



## OPEN Evaluation and heterogeneity of the green total factor productivity of Shandong Province, China: a super-SBM and GML analysis

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As a pioneering zone for the transformation of old and new growth drivers, the characteristics and issues manifested by Shandong Province during the course of industrial structure adjustment and economic transformation can best represent the green transformation and sustainable development of the Chinese economy. On the basis of multidimensional panel data from 2007 to 2020, this study employs the superefficiency slack-based measure (super-SBM) model, which considers undesirable outputs, and the global Malmquist–Luenberger (GML) index to measure the green total factor productivity (GTFP) of 16 cities in Shandong Province and analyzes the dynamic characteristics of GTFP and its growth drivers from three dimensions—overall characteristics, regional differences, and urban scale levels. The results show that (1) the GTFP of Shandong Province exhibited a year-on-year decline before 2011, transformed into slow growth during 2011–2015, and then presented rapid growth after 2015. Overall, GTFP, technical efficiency, and technological progress increased at average annual rates of 0.95%, 0.74%, and 0.21%, respectively. Before 2015, the variation in GTFP relied mainly on technical efficiency, whereas after 2015, technological progress made a greater contribution to GTFP. (2) The Jiaodong Economic Circle experienced the greatest growth in GTFP, followed by the Provincial Capital Economic Circle, whereas the Lunan Economic Circle exhibited an overall downward trend. The enhancement of technical efficiency was the main driving force for the growth of GTFP in each economic circle and the main cause for the formation of the GTFP gap among economic circles. (3) Compared with other cities, regional megacities such as Jinan and Qingdao possess unparalleled advantages in terms of economy, talent, and infrastructure; therefore, the growth rate of GTFP is significantly greater in these megacities than in other cities.

**Keywords** Green total factor productivity, Super-SBM, GML index, Heterogeneity

In the global context of actively responding to climate change and promoting sustainable development, the concept of green development has emerged as a significant orientation for economic development in countries worldwide. With the acceleration of industrialization and urbanization processes, problems such as resource scarcity and environmental pollution have become increasingly acute, presenting immense challenges to the traditional economic growth model<sup>1–4</sup>. In this situation, green total factor productivity (GTFP), as a key metric for gauging sustainable economic development, has garnered extensive attention from both the academic community and policy-makers. GTFP not only considers the contributions of traditional factors such as capital and labor to economic growth but also integrates environmental factors, evaluating the comprehensive performance of economic activities in terms of resource utilization efficiency and environmental impact, thereby providing crucial theoretical support and practical guidance for achieving a win-win outcome between economic growth and environmental protection<sup>5–8</sup>.

As a major economic and industrial province in China, Shandong Province holds a pivotal position in the national economic landscape. Shandong Province not only ranks third in terms of the economy nationwide but, more significantly, is the sole province in China that encompasses all 41 major industrial categories. In recent years, Shandong's economy has maintained a relatively rapid growth rate, yet it also is faced with issues such as high-level resource consumption and severe environmental pollution. On the basis of relevant

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statistical data, the total energy consumption and total pollutant emissions of Shandong Province are both relatively high throughout the country, and the contradiction between economic development and the resource and environmental situation is rather salient. Against the current strategic backdrop of the country's vigorous promotion of ecological civilization construction and green development, it is particularly urgent for Shandong Province to accelerate the pace of economic transformation and sustainable development<sup>9,10</sup>.

This research measures the GTFP of 16 cities in Shandong Province via the SBM-GML model. By accurately evaluating the performance of Shandong Province in terms of resource utilization and environmental protection, it is possible to gain an in-depth understanding of the quality and efficiency of economic development in Shandong Province, reveal the intrinsic relationship between economic growth and the environment, clearly identify the strengths and weaknesses in the economic development process, and provide a scientific decision-making basis for the economic transformation and sustainable development, facilitating greater achievements on the path of green development in Shandong Province. Moreover, through this study, not only can data support be provided for the transformation of various cities within a province toward high-quality development, but beneficial references and exemplars can also be furnished for the green development of other regions, jointly facilitating the green transformation and sustainable development of China's economy.

In contrast to the previous research, the contribution of this study is threefold. First, in terms of methodology, a super-SBM model was constructed with undesirable outputs. Combined with the GML index based on global benchmark technology, key issues such as variable relaxation, distinguishability of effective DMU, and intertemporal comparability in the measurement of GTFP were scientifically solved. It ensures the robustness of the measurement results. Second, this study took Shandong Province, which has the most representative industrial structure, as the research object, rather than the national level that most literatures focus on. It could analyze regional development policies more specifically and reduce the differences in GTFP caused by the development gap between administrative regions. As a pioneer zone of the old and new growth drivers transformation, the development trend of GTFP in Shandong Province has reference significance for similar industrial zones at home and abroad. Third, from the research perspective, the characteristics of GTFP were examined from four dimensions: overall features, regional differences, and different urban scale levels. It is conducive to in-depth analysis of the regional differences in economic growth quality among different cities in Shandong Province and their sources, providing corresponding theoretical references for the further development of each city.

## Literature review

### Green total factor productivity (GTFP)

GTFP is a crucial indicator that comprehensively assesses the multifaceted integrated performance of economic activities in terms of resource utilization efficiency, environmental protection, and economic growth on the basis of traditional total factor productivity (TFP) and considers resource and environmental factors. Traditional TFP methods pay attention to the contributions of production factors such as capital and labor to economic growth<sup>11–13</sup>. However, GTFP further extends this notion, emphasizing the realization of efficient resource utilization and effective environmental protection during the economic development process and the pursuit of the coordinated and sustainable development of the economy, society and environment<sup>14–18</sup>.

With the profound advancement of environmental economics and sustainable development theory, the concept and accounting framework of GTFP have been constantly refined, and its research has gradually shifted from a sole economic efficiency evaluation to a comprehensive assessment of the coordinated development of the economy and the environment<sup>19–21</sup>. Chung et al. initially incorporated environmental factors into the measurement of total factor productivity and proposed a directional distance function (DDF), laying a significant foundation for research on GTFP and enabling the comprehensive consideration of the relationship between economic growth and the environment<sup>22</sup>. Since then, numerous scholars have continuously expanded and deepened such research on this basis. For example, Färe et al. further enhanced the measurement approach of GTFP based on the DDF and evaluated the resource utilization efficiency and environmental performance in economic activities more accurately by constructing a more scientific and rational production frontier<sup>23</sup>.

The measurement approaches of GTFP include data envelopment analysis (DEA), stochastic frontier analysis (SFA) and the Malmquist–Luenberger index. DEA, a nonparametric method based on linear programming, does not require prespecification of the specific form of the production function and can effectively handle complex systems with multiple inputs and outputs<sup>24–26</sup>. In the measurement of GTFP, the DEA method can incorporate resource inputs, desirable outputs (such as GDP), and undesirable outputs (such as pollutant emissions) into a unified framework for analysis<sup>27–29</sup>. SFA, a parametric method, demands prior determination of the specific form of the production function and typically assumes the presence of technical inefficiency terms in the production process, capturing random factors in the production process through random error terms. SFA has advantages in considering technical heterogeneity and random errors and is thus extensively applied in GTFP studies<sup>30,31</sup>. The Malmquist–Luenberger index was proposed by Chung et al. In combination with the directional distance function, it is capable of dynamically gauging the changes in GTFP and has emerged as one of the mainstream methods for analyzing the growth of productivity<sup>22</sup>.

To integrate the advantages of diverse methods, scholars have commenced attempting to combine multiple approaches. For example, the SBM-GML method, which combines the capacity of the SBM model in handling undesirable outputs and slack variables and the superiority of the GML index in dynamic analysis, has been extensively utilized in recent years<sup>32,33</sup>.

### Superefficiency slack-based measure (super-SBM) method

The super-SBM model is a significant approach within the DEA framework and is particularly applicable for addressing efficiency assessment issues involving undesirable outputs such as pollutant emissions. With in-depth research on GTFP, the super-SBM model has achieved notable advancements both at the theoretical and

application levels. Traditional DEA models are radial and angular models that disregard the slack variables of inputs or outputs, potentially overestimating the efficiency of decision-making units (DMUs). Simultaneously, traditional DEA models fail to fully account for the possible undesirable outputs generated during the production process, such as environmental pollution and resource waste, thereby entailing conspicuous limitations when dealing with the assessment of production efficiency involving multiple inputs and outputs.

To overcome the deficiencies of traditional models, Tone proposed the SBM model, which is nonradial and nonangular. This model considers the slack of all input and output variables and is capable of effectively handling undesirable outputs, integrating them into the efficiency evaluation system and thereby measuring the efficiency of DMUs more precisely<sup>34</sup>. Concurrently, the SBM model does not necessitate prespecification of the functional relationship between inputs and outputs, as it is strongly objective and applicable. Although the SBM model has achieved breakthroughs in dealing with undesirable outputs, it still presents certain limitations when comparing the efficiency of multiple effective decision-making units. In the traditional SBM model, since the efficiency values of effective DMUs are all 1, further differentiating the efficiency disparities among these units is infeasible. To address this issue, Tone further proposed the super-SBM model, which permits efficiency values to exceed 1. By excluding the evaluated decision-making unit from the reference set and reconstituting the production frontier, it can further discriminate and rank DMUs with an efficiency value of 1<sup>35</sup>. This enhancement renders the super-SBM model more preponderant in practical applications and enables a more meticulous analysis of the efficiency variances among different DMUs.

Currently, the super-SBM model, which considers undesirable outputs, has emerged as one of the crucial tools for GTFP measurement<sup>36–38</sup>.

### Global Malmquist–Luenberger (GML) index

The GML index was proposed by Oh and is a significant instrument for the dynamic measurement of GTFP<sup>39</sup>. The traditional Malmquist index is constructed on the basis of distance functions and is capable of effectively gauging the variations in total factor productivity within the framework of multiple inputs and multiple outputs. Nevertheless, the traditional index possesses a prominent drawback, namely, that this index relies on the production technology of each period. When production technology undergoes alterations, the Malmquist indices of distinct periods lack direct comparability, and a unified production frontier cannot be established. This situation substantially constrains its application in the dynamic analysis of GTFP<sup>40</sup>. In 1997, Chung et al. proposed the Luenberger productivity indicator based on directional distance functions, which takes undesirable outputs into account and offers a novel perspective for the measurement of GTFP<sup>22</sup>. Nevertheless, the Luenberger productivity indicator is also restricted by disparities in production technology across different periods, making it difficult to directly contrast the results from various periods. To address these problems, Oh and Heshmati proposed the GML index in 2010. The GML index constructs a global production technology that incorporates the observations of all periods and uses this as a basis for computing the changes in total factor productivity. This methodology enables the comparison of variations in GTFP across different periods under the same production frontier, effectively surmounting the limitations of the traditional Malmquist index and the Luenberger productivity indicator and providing a more dependable tool for the dynamic analysis of GTFP<sup>41,42</sup>.

The GML index can be further decomposed into two components—global technical efficiency change (GEC) and global technological progress (GTC). Technical efficiency change reflects the extent to which DMUs approach the production frontier in different periods, that is, the variation in the resource allocation efficiency of DMUs under the existing technological level. Technological progress represents the movement of the production frontier, that is, the influence of technological innovation and improvement on GTFP<sup>39</sup>. During the process of economic development, technological progress and efficiency change are two crucial factors influencing GTFP. Through the decomposition of the GML index, it is feasible to analyze the sources and driving forces of the growth of GTFP in a more in-depth manner and provide a basis for formulating targeted policies<sup>43,44</sup>.

### Application of the SBM-GML method in GTFP measurement

By integrating the advantages of the SBM model in dealing with undesirable outputs and the feature of the GML index in considering technological progress, the SBM-GML model is capable of measuring GTFP and its decomposed components more accurately and has been extensively utilized in the study of the dynamic variations in GTFP. Wang et al. utilized the directional distance function based on SBM and the ML index to measure the GTFP of China's industrial sectors. The findings revealed that technological progress was the primary driving force for the growth of China's industrial GTFP, whereas the enhancement of technical efficiency was relatively lagging<sup>45</sup>. Lv et al. employed the super-SBM model and the GML index to conduct an in-depth investigation into the air quality and environmental efficiency in Shandong Province, revealing the temporal differentiation characteristics within the region<sup>46</sup>. Meng and Qu proposed that although overall green energy efficiency in China has shown a downward trend, technological progress remains an important factor driving efficiency improvement. From a regional perspective, the differences in green energy efficiency are closely related to geographical location, with the eastern region generally having higher efficiency than does the western region<sup>47</sup>. Wu and Zhang constructed the SBM-GML index to explore in detail how to measure GTFP in sustainable agricultural development<sup>48</sup>. Fu et al. measured the growth trend of agricultural GTFP in 31 provinces of China via the SBM-GML model and noted that the growth momentum originated from technological progress<sup>49</sup>. Deng et al. employed the super-SBM model and GML index to comprehensively measure the green development efficiency of cold chain logistics in 30 provinces of China from 2012 to 2020. The above authors noted that the main way to enhance the green development efficiency of cold chain logistics is through technological progress<sup>50</sup>. Lin et al. demonstrated that clean air policies can promote the growth of GTFP by facilitating green technological progress and efficiency changes<sup>14</sup>. Wang analyzed the GTFP of China's grain industry and explored the impact of grain industry agglomeration on it. Research has indicated that the GTFP

of the grain industry fluctuates and grows with the advancement of green technology<sup>51</sup>. He et al. noted that the green development efficiency of urban agglomerations in the middle reaches of the Yangtze River Basin has a fluctuating upward trend and that this dynamic change is influenced by multiple factors, such as urban economic development, the industrial structure, and openness. The analysis indicates that technological progress is the main driving force behind improvements in green development efficiency<sup>52</sup>.

## 2.5 Research on GTFP in other industrial regions

A lot of research on GTFP has also been carried out in industrial regions like Shandong Province. The following is a comparison with these literatures to further clarify the global green development trend from an international perspective. Organization for Economic Co-operation and Development (OECD) countries have a strong economic foundation and obvious advantages in areas such as science and technology. They have played a leading role in promoting green growth over the past two decades. Therefore, it has been widely studied as a representative research sample. According to the ranking of the average value of GTFP, the sample of OECD countries was split equally into three groups, high GTFP, medium GTFP and low GTFP. The potentials in directions of energy saving, GHG abatement and industrial growth of each country were further estimated<sup>53</sup>. For the countries with a high GTFP, the further improvement of green productivity relies on technological breakthrough. For the countries with a medium GTFP, both clean energy and green innovation are efficient ways to increase green productivity. The countries with a low level of green productivities could have been more efficient in energy consumption, GHG emissions and industrial growth. Besides, the GTFP of OECD and BRICS countries were compared by Sun<sup>54</sup>, it found that the GTFP of OECD countries is significantly higher than that of BRICS countries. For OECD countries, the average annual growth rate showed an encouragingly upward trend during 2003–2012. The average annual growth rate remained around 0.6 from 2003 to 2009, rose to a peak of 0.86 in 2010, dropped to 0.72 in 2011 and finally slowly increased to 0.78 in 2012. For BRICS countries, the average annual growth rate slightly decreased during 2003–2009 and then rose rapidly to 0.6438 in 2010, dropped to 0.4584 in 2011. Among the BRICS countries, Brazil exhibits the highest value and China has the minimum value.

The GTFP of EU countries and regions has also been widely studied. For European NUTS2 regions, the average values of the GTFP were analyzed from 2009 to 2021, and a general improvement in GTFP was observed over the period with two notable peaks in 2013 and 2019. Specifically, following the Great Recession (2007–2009), there was a sharp decline in GTFP in 2010. A similar pattern was seen with the COVID-19 crisis, as 2020 was a particularly challenging year for GTFP. GTFP levels tend to be highest along the London–Amsterdam–Munich–Milan axis and lowest in peripheral regions in Eastern Europe<sup>55–57</sup>. Regional differences in terms of economic geography, historical development paths and trust play a key role in explaining why some regions have higher TFP levels than others. There is a strong local dimension to technology and knowledge, even within the same country, suggesting that the spatial diffusion of technology and efficient production practices is limited. The GTFP of the EU countries and the six Western Balkan countries was also compared and analyzed. Western Balkan countries experience a decline in GTFP ( $\text{GTFP} < 1$ ) for most of the years during the observed period from 2015 to 2020. This decline is particularly noticeable for Bosnia and Herzegovina, where GTFP values exhibit a declining trend at both the beginning and the end of the period<sup>58</sup>. When conducting a comparative analysis of GTFP for each individual Western Balkan country with the EU average, it becomes evident that Western Balkan countries are in a significantly disadvantaged position. By analyzing the decomposition of GTFP, it can be observed that technological progress contributes more to the growth of GTFP compared to technological efficiency.

Although India's conventional TFP growth stands out to be one of the highest globally, the average annual GTFP growth was at almost 0% since 2000. It suggests that the economic growth during the 2000s may not be environmentally sustainable. India's GTFP growth improved marginally to 0.1% during the 2010s, which reflects the of counteremission measures undertaken by India would probably balance the country's emission per unit of GDP and the carbon dependence<sup>59</sup>.

The GTFP of the Belt and Road (B&R) countries has also been studied. The B&R countries have seen an increase in their overall levels of GTFP over time. China's Belt and Road Initiative (BRI) is beneficial to B&R countries and consequently to global green development. There are regional differences in the levels of GTFP, with higher efficiency in Western Asia and Central and Eastern Europe, and lower efficiency in Southeast and Central Asia. The GTFP and the level of economic development have a certain correlation. The main driving force for GTFP promotion in Asian countries came from technical change, while in European countries, it comes from efficiency change<sup>60</sup>.

Although extensive studies have been conducted on GTFP and the application of the SBM-GML model, certain deficiencies still remain. Presently, the majority of research sample data are focused at the provincial level, with relatively few studies concentrating at the city level. With respect to the research objects, systematic investigations into the GTFP of specific provinces, such as Shandong Province, are relatively limited, and the exploration of the complex relationship between economic development and the resource environment in Shandong Province is not sufficiently profound. This paper, on the basis of existing research, focuses on the city level, conducts an in-depth analysis of the dynamic evolution characteristics of the GTFP of each city in Shandong Province, and provides more targeted suggestions for the green development of Shandong Province to compensate for the deficiencies of current studies.

## Methods and data

### Super-SBM method

The super-SBM model considering undesirable outputs was employed to calculate the GTFP of 16 cities in Shandong Province. This model possesses the following three merits. First, when multiple DMUs are concurrently

fully efficient, the model can effectively address the issues of discrimination and ranking among these decision-making units. Second, the model can effectively handle the problem of variable slackness. Third, the model takes the issue of undesirable outputs into full account.

The super-SBM model considering undesirable outputs can be defined as follows:

$$\min \rho_G^* = \frac{\frac{1}{k} \sum_{i=1}^k \frac{\bar{x}_i}{x_{i0}}}{\frac{1}{l_1+l_2} \left( \sum_{q=1}^{l_1} \frac{\bar{y}^g}{y_{q0}^g} + \sum_{q=1}^{l_2} \frac{\bar{y}^b}{y_{q0}^b} \right)}$$

$$s.t. \begin{cases} \bar{x} \geq \sum_{j=1, j \neq 0}^n x_{ij} \lambda_j, \quad i = 1, 2, \dots, k \\ \bar{y}^g \leq \sum_{j=1, j \neq 0}^n y_{qj}^g \lambda_j, \quad q = 1, 2, \dots, l_1 \\ \bar{y}^b \geq \sum_{j=1, j \neq 0}^n y_{qj}^b \lambda_j, \quad q = 1, 2, \dots, l_2 \\ \lambda_j \geq 0, \quad j = 1, 2, \dots, n; j \neq 0 \\ \bar{x} \geq x_0, \bar{y}^g \leq y_0^g, \bar{y}^b \geq 0, y^b \geq y_0^b \end{cases} \quad (1)$$

In the equation,  $x$  and  $y$  stand for the input variables and output variables of each DMU, respectively;  $i$  and  $q$  denote the numbers of input and output indicators, respectively;  $\bar{x}$ ,  $\bar{y}^g$ , and  $\bar{y}^b$  indicate the slack variables of input, desirable output, and undesirable output, respectively; and  $\lambda_j$  is the weight vector of input and output.  $\rho_G^*$  is the efficiency value of the DMU, herein denoting the GTFP values of different cities to be estimated. The greater the  $\rho_G^*$  value is, the higher the level of GTFP. When  $\rho_G^* < 1$ , it implies that the DMU is inefficient; if  $\rho_G^* > 1$ , then it indicates that with the input remaining constant, reducing the output or with the output remaining unchanged and increasing the input, an efficient state can be achieved.

### GML index

The super-SBM model is only applicable for measuring the static GTFP and is incapable of effectively computing its dynamic variations. Consequently, in this research, the GML index is utilized to measure and decompose the dynamic alterations in the GTFP of 16 cities in Shandong Province. The GML index method has significant advantages over the traditional methods based on concurrent benchmarks. The traditional method only uses the data of the current period to construct the frontier surface, while the GML index method incorporates the observation data of all periods into the construction of a unified production frontier surface (i.e., the global production technology set), forming a common reference system throughout the entire time span. Therefore, the GML index can eliminate the “frontier bias” caused by short-term shocks (such as economic crises and sudden policy changes), and the calculation results can be compared across periods. Meanwhile, the GML index can avoid the problem of linear programming without solution, satisfy the circularity property, and make the result transitive.

The GML index can be decomposed into the global technological progress (GTC) index and the global technical efficiency (GEC) index as follows:

$$GML = GEC^* GTC$$

$$= \frac{E^g(x^{t+1}, y^{t+1})}{E^g(x^t, y^t)} = \frac{E^{t+1}(x^{t+1}, y^{t+1})}{E^t(x^t, y^t)} \quad (2)$$

$$\left[ \frac{E^g(x^{t+1}, y^{t+1})}{E^{t+1}(x^{t+1}, y^{t+1})} \frac{E^t(x^t, y^t)}{E^g(x^t, y^t)} \right]$$

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

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

where  $x^t$  and  $y^t$  represent the input and output values of the evaluated unit in period  $t$ , respectively, and  $E^g$  and  $E^t$  represent the efficiency values of the global frontier and the frontier in period  $t$ , respectively.

Within the nonparametric framework, on the basis of the super-SBM model considering undesirable outputs, a nonangular and nonradial MPI is constructed in this paper. The formula is as follows:

$$GML_o^{T,T+1} = \frac{\rho_o^{T+1}(x_o^{T+1}, y_o^{g,T+1}, y_o^{b,T+1})}{\rho_o^T(x_o^T, y_o^{g,T}, y_o^{b,T})} * \left[ \frac{\rho_o^g(x_o^{T+1}, y_o^{g,T+1}, y_o^{b,T+1})}{\rho_o^{T+1}(x_o^{T+1}, y_o^{g,T+1}, y_o^{b,T+1})} * \frac{\rho_o^T(x_o^T, y_o^{g,T}, y_o^{b,T})}{\rho_o^g(x_o^T, y_o^{g,T}, y_o^{b,T})} \right] = GEC_k^{T,T+1} \times GTC_k^{T,T+1} \quad (5)$$

where  $GML_o^{T,T+1}$  represents the change in GTFP from period T to period T + 1;  $\rho_o^T(x_o^T, y_o^{g,T}, y_o^{b,T})$  and  $\rho_o^{T+1}(x_o^{T+1}, y_o^{g,T+1}, y_o^{b,T+1})$  represent the efficiency values of the DMU in period T and period T + 1, respectively;  $\rho_o^g(x_o^T, y_o^{g,T}, y_o^{b,T})$  and  $\rho_o^g(x_o^{T+1}, y_o^{g,T+1}, y_o^{b,T+1})$  are the efficiency values based on the global production technology in each period and the input-output value in period T and period T + 1, respectively; and  $\frac{\rho_o^T(x_o^T, y_o^{g,T}, y_o^{b,T})}{\rho_o^g(x_o^T, y_o^{g,T}, y_o^{b,T})}$  and  $\frac{\rho_o^g(x_o^{T+1}, y_o^{g,T+1}, y_o^{b,T+1})}{\rho_o^{T+1}(x_o^{T+1}, y_o^{g,T+1}, y_o^{b,T+1})}$  reflect the proximity of frontier T and frontier T+1 to the global frontier, respectively. A value of  $GML_o^{T,T+1} < 1$  indicates GTFP regression,  $GML_o^{T,T+1} = 1$  indicates no change in GTFP, and  $GML_o^{T,T+1} > 1$  indicates GTFP progression. A  $GEC > 1$  ( $< 1$ ) represents improvement (decrease) in technical efficiency, and  $GTC > 1$  ( $< 1$ ) represents technological progress (regression).

## Variable description and data sources

### Variable description

To measure GTFP precisely, this research selects a series of representative indicators from three dimensions—input, desirable output, and undesirable output. The selection of these indicators fully accounts for the availability and reliability of the data, as well as their correlation with the GTFP, with the aim of comprehensively and objectively reflecting the resource utilization efficiency and environmental impact in the economic development process of Shandong Province.

- (1) Labor input. The total number of employed individuals at year end is chosen to represent labor input.
- (2) Capital input. Capital stock is used to represent the capital input indicator. Regarding the estimation of capital stock, the perpetual inventory method calculation formula is  $K_{i,t} = (1 - d) K_{i,t-1} + I_{i,t}$ , where subscripts i and t represent regions and years, respectively; K and I represent capital stock and new social fixed asset investment, respectively; and d represents the fixed asset depreciation rate. In this work, to ensure the consistency of the statistical caliber of the input and output variables, the capital stock is converted with 2006 as the base period, and the depreciation rate is taken as 10%.
- (3) Energy input. The energy input indicator is represented by the annual energy consumption of each prefecture-level city. Considering that the majority of energy sources in these cities are traditional fossil fuels with a very small proportion of renewable energy, and on the basis of the availability of data, the energy consumption of raw coal, gasoline, diesel and natural gas is converted into standard coal, which is taken as the energy input indicator for cities. The conversion coefficients of raw coal, gasoline, diesel and natural gas are 0.7143, 1.4714, 1.4571 and 1.33 respectively, and the units are kg standard coal/kg, except that the conversion coefficient of natural gas is kg standard coal/cubic meter.
- (4) Desirable output. The output indicator is represented by the actual GDP of the entire city. Taking 2006 as the base period, the GDP deflator is calculated on the basis of the annual GDP index, and then, the nominal GDP of each city over the years is deflated to eliminate the influence of price factors.
- (5) Undesirable outputs. With respect to the relevant studies, this paper takes the total sulfur dioxide emissions, industrial wastewater emissions and industrial smoke dust emissions of the entire city's industry as undesirable outputs.

### Data sources

The raw data of the indicators selected in this paper all originate from the Shandong Statistical Yearbook, Shandong Environmental Statistical Yearbook, and the statistical bulletins of various regions. Since Laiwu city was abolished as a prefecture-level city and incorporated into Jinan city in 2019, to guarantee the completeness of the sample data, all the sample data of Laiwu city from 2006 to 2019 in this paper were merged with those of Jinan city. The missing data of individual cities were supplemented by interpolation. The descriptive statistics of each variable of the input-output indicators are presented in Table 1.

## Results and discussion

### Overall characteristics and Temporal trends of GTFP in Shandong Province

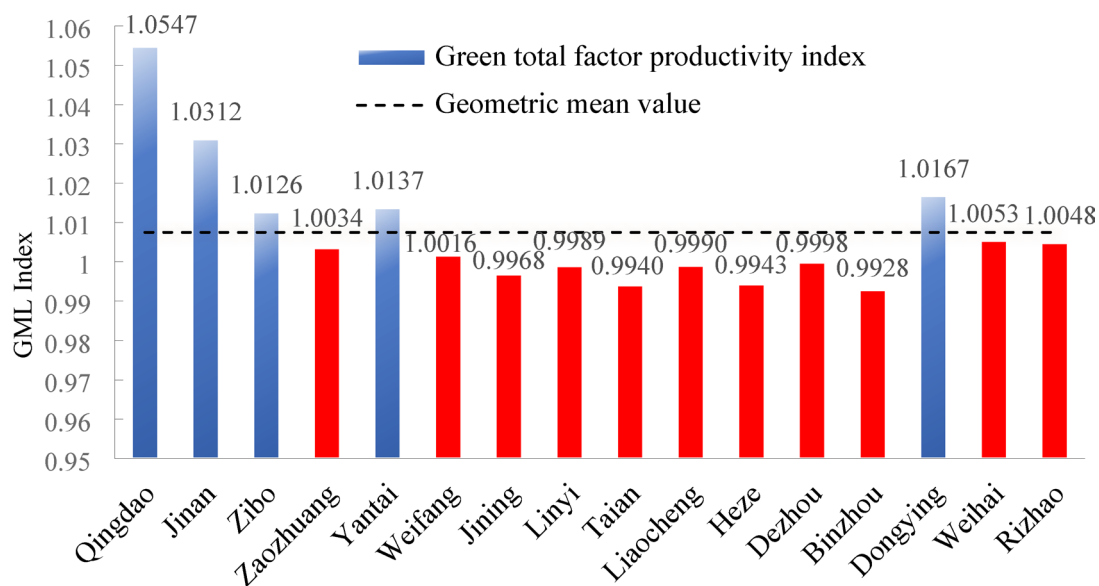
On the basis of the super-SBM model considering undesirable outputs and the GML index approach with a global reference, this paper measures the GTFP indices of 16 cities in Shandong Province during 2007–2020. This paper analyzes the overall characteristics and temporal trends of the changes in GTFP from four aspects—the geometric mean annual growth rate of the GTFP of the 16 cities in Shandong Province, the classification statistics of the growth types of GTFP, the temporal variations in the GML index and its decomposition items, and the classification statistics of the growth sources of GTFP.

#### Analysis of the average annual growth rate of GTFP in 16 cities in Shandong Province from 2007 to 2020

Figure 1 shows the geometric mean of the GML index of 16 cities in Shandong Province during the sample period. The GML index of 9 cities exceeds 1, whereas that of 7 cities is less than 1. This finding implies that

Variable	Unit	Number of observations	Mean	Standard deviation	Min.	Max.
Labor	10,000 persons	240	36.6	28.79	9.45	145.30
Capital	CNY 100 million	240	5659.82	4140.16	777.70	24917.12
Energy	10,000 tons of standard coal	240	2276.95	1384.75	519.91	6733.24
GDP	CNY 100 million	240	1538.42	1685.30	505.81	10739.22
SO <sub>2</sub>	10,000 tons	240	66609.09	44781.73	1724	228,815
Wastewater	Ton	240	10589.51	5384.63	1947	28,191
Smoke dust	Ton	240	26899.44	21897.44	1795	119,822

**Table 1.** Description of the variables used in this study.



**Fig. 1.** Geometric means of the GML indices of 16 cities in Shandong Province.

over half of the cities in the province have achieved growth in GTFP to varying extents. Among them, Qingdao demonstrates the fastest growth in GTFP, with the geometric average rate of change in the GML index reaching 1.0547, followed by Jinan at 1.0312. Among all the cities in the province, Binzhou and Tai'an exhibit the greatest average annual decline in the GML index, with the decline rates reaching 0.72% and 0.6%, respectively. From the overall perspective of the cities in Shandong Province, the GTFP of Shandong Province has an average annual growth rate of 0.95% from 2007 to 2020.

#### *Classification and statistics of the growth types of GTFP*

This paper classifies and statistically analyzes the degree of change in the GTFP of 16 cities in Shandong Province over time. These cities are divided into four types—high-growth-rate cities (GTFP change  $\geq 10\%$ ), medium-growth-rate cities ( $5\% \leq$  GTFP change  $< 10\%$ ), low-growth-rate cities ( $0\% \leq$  GTFP change  $< 5\%$ ), and negative-growth-rate cities (GTFP change  $< 0\%$ ). The distributions of the four types of cities in different time periods are shown in Table 2.

First, through observing the number of cities with negative growth rates, the research period can be divided into three stages. The first stage was from 2007 to 2011. Cities with negative growth in GTFP held absolute dominance. The number of cities with positive growth in GTFP was basically less than 30%, and the growth rates were all very small, with no city having a growth rate exceeding 5%. The main reason for this is that the economic growth mode of Shandong Province was originally extensive. Affected by the global financial crisis in 2008, external demand weakened significantly, and trade protectionism gradually emerged. Foreign trade in Shandong Province has been severely impacted, and the momentum of economic growth has been severely restrained. Moreover, to cope with the international financial crisis, the government launched a 4-trillion yuan investment project in 2009 to counter the risk of a hard landing of the economy, which led to the resurgence of a batch of projects that could generate economic growth quickly but were highly energy-consuming and highly polluting, thereby causing a large number of cities to experience negative growth in GTFP during this stage.

The second stage ranged from 2012 to 2015. During this period, the number of cities with negative growth in GTFP declined, and the proportion of cities with positive growth in GTFP exceeded 50%; however, the growth rate remained relatively low, mostly less than 5%. This finding can be attributed to the implementation

Year	Negative-growth-rate cities/Number	Low-growth-rate cities/ Number	Medium-growth-rate cities/Number	High-growth-rate cities/ Number
2007	13	3	0	0
2008	8	8	0	0
2009	14	2	0	0
2010	12	4	0	0
2011	13	3	0	0
2012	8	8	0	0
2013	9	7	1	0
2014	8	8	0	0
2015	11	5	0	0
2016	4	8	2	2
2017	0	7	6	3
2018	0	5	7	4
2019	9	6	0	1
2020	1	12	2	1

**Table 2.** Statistics on the number of GTFP growth Types.

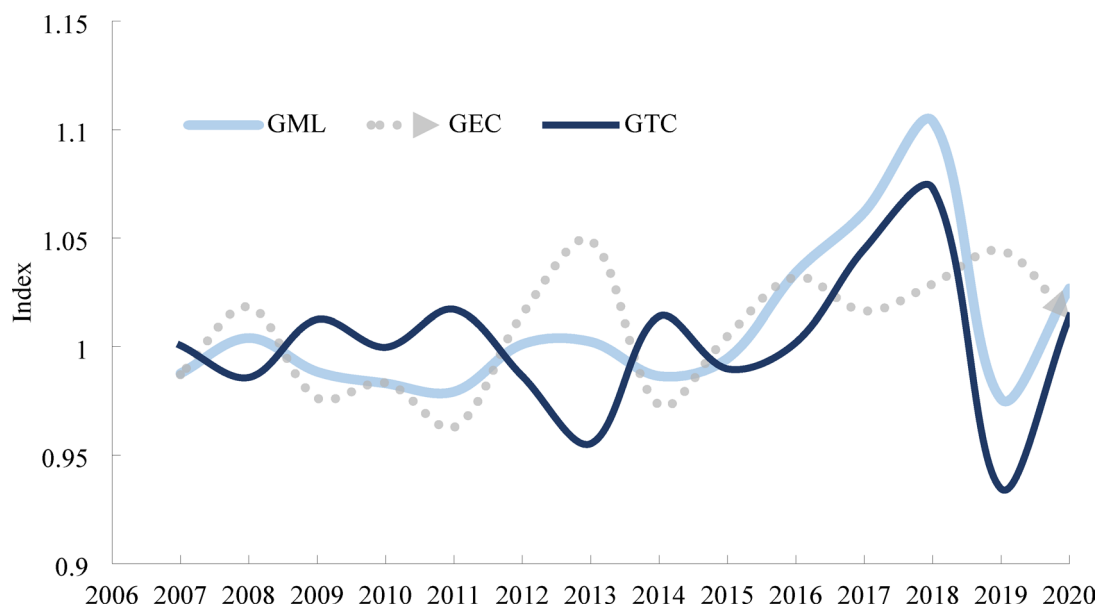
of industrial transformation and upgrading in Shandong Province during the 12th Five-Year Plan period. Local governments advanced the “transformation of the development mode and adjustment of the economic structure”. On the one hand, they cultivated and developed high-tech industries and strategic emerging industries. On the other hand, they enhanced the development of traditional industries. During the 12th Five-Year Plan period, the annual average growth rate of industrial technological transformation investment in the province was approximately 20%, the annual average growth rate of high-tech industry output value was 16.6%, and the value added of strategic emerging industries accounted for more than 10% of the regional GDP. Concurrently, the 12th Five-Year Plan emphasized the policy goals of environmental protection, energy conservation, and emission reduction and implemented an air pollution prevention and control plan and action plan, which compelled enterprises at the micro level to innovate in production process technology, process technology, and emission reduction technology.

The third stage spanned from 2016 to 2020. The number of cities with negative growth in GTFP decreased significantly. The majority of cities experienced positive growth in GTFP. The number of cities with a growth rate greater than 10% was 2 to 4, and the number of cities with a growth rate greater than 5% was 6 to 7. More notably, all 16 cities in the province achieved consecutive positive growth in 2017 and 2018. During this stage, the national economy remained stable and on an upward trajectory. Economic growth shifted from decline to stability. In 2017, the GDP growth rate exhibited a continuous downward trend since 2010 and achieved the first annual year-on-year rebound. This was related to the external market environment. The global economy gradually recovered, international trade resumed its vitality, and China’s export situation gradually improved. As a major coastal province with a significant volume of foreign trade, Shandong Province experienced rapid economic growth. More importantly, since the 13th Five-Year Plan, China has adopted supply-side structural reform measures to drive economic structural adjustment, transformation, and upgrading. The new economic characteristics centered on enhancing quality and efficiency and reducing emissions and energy consumption have become increasingly pronounced. Shandong Province has fully implemented the “Four Reductions and Four Increases” strategy, which has significantly elevated its GTFP. During the “13th Five-Year Plan” period, the installed capacity of new and renewable energy power generation in Shandong province increased by an average of 33.9% annually, and the power generation accounted for 14.2% of the province’s total power generation. For industrial regions like Shandong, where traditional industries such as steel, chemical engineering and coal account for a high proportion, the new energy transition can not only significantly reduce energy intensity and pollution emissions, but also force the upgrading of high energy-consuming industries. For instance, electrolytic aluminum enterprises can lower carbon emissions and promote the growth of GTFP by replacing coal power with green electricity. Meanwhile, the development of the new energy industry (such as offshore wind power and photovoltaic equipment) has formed new economic growth points, which can optimize the industrial structure of Shandong province and enhance the “technical efficiency” in GTFP.

However, in 2019, the growth rate of GTFP in all cities of the province plummeted abruptly, with nine prefectural-level cities experiencing negative growth. In 2020, the GTFP of the majority of cities in the province resumed a marginal increase. This occurred because Shandong Province initiated the transformation of old and new growth drivers, which voluntarily closed nearly 100,000 “scattered, disorderly and polluting” enterprises. The investment in high-energy-consuming industries and industries with excess capacity declined by 8.8% and 10.9%, respectively, sacrificing a portion of the economic growth rate. This stage was a period of hardship for economic transformation and upgrading. Furthermore, the significant decline of GTFP in 2019 is also closely related to the China-United States trade war. As the United States is China’s largest trading partner, the trade war seriously affected China’s foreign exports and caused a significant slowdown in the trade-oriented economy growth in the short term. But in the long term, in the face of the pressure of the trade war, China stimulates the potential of innovation-driven development and promotes the upgrading of the industrial structure.

Year	2007	2008	2009	2010	2011	2012	2013	Average
GML	0.988	1.004	0.988	0.983	0.979	1.001	1.002	GML = 1.0095 GEC = 1.0074 GTC = 1.0021
GEC	0.987	1.018	0.976	0.983	0.963	1.015	1.049	
GTC	1.001	0.986	1.013	1.000	1.017	0.986	0.955	
Year	2014	2015	2016	2017	2018	2019	2020	
GML	0.986	0.995	1.034	1.062	1.104	0.976	1.027	
GEC	0.973	1.005	1.032	1.016	1.029	1.044	1.013	
GTC	1.014	0.990	1.002	1.045	1.073	0.935	1.014	

**Table 3.** GML index, GEC index and GTC index from 2007 to 2020 for Shandong Province.



**Fig. 2.** Changing trends of the GML index, GEC index and GTC index for Shandong Province.

#### Temporal variation trends of the GML index and its decomposition components

The GML index and its decomposition indicators, namely, the GEC index and GTC index, of the 16 cities in Shandong Province from 2007 to 2020 are presented in Table 3. The geometric average annual growth rates of the GML, GTC, and GEC indices are 0.95%, 0.74%, and 0.21%, respectively. Figure 2 shows the changing trends of the GML index, GEC index and GTC index. Prior to 2015, the changing trends of the GML index and the GEC index were identical and contrary to those of the GTC index; however, after 2015, the changing trend of the GML index was consistent with that of the GTC index and opposite that of the GEC index. This finding implies that before 2015, the variations in GTFP relied mainly on technical efficiency, whereas after 2015, technological progress contributed more significantly to GTFP. This finding is largely in line with the current economic development status and development stage of Shandong Province. During the research period, Shandong Province was in the middle-late stage of industrialization, with a considerable proportion of traditional industries and heavy chemical industries. Although high-tech industries and strategic emerging industries have developed steadily, the adjustment of the economic structure and the fundamental transformation of the development mode require relatively long periods of time. In the short term, technical efficiency dominates the impact on green development. Nevertheless, with the deepening and consolidation of industrial transformation and upgrading, in the long run, technological progress will emerge as the main impetus for GTFP growth.

Furthermore, the trends of the changes in the GML index, GEC index and GTC index were analyzed in stages. As shown in Fig. 2, before 2011, the GML index was basically less than 1 and showed a decreasing trend year on year. Although technological progress experienced an enhancement, technical efficiency declined substantially. This situation was attributed predominantly to the international financial crisis in 2008, which resulted in a decrease in expected output. To stabilize the economy, China implemented a two-year economic stimulus plan in 2009. Under the influence of the 4-trillion-yuan investment and its potent monetary multiplier effect, local governments promptly initiated a large quantity of fixed asset investments, mostly in the infrastructure sector. The proportion of heavy industry increased once again. China's GDP growth target of 8% was accomplished, yet it also gave rise to overcapacity and environmental pollution. Shandong Province was at the forefront of being affected. Its industrial structure, characterized by the absolute dominance of traditional industries and heavy industry, led to a significant drop in technical efficiency during this phase, which subsequently decreased GTFP.

From 2011 to 2013, accompanied by a marked increase in technical efficiency, the GML index gradually increased, and the GTFP shifted from negative growth to positive growth. Concurrently, technological progress has experienced a setback. During the 12th Five-Year Plan period, Shandong Province vigorously advanced “transforming the mode of development and adjusting the economic structure”, and “green development” became a crucial assessment indicator for local governments. While achieving economic growth, attention was also paid to ecological and environmental protection. As technological progress was difficult to materialize in the short term, local governments and enterprises focused on improving green technical efficiency and resource allocation efficiency. Consequently, a situation in which technical efficiency increased significantly and GTFP stabilized and rebounded emerged.

After 2015, both the GEC index and the GTC index gradually increased. GTFP exhibited positive growth for four consecutive years, attaining a maximum growth rate of 10.4% in 2018. Owing to favorable external conditions such as the recovery of the world economy and the resumption of global trade, during the 13th Five-Year Plan period, Shandong Province actively adopted supply-side structural reform measures. Coupled with the vigorous promotion of the innovation-driven strategy by the state, economic growth in various regions of Shandong has been robust. The new economic growth characteristics, with quality improvement, efficiency enhancement, emission reduction and energy consumption reduction as the main goals, will become increasingly prominent.

However, influenced by the transformation of old and new growth drivers, the GML index and the GTC index declined sharply in 2019, and the GTFP of Shandong Province decreased substantially. Nevertheless, the elimination of high-energy-consuming and high-pollution enterprises enhanced green technical efficiency, resulting in an increase in the GEC index, contrary to the trend. In 2020, as the newly attracted projects began production, the new growth drivers of the economy gradually recovered, and the GML index returned to above 1, with GTFP resuming its positive growth.

#### *Classification and statistical analysis of the growth sources of GTFP*

The classification results of the variations in the GML index, GEC index and GTC index are presented in Table 4.

The sources of growth in GTFP include technological progress and technical efficiency promotion. The interaction effect of the two constitutes the growth effect of GTFP. Among them, technological progress represents “green hard technology”, which enables the production possibility frontier to extend outward in a greater direction through technologically independent innovation or technological introduction and imitation, whereas technical efficiency promotion represents “green soft technology”, which is typically based on existing technology and improves the efficiency of resource allocation and enhances the industrialization capacity of green technology, thereby promoting the actual input-output model to approach the “optimal production frontier” through institutional innovation and policy incentives macroscopically and “soft measures”, such as technological management model innovation microscopically.

The statistical data in Table 4 indicate that during 2007–2020, 56.2% of the cities in Shandong Province experienced an improvement in GTFP, 75% of the cities achieved an increase in technical efficiency, and 50% of the cities experienced positive growth in technological progress. The number of cities where technical efficiency was enhanced is the greatest, indicating that it is relatively easy to achieve GTFP growth by increasing technical efficiency.

Among the 9 cities that experienced positive growth in GTFP, 77.8% experienced positive growth in both technical efficiency and technological progress. Only 2 cities improved in technical efficiency alone, and no city experienced an increase in the technological progress index alone. This finding implies that the enhancement of GTFP relies mainly on the joint improvement in technical efficiency and technological progress. Merely depending on the improvement in one aspect cannot effectively facilitate the positive growth of GTFP. Simultaneously, this finding also reflects that for the improvement in GTFP in cities in Shandong, the contribution of technical efficiency is predominant.

Indicator	Number of cities with a corresponding indicator greater than 1	Proportion
GML index	9	56.25%
GEC index	12	75%
GTC index	8	50%
Total number of cities with GTFP improved	9	–
GEC > 1	9	100%
GTC > 1	7	77.78%
GEC > 1 and GTC > 1	7	77.78%
Total number of cities with GTFP declined	7	–
EC > 1	3	42.85%
TC > 1	1	14.28%

**Table 4.** Classification and statistical results of the GML of 16 cities in Shandong Province.

Among the seven cities with a decline in GTFP, the technical efficiency of three cities was enhanced, and the green technological progress of one city exhibited positive growth. This finding not only further confirms that enhancing GTFP alone cannot effectively improve GTFP but also indicates that the negative growth of GTFP in cities in Shandong is attributed to a significant deficiency in technological progress. This is consistent with the research results of Li et al. on the carbon emission reduction potential in Shandong Province. They pointed out that most cities' carbon emission reduction potential in Shandong Province are medium, and the carbon-control path should focus on increasing investment in green technology, especially oxy-combustion technology<sup>61</sup>. It is not difficult to infer that they also believe that the green transition of Shandong Province should mainly rely on the progress of green technologies. This reflects from the side that the relatively low GTFP level in Shandong cities is attributed to the deficiency in technological progress.

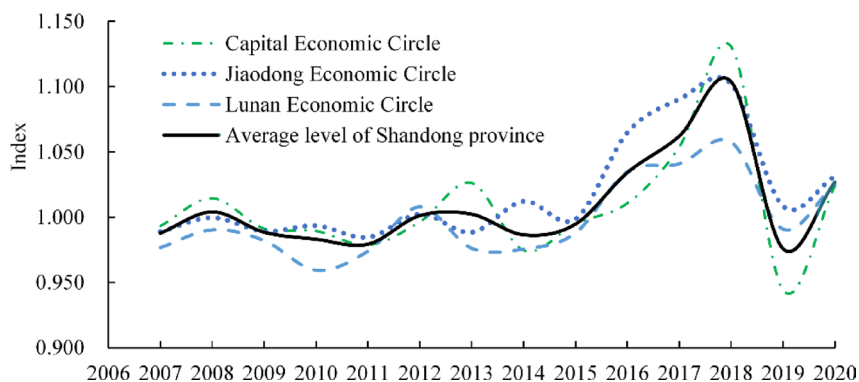
### Heterogeneity analysis of GTFP in the three major economic circles of Shandong

The 16 cities in Shandong Province can be categorized into three major economic circles—the provincial capital economic circle, the Jiaodong economic circle, and the Lunan economic circle. The changes in the GML indices of the three economic centers over time are presented in Fig. 3.

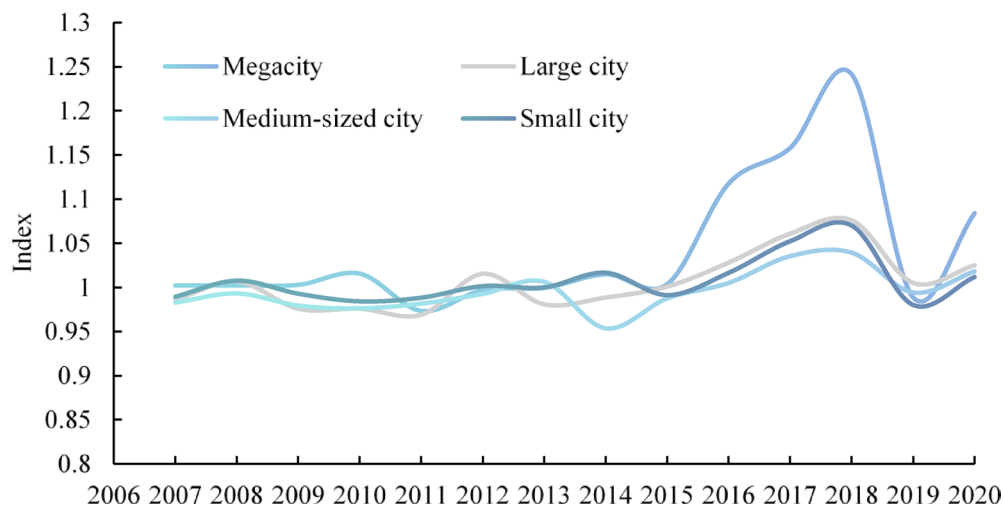
Overall, the changing trends of the GML index in the three economic centers are largely similar. Before 2014, they fluctuated but remained generally stable overall. Starting in 2015, they experienced a marked increase, and in 2019, they plummeted abruptly. The GML index of the provincial capital economic circle displayed the most pronounced fluctuations, with both the maximum and minimum values belonging to this circle. The geometric average of the GML index in the Jiaodong economic circle was the greatest, and its GTFP growth was the highest during the research period. The GML index of the Lunan economic circle was lower than those of the other two economic circles and lower than the provincial average. The geometric average was less than 1 during the research period, suggesting that GTFP ultimately decreased.

Furthermore, the changes in the GML index of the three major economic centers were analyzed in stages. Prior to 2011, the GML index of all three economic circles was essentially less than 1 and presented a downward trend. The GML index of the Lunan Economic Circle declined the most, whereas that of the Jiaodong Economic Circle was the most stable. This finding implies that throughout this period, the GTFP of the entire province was in a state of continuous decline, with the Lunan Economic Circle experiencing the greatest reduction and the Jiaodong Economic Circle the slightest. From 2011 to 2015, the GML indices of the Provincial Capital Economic Circle and the Jiaodong Economic Circle fluctuated significantly approximately 1, whereas that of the Lunan Economic Circle remained steadily less than 1. After 2015, the GML indices of all three economic circles substantially increased. The Jiaodong Economic Circle had the fastest growth rate, while the Provincial Capital Economic Circle began to grow the latest, but its subsequent growth trend continued to strengthen. In 2018, the GML index reached a maximum value of 1.131. In 2019, due to the implementation of the transformation from old growth drivers into new drivers, a number of “scattered, disorderly and polluting” enterprises were voluntarily shut down, and some backward production capacity was phased out. This situation led to a considerable decrease in the economic growth rate, thereby causing a sudden drop in the GML index. The Provincial Capital Economic Circle experienced the most significant decline. The GTFP of the Provincial Capital Economic Circle and the Lunan Economic Circle exhibited negative growth, whereas only the GTFP of the Jiaodong Economic Circle still maintained positive growth.

From the viewpoint of the sources of growth in the GTFP of the three major economic circles, the leading position of the Jiaodong Economic Circle in the GML index relies on technological efficiency. The enhancement of technological efficiency still constitutes the main impetus for the growth of GTFP in each economic circle, while the contribution of technological progress to GTFP is inadequate. The three major economic circles differ in terms of location, resource endowment, development stage and level. Consequently, they confront distinct development tasks and naturally play varying roles in the overall regional development of Shandong. The Provincial Capital Economic Circle has advantages in terms of policy and transportation. Jinan, as the leading city, has an edge in developing high-tech industries. However, currently, the other cities within this circle have not fully achieved synergy with Jinan. The Jiaodong Economic Circle possesses ports and marine resources, enjoying exceptional advantages for developing foreign trade. With its preeminent location advantages in terms



**Fig. 3.** Changes in the GML indices of different economic circles from 2007 to 2020.



**Fig. 4.** Changes in the GML index under the urban hierarchy from 2007 to 2020.

of infrastructure, technology, talent and information, its industrial structure outperforms other regions within the province. Additionally, cities in the Jiaodong area have close connections and have formed an effective and rational division of labor and cooperation mechanism in research and development and production processing. This area constitutes a concentration area for advanced manufacturing and high-end services in Shandong Province. The Lunan Economic Circle has the smallest scale in terms of cities, population and economy among the three circles. Its economic development foundation is the weakest, and it lacks seaports and a core city with absolute strength. The degree of internal economic collaboration is relatively low, and the development of low-carbon and high-tech industries is insufficient. It is difficult to increase the efficiency of resource allocation through effective market forces. Hence, its growth in GTFP is significantly lower than that of the Provincial Capital Economic Circle and the Jiaodong Economic Circle.

#### Heterogeneity analysis of GTFP under the urban hierarchy system

On the basis of the administrative levels of different cities and considering multiple factors such as GDP, transportation, population, and business, the 16 cities in Shandong Province are classified into the following four grades: megacities—Jinan and Qingdao; large cities—Yantai, Weifang, Linyi, and Zibo; medium-sized cities—Jining, Heze, Tai’an, Dezhou, Liaocheng, and Binzhou; and small cities—Weihai, Dongying, Zaozhuang, and Rizhao. The statistical results of the GML index of cities at different levels from 2007 to 2020 are presented in Fig. 4.

Prior to 2015, the GML indices of the four types of cities were approximately the same and remained in a state of dynamic stability. After 2015, the GML indices of all four types of cities began to increase, yet the growth rates of the GML indices in the two megacities, Jinan and Qingdao, were evidently greater than were those of other cities.

In general, the GML index of medium-sized cities was the smallest, and the GML index of large cities was comparable to that of small cities. Before 2015, the GML index of small cities was even higher than that of large cities and was second only to those of the two megacities, Jinan and Qingdao.

Jinan and Qingdao possess advantages such as human capital reserve superiority, economies of scale in the agglomeration economy, and well-established public infrastructure. These factors constitute significant driving factors for enhancing GTFP. Simultaneously, they are relatively strong in terms of public environmental consciousness and the implementation intensity of environmental policies. All these factors are beneficial for enterprises to form “sharing effects” and “learning effects” and to promote high-quality economic development through green technological innovation and improved technical efficiency.

For small cities, Dongying and Zaozhuang have resource advantages such as oil and coal, whereas Rizhao and Weihai, two coastal cities, possess geographical location advantages. All of these cities have identified distinctive industrial development patterns that are suitable for their own resource endowments and geographical location characteristics. As a result, the growth of GTFP in these cities is relatively substantial. However, for resource-based cities like Dongying and Zaozhuang, there is a risk of over-reliance on energy and insufficient development momentum. Their own resource endowments may instead restrict energy transition and hold back sustainable development. This is the energy trilemma that is increasingly being widely studied in the academic community<sup>62</sup>. Therefore, for the green transition of resource-based cities, the government should provide special funds to help establish a sustainable and resilient energy framework to cope with the energy transition.

Medium-sized cities neither possess the advantages of small cities nor evade the drawbacks of large cities. High-energy-consuming and high-pollution industries in megacities and large cities tend to be relocated to large and medium-sized cities rather than to smaller cities, thereby resulting in a relatively low GML index for medium-sized cities. For large and medium-sized cities, moderately expanding the population scale is beneficial

for further intensifying the pulling effects of the scale economy, the labor reservoir effect and the knowledge spillover effect on the growth of GTFP.

### Conclusions and policy implications

On the basis of the SBM-GML model, this paper measures the index of GTFP and its decomposed components of 16 cities in Shandong Province from 2007 to 2020. A spatiotemporal characteristic analysis of GTFP and its growth impetus is conducted from three dimensions: overall characteristics, regional variances, and urban scale hierarchies. The research indicates the following:

- (1) Overall, the GTFP, technical efficiency, and technological progress in Shandong Province have increased at average annual rates of 0.95%, 0.74%, and 0.21%, respectively. Prior to 2011, GTFP exhibited a year-on-year downward trend. During the period from 2011 to 2015, GTFP shifted to a slow growth trend. After 2015, it demonstrated significant positive growth. Before 2015, the variation in GTFP relied mainly on technical efficiency. After 2015, technological progress made a greater contribution to GTFP.
- (2) During the study period, the growth of GTFP in the Jiaodong Economic Circle was the greatest, followed by that in the Provincial Capital Economic Circle, whereas the overall trend in the Lunan Economic Circle declined. The enhancement of technical efficiency was the main impetus for the growth of GTFP and the principal cause for the disparity in GTFP among the economic circles. Strengthening the internal inter-connections within each economic circle and establishing an effective division of labor and collaboration mechanism to facilitate the improvement in resource allocation efficiency is an effective approach for each economic circle to increase GTFP in the short term. Nevertheless, in the long run, green technological innovation is the fundamental means through which to increase GTFP.
- (3) Within Shandong Province, the growth rates of GTFP in the two megacities of Jinan and Qingdao are clearly higher than those in other cities. The growth amplitude of the GTFP in medium-sized cities was the smallest, while the growth rate of the GTFP in small cities was second only to that of the two megacities after 2015. Regional megacities such as Jinan and Qingdao have advantages in terms of economy, talent, and infrastructure that are incomparable to those of other cities. Their GTFP growth has always led other cities, and they should exert their leading role.
- (4) This study has certain limitation in undesirable outputs. Only sulfur dioxide emissions, industrial wastewater emissions and industrial smoke dust emissions were selected, and carbon emissions were not considered. Although this limitation greatly reduces the practical value of this study, these selected undesired output indicators still meet the basic requirement for the evaluation of “green” performance. Sulfur dioxide, wastewater and smoke dust are the most commonly used and representative industrial pollution emission indicators in environmental statistic and academic research in China and even the world, covering the most major gaseous pollutants and water pollutants. Meanwhile, CO<sub>2</sub>, SO<sub>2</sub> and smoke dust have common main sources. The emissions of SO<sub>2</sub> and smoke dust can be indirectly related to carbon emissions to a certain extent. Therefore, selecting sulfur dioxide, wastewater and smoke dust as undesirable outputs can effectively represent the environmental pressure caused by the production activities, and can reflect the “green” connotation in reducing the traditional pollution emissions intensity and improving the resources utilization efficiency.

On the basis of the above research conclusions, the below policy implications are drawn.

From the growth trend and sources of GTFP in Shandong Province, it can be known that the improvement of GTFP mainly comes from the contribution of technical efficiency. This reflects that the promoting effect of technical efficiency on GTFP is mild and continuous. Improving technical efficiency provides a basic positive guarantee for the growth of GTFP. Therefore, through the means of resource integration and factor reset, the re-optimal combination of industries should be achieved. Relying on a scientific and green development approach, the efficiency of resource utilization should be promoted, thereby realizing the growth of GTFP. With the implementation of the old and new growth drivers transformation strategy in Shandong Province, the GTFP has significantly increased, and the contribution of technological progress to the GTFP has begun to dominate. This indicates that for industrial regions like Shandong where the proportion of traditional industries is relatively large, efforts should be made in technological innovation to enhance the GTFP. First of all, it is necessary to strengthen innovation-driven development and cultivate new growth drivers for rapid growth. Secondly, it is necessary to accelerate the application of new technologies in various fields such as industry and agriculture. Finally, it is necessary to accelerate the cultivation of scientific and technological talents and improve the quality of ordinary workers.

Second, based on the heterogeneity of GTFP in the three major economic circles within Shandong Province, it is necessary to scientifically coordinate the regional development layout, implement a regionally differentiated green economic development model, and give full play to the regional factor endowment. The provincial capital economic circle with Jinan at its core has a natural advantage in policy formulation and resource allocation. It can concentrate efforts on promoting major projects and infrastructure construction. We should make good use of policy opportunities such as the strong provincial capital strategy and the high-quality development of the Yellow River Basin, and strengthen regional coordinated development. Besides, it is necessary to accelerate the layout of emerging industries, and cultivate and expand strategic emerging industries such as artificial intelligence, big data, biomedicine and new energy. The Jiaodong economic circle has distinct characteristics of an export-oriented economy, obvious advantages in ports, and a relatively good industrial foundation. It should further give full play to its location advantage and make good use of the policy dividends of foreign trade towards South Korea, Japan, etc. Meanwhile, the five cities in Jiaodong have good industrial complementarity. They should do a good job in regional integrated development and vigorously develop the marine economy and

high-end equipment manufacturing fields. The development of the Lunan economic circle is relatively slow. It lacks a regional core city with strong radiation and driving effects, and its attraction to elements such as talents and funds is relatively insufficient. Its technological innovation capacity is relatively backward. However, in the national productive force layout, the Lunan economic circle has the location advantage of connecting the east and the west and linking the north and the south, with convenient transportation, which is conducive to exchanges and cooperation with the surrounding areas. Therefore, support should be given to the Lunan economic circle to undertake the industrial transfer from the Yangtze River Delta. Meanwhile, the Lunan economic circle should make good use of their labor force advantages, cultivate high-tech talents and enhance the competitiveness of regional human capital.

Third, taking into account the scale of the city and its resource endowment, provide classified guidance for the high-quality development. Regional core cities such as Jinan and Qingdao usually have a relatively high level of economic development and technological innovation capabilities. They have already achieved a high level of GTFP. The focus of their development should be on promoting technological innovation, strengthening the research of green technologies, and so on, in order to achieve breakthroughs in technological progress. In addition, by establishing and improving the innovation incentive mechanism, increasing investment in science and technology, and promoting the in-depth integration of industry, academia, research and application, its technological advantages and leading position in the green field can be further enhanced. Large cities like Yantai and Weifang have relatively developed economies and good industrial development. However, the lack of support in terms of talents and policies like in megacities makes the GTFP slightly insufficient. Therefore, exchanges and cooperation with core cities such as Jinan and Qingdao should be strengthened, advanced green technologies and management models should be introduced, and technical progress should be achieved. The size of a city is not necessarily the larger the better. The GTFP of a medium-sized city is not as good as that of a small city. Medium-sized cities have a larger population. Due to the lack of industries to drive employment, they can only receive industrial transfers from big cities, which may lead to relative backwardness in economic development and technological progress, and there are relatively serious pollution problems. Therefore, medium-sized cities should transform their economic development mode and strengthen environmental control. The focus of development should lie in enhancing technology introduction and utilization. Small cities usually have advantages in resource endowment and relatively high GTFP levels. However, the resource endowment of small cities is often a double-edged sword. Problems such as resource traps, population outflow, and location marginalization may also be exposed. Therefore, small cities should, in light of their own resource endowments and industrial foundations, actively explore green development paths suitable for their regions and should not blindly pursue GDP. The government needs to strengthen the ecological protection and compensation mechanism. It is necessary to provide special fund support for small cities with a relatively high degree of resource dependence to improve the GTFP.

## Data availability

The datasets used and/or analyzed in this study are available upon request from the corresponding author.

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M.M.: Conceptualization, Writing-original draft, Methodology, Discussion.Y.Y.: Methodology, Data collection.Y.M.: Data collection.Z.W.: Conceptualization, Methodology, Discussion, Review and editing.All authors reviewed the manuscript.

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### Declarations

### Competing interests

The authors declare no competing interests.

### Additional information

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