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The green productivity of broiler production in China: Considering the resource utilization of manure

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ABSTRACT

Resource constraints and environmental challenges have emerged as serious impediments to the sustainable development of China's broiler industry, with potentially adverse consequences. The pursuit of sustainable development in China's broiler industry is predicated on significant reductions in manure and pollutant emissions from broiler farming. This study utilizes the slacks-based model and the global Malmquist-Luenberger index to calculate the green total factor productivity of broiler breeding across various provinces and scales from 2005 to 2020 within a joint production framework of considering undesirable outputs and desirable outputs. Fluctuations in economic distribution of broiler breeding are characterized using the kernel density estimation, and a convergence analysis is performed via absolute and conditional β convergence methods. The results revealed an overall upward trend in China's broiler farming green total factor productivity from 2005 to 2020, corresponding to green total factor productivity in small-, medium-, and large-scale broiler breeding were 1.015, 1.017, and 1.009, respectively. The kernel density curve implies a narrowing trend in the discrepancy of green total factor productivity levels among provinces in broiler breeding of varying scales. For all scales, broiler breeding's green total factor productivity demonstrates considerable conditional and absolute β convergence. Therefore, improving the efficiency of broiler breeding while addressing externalities requires the cultivation of broilers at different scales across diverse regions, coupled with an increased focus on improving the utility efficiency of broiler waste fertilization.

1. Introduction

The broiler sector has become the most industrialized industry in China's animal husbandry sector with its inherent advantages of high efficiency and low costs. In 2021, China's broiler production reached 14.7 million tons, cementing its status as the world's second largest broiler producer [1]. The increase in broiler production capacity has provided the market with ample supplies of chicken meat. With changing consumption patterns, there has been a marked increase in white meat intake in China, particularly chicken. Presently, the per capita consumption of chicken meat is second only to pork, underscoring its role as an important source of protein for the Chinese people [2]. The rapid growth of broiler chickens has made an important contribution to the improvement of people's nutritional level, accompanied by a large amount of broiler manure. Nitrogen excretion from manure produced by poultry and broiler farming in China has increased from 53.9 kt in 1961 to 762.4 kt in 2022, according to FAO estimates (faostat.fao.org). In further research, scholars have established that the rising demand for animal products is fueling this growing amount of manure produced.

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This situation dwarfs livestock manure as the main environmental threat, driving the planet ever further beyond its carrying capacity [3,4]. However, the nutrient-rich composition of poultry manure, largely due to its short digestive tract and low feed utilization rate, coupled with its low water content, makes it a viable resource for the production of biogas, organic fertilizer, and activated carbon [5,6]. Therefore, considering the resource utilization of broiler manure is necessary for a comprehensive assessment of broiler breeding.

Scale is the key to modernizing agriculture as it enhances total production capacity and reduces production costs. Over the past six decades, this input intensification has been the primary engine of agriculture's average annual growth of 2–2.5 %. In recent years, China's broiler farming mode gradually transitioned from free-range to large-scale breeding due to the rising costs of livestock and poultry cultivation brought on by rising agricultural labor and grain prices [7–10]. Broiler farming demonstrates considerable heterogeneity across different scales. For example, large-scale broiler farming has strengths in energy consumption and pollutant control costs, buoyed by advanced technological equipment and proficient management experience. This makes scale-based analysis of broiler production important [11]. While large-scale farming yields significant economies of scale, it simultaneously demands an increased emphasis on managing the environmental impacts of manure production-a facet frequently disregarded by farmers. In light of China's commitment to peak CO2 emissions by 2030 and reach carbon neutrality by 2060, it becomes incumbent on broiler farmers to balance economic profitability with ecological stewardship [12,13]. It starts with the primary goal of boosting desirable agricultural output coupled with minimizing undesirable output. Therefore, it is vital to study the pollution management strategies of broiler farming at different scales in the context of large-scale farming to realize the green development of agriculture.

Total factor productivity (TFP), an important indicator of productivity in the production system, serves a pivotal role in driving agricultural economic growth. Since the 1990s, innovations aimed at increasing the efficiency of labor, land, capital, and other inputs have primarily fueled global agricultural output growth, i.e., TFP growth [7]. TFP measurements have traditionally been calculated using parametric and non-parametric methods, among which data envelopment analysis was the most representative in non-parametric method [14,15]. A study utilizing Data Envelopment Analysis (DEA) found exceptionally high technical efficiency in broiler production in Northern Thailand from 2015 to 2019. Factors such as farmer literacy, season, and age positively impacted the technical efficiency of broiler production [16]. Parametric methods such as stochastic frontier models have gained wide acceptance in economic research to measure production efficiency. An assessment of broiler farming productivity in Thailand using a stochastic frontier approach revealed low technical efficiency of broiler farms in Chiang Mai, Thailand. Feed, bird stock, fixed costs, and total variable costs were important factors affecting broiler production in Chiang Mai [17].

Green total factor productivity (GTFP) is a further development of TFP, including the inclusion of undesirable outputs, which can effectively reflect the real agricultural production efficiency and the level of agricultural economic development [18]. A considerable number of scholars have studied the level of green development in agriculture using GTFP. Utilizing two DEA models to measure China's agricultural GTFP from 1998 to 2019, it was found that China's agricultural GTFP made great progress over the study period, with the greatest growth of Green Luenberger productivity indicator in the central region, followed by the western and eastern regions [19]. A more comprehensive assessment of GTFP was carried out using a non-separable undesirable output-modified, three-stage DEA, which indicated an upward trend in actual AGTFP in the sample [20]. Spatially, there are clear regional differences across the country. The environmental total factor productivity (ETFP) of animal husbandry was measured using the slack-based measure directional distance and meta-frontier efficiency functions in all provinces and six major livestock-producing regions from 2001 to 2017. It was discovered that the mean value of ETFP exceeded that of traditional total factor productivity, with technological advances as the primary driver of ETFP growth [21]. Tone [22] proposed a non-radial and non-angular distance function model, known as the Slacks-Based Measure (SBM) model, which can provide more accurate and realistic efficiency scores for DMUs, albeit lacking the capacity to manage undesirable outputs. Tone [23] further developed the SBM model to calculate of undesirable outputs directly. This enhanced model has since laid the foundation for a considerable amount of subsequent research in the field of efficiency measurement. Sun et al. [24] employed the SBM-ML model to assess the energy efficiency of the service industry across various provinces in China from 2007 to 2017, and the findings revealed that the overall energy efficiency of the service industry exhibited a W-shaped fluctuation, with the improvement of energy efficiency in the sector primarily driven by technological advancement. Li & Chen [25] applied the SBM-ML model to measure GTFP of urban agglomerations in the Pearl River Delta. Their research indicated a wave-like growth pattern in PRD cities' GTFP, with Shenzhen's GTFP consistently demonstrating a top-tier level throughout the sample period. Existing studies on undesirable outputs of livestock farming have predominantly focused on non-point source pollution and carbon emissions, largely overlooking the implications of livestock excrement [19,26–28]. Therefore, this study incorporates poultry and livestock manure in the analysis of GTFP as an undesirable output, while the potential carbon sequestration resulting from effective manure utilization is assessed as a desirable output.

With regard to an overview of the existing research, when contrasting the GTFP with traditional total factor productivity, it is important to highlight that the GTFP indicator offers a comprehensive assessment of production efficiency and ecological efficiency [29,30]. GTFP is a critical indicator for assigning significance to sustainable practices in the utilization and management of environmental, resource, social, and economic aspects within production activities. This holistic approach results in a more robust and objective assessment of the growth of both the green industry and the overall economy [31,32]. Yet, the majority of current research on GTFP predominantly centers around specific sectors, such as manufacturing, aquaculture, agriculture, etc., and a limited number of studies have delved into assessing specific varieties within these industries [33–35]. Therefore, the novel and rational application of this index to measure the green productivity of Chinese broilers is an innovative effort. With the conventional SBM-ML model and DDF-ML model constituting the prevailing methodologies in current studies for calculating GTFP, the approach in this study is the application of SBM-GML. It not only addresses the inadequacy of the standard DEA method in handling undesired output but also addresses the inherent limitations of linear programming by integrating the production unit into the global reference set of the GML index [36–38]. In summary, this study utilizes the SBM-GML model to measure GTFP of broiler farming across different scales and provinces in China, spanning the period from 2005 to 2020. The kernel density estimation is applied to portray the dynamics of broiler farming's GTFP, and both absolute β convergence and conditional β convergence are employed to conduct convergence analysis on GTFP of broiler farming.

The main contributions of this paper are as follows. First, the SBM-GML model was used to calculate GTFP at different scales of broiler farming in China and further decompose it into efficiency change (EC) and best-practice change (BPC). This theoretically expands the research boundary of GTFP and provides a new research idea for the green production efficiency of specific agricultural product varieties. Second, it takes into account the manure generated in the broiler farming process comprehensively, and includes the amount of carbon sequestration from manure utilization as a desirable output, which provides a new research direction for agricultural waste management. Before that, resource-based manure was often ignored or regarded as an undesirable output. Third, the dynamic evolution trend of GTFP of broiler farming at various scales in China was depicted using kernel density estimation. These results can provide valuable decision-making references for regional different scales of broiler breeding, environmental protection, and sustainable development policies. Fourth, the convergence of GTFP of broiler farming was analyzed using conditional β convergence and absolute β convergence.

This article is structured in six sections. The first section describes the background and the relevant literature on GTFP and SBM-GML. The second section is main methods. The third section is data sources employed in this paper. Section 4 presents and demonstrates the empirical results. Section 5 discusses the contribution and limitations of this research. Section 6 provides policy implications.

2. Methodology

The DEA model, based on linear programming, is a widely employed tool to identify the economic production frontier, and therefore measure the production efficiency of decision-making units (DMUs) [39]. However, the conventional DEA models, both radial and angular, have certain limitations. Radial DEA models are prone to overestimate the efficiency value of DMUs; and angular DEA models, on the other hand, cannot avoid the bias of angle selection and lead to discrepancies in the efficiency values of DMUs. To address the above problems, a non-radial and non-angle SBM distance function model is proposed [40]. The equation is expressed as follows (1):

$$
\begin{aligned}
&\rho^{*} = \min\left[\left(1-\frac{1}{N}\sum_{n=1}^{N}\frac{s_n^x}{x_{k'n}^t}\right)\Big/\left(1+\frac{1}{M}\sum_{m=1}^{M}\frac{s_m^y}{x_{k'm}^t}\right)\right]\\
&s.t.\sum_{k=1}^{K}\lambda_k^t x_{kn}^t + S_n^x = x_{k'n}^t, n=1,\dots,N\\
&\sum_{k=1}^{K}\lambda_k^t y_{km}^t - S_m^y = y_{k'm}^t, m=1,\dots,M\\
&\lambda_k^t \geq 0, S_n^x \geq 0, S_m^y \geq 0, k=1,\dots,J
\end{aligned}
\tag{1}
$$

The objective of measuring broiler chickens' GTFP in China under environmental constraints is to increase desirable outputs while reducing undesirable outputs. The non-radial and non-angular SBM distance function model lacks a direct mechanism for dealing with undesirable outputs, thus Tone modified the SBM model, leading to the proposition of a revised SBM distance function model capable of effectively managing undesirable outputs [41].

$$
\begin{aligned}
&\overrightarrow{S^t}\left(x_k^t, y_k^t, z_k^t\right) = \rho^{*} = \min\left\{\left(1-\frac{1}{N}\sum_{n=1}^{N}\frac{s_n^x}{x_{k'n}^t}\right)\Big/\left[1+\frac{1}{M+J}\left(\sum_{m=1}^{M}\frac{s_m^y}{y_{k'm}^t}+\sum_{j=1}^{J}\frac{s_j^z}{z_{k'j}^t}\right)\right]\right\}\\
&s.t.\sum_{k=1}^{K}\lambda_k^t x_{kn}^t + s_n^x = x_{k'n}^t, n=1,\dots,N\\
&\sum_{k=1}^{K}\lambda_k^t y_{km}^t + s_m^y = y_{k'm}^t, m=1,\dots,M\\
&\sum_{k=1}^{K}\lambda_k^t z_{kj}^t + s_j^z = z_{k'j}^t, j=1,\dots,J\\
&\lambda_k^t \geq 0, s_n^x \geq 0, s_m^y \geq 0, s_j^z \geq 0, k=1,\dots,K
\end{aligned}
\tag{2}
$$

In equation (2), $\underset{s^t}{\rightarrow}$ represents the SBM distance function, s_n^x is the input slack variables indicating input excess, s_m^y and s_j^b are the output slack variables indicating desirable outputs deficit and undesirable outputs excess, respectively. λ_k^t is the weight coefficient vector.

The productivity for DMUs is calculated for each period utilizing the directional distance function after establishing the production frontier based on the benchmark period. The geometric mean of the productivity index for the two adjacent periods is then solved, and it is used to calculate the productivity change to obtain the productivity index. Fare constructed a DEA-based Malmquist productivity index, and decomposed the M productivity index into a technical progress index and a technical efficiency change index. When the M index is calculated using linear programming, the model cannot be solved. Pastor and Lovell developed the GM index that satisfied the circularity requirements while generating solutions and existing technical regression, and further decomposed into EC and BPC to estimate broiler production in China [42,43].

$$\begin{aligned} M_c^G\left(x^t, y^t, x^{t+1}, y^{t+1}\right) &= \frac{D_c^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_c^t\left(x^t, y^t\right)} \times \left\{\frac{D_c^G\left(x^{t+1}, y^{t+1}\right)}{D_c^{t+1}\left(x^{t+1}, y^{t+1}\right)} \times \frac{D_c^t\left(x^t, y^t\right)}{D_c^G\left(x^t, y^t\right)}\right\} \\ &= \frac{TE_c^{t+1}\left(x^{t+1}, y^{t+1}\right)}{TE_c^t\left(x^t, y^t\right)} \times \left\{\frac{D_c^G\left(x^{t+1}, y^{t+1}\right)/D_c^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_c^G\left(x^t, y^t\right)/D_c^t\left(x^t, y^t\right)}\right\} \\ &= EC_c \times \left\{\frac{BPG_c^{G,t+1}\left(x^{t+1}, y^{t+1}\right)}{BPG_c^{G,t}\left(x^t, y^t\right)}\right\} \\ &= EC_c \times BPC_c \end{aligned} \tag{3}$$

Equation (3) is GML index and its decomposition. EC measures the proximity of production units from the actual production point to the production possibilities frontier from period t to t+1; the change in BPC is a geometric mean that measures the dynamic change in an outward shift of the production possibilities frontier. GTFP, BPC, and EC > 1 indicate improvements in green productivity growth, green technology progress, and green technology efficiency, respectively. Conversely, GTFP, EC, and BPC <1 indicate a deterioration in green productivity, green technology progress, and green technology efficiency, respectively.

Kernel density estimation (KDE) was a non-parametric method widely used in modern empirical studies to describe the distribution state of research objects [44,45]. It is applied to estimate the density of GTFP of broiler chickens in China, which can effectively explore the dynamic evolution trend of broiler sample distribution. Assuming the density function of the random variable x is f(x), the density at point x can be estimated as follows:

$$f(x) = \frac{1}{Nh} \sum_{i=1}^{N} K\left(\frac{X_i - x}{h}\right) \tag{4}$$

In equation (4), N is the number of observations, h is the bandwidth, X_i is the sample value of GTFP of broiler chickens, and x is the mean of GTFP.

This study briefly introduces the absolute β convergence model and the conditional β convergence model adopted in previous research to identify GTFP convergence of broiler chickens in China [46,47].

$$\frac{1}{T} \ln\left(\frac{GTFP_{i,t}}{GTFP_{i,0}}\right) = \alpha + \beta \ln GTFP_{i,0} + \varepsilon_i \tag{5}$$

Equation (5) is the absolute β convergence model, where $GTFP_{i,0}$ and $GTFP_{i,t}$ denote GTFP in i region of the base and end periods, T is the number of periods; ε_i is the random error term; α and β are the estimated coefficient, and $\beta < 0$ indicates that GTFP has an absolute β convergence trend.

Since the underlying conditions of agricultural production are regional heterogeneity, the absolute β convergence is difficult to be satisfied. The conditional β convergence model is typically based on the absolute β convergence test model, with some control variables reflecting different individual characteristics added. According to Miller and Upadhyay, the two-way fixed effects model accounts for both the fact that different individuals have different steady-state equilibrium levels and that the steady-state equilibrium levels of these different individuals are affected by time changes, so this study directly employs the two-way fixed effects model to test the conditional β convergence of GTFP in broiler chickens [48]. The model is designed as follows:

$$\ln\left(\frac{GTFP_{i,t}}{GTFP_{i,t-1}}\right) = \alpha + \beta \ln GTFP_{i,t-1} + \mu_i + \delta_t + \varepsilon_i \tag{6}$$

Equation (6) is the conditional β convergence model, where $\ln \frac{GTFP_{i,t}}{GTFP_{i,t-1}}$ denotes the growth rate of GTFP of broiler farming from period t-1 to period t, μ_i and δ_t denote individual fixed effects and time fixed effects, and $\beta < 0$ indicates that GTFP has a conditional β convergence trend.

Table 1
Selection of main sample provinces.

Type	Sample size	Province
Large Scale	153	Anhui, Beijing, Fujian, Guangdong, Guangxi, Henan, Hunan, Tianjin, Yunnan
Middle Scale	272	Fujian, Guangdong, Guangxi, Hainan, Henan, Heilongjiang, Hubei, Hunan, Jilin, Liaoning, Inner Mongolia, Ningxia, Shandong, Shanxi, Yunnan, Zhejiang
Small Scale	68	Hainan, Henan, Heilongjiang, Jilin

3. Data

Compilation of National Agricultural Product Cost Benefit Data (2004–2020), issued by the Price Department of the National Development and Reform Commission, contains information on the cost-benefit, costs, and labor information of broiler chickens used in this study. As shown in Table 1, this text selects sample provinces for broiler farming at various scales. The large scale includes 9 provinces (Anhui, Beijing, Fujian, Guangdong, Guangxi, Henan, Hunan, Tianjin, Yunnan); the middle scale includes 16 provinces (Fujian, Guangdong, Guangxi, Hainan, Henan, Heilongjiang, Hubei, Hunan, Jilin, Liaoning, Inner Mongolia, Ningxia, Shandong, Shanxi, Yunnan, Zhejiang); and the small scale includes 4 provinces (Hainan, Henan, Heilongjiang, Jilin). We defined large, middle, and small scales for broiler farming following the categories of official statistical yearbook, in which small scale broiler farming refers to farms with an annual output of less than 2000 birds per year, middle scale broiler farming ranges from 2001 to 10000 birds, and large scale broiler farming exceeds 10000 birds.

According to the principles of scientificity, objectivity, and availability of data selection, this paper selects the following indicators to measure GTFP of broiler chickens.

(1) Inputs include material costs, number of labors, number of concentrates, and number of food consumption. Material cost is the price indicator, which is the sum of Piglet fee, water and fuel power fee, and other costs, converted to 2004 constant prices using the Price Index of Agricultural Means of Production in the "China Statistical Yearbook".
(2) Outputs refer to broiler meat production and the amount of carbon sequestered from manure produced in broiler farming.
(3) Undesirable outputs refer to pollutant emissions and manure emissions in broiler farming.

$$UF = Days \times Coef_{UF} \tag{7}$$

The amount of manure produced is calculated in Equation (7), where UF represents the amount of manure produced in broiler farming. Days is the number of feeding days, $Coef_{UF}$ is the coefficient of manure production [49].

$$CS = UF \times Coef_{CS} \tag{8}$$

Manure utilization contributes to carbon sequestration as it can be used to create organic fertilizers by converting to biomass energy. Equation (8) is used to calculate the amount of manure carbon sequestration produced in broiler farming. Where UF is the amount of manure in equation (7), CS is the amount of manure carbon sequestration, and $Coef_{CS}$ is the coefficient of carbon sequestration [50,51].

$$FD = Days \times Coef_{FD} \tag{9}$$

With reference to the calculation method of Zhong et al. (2021), Equation (9) calculates the number of various pollutants produced during broiler farming, mainly including OCD, TN, and TP, where FD denotes the emission amounts of a certain pollutant, Days denotes the number of feeding days and $Coef_{FD}$ denotes the emission coefficient of a certain pollutant [52].

Table 2
Descriptive statistics of input and output indicators.

Type	Criterion layer	Index	Mean	Std. Dev	Max	Min
Small Scale	Input	Labor hours	5.55	2.22	13.65	2
		material fees	1319.23	149.69	1628.9	1021.98
		grain concentrate	583.35	110.51	735.3	371
		Grain consumption	412.06	86.6	569.8	246.8
	Desirable outputs	Main product output	247.17	65.59	350	133.5
		carbon sequestration	152.39	63.62	228.96	54.61
	Undesirable output	Total pollutants	99.63	55.89	166.89	26.46
		Urine feces	718.83	300.1	1080	257.64
Middle Scale	Input	Labor hours	3.91	1.87	14.8	0.74
		material fees	1330.85	351.63	3441.44	658.75
		grain concentrate	547.56	149.54	1603.5	243.11
		Grain consumption	390.23	120.79	1379.01	30.68
	Desirable outputs	Main product output	225.65	56.79	409.42	118.3
		carbon sequestration	178.94	113.39	725.25	54.24
	Undesirable output	Total pollutants	90.15	52.59	326.97	21.74
		Urine feces	844.06	534.87	3421	255.84
Large Scale	Input	Labor hours	2.35	1.09	6.3	0.76
		material fees	1486.41	417.36	2433.49	603.08
		grain concentrate	520.95	147.79	990.92	42.03
		Grain consumption	370.32	111.51	792.73	39.97
	Desirable outputs	Main product output	211.04	48.19	303	100
		carbon sequestration	167.55	136.69	563.55	53.92
	Undesirable output	Total pollutants	78.09	76.32	295.67	19
		Urine feces	790.32	644.77	2658.26	254.34

$$Total \quad pollutants = \frac{COD}{40} + \frac{TN}{2} + \frac{TP}{0.4} \tag{10}$$

According to class GB3838-2002 water quality standard in V, Equation (10) is used to calculate the total pollutants as the second undesirable output. Descriptive statistics of input and output indicators are shown in Table 2.

4. Results

Through calculation, the average GTFP and decomposition of different scales in China's broiler farming from 2005 to 2020 is shown in Table 3.

The overall GTFP shows a positive trend (Fig. 1). From 2005 to 2020, GTFP of large-, middle- and small-scale broiler farming is 1.015, 1.017 and 1.015, and the average annual growth rates are 1.5 %, 1.7 % and 0.9 % respectively, with middle scale showing the greatest degree of improvement, followed by large scale, and small scale showing the lowest growth.

In terms of the influencing factors on GTFP of broiler farming in China, both EC and BPC show positive contributions (Fig. 2a and b). From 2005 to 2020, the EC for large-, middle-, and small-scale was 1.009, 1.002, and 1.005, with average annual growth rates of 0.9 %, 0.2 %, and 0.5 %, respectively. The BPC for large-, middle-, and small-scale was 1.014, 1.020, and 1.006, with annual growth rates of 1.4 %, 2 %, and 0.6 %, respectively. Notably, BPC primarily facilitates the faster growth of GTFP in middle- and large-scale broiler farming sectors, since large-scale and medium-scale farming subjects (farms/households) demonstrate a higher propensity for technological innovation and technology application. In contrast, the slow growth of both EC and BPC constrains GTFP in small-scale farming, mainly due to the limited financial capacity of these farmers to adopt advanced technologies and the practical obstacles hindering the achievement of optimal technical efficiency. Analysis of the temporal trend reveals that GTFP in middle-scale broiler farming experiences consistent and gradual fluctuations over time, in sharp contrast to the significant fluctuations observed in both small- and large-scale sectors. Post-2012, there was a marked performance in GTFP growth trend. This enhancement can be attributed to the general policy issued by the Chinese government, which emphasizes a shift towards sustainable development practices in response to escalating environmental concerns. From the decomposition index of GTFP, small scale sector is underperformed in both EC and BPC from 2005 to 2020, serving as the primary explanation for the slow growth of GTFP. For medium-scale subjects, the influence of BPC surpasses that of EC, driven by these farmers' willingness to adopt innovative technologies and increase the scale of farming to boost income. However, limited technological adoption and a lack of skilled proficiency negatively affect the EC. As for the large-scale sector, both EC and BPC play a vital role in promoting GTFP.

In terms of regional comparison, the top three provinces of GTFP in large-scale are Hunan (1.028), Fujian (1.026), and Beijing (1.024), representing the average annual growth rates of 2.8 %, 2.6 %, and 2.4 %, respectively. While the bottom three provinces are Tianjin (1.005), Yunnan (1.003), and Anhui (0.995). In the context of medium-scale broiler farming, Hubei, Henan, and Heilongjiang emerge as the top performers with GTFP of 1.051, 1.043, and 1.042, with the average annual growth rates of 5.1 %, 4.3 %, and 4.2 %, respectively; whereas slow GTFP growth is observed in Ningxia, Shanxi, and Yunnan, with average annual growth rates of 0.2 %, 0.3 %, and −0.4 %, respectively. Given the small-scale sector, GTFP in Heilongjiang, Henan, Hainan, and Jilin is 1.017, 1.017, 1.008, and 0.994, the respective average annual growth rates are 1.7 %, 1.7 %, 0.8 %, and −0.06 % (Fig. 3a–c).

The KDE is employed to explore the dynamic evolution pattern of GTFP in China's broiler farming throughout the study period. This approach not only describes the overall distribution pattern across various scales, but also analyzes the dynamic evolution characteristics of the green production level in broiler farming by comparing different periods.

In this study, the dynamic evolution of GTFP in broiler farming at different scales in China is studied using the KDE (Fig. 4). This analytical approach facilitates a comprehensive portrayal of distribution characteristics across varying scales and analyzes the dynamic evolution of green production levels of broilers in different periods.

Fig. 4a reflects the evolution trend of GTFP in large-scale broiler farming. The trailing of the annual kernel density curve paints a left-right-left shift, indicating a widening gap between provinces due to the slower GTFP growth rate in large-scale regions. The curve transitions from a unimodal distribution to a bimodal distribution, highlighting a bipolarity characteristic in GTFP across large-scale sectors. The main peak height follows an "increase-decrease-increase" pattern, revealing the interprovincial imbalance in large-scale sectors. The center of the kernel density curve substantially skews to the left, with all values are greater than 1, signifying a slower growth rate in GTFP.

Fig. 4b represents the evolution trend of GTFP in medium-scale broiler farming. The left trailing of the kernel density curve is shorter than the right trailing, and the curve's variation range shows a narrowing-then-widening pattern, revealing a similarly fluctuating trend in the development gap of GTFP in medium-scale broiler farming. Regarding peak shape, a transition from a double-peak in 2005 to a single-peak in 2020 signifies a unipolarity development pattern. The height of main peak first rises and then decreases, indicating a shrinking-then-expanding development gap in the medium-scale sector. The central position of the kernel density curve

Table 3
The average GTFP and Decomposition of different scales in 2003–2020.

Type	GTFP	EC	BPC
Large Scale	1.015	1.009	1.014
Middle Scale	1.017	1.002	1.02
Small Scale	1.009	1.005	1.006

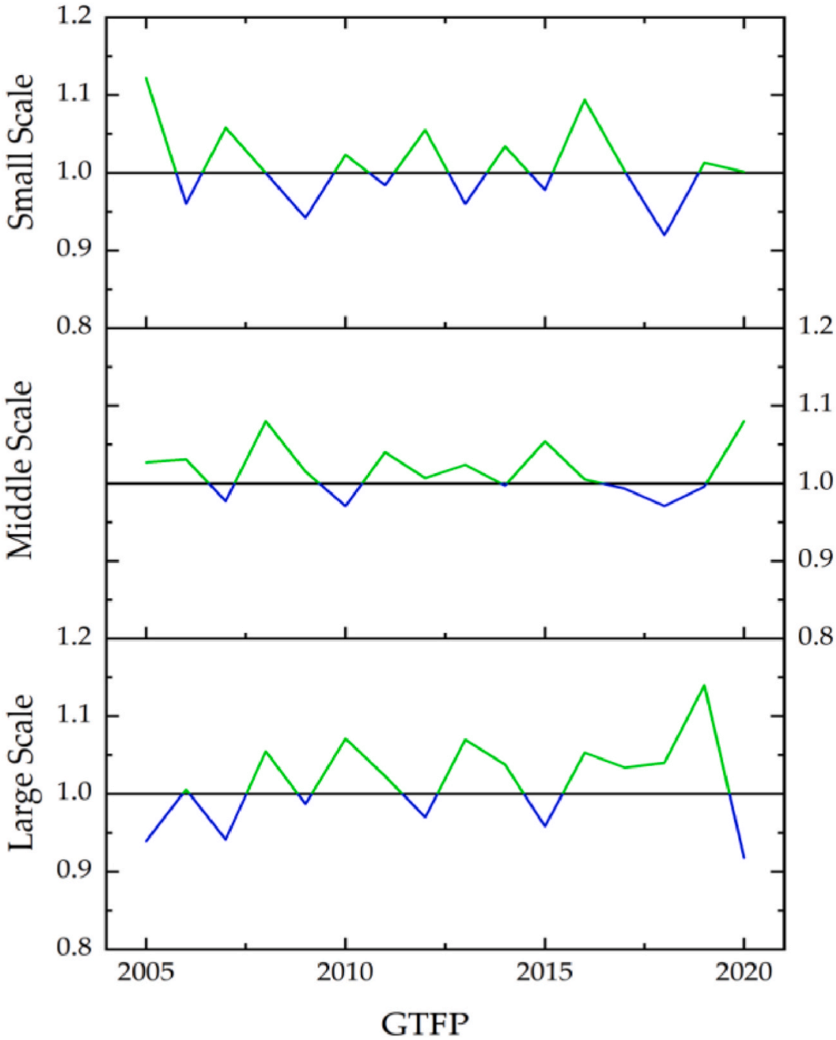


Fig. 1. Time trends for different scales of GTFP.

exhibits a slight left-skewed distribution, but all values are to the right of 1, implying a slower GTFP growth rate in the medium-scale sector. In 2014, the Regulation on the Prevention and Control of Pollution from Large-scale Breeding of Livestock and Poultry was issued by the State Council of the People's Republic of China, aimed at mitigating pollution from livestock and poultry farming incorporated considerations of the environmental carrying capacity and the requisites for pollution prevention, inadvertently widened the development gap in GTFP, resonating more with middle- and large-scale farmers across provinces.

Fig. 4c displays the evolution trend of GTFP in small-scale broiler farming. The disappearing trailing of the kernel density curve signals a reduction in inter-provincial differences of GTFP in small-scale broiler sectors. The steadily rising main peak height illustrates a narrowing development gap of GTFP on small-scale sectors after 2010. Over time, the center position of the kernel density curve approaches 1, indicating a gradual stagnation in GTFP growth. Government regulations implemented since the 18th CPC National Congress, specifically targeting pollution prevention and control in livestock and poultry farming, forced many small-scale farmers who are unable to meet environmental standards to exit the market. This further contributed to narrowing the development gap within small-scale broiler farming.

The estimation results, obtained through the least squares method (equation (5)), are presented in Table 4. These results illustrate that the coefficients of the initial condition variables for large-, middle- and small-scale broiler farming are significantly negative, indicating a significant absolute β convergence trend of GTFP in all breeding scales.

The study estimates the absolute β convergence of GTFP in broiler farming using a two-way fixed effect model. The results are presented in Table 5, where the coefficients of large-, medium- and small-scale sectors are −1.357, −1.427 and −1.352, respectively. These coefficients are statistically significant at the 1 % significance level, indicating a significant β convergence of GTFP across all scales. Through this convergence analysis, this paper illustrates a decline in GTFP growth rate and the convergence towards a stable equilibrium of GTFP in three breeding scales in China.

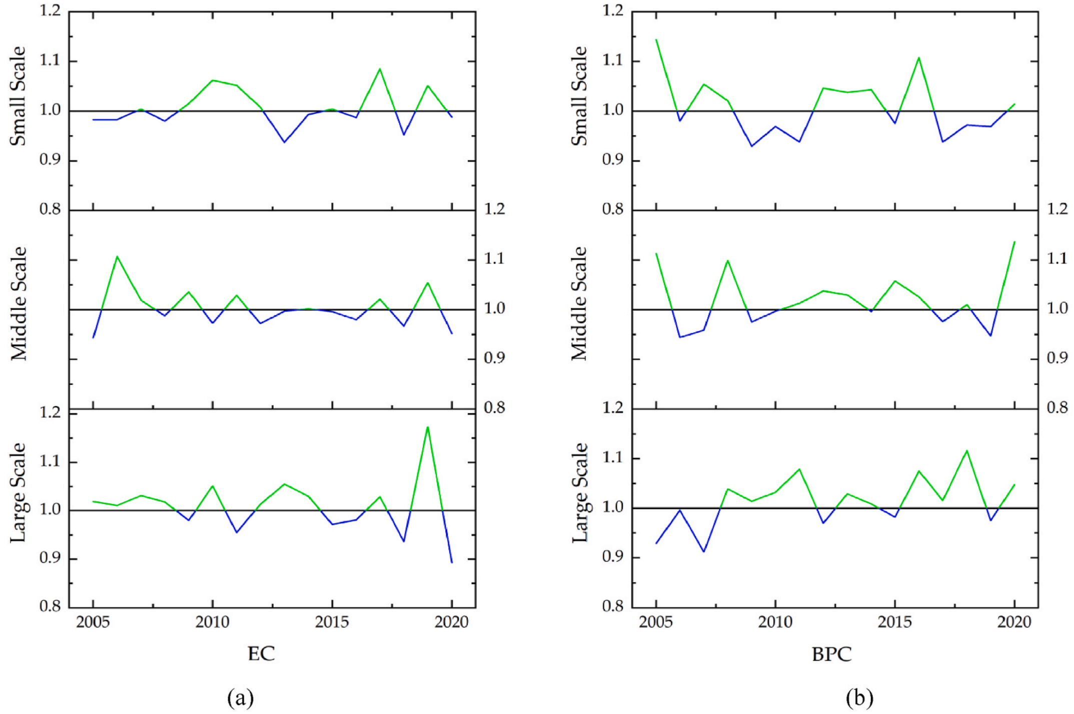


Fig. 2. (a). Time trends for different scales of BPC. (b). Time trends for different scales of EC.

5. Discussion

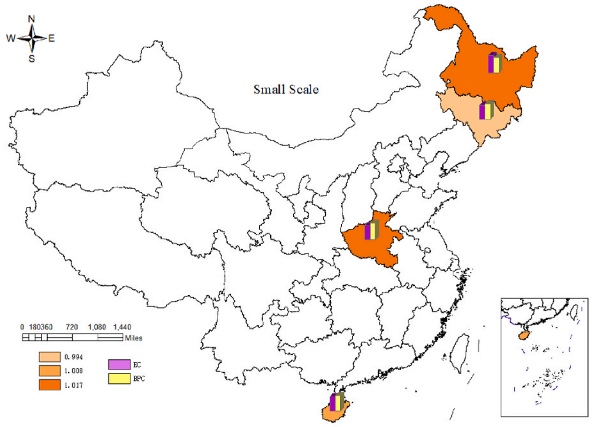
Concurrently, the environmental challenges posed by livestock and poultry farming have serious impediments to the industry's sustainable development. Improper treatment of livestock manure and poultry wastes not only worsens the environment but also directly impedes the overall enhancement of the benefits of the broiler industry. Considering the potential resource utilization of broiler manure, this study selects sample provinces in China, specifically nine for large-scale broiler farming, sixteen for medium-scale broiler farming, and four for small-scale broiler farming, covering the period from 2004 to 2020. Using the SBM-GML model, the kernel density estimation method, absolute β convergence and conditional β convergence, this study calculates GTFP of broiler farming, illustrates its evolution trend at various scales and analyzes the convergence.

The estimation results suggest that GTFP of large-, middle- and small-scale broiler farming from 2005 to 2020 was 1.015, 1.017 and 1.015, respectively. The average annual growth rates were 1.5 %, 1.7 % and 0.9 %, respectively. In terms of temporal trends, the middle-scale broiler farming exhibited the smallest fluctuation range, followed by the small-scale and then large-scale sector. Middle-scale broiler breeders display a more sensitive response to the latest policies compared to small-scale and large-scale ones.

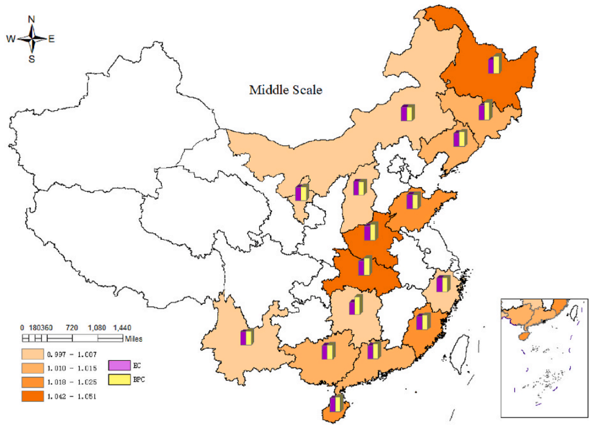
Index decomposition analysis reveals the coexistence of low EC and low BPC in small-scale broiler farming. In middle-scale farming, the contribution of BPC, driven by farmers' willingness to adopt new technologies and expand the breeding scale, was greater than EC. Large-scale farmers, with the ability to adopt and effectively apply advanced technologies, achieved the highest GTFP among the three scales, driven by both BPC and EC.

From the perspective of dynamic evolution, the center of the kernel density curve of GTFP in all scales shifted to the left, revealing a decreasing growth rate of GTFP. The development gap between provinces of middle-scale and large-scale sectors has widened, while a narrowing trend is observed in small-scale sectors. This trend can be attributed to a series of regulatory documents targeting the mitigation of pollution from livestock and poultry farming, promulgated by the Chinese government after the 18th National Congress. Such regulations led to the elimination of a significant portion of small-scale broiler farming that fails to comply with environmental standards, thereby narrowing the gap within small-scale sectors. Moreover, the variable responsiveness of middle- and large-scale farmers to policy changes across provinces has gradually widened the green development gap. The presence of absolute β convergence and conditional β convergence across all scales signifies a convergence of broiler farming's GTFP towards a state of equilibrium over time.

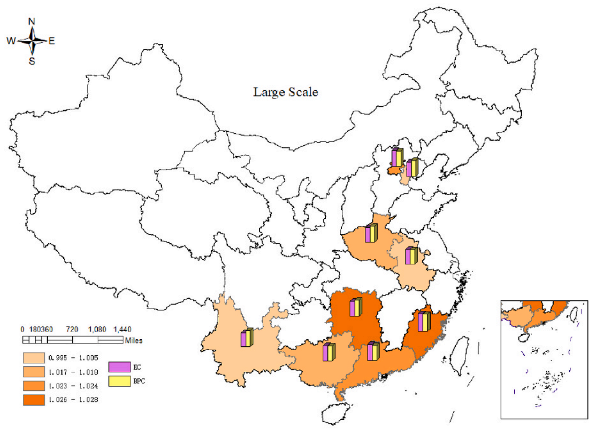
By factoring in the resource utilization of broiler manure, this study conducted a comprehensive review of the spatiotemporal evolution and convergence of CTFP within the broiler chicken industry in China. On the one hand, these findings have considerable theoretical and managerial significance in the context of investigating Green Total Factor Productivity (GTFP). Through an in-depth analysis of GTFP in broiler breeding, this research broadens the boundaries of GTFP research in the field of broiler farming, provides novel research ideas on the green production efficiency of specific agricultural breeds. Furthermore, it has contributed to advancing the analytical framework and methodological tools employed in the existing body of literature on broiler breeding, which enhances the



(**a**)



(**b**)



(**c**)

Fig. 3. (a). GTFP and index decomposition of broiler farming in small-scale. (b). GTFP and index decomposition of broiler farming in middle-scale. (c). GTFP and index decomposition of broiler farming in large-scale.

accuracy of assessments of the environmental sustainability of broiler breeding. On the other hand, the findings offer important management implications for policy makers, underscoring the potential to enhance GTFP through the strategic optimization of broiler farming layouts at different scales. Meanwhile, it is a valuable reference point for countries and regions characterized by varying agricultural resource endowments to layout different scales of broiler farming, which may have some international implications. Nevertheless, there remains room for enhancement. For example, GTFP of broiler chickens might be influenced by different regional resource endowments, which warrants further examination in future studies.

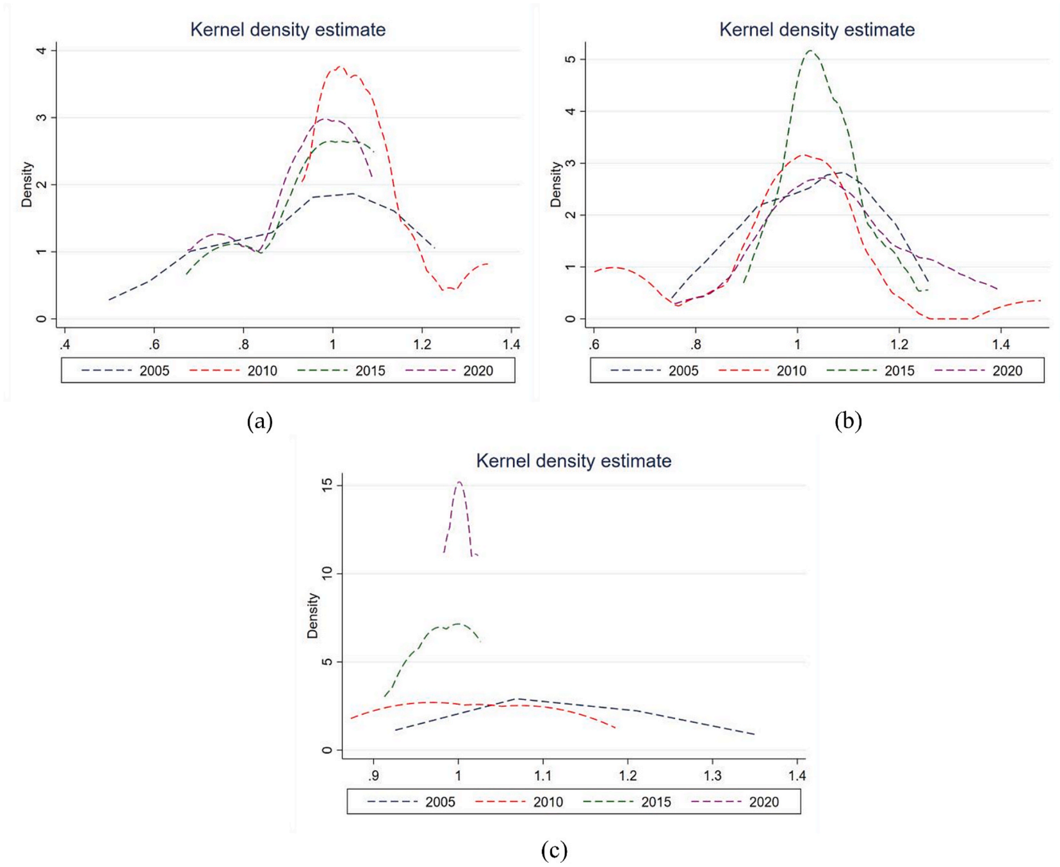


Fig. 4. (a). Dynamic evolution of GTFP for broiler farming of large scale. (b). Dynamic evolution of GTFP for broiler farming of middle scale. (c). Dynamic evolution of GTFP for broiler farming of small scale.

Table 4
The absolute β Convergence test results.

Coefficient	Large Scale	Middle Scale	Small Scale
β	−1.355[a] (0.114)	−1.398[a] (0.061)	−1.348[a] (0.114)
α	0.011 (0.013)	0.011 (0.007)	−0.002 (0.012)
R^2	0.688	0.695	0.711

[a] denotes statistical significance at the 1 % level.

Table 5
The conditional β Convergence test results.

Coefficient	Large Scale	Middle Scale	Small Scale
β	−1.357[a] (0.086)	−1.427[a] (0.064)	−1.352[a] (0.141)
α	−0.051 (0.062)	0.003 (0.040)	−0.005 (0.055)
R^2	0.726	0.722	0.774

[a] denotes statistical significance at the 1 % level.

6. Conclusions and Recommendations

Previous studies on livestock farming have generally viewed carbon emissions and pollutants as undesirable outputs, while overlooking the significance of manure and its carbon sequestration effect, as well as resource use efficiency. In this study, manure alongside pollutant emissions generated in broiler farming was included in undesirable outputs. Additionally, carbon sequestration of manure resource utilization in the farming process were considered to measure GTFP of broiler farming across different scales in China using the SBM-GML index. The results revealed an overall increasing trend in GTFP of broiler farming on a national scale from 2005 to

2020, with respective GTFP values of 1.015, 1.017, and 1.009 for small-scale, medium-scale, and large-scale farming. There is also a significant imbalanced in development between small-scale, medium-scale, and large-scale farming, signified by a widening development gap between medium-scale and large-scale farming, and a narrowing gap within small-scale farming. Furthermore, it demonstrates absolute β convergence and conditional β convergence across all three scales.

(1) Encourage the moderate expansion of broiler farming scale. Smaller-scale broiler farming faces challenges in adopting new technologies and achieving economic technical efficiency. The government should further facilitate the scaling up of livestock and poultry production to improve scale efficiency and drive high-quality development of broiler farming. Meanwhile, attention should be paid to promoting of moderate technology innovation and adaptation, adopting the most fitting technologies to achieve optimum technical economic efficiency.
(2) Optimize the production layout of broiler farming. Considering the differences in interprovincial development and the spatial layout efficiency of broiler farming, it is pivotal to adapt broiler farming practices to local conditions, thus improving the GTFP and the level of sustainable production.
(3) Advocate for the comprehensive utilization and harmless treatment of livestock and poultry breeding waste. Although broiler manure is a pollutant produced during the farming process, it is rich in organic matter. Therefore, initiatives to maximize the resource utilization of broiler manure, such as field recycling, biogas production, and organic fertilizer manufacturing via biogas preparation, and separation facilities for biogas residue and slurry, are crucial to improving the clean production level of broiler farming.

Consent for publication

All authors agreed to publish the paper.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Wei Guo: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Shuangshuang Dong:** Data curation, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. **Jiarong Qian:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of Competing interest

The authors declare that they have no potential conflict of interest that could have appeared to influence the work reported in this paper.

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Appendix 1

GTFP	Green Total Factor Productivity
SBM	Slacks-Based Model
GML	Global Malmquist–Luenberger
KDE	Kernel Density Estimation
EC	Efficiency Change
BPC	Change in Best Practice Gap
COD	Chemical Oxygen Demand
TN	Total Nitrogen
TP	Total Phosphorus
DMU	Decision-Making Unit

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