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SPECIALTY SECTION
This article was submitted to
Environmental Economics and
Management,
a section of the journal
Frontiers in Environmental Science

RECEIVED 10 June 2022
ACCEPTED 06 July 2022
PUBLISHED 09 August 2022

CITATION
Guan Y, Wang H, Guan R and Ding L
(2022), Measuring inclusive green total
factor productivity from urban level
in China.
Front. Environ. Sci. 10:966246.
doi: 10.3389/fenvs.2022.966246

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Measuring inclusive green total factor productivity from urban level in China

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Background: Inclusive green development aims to combine economic inclusiveness with greenness, which is an important goal of current economic development for China to achieve common prosperity. Measuring inclusive green total factor productivity (IGTFP) is of great significance for evaluating the quality of inclusive economic growth and accelerating inclusive economic growth.

Method: This study establishes an index evaluation system of IGTFP from four aspects of high quality, efficient, fair, and sustainable development, using super-SBM to measure IGTFP based on panel data of 276 cities in China from 2006 to 2019, and conducts empirical comparative analysis from national central cities, provincial capitals, and ordinary prefecture.

Result: 1) The IGTFP and technical progress rate in the central city and the provincial capital are significantly higher than that of the ordinary prefecture, but there is no significant difference in technical efficiency; the growth rate of IGTFP in the most central city remains around 10%, which is significantly higher in the south than that in the north. 2) According to the index decomposition result, all cities have basically realized the double-line improvement of technological efficiency and technological progress rate, but the technological efficiency is mostly lower than the technological progress rate. 3) From the perspective of economic convergence, only the IGTFP of provincial capitals shows the σ convergence feature, that is, the phenomenon of intra-group convergence; the IGTFP of all cities in three levels shows the β convergence feature, indicating that there is an obvious catch-up phenomenon within the group.

Conclusion: The integration of “technology” and “efficiency” is the main driving force and path to realize the sustainable improvement of IGTFP in cities. Inclusive green growth needs to break “regional boundaries,” including north–south boundaries and urban boundaries.

KEYWORDS

inclusive green total factor productivity, index evaluation system, urban level, super-SBM, economic convergence

Introduction

Common prosperity is the essential requirement of socialism and an essential feature of Chinese-style modernization. Since the 18th National Congress of the Communist Party of China (CPC), China has taken various measures to ensure and improve people's livelihood and achieved comprehensive poverty alleviation in 2020. However, over the past 40 years of reform and opening-up, China's economic development has paid a substantial environmental and social cost. On the one hand, the extensive growth with high input, high consumption, heavy pollution, and low efficiency leads to resource exhaustion, environmental pollution, and ecological destruction. On the other hand, the development opportunities brought by economic growth are not distributed equally among members of the society, and the achievement of growth is not equally distributed, which leads to the widening income gap and the aggravation of social inequality (Wan, 2010). Based on this background, the Chinese government put forward in the "14th Five-Year Plan" that "coordinated development and inclusive growth must be the trend of China's economic and social development." This means that the future of China's economic development should improve the total factor productivity and improve the efficiency of inclusive green growth, and promote inclusive economic development.

Since the Asian Development Bank put forward the concept of inclusive growth in Strategy 2020 in 2008, the academia has not formed a unified definition of inclusive growth. Regarding the theoretical connotation and policy significance of inclusive growth, the research of Sun et al. (2018) shows that the essence of inclusive growth was to reduce the income gap. Rachel thought that inclusive growth should include income growth and welfare growth (Rachel, 2012; World Bank, 2012), while Ali and Son (2007) focused on the opportunity of intergroup welfare access (Ali and Son, 2007). On this basis, some scholars incorporated "green" into the inclusive growth system to comprise inclusive green growth. Similar to inclusive growth, inclusive green growth has not constituted a unified definition. D. Doumbia et al. believed that inclusive green growth should pay attention to current and future generations' welfare growth and intergenerational inheritance when weighing the relationship between economic growth, inclusiveness, and green (Grosse et al., 2008; Dinda, 2014; Doumbia, 2019). Berkhout et al. (2017) show that "inclusive green growth is an economic growth path that aims to reduce regional differences, takes into account ecological environmental protection, and provides more opportunities for poor areas and people" (Hill et al., 2012; Dinda, 2013; Berkhout et al., 2017). By combing through relevant studies on inclusive green growth, we can know that inclusive green growth has not formed a unified concept, but its connotation includes three aspects: economic growth, ecological environmental protection, and social inclusion (Dollar et al., 2014; Ahmad, 2021; Gu et al., 2021; He and Du,

2021). Therefore, the inclusive green growth in our research is an economic development path that takes economic growth as its goal and simultaneously considers ecological environmental protection and social opportunity equity.

Total factor productivity is an important engine of economic growth. The report of the 19th National Congress of the Communist Party of China has made a critical judgment that China's economy has shifted from a high-speed growth stage to a location of high-quality development and put forward urgent requirements for improving total factor productivity. Due to the limited resources and increasingly serious environmental pollution, the concept of green development and sustainable development has attracted people's attention. Resources and the environment are not only endogenous variables that affect economic development, but also rigid constraints that limit the quality of economic development. Compared with the total factor productivity that only considers the expected output, the green total factor productivity that incorporates unexpected output such as pollutant emissions into the indicator system is more comprehensive and objective. Therefore, some scholars (Wang et al., 2019; Song et al., 2020; Wang et al., 2020) have begun to use resource consumption and environmental pollution as measurement indicators and incorporated them into the calculation system of total factor productivity to evaluate industrial development and economic growth. The total factor productivity obtained from this is green total factor productivity.

At the same time, the expansion of the income gap and socially sustainable development poses a severe challenge. On this basis, some scholars (Chen and Qin, 2014; Li and Dong, 2021) have begun to consider the inclusiveness of GTFP. They believe that the government should pay attention to the environmental protection and benefit equity of economic achievements while increasing the TFP. Therefore, IGTFP was proposed. How to realize the common prosperity and realize the harmonious development become the urgent need to solve the strategic problem, inclusive green growth will become a new opportunity, and crack the issue of reasonable measure IGTFP is particularly important.

Compared with the total factor productivity that only considers the expected output, the green total factor productivity that incorporates undesired outputs such as pollutant emissions into the indicator system is more comprehensive and objective. Therefore, many scholars began to use resource consumption and environmental pollution as measurement indicators and incorporated them into the calculation system of total factor productivity to evaluate industrial development and economic growth. The total factor productivity obtained from this is green total factor productivity.

The research on total factor productivity has been relatively complete. Song et al. (2018) studied the traditional total factor productivity and the green total factor productivity with

environmental factors, which significantly improved the scientific and accurate estimation of total factor productivity (Chirisa et al., 2016; Song et al., 2018; Cui et al., 2019; Peng et al., 2020). However, China's current development goal is to achieve inclusive economic growth by protecting the environment and saving resources to achieve common prosperity, so social equity is also one of the urgent issues that should be solved. The study of Chen and Qin (2014) shows that the income gap is an undesired output in economic development and incorporated it into the input–output system. However, it only studies the provincial level and does not consider the increasingly severe imbalance in economic development within provinces and among different urban strata. Although Sun et al. (2018) took cities as the research object, they only studied green total factor productivity in the traditional sense and did not involve the fundamental problem of the income gap in the input–output system. The existing measurement methods on inclusive green growth, whether through depicting the opportunity function or building a comprehensive index system, are all essentially measured by a current indicator. It is difficult to judge whether its economic growth is an extensive development with high input and high output or an efficient development with low input and high output. Using super-efficiency SBM to measure inclusive green growth by measuring total factor productivity, on the one hand, we can observe whether China's economic operation keeps efficient development; second, it can analyze whether “inclusive” and “green” achieved at the same time of economic growth (Zhang et al., 2019; Zhu and Azhong., 2018; Sun et al., 2020; Xin et al., 2022).

To sum up, this study first incorporates the income gap as the core concept of inclusive growth. The IGTFP was defined under the new input–output system and was estimated and analyzed based on the super-efficiency SBM model. While observing whether China's economic operation has maintained efficient growth, it also examines whether it has realized “inclusive” and “green,” which can scientifically grasp the basis of China's high-quality economic development and promote China's green coordinated development and high quality, balanced development (Parikh, 2014; Chen et al., 2020; Ren et al., 2022). This study empirically investigates the spatial–temporal evolution characteristics of IGTFP growth. It is of great theoretical and practical significance for formulating differentiated regional development policies, realizing coordinated development of economic growth, resource conservation, and environmental protection in various regions of China, and realizing common prosperity.

The marginal contributions of this study are as follows. First, the concept of IGTFP is defined. It is considered that IGTFP is a measurement system about high-quality economic development based on economic growth while including ecological environmental protection and equal distribution of social resources. Second, the income gap index and environmental index are incorporated into the input–output system as

“green” and “inclusive” indicators, respectively, to construct the input–output system from the inclusive perspective and carry out positive measurement and analysis of IGTFP based on the city level.

Measurement system of inclusive green total factor productivity

The essence of inclusive green growth is to reduce the gap between the rich and the poor while achieving green economic development and balanced development, and common prosperity (Re and Grosskopf, 2010; Li et al., 2021; Sun et al., 2022). Therefore, based on the connotation of inclusive green growth, in the measurement of IGTFP, based on the measurement system of total factor productivity, this study adds “three industry wastes” and urban–rural income ratio that hinders “green” and “inclusive” (Table 1).

In terms of input factors, this study mainly measures from four dimensions. It includes not only the labor and capital factors that are common in the macro production function, but also the measurement of technology and resources. In the dimension of output factors, in addition to the GROSS regional product, urban and rural residents' income and consumption levels are also included in the expected output. Undesired output includes “three industrial wastes” and the urban–rural income ratio. The total factor productivity is judged to be “green” and “inclusive,” respectively.

Input indicators

Labor input

The total number of employed persons represents the labor input of each city, and employed persons include employees of units, individuals, and private enterprises.

Capital input

Fixed capital stock, with 2000 as the base period, is expressed by the perpetual inventory method.

Resource input

The balance between economic development and resource utilization is the primary basis of inclusive economic development (Xin et al., 2021; Zhao et al., 2022). Efficient utilization of resources is an essential symbol of high-quality economic transformation. This study selects the total amount of industrial and agricultural land, power consumption, and water supply as the land, energy, and water resources metrics. Land resources are the necessary conditions for production and the most basic means of

TABLE 1 Input–output system and interpretation.

Indicator type	Indicator meaning	Indicator measuring	Unit	
Input	Labor	Total number of employees (Per 10,000 people)	Ten thousand people	
	Capital	Fixed capital stock	Ten thousand yuan	
	Technology		Public service spending	Billion yuan
			Education expenditure	Billion yuan
			Scientific expenditure	Billion yuan
	Resource	Land Resources	Industrial and agricultural land	Universal
	Energy		Electricity consumption	Billion Kilowa
Water resource		Total water supply	Billion cubic meters	
Output	Expect output	GDP	Ten thousand yuan	
	Unexpected output	Industrial waste water emissions	Billion ton	
		Industrial waste gas emissions	Billion cubic meters	
		Industrial solid waste emissions	Ten thousand tons	
		Urban-rural income ratio	%	

production. In terms of energy input, this study draws lessons from the practice of Li et al. (2020), taking power consumption as the measurement index of energy input. Water resources are the essential input of economic activities (Li et al., 2020). In this study, the total water supply is selected as the measurement index of water resources.

Technology input

This study adopts public service expenditure, science and technology research expenditure, and education expenditure as the measurement index of expenditure input. Public service expenditure in this study refers to the expenditure part of public finance expenditure except science, technology, and education expenditure, such as medical treatment, pension, housing security, and other related expenditure. Expenditure on public services is the most direct way to increase the well-being of people. And education expenditure is the way to improve the core competitiveness of the next generation in poor areas, to avoid intergenerational transfers of poverty and make economic growth more inclusive; science and technology expenditure can realize green economic development to a certain extent and improve the “green proportion” in total factor productivity.

Output indicators

Expected output

This study selects GDP as the measurement indicator of expected output.

Unexpected output

IGTFP should be “inclusive” based on green total factor productivity. Therefore, this study takes “three industrial wastes” as the unexpected output and incorporates the “urban–rural income ratio,” which measures the urban-rural income gap, into the undesired output system. The “three industrial wastes” are industrial waste gas emissions, industrial wastewater, and solid waste emissions, respectively, by sulfur dioxide, industrial smoke, and industrial wastewater emissions. The urban–rural income ratio is the ratio of the per capita disposable income of urban residents to rural residents’ per capita net income.

Theoretical models

Based on relative efficiency, the Data Envelopment Analysis (DEA) could use mathematical programming and statistical data to evaluate the relative effectiveness of decision-making units. However, traditional non-parametric DEA measures efficiency from radial and Angle (Wang et al., 2019; Feng et al., 2020; Yang et al., 2022). Therefore, it lacks the slack of considering input and output and cannot distinguish whether multiple decision units are effective or not. Therefore, the accuracy of the efficiency value obtained is difficult to guarantee. However, the SBM model and super-efficiency DEA can directly put the “relaxation” variable into the objective function (Zhou and Wu, 2018; Li et al., 2020). Moreover, it can sort and distinguish multiple decision units. Since the input–output system in this study includes “three industry wastes” and the urban–rural income gap as undesired outputs, this study attempts to use the super-efficiency Slack Based Measure (SBM) model containing

undesired outputs to Measure IGTFP of 276 cities in China under the condition of variable returns to scale. There are n DMU (decision units), and each DMU has m kinds of inputs, q_1 expected outputs, and q_2 unexpected outputs. The expression of super-efficiency SBM containing unexpected outputs is as follows:

$$\min \delta = \frac{1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 - \frac{1}{q_1 + q_2} \left(\sum_{r=1}^{q_1} \frac{s_r^+}{y_{rk}} + \sum_{t=1}^{q_2} \frac{s_t^{b-}}{b_{tk}} \right)} \quad (1)$$

$$\text{s.t.} \left\{ \begin{array}{l} \sum_{i=1, j \neq k}^n x_j \lambda_j - s_i^- \leq x_{jk} \\ \sum_{i=1, j \neq k}^n y_j \lambda_j - s_r^+ \geq y_{rk} \\ \sum_{i=1, j \neq k}^n b_j \lambda_j - s_t^{b-} \leq b_{tk} \\ 1 - \frac{1}{q_1 + q_2} \left(\sum_{r=1}^{q_1} \frac{s_r^+}{y_{rk}} + \sum_{t=1}^{q_2} \frac{s_t^{b-}}{b_{tk}} \right) > 0 \\ \lambda_j, s_i^-, s_r^+, s_t^{b-} \geq 0 \\ i = 1, 2, \dots, m; r = 1, 2, \dots, q_1; \\ t = 1, 2, \dots, q_2; j = 1, 2, \dots, n; j \neq k. \end{array} \right. \quad (2)$$

In Eqs. 1, 2, δ is the efficiency value, j is the decision-making unit, λ_j is the intensity variable, s represents the relaxation variable of each variable, s_i^- represents the relaxation variable of input, and s_r^+ and s_t^{b-} are relaxation variables of expected output and unexpected output, respectively. x represents input (for example, x_{ik} is the input item i of the k^{th} decision unit), y and b represent expected output and unexpected output, respectively, y_{rk} represents the expected output item r of the k^{th} decision unit; b_{tk} represents the undesired output of the t^{th} term of the k^{th} decision unit.

The Inclusive Global Malmquist–Luenberger (IGML) index represents IGTFP, reflecting the efficiency of inclusive and green economic growth with current factor inputs. IGML index also includes the relative relationship between actual production and production frontier as well as the change of production frontier boundary of each DMU. Therefore, it can be decomposed into GTC (Global Technical Change) and GEC (Global Efficiency Change). GEC refers to the change of relative efficiency under the condition of constant return to scale and free disposal of elements. It measures the degree to which the production system catches up with the production possibility boundary from the current period to the next period. If $GEC > 1$, technical efficiency is improved. On the contrary, it means that technical efficiency decreases; GTC represents the change degree of the production technology of the production system from the current period to the next period, that is, the innovation degree of production technology. If $GTC > 1$, it indicates that the production technology has improved. Conversely, explain production technology retreat.

$$IGML = GEC \times GTC = \frac{E^g(x^{t+1}, y^{t+1})}{E^g(x^t, y^t)} = \frac{E^{t+1}(x^{t+1}, y^{t+1})}{E^t(x^t, y^t)} \times \frac{E^g(x^{t+1}, y^{t+1})}{E^{t+1}(x^{t+1}, y^{t+1})} \frac{E^t(x^t, y^t)}{E^g(x^t, y^t)} \quad (3)$$

$$GEC = \frac{E^{t+1}(x^{t+1}, y^{t+1})}{E^t(x^t, y^t)} \quad (4)$$

$$GTC = \frac{E^g(x^{t+1}, y^{t+1})}{E^{t+1}(x^{t+1}, y^{t+1})} \frac{E^t(x^t, y^t)}{E^g(x^t, y^t)} \quad (5)$$

In the above formula, x^t represent the input and y^t represent the output value of the evaluated unit in t period, E^g and E^t represent the efficiency value of the global frontier and frontier t period, respectively.

Empirical results

This study takes 276 prefecture-level cities in China as the research object and analyses the IGTFP at the national, regional, and urban levels. The data were obtained from *China Statistical Yearbook*, *China Energy Statistical Yearbook*, and *China Urban Statistical Yearbook* and China Economic Network (Table 1).

General characteristics

The contribution of different urban economic conditions to IGTFP is different. This study takes the proportion of urban GDP in the total urban GDP as the weight and obtains the IGTFP. IGTFP in China basically maintained positive growth from 2006 to 2019 (Figure 1). This shows that China’s economic development in recent years has considered both “equity” and “efficiency” to some extent. From the perspective of time, Chinese cities’ IGTFP has maintained positive growth during the 11th Five-Year Plan period (2006–2010), except for less than 1 in 2007. The rest showed positive growth; from the decomposition point of view, the rate of technological progress has already exceeded the technical efficiency by the end of the eleventh Five-Year Plan. This indicates that the rate of technological progress has increasingly become the primary driver of IGTFP.” During the 12th Five-Year Plan period (2011–2015), the growth of the three indexes showed a relatively stable trend. Although the technical efficiency was lower than 1 in some years, it generally maintained positive growth.” IGTFP maintained a high growth level in the first 2 years of the 13th Five-Year Plan period. IGTFP exceeded 1.5 in 2017 and maintained a positive growth trend in the following 2 years, although the growth rate slowed down. In the report to the 19th CPC National Congress in 2017, the CPC Central Committee, for the first time, proposed “establishing and improving the economic system of green, low carbon, and circular development.” China has paid more attention to

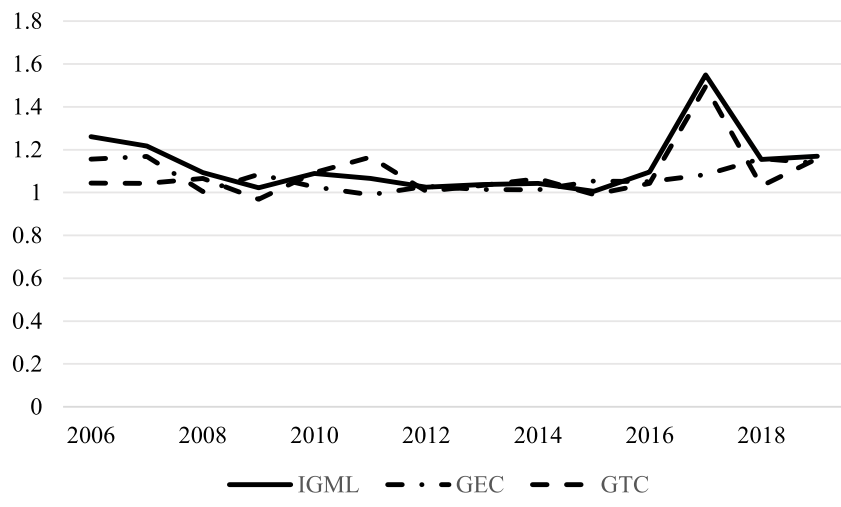


FIGURE 1
National IGTFP and its decomposition.

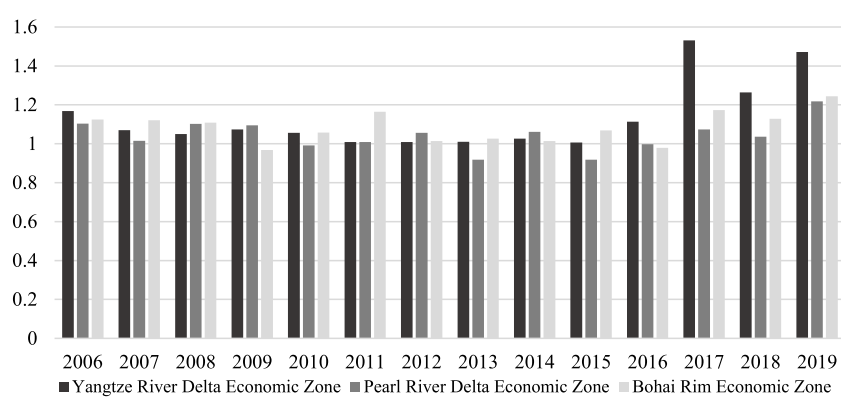


FIGURE 2
IGTFP in three major economic zones.

environmental protection while building a “modern economic system.”

Inclusive green total factor productivity in regions

The establishment of national strategic urban agglomeration is an important measure to strengthen the leading role of central cities to surrounding cities, strengthen inter-city cooperation and promote regional integration in China. Yangtze River Delta Economic Zone, Pearl River Delta Economic Zone, and Bohai Rim, as three national

strategic city clusters in China, represent the highest level of China’s economic development to a large extent and shoulder the responsibility of taking the lead in realizing modernization. Therefore, this study takes the three economic zones as the research object and explores the “inclusiveness” of China’s regional economic growth by analyzing their total inclusive factor productivity.

Figure 2 shows IGTFP and fluctuations in the three economic zones. In general, the PEARL River Delta economic zone’s IGTFP level is slightly lower than that of the Yangtze River Delta Economic Zone and the Bohai Rim Economic Zone. From 2006 to 2010, the IGTFP of the three economic zones remained the same. Since 2010, the Bohai Rim economic

TABLE 2 Measurement and decomposition of IGTFP.

City category	National central city			Provincial capital city			Ordinary prefecture-level city		
Index category	IGML	GEC	GTC	IGML	GEC	GTC	IGML	GEC	GTC
2006	1.3045	1.2379	1.0538	1.2494	1.2198	1.0242	1.1169	1.1729	0.9523
2007	1.4380	1.1708	1.2282	1.3338	1.3225	1.0085	1.0741	1.1153	0.9631
2008	1.1080	1.0250	1.0810	1.0854	1.0352	1.0486	1.0326	0.9574	1.0785
2009	1.1548	1.1439	1.0096	1.0863	1.0954	0.9917	0.9974	1.0639	0.9375
2010	1.1497	1.0675	1.0770	1.1284	1.0603	1.0643	1.0580	0.9436	1.1212
2011	1.1847	0.9798	1.2091	1.1388	0.9987	1.1404	1.0457	1.0009	1.0502
2012	1.1594	1.0664	1.0873	1.1503	1.1363	1.0123	1.0012	1.0328	0.9694
2013	1.0912	1.0747	1.0153	1.0455	0.9914	1.0837	1.0082	1.0027	1.0054
2014	1.2052	0.9817	1.2276	1.0328	0.9706	1.0640	1.0184	1.0136	1.0047
2015	1.1263	1.0695	1.0530	1.1120	1.0969	1.0138	1.0005	1.0230	0.9780
2016	1.1171	1.0343	1.0800	1.0733	1.0496	1.0465	1.0648	1.0685	1.0012
2017	1.6454	1.1484	1.4328	1.6707	1.0681	1.5642	1.2193	1.0147	1.2017
2018	1.2601	1.2088	1.0424	1.2174	1.1003	1.1064	1.1147	1.0896	1.0231
2019	1.1934	1.0747	1.1105	1.1670	1.1591	1.0068	1.1663	1.0080	1.1570

Zone's IGTFP has been significantly improved, especially in 2011 and 2015. It ranked first among the three economic zones. Since 2016, the inclusive total factor productivity of the Yangtze River Delta Economic Zone and Bohai Rim Economic Zone has gradually opened a gap with that of the Pearl River Delta Economic Zone. From 2017 to 2019, there was a trend of "Yangtze River Delta > Bohai Rim > Pearl River Delta." The reason for this difference is that there are great differences in the level of economic development between cities in the Pearl River Delta. For example, in 2018, the per capita GDP of the core area of the Pearl River Delta has reached over 100,000 yuan, which has reached the level of high-income countries or regions. For example, the per capita GDP of eastern, western, and northern Guangdong is around 40,000 yuan, far lower than the national average. The low-level cities in the Pearl River Delta economic zone have a relatively low level of professional production technology, and a large number of input production factors cannot get the corresponding except output, while the difference in the level of urban economic development in the Yangtze River Delta is small, and its convenient transportation conditions facilitate the high-frequency technical exchanges between cities, thus promoting the formation of a low input and high-yield industrial chain, It has promoted the overall improvement of inclusive green total factor productivity. As a result, the IGTFP of the PEARL River Delta economic Zone is lower than that of the other two regions.

The IGTFP of the Bohai Rim Economic Zone and the Yangtze River Delta Economic Zone was the same from 2006 to 2017. Only in 2011 and 2015, the Bohai Rim Economic Zone was slightly higher

than the Yangtze River Delta Economic Zone. However, from 2016, the inclusive total factor productivity of the Yangtze River Delta economic Zone exceeded that of the other two regions. The reason is that the total economic volume of Shanghai and Zhejiang provinces in the Yangtze River Delta economic zone has declined slightly. Nevertheless, the proportion of Jiangsu province and Anhui province has achieved different rising degrees. The balanced economic development has promoted IGTFP in the Yangtze River Delta region.

Inclusive green total factor productivity in urbans

From the perspective of city classification, the IGTFP of cities of different sizes is different. The specific performance is shown in Table 2. According to the classification of city size, IGTFP showed a phenomenon of "national central city > provincial capital city > prefecture-level city." It indicates that cities' level of economic development and political status positively affects IGTFP to a certain extent. This also confirms the significance of establishing a national central city from the perspective of urban green development. It also shows that China's economic growth still has a certain degree of agglomeration effect. The higher the administrative level of a city, the better it is equipped with transportation and other infrastructure. At the same time, more universities, scientific research talents, and even leading enterprises will gather in this city, thus stimulating the agglomeration effect of urban economic growth.

TABLE 3 National center city.

City	Beijing	Chengdu	Guangzhou	Shanghai	Tianjin	Wuhan	Xi'an	Zhengzhou	Chongqing
IGML	1.2458	1.3146	1.1024	1.1427	1.0970	1.2708	1.2511	1.0826	1.1087
GEC	1.0423	1.1497	1.0368	1.0620	0.9992	1.1063	1.0993	1.0467	1.0708
GTC	1.1952	1.1435	1.0634	1.0518	1.0978	1.1487	1.1380	1.1678	1.0272

From the decomposition results of IGTFP, there is not much difference between the technical efficiency coefficients of the national central city, provincial capital city, and ordinary prefecture-level city, and even the technical efficiency coefficients of the ordinary prefecture-level city exceed that of the provincial capital city and national central city in some years. On the one hand, China's ordinary prefecture-level cities have relatively sufficient land, labor, and other factors of production. On the other hand, the utilization of resources in Chinese cities is relatively complete. The resources of ordinary prefecture-level cities have been brought into full play through policy. However, we can see that the rate of technological progress of ordinary prefecture-level cities is significantly lower than that of provincial capitals and central cities. This is why the IGTFP of ordinary prefecture-level cities is lower than that of national central cities and provincial capitals. It also shows that the production technology of ordinary prefecture-level cities is different from that of national central cities and provincial capital cities. The dividend of the vigorous development of science and technology in China is more applied in major cities.

The national central city is the top-level legal planning in urban and rural planning. It is the overall arrangement of urban development and urban spatial layout, a vital policy basis for actively and steadily promoting urbanization, and the basis for all localities to formulate regional urban system planning and overall urban planning. The development of national central cities has a maximum effect on other cities and even society. Therefore, national central cities' IGTFP is analyzed separately. According to the analysis results in Table 3, the IGTFP of central cities in each country increased from 2006 to 2019. Among them, the geometric mean productivity growth rate of most cities like Chongqing and Beijing reached more than 10%, and five cities like Chongqing, Beijing, Wuhan, Chengdu, and Shanghai even exceeded 14%. The southern cities have comprehensively surpassed the northern cities in terms of region. Among the northern cities, only Beijing and Xi'an have achieved an average growth rate of more than 10%, while all the southern cities have exceeded 10%. This also shows that China's economic development center is still in the south. In the future, more attention should be paid to the economic development of the northern central cities. On the other hand, it also reflects the more stable and "inclusive" development of central cities in the south. The income gap between urban and rural areas in northern China is relatively large, and the "inclusive" level of economic growth is slightly delayed.

From exponential decomposition, all cities have realized the double-line improvement of technological efficiency and progress rate. Although the technical efficiency coefficients of Guangzhou and Tianjin are lower than 1, it also reaches more than 0.99, basically maintaining a stable state. The analysis shows that the technical efficiency coefficients of almost every city are lower than the technological progress rate coefficients. The reason is that China's economy has been growing faster in recent years. The economic growth rate of the country's central cities is leading the country. Large base and resources have been fully utilized, resulting in a slow growth rate of technical efficiency. In recent years, the level of scientific and technological development in China has developed rapidly, and the number of scientific and technological output in China has jumped to the second place in the world. The application of many scientific and technological achievements promotes rapid technological progress in China's production process.

Convergence analysis of inclusive green total factor productivity

In order to further analyze the trend of IGTFP in China, our research uses the σ convergence model and absolute β convergence model to quantitatively study the convergence characteristics of IGTFP. This will provide a more directional reference for promoting China's economy's "green" and "inclusive" development.

σ convergence

The σ convergence reflects the deviation degree of IGTFP of a single city from the overall city level where the city is located. σ convergence of IGTFP means that the divergence of IGTFP among cities tends to decline over time. The convergence model of IGTFP can be expressed as:

$$\sigma_t = \sqrt{\frac{1}{n} \sum_{i=1}^n \left(\ln s_{it} - \frac{1}{n} \sum_{i=1}^n \ln s_{it} \right)^2} \quad (6)$$

In the above formula, t is the year, i is the city, and n is the number of cities at the corresponding level. In s_{it} represents the

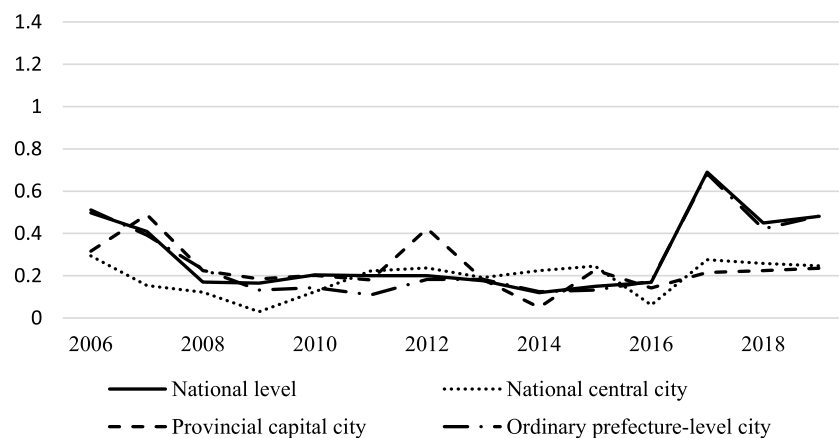


FIGURE 3
 σ convergence coefficients.

log value of IGTFP of i city in t year, and σ_t represents the σ convergence test coefficient of IGTFP in t year. If $\sigma_{t+1} < \sigma_t$, there is σ convergence in IGTFP.

According to the national σ convergence coefficients (Figure 3), the σ convergence feature of IGTFP in China is not apparent. Although there were occasional fluctuations, the σ convergence coefficients of IGTFP in national central cities showed a downward trend from 2006 to 2017. However, the overall downward trend is pronounced, indicating that the overall gap between central cities of the country was not large during this period. From 2017 to 2019, the σ convergence coefficients of national central cities increased first and then decreased. The reason is that in 2018, the IGTFP of Wuhan city has been dramatically improved. However, some provinces' green total factor productivity (such as Chongqing) decreased this year, leading to a more extensive convergence coefficients of national central cities this year. Since 2007, the σ convergence coefficients of provincial capital cities have shown a declining trend, indicating that these cities' IGTFP has a particular convergence phenomenon. The σ convergence coefficients of ordinary prefecture-level cities generally decreased first and then increased, indicating a significant difference within this kind of city group. The reason is that the IGML coefficients of some provinces have been lower than 1 since 2015 (for example, the IGTFP of Huludao in 2016 was less than 0.7, while the IGML coefficients of Xuzhou were close to 1.9). The expansion of IGTFP among cities leads to an increase in the σ convergence coefficients of ordinary prefecture-level cities. Therefore, there are still significant differences in IGTFP among cities in China. Except for provincial capital cities, the convergence of other tier cities is not apparent, further indicating

significant differences in economic growth efficiency, income gap, and eco-environmental protection intensity.

Absolute β convergence

Absolute β convergence means that cities with low initial IGTFP have a faster growth rate than cities or regions with high IGTFP without considering external factors. And all cities' IGTFP will converge to the same state. Its specific expression is:

$$\frac{(\ln s_{it} - \ln s_{i0})}{t} = \alpha + \beta \ln s_{i0} + \varepsilon_{it} \quad (7)$$

S_{it} and S_{i0} represent IGTFP of city i in phase t and early stage, respectively, t represents the period. α , β , and ε_{it} represent constant term, absolute β convergence coefficients, and the random error term, respectively. $\beta < 0$ indicates that cities' IGTFP at this level have absolute β convergence, and the larger $|\beta|$ is, the faster the convergence rate is.

Table 4 shows the absolute β convergence coefficients of cities' IGTFP at different levels. From the results, the absolute β convergence coefficients are significantly negative at both the national and each city levels. It indicates that China's IGTFP exists in apparent absolute β convergence. In other words, cities with low inclusive total factor productivity are catching up with cities with high IGTFP. In terms of the convergence rate, the absolute value of the absolute convergence coefficients at all levels shows *national central city* > *provincial capital city* > *prefecture-level city*. This indicates that the convergence rate of absolute β convergence in national central cities is significantly faster than others, and further indicates that the higher the city level is, the larger the city size is, the more pronounced the catch-up effect is.

TABLE 4 Absolute β convergence coefficients.

City category	National level	National central city	Provincial capital city	Ordinary prefecture-level city
β	-0.059*** (-5.51)	-0.085** (-2.91)	-0.084*** (-3.62)	-0.060*** (-5.24)
constant	0.042*** (10.62)	0.042*** (8.60)	0.025*** (10.55)	0.045*** (12.97)
F value	26.50	8.47	13.82	27.47

*, **, *** represent a significant level of 10%, 5%, and 1%, which is T value in parentheses.

Conclusion

From the perspective of inclusive green growth, we establish the index evaluation system of inclusive green growth. By using the method of super-SBM, we measure the inclusive green total factor productivity (IGTFP) of China from the city level and explore and analyze the IGTFP index and its decomposition and evolution trend of coefficients of economic convergence. Empirical analysis results are as follows.

First, IGTFP in China has maintained a steady but rising trend both at the national level and at all levels of city, especially after 2008. Second, from the decomposition of IGTFP, there is a positive correlation between the rate of technological progress and the scale of urban development. In addition, the technical efficiency of the country and higher-level cities are generally lower than the rate of technological progress. Third, from the economic region level, the regional development of IGTFP in China is unbalanced. Fourth, the IGTFP of southern cities is significantly higher than that of northern cities, indicating that the southern cities are more substantial than the northern cities in terms of green economic development and social equity. Finally, from the economic convergence, only the IGTFP of provincial capitals shows the σ convergence feature, that is, the phenomenon of intra-group convergence; the IGTFP of all cities in three levels shows the β convergence feature, indicating that cities with a lower level of IGTFP are catching up with that with a higher level.

The policy implications of this study are as follows: first, we should adhere to the concept of inclusive green development and achieve high-quality economic development through energy conservation and emission reduction and promoting social equity. On the one hand, it is necessary to increase investment in enterprise R&D and create a more relaxed R&D environment for enterprises, such as R&D incentives and tax exemptions. On the other hand, we should improve the income distribution system and strengthen the guidance of tertiary distribution on the basis of giving full play to secondary distribution to realize the organic unity of efficiency and fairness. Second, we need to break down the “regional” boundaries including the geographical boundaries (such as the north–south

boundary) and the boundaries at the city level, between city scales, and within the economic zone. Third, we should strengthen the core driving function of green technology innovation and progress. The integration of technology and efficiency is the main driving force and path to realize the sustainable improvement of IGTFP in cities. For example, promoting the cooperation between “resource-first” enterprises in underdeveloped cities and “technology-first” enterprises in developed cities, accelerating the upgrading of industrial structure, and realizing the “two-wheel drive” of IGTFP. In addition, cities with low IGTFP can develop rural tourism, e-commerce, and other related industries according to local characteristics, and form an economic form with low input, high output, and lower-income gap with business models such as “New Economy” and “Digital Economy.” While promoting rural revitalization, the “digital economy” can also reduce the income gap between urban and rural areas, which can not only promote the improvement of IGTFP level, but also achieve China’s common prosperity goal.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YG: Data Curation, Formal Analysis and Writing - Original Draft. HW: Conceptualization, Funding Acquisition and Visualization. RG: Resources and Software. DL: Supervision, Validation and Writing - Review & Editing.

Funding

Supported by the disciplinary funding of Central University of Finance and Economics, Supported by Program for Innovation Research in Central University of Finance and

Economics, supported by the Emerging Interdisciplinary Project of CUFU.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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