level (STL), have a positive role in promoting green total factor productivity; the higher the level of economic development and scientific and technological achievement is, the higher the level of industrial green development is. The level of economic development improves the level of industrial green development through the renewal of industrial equipment and comprehensive resource utilization. The improvement in scientific and technological levels is reflected in more research and development, and the use of clean energy. Actively carrying out green low-carbon technology research and development aids industrial green development, reduces the consumption of coal, oil, natural gas, and other traditional energy sources, promotes industrial green transformation, and improves green total factor productivity. The scale of industrial enterprises (IES) and foreign investment (FI) has a negative effect on green total factor productivity; when the industrial scale expands, carbon emissions and energy consumption increase, which is not conducive to the green development of industry and has a negative effect on green total factor productivity. Foreign investment in China is mainly concentrated in the industrial sector, so foreign investment increases the output value of the industry, but in the process, energy consumption and pollution also increase, inhibiting the green development of industry. The influence of government intervention (GOV) on green total factor productivity is not significant, which may be due to the lag in government intervention.

Industrial structure upgrading has a positive effect on green total factor productivity. Both Model 2 and Model 3 pass the test at the 5% significance level, which verifies Hypothesis 2. The upgrading of industrial structure leads to the development of tertiary industry, cleaner and pollution-free industries, and reduced industrial waste, which leads to an improvement in green total factor productivity. Among the control variables, the level of economic development (GDP) has a positive effect on green total factor productivity, as economic development leads to optimization and upgrading of industrial structure, promoting the green development of industry. Government intervention (GOV) and foreign investment (FI) have a negative effect on green total factor productivity; an increase in government intervention leads to *de-industrialization* (Guo & Yan 2020), which inhibits the promotion of green total factor productivity. Foreign investment increases investment in industry, which is not conducive to the upgrading of industrial structure, so it is not conducive to industrial green development either. In Model 2, the level of STL and the scale of industrial enterprises (IES) have no significant influence on green total factor productivity.

Second, when carbon constraints and industrial structure upgrading are included in Model 3, they play a synergistic role. The regression coefficient of carbon constraints changes from −0.2517 to −0.3155, and the regression coefficient of industrial structure upgrading changes from 0.0653 to 0.0714, which shows that their influence on green total factor productivity increases significantly. Therefore, we should give more attention to their synergistic role, as their simultaneous effects are more conducive to industrial green development. In this model, the level of economic development (GDP), government intervention (GOV), and foreign investment (FI) have a significant effect on green total factor productivity. The level of economic development promotes improvement in green total factor productivity, while government intervention and foreign investment inhibit green total factor productivity. The level of STL and the scale of industrial enterprises (IES) have no significant effect on green total factor productivity. There is an inevitable relationship between the level of science and technology and green development, but in the process of science and technology development, a lot of manpower and funds need to be invested to provide a power source for scientific and technological innovation to promote the green development of industry. So the process takes a long time. Although scientific and technological innovation can promote the green transformation of industry through industrial production efficiency, energy structure optimization, and resource recycling, the promotion effect has not been significantly demonstrated. The expansion of the scale of industrial enterprises is conducive to the increase of industrial output value and plays an important role in the development of industrial economy, but there is a lag effect in this process. So its impact on industrial green total factor productivity has not been brought into play during this period. Based on the above results, it is found that the provinces in the Yangtze River Economic Belt should reduce carbon emissions, build a green and low-carbon product supply system, actively promote the upgrading of industries, and make efforts to improve industrial green total factor productivity.

4.3. Intermediary effect analysis

This study analyzed the basic relationship among carbon constraints, industrial structure upgrading, and green total factor productivity with an econometric model, and the results show that the synergistic effect of carbon constraints and industrial structure upgrading has a greater impact on improving green total factor productivity. In the following sections, we further explore how carbon constraints influence green total factor productivity through the intermediary effect, and consider industrial structure upgrading as an intermediary variable for analysis. The panel regression results of Model 4–Model 6 are shown in Table 5.

In Table 5, Model 4 is the total effect model of carbon constraints on green total factor productivity, Model 5 is the direct effect model of carbon constraints on industrial structure upgrading, and Model 6 is the direct effect model of carbon constraints on green total factor productivity. It is different from previous research; this study made a detailed flow chart for the test of the intermediary effect. As can be seen from Figure 1, the coefficients of carbon constraints and industrial structure upgrading pass the significance test; δ_1, γ_1, and δ_2 are all significant, and $\gamma_1\delta_2$ has the same sign as δ_1. The regression results of Model 4 show that the total effect coefficient β_1 of carbon constraints on green total factor productivity is -0.1706. The regression results of Model 5 show that carbon constraints have a positive effect on industrial structure upgrading, which verifies Hypothesis 3.

The regression results of Model 6 show that the direct effect of carbon constraints on green total factor productivity is positive. To sum up, the upgrading of the industrial structure shows a partial intermediary effect on industrial green development in terms of carbon constraints; a part of carbon constraints directly improves green total factor productivity, while a part of carbon constraints indirectly improves green total factor productivity through industrial structure upgrading, which verifies Hypothesis 4. According to the intermediary effect $\gamma_1\delta_2/\beta_1$, the final intermediary effect is 4.5%; industrial structure upgrading has an intermediary effect of 4.5% in the process of carbon constraint's role in industrial green development. In summary, the important task of energy conservation and carbon emissions reduction should be realized by adjusting the internal structure of the three industries and improving the technical level, especially by promoting the low-carbon upgrading of secondary industry, so as to improve the level of industrial green development.

Table 5 | Panel regression results

Variable	Model 4 GTFP	Model 5 IND	Model 6 GTFP
ER	– 0.1706** (0.015)	– 0.1117** (0.015)	– 0.1634** (0.041)
IND			0.0685** (0.005)
LnGDP	0.0538** (0.013)	0.3407*** (0.000)	0.0246 (0.347)
LnHR	0.0994 (0.166)	– 0.6431*** (0.000)	0.1767** (0.031)
LnFI	0.0149 (0.184)	0.0866*** (0.000)	0.0045 (0.721)
Constant term	0.0859 (0.636)	0.4898* (0.070)	0.0113 (0.951)

Note: ***, **, and * show significance at 1%, 5%, and 10% levels, respectively, and p values are in parentheses.

4.4. Robustness tests

The regression results shown in Tables 4 and 5 support the hypotheses of this study, showing that carbon constraints and industrial structure upgrading influence green total factor productivity. However, each variable has a different measurement method, and the information conveyed by each method is also different. Therefore, in the robustness test, the measurement methods of some of the variables are first changed and then the empirical test is carried out. Previous findings have done less on the robustness tests, so this study can improve the related research. A robustness test can test the model better and enhance the reliability of the results. Table 6 shows the regression results of the robustness test after changing some of the indexes. The measurement method of carbon constraints is changed to CO_2 emissions per industrial added value, and there is a reverse relationship between carbon constraint intensity and this index, similar to the above measurement standard of carbon constraints. The measurement method of some of the control variables is also changed. As the control variables are not the focus of this study, their results have not been tabulated. Table 6 shows that all the regression results of Model 1–Model 6 pass the significance test, which is consistent with the regression results in Tables 4 and 5, and once again supports the hypotheses. The results of robustness tests showed that the models are not only applicable to the Yangtze River Economic Belt, but also can be generalized to other similar countries or regions, especially to developing countries.

5. CONCLUSIONS AND POLICY RECOMMENDATIONS

Using data of 11 provinces in the Yangtze River Economic Belt and by calculating green total factor productivity, this study empirically tests the internal relationship among carbon constraints, industrial structure upgrading, and green total factor productivity, as well as how they influence each other, and draws the following conclusions: (1) Over time, green total factor productivity in the Yangtze River Economic Belt fluctuates and rises. In space, the green total factor productivity of provinces in the Yangtze River Economic Belt is characterized by 'a gradient decreasing spatial distribution from the Yangtze River Delta to the Urban Agglomeration in the Middle Reaches to the Chengdu–Chongqing Economic Zone.' (2) Carbon constraints and industrial structure upgrading have a positive effect on green total factor productivity. Their synergistic effect also has a positive effect on green total factor productivity. The coefficient of the effect of carbon constraints on green total factor productivity is greater than the coefficient of industrial structure upgrading. (3) The level of economic development and STL promote green total factor productivity, while government intervention, scale of industrial enterprises, and foreign investment inhibit green total factor productivity. (4) Carbon constraints can directly and indirectly promote green total factor productivity. In addition, carbon constraints are conducive to giving impetus to industrial structure upgrading, which, in turn, directly facilitates the green development of industry. Industrial structure upgrading has a partial intermediary effect in the process of carbon constraints promoting green total factor productivity, which accounts for 4.5% of the total effect. The above findings support the four hypotheses of this study.

The results of this study have the following policy recommendations: (1) Reducing carbon emissions and energy consumption is of great significance for improving green total factor productivity, so the publicity of green and low-carbon transformation strategy should be strengthened. Implementing the green and low-carbon transformation strategy can not only promote high-quality economic development, but also be an important measure to deal with global climate change, so as to achieve sustainable economic and ecological development. (2) Provinces in the Yangtze River Economic Belt

Table 6 | Regression results of robustness test from 2006 to 2020

Variable	GTFP Model 1	GTFP Model 2	GTFP Model 3	GTFP Model 4	IND Model 5	GTFP Model 6
ER	– 0.0101*** (0.000)		– 0.0059** (0.005)	– 0.0102*** (0.000)	– 0.0116** (0.010)	– 0.0049* (0.058)
IND		0.0532** (0.032)	0.0657** (0.006)			0.0576** (0.009)
Control	YES	YES	YES	YES	YES	YES
Constant term	0.5912** (0.002)	– 0.1075 (0.561)	0.0997 (0.612)	1.0580*** (0.000)	1.8440*** (0.000)	0.2289* (0.081)

Note: ***, **, and * show significance at 1%, 5%, and 10% levels, respectively, and p values are in parentheses.

should accelerate the upgrading of industrial structure, vigorously promote industrial energy saving and carbon reduction, comprehensively improve the efficiency of resource utilization, actively implement the transformation of clean production, and focus on building an efficient, clean, low-carbon, circular green manufacturing system. They should encourage the development of low-carbon industries, comprehensively consider the economic growth effect and carbon emission effect of various industries, and support the development of industries with good economic benefits and high ecological benefits. Also, they should promote the rationalization of industrial structure and the development of industrial structure to tertiary industry to realize the rapid improvement of industrial green total factor productivity. (3) Government departments in the Yangtze River Economic Belt should increase investment in scientific and technological innovation, optimize the investment structure of industrial technological innovation, and give full play to the role of innovation in promoting the green development of industry. Unreasonable government intervention leads to *de-industrialization*, which is not conducive to industrial development. Decision-makers in the Yangtze River Economic Belt should appropriately reduce the scale of industrial enterprises and foreign investment, and develop economy on the premise of reducing the pressure of carbon emissions and energy consumption on the environment, and promote a green and low-carbon transition in industry to realize the coordinated development of economy and ecology. (4) In the process of carbon constraints promoting green total factor productivity, it is necessary to give full play to the intermediary role of industrial structure upgrading. Cleaner production is an important way to realize the synergy of pollution reduction and carbon reduction, and is conducive to realizing the green and sustainable development of industry and then to promoting high-quality economic development and high-level protection of the ecological environment. (5) The Yangtze River Economic Belt is the largest inland river industrial belt and manufacturing base in China, which has abundant freshwater resources and a large number of energy-consuming enterprises. The abundant water resources are beneficial to the adjustment of the temperature change, and are also important channels for the transportation of goods. In recent years, the provinces have increased investment in clean energy, low-carbon economy, and other fields, promoted the upgrading of industrial structure, and formulated emission reduction plans to slow down the process of climate change. The ecological environment protection of the Yangtze River Economic Belt has undergone a turning change, and economic and social development has made historic achievements. The results are enlightening for the promotion of ecological protection and high-quality development of other river basins in the world, and have guiding significance for developing countries.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Apeaning, R. W. 2021 Technological constraints to energy-related carbon emissions and economic growth decoupling: a retrospective and prospective analysis. *Journal of Cleaner Production* **291**, 125706. https://doi.org/10.1016/j.jclepro.2020.125706.

Boudreaux, C. J. 2020 The importance of industry to strategic entrepreneurship: evidence from the Kauffman Firm Survey. *Journal of Industry, Competition and Trade* **20** (1), 93–114. https://doi.org/10.1007/s10842-019-00310-7.

Dong, B., Zhang, M., Mu, H. & Su, X. 2016 Study on decoupling analysis between energy consumption and economic growth in Liaoning Province. *Energy Policy* **97**, 414–420. doi:10.1016/j.enpol.2016.07.054.

Dong, D., An, H. & Huang, S. 2017 The transfer of embodied carbon in copper international trade: an industry chain perspective. *Resources Policy* **52**, 173–180. https://doi.org/10.1016/j.resourpol.2017.02.009.

Dong, B., Xu, Y. & Fan, X. 2020 How to achieve a win-win situation between economic growth and carbon emission reduction: empirical evidence from the perspective of industrial structure upgrading. *Environmental Science and Pollution Research* **27** (35), 43829–43844. https://doi.org/10.1007/s11356-020-09883-x.

Ghobakhloo, M. 2018 The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *Journal of Manufacturing Technology Management* **29** (6), 910–936. https://doi.org/10.1108/JMTM-02-2018-0057.

Ghobakhloo, M. 2020 Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production* **252**, 119869. https://doi.org/10.1016/j.jclepro.2019.119869.

Guo, H., Fan, B. & Pan, C. 2021 Study on mechanisms underlying changes in agricultural carbon emissions: a case in Jilin Province, China, 1998–2018. *International Journal of Environmental Research and Public Health* **18** (3), 919. doi:10.3390/IJERPH18030919.

Guo, J. & Yan, T. X. 2020 Analysis of the impact of government intervention on the 'de-industrialization' of China's provinces. *Productivity Research* **11**, 68–71 + 106.

Han, M. C. & Zhao, Z. B. 2022 Research on the impact of industrial intelligence on regional economic disparity from the perspective of carbon emission constraint. *Industrial Technology Economy* **41** (1), 3–11.

He, L., Wang, B., Xu, W., Cui, Q. & Chen, H. 2022 Could China's long-term low-carbon energy transformation achieve the double dividend effect for the economy and environment? *Environmental Science and Pollution Research* **29** (14), 20128–20144. https://doi.org/10.1007/s11356-021-17202-1.

Huang, L. & Wu, C. Q. 2021 Research on the innovation efficiency and dynamic mechanism of green technology in cities of Yangtze River Economic Belt. *Journal of Chongqing University (Social Science Edition)* **27** (1), 50–64.

Li, D. & Zeng, T. 2020 Are China's intensive pollution industries greening? An analysis based on green innovation efficiency. *Journal of Cleaner Production* **259**, 120901. https://doi.org/10.1016/j.jclepro.2020.120901.

Liu, Y., Yang, Y., Li, H. & Zhong, K. 2022 Digital economy development, industrial structure upgrading and green total factor productivity: empirical evidence from China's cities. *International Journal of Environmental Research and Public Health* **19** (4), 2414. https://doi.org/10.3390/ijerph19042414.

Mao, J. H. & Wang, L. T. 2022 Constraints of energy saving and carbon reduction, R&D investment and industrial green total factor productivity growth – an empirical analysis of the urban agglomeration in the Yellow River Basin under the background of 'double carbon'. *Journal of Northwest Normal University (Social Science Edition)* **59** (2), 75–85.

Ouyang, X. & Lin, B. 2015 An analysis of the driving forces of energy-related carbon dioxide emissions in China's industrial sector. *Renewable and Sustainable Energy Reviews* **45**, 838–849. https://doi.org/10.1016/j.rser.2015.02.030.

Sanguinet, E. R., Azzoni, C. R. & Alvim, A. M. 2022 Resource-based industries and CO_2 emissions embedded in value chains: a regional analysis for selected countries in Latin America. *Atmosphere* **13** (6), 856. https://doi.org/10.3390/atmos13060856.

Wang, Q. & Jiang, R. 2019 Is China's economic growth decoupled from carbon emissions? *Journal of Cleaner Production* **225**, 1194–1208. https://doi.org/10.1016/j.jclepro.2019.03.301.

Wang, Q. & Zhang, F. 2020 Does increasing investment in research and development promote economic growth decoupling from carbon emission growth? An empirical analysis of BRICS countries. *Journal of Cleaner Production* **252**, 119853. https://doi.org/10.1016/j.jclepro.2019.119853.

Wang, W. J. & Xiang, Q. F. 2014 China's industrial structure adjustment and its energy saving and emission reduction potential evaluation. *China Industrial Economics* **2014** (1), 44–56.

Wen, Z. L. & Ye, B. J. 2014 Intermediary effect analysis: method and model development. *Advances in Psychological Science* **22** (5), 731–745.

Wichmann, R. L., Eisenbart, B. & Gericke, K. 2019 The direction of industry: a literature review on Industry 4.0. In: *Proceedings of the Design Society: International Conference on Engineering Design*, Cambridge University Press, Cambridge, UK, pp. 2129–2138. https://doi.org/10.1017/dsi.2019.219.

Wu, S. & Zhang, K. 2021 Influence of urbanization and foreign direct investment on carbon emission efficiency: evidence from urban clusters in the Yangtze River Economic Belt. *Sustainability* **13** (5), 2722. doi:10.3390/SU13052722.

Wu, J., Li, M., Zhu, Q., Zhou, Z. & Liang, L. 2019 Energy and environmental efficiency measurement of China's industrial sectors: a DEA model with non-homogeneous inputs and outputs. *Energy Economics* **78**, 468–480. https://doi.org/10.1016/j.eneco.2018.11.036.

Xu, S. C., He, Z. X. & Long, R. Y. 2014 Factors that influence carbon emissions due to energy consumption in China: decomposition analysis using LMDI. *Applied Energy* **127**, 182–193. https://doi.org/10.1016/j.apenergy.2014.03.093.

Yan, Y., Sun, Y. R. & Geng, Y. N. 2020 An empirical study of innovation driving industrial green development under environmental regulation policy: based on the extended CDM method. *Economic Issues* **2020** (8), 86–94.

Yang, O. & Wang, Y. 2020 Optimization of time and power resources allocation in communication systems under the Industrial Internet of Things. *IEEE Access* **8**, 140392–140398. doi:10.1109/ACCESS.2020.3006736.

Yu, C., Dijkema, G. P. J., de Jong, M. & Shi, H. 2015 From an eco-industrial park towards an eco-city: a case study in Suzhou, China. *Journal of Cleaner Production* **102**, 264–274. doi:10.1016/j.jclepro.2015.04.021.

Zeng, J., Tong, W. & Tang, T. 2020 How do energy policies affect industrial green development in China: renewable energy, energy conservation, or industrial upgrading? *Chinese Journal of Population, Resources and Environment* **18** (2), 79–86. https://doi.org/10.1016/j.cjpre.2021.04.020.

Zhu, B., Zhang, M., Zhou, Y., Wang, P., Sheng, J., He, K., Wei, Y. & Xie, R. 2019 Exploring the effect of industrial structure adjustment on interprovincial green development efficiency in China: a novel integrated approach. *Energy Policy* **134**, 110946. https://doi.org/10.1016/j.enpol.2019.110946.

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