The Dynamic Evolution of Green Total Factor Productivity in China's Logistics Industry and Its Convergence

Jiajia Xu
School of Management, Zhengzhou University, Zhengzhou, China

Abstract: In order to comply with the development requirements of green concept in the new century and the development trend of modern logistics, combining green concept and logistics to build green logistics system is the driving force for the healthy and sustainable development of logistics industry. This paper uses the super-efficiency EBM model based on non-expected output, the Global Malmquist-Luenberger index and the convergence model to calculate and analyze the GTFP of China's logistics industry from 2005 to 2021 from the static and dynamic perspectives. The regional difference and dynamic evolution trend of GTFP of logistics industry in northeast, East, central and western regions were deeply analyzed, in order to provide beneficial guidance for the healthy development of green logistics industry.

Keywords: Logistics Industry; Green Total Factor Productivity; Dynamic Evolution; Regional Difference; Convergence

1. Introduction

Over the course of four decades since the initiation of reform and opening-up policies, the status of China's logistics industry has continued to rise, from its beginnings, exploration, transformation and upgrading, to its rapid development into a “logistics power”. In 2022, the total value of China's logistics industry reached 347.6 trillion yuan, reflecting a year-on-year increase of 3.4% at comparable prices. This growth signifies a new milestone in the scale of logistics demand, demonstrating consistent and steady expansion. Documents from relevant departments outlines a grand blueprint for the construction and development of China's modern logistics system. It pointed out problems such as the irrational allocation and insufficient utilization of logistics resources, and the need to further reduce logistics costs and increase efficiency. The principles of incorporating green concepts into the entire modern logistics chain and enhancing the sustainability of logistics are proposed, fully demonstrating the importance of improving the Green total factor productivity (GTFP) level of the logistics industry to its development.

However, frequent logistics activities and changes in logistics management, accompanied by high energy consumption and carbon emissions, pose a huge challenge to the sustainable development of the social economy and the protection of the ecological and environmental environment. The tension between the growth of the logistics sector and the preservation of ecological and environmental resources is becoming increasingly pronounced. Advancing the green transformation and decarbonization of the logistics industry is a crucial step in shifting its development focus from rapid expansion to high-quality progress. This transition also serves as a vital driver for fostering the sustainable enhancement of productivity within the logistics field. Achieving this balance is essential for ensuring long-term, environmentally responsible growth in the industry. GTFP in the logistics sector signifies a shift toward low-carbon transformation and upgrading, contributing significantly to green and sustainable development. Consequently, investigating regional disparities, dynamic trends, convergence patterns, and influencing factors of GTFP in the logistics industry—while incorporating energy and ecological constraints into its development framework and utilizing efficiency evaluation methods—holds substantial theoretical and practical importance. Such research is essential for advancing high-quality growth in the logistics sector, accelerating the transition to environmentally friendly development models, and actively supporting efforts to achieve carbon peak and neutrality goals. This approach fosters a more sustainable and resilient future for the industry.

2. Literature Review

A review of existing literature reveals that research on total factor productivity (TFP) in the logistics industry, both domestically and internationally, primarily concentrates on two areas: the productivity of the traditional logistics industry and GTFP, which incorporates resource consumption and environmental pollution. The fundamental concept of GTFP is to achieve a balance between economic and environmental benefits, thereby maximizing economic output while minimizing resource and environmental costs, aligning with the principles of green sustainable development. Studies on TFP in the logistics industry predominantly focus on traditional efficiency measurement, as well as the methodologies for measuring and evaluating GTFP.

In terms of traditional efficiency measurement, researchers mainly focus on the productivity, technical efficiency and financial performance of regional and logistics operators at different scales from an economic perspective. Research on regional logistics efficiency mainly evaluates logistics efficiency at the international, national, economic belt, inter-provincial and city levels. Studies on the efficiency of regional logistics mainly evaluate the efficiency of logistics in terms of international, national, economic belt, inter-provincial and urban levels. In terms of international logistics, since the logistics industry in developed countries in Europe and the United States has a relatively comprehensive support system and the industry is maturing, academia is more concerned with improving logistics and supply chain management at the enterprise level [1]. On a national level, the main focus is on evaluating the efficiency of 30 provinces and cities and economic regions across the country as a whole, exploring the temporal and spatial differences and dynamic evolution of China's logistics industry efficiency [2]. Research findings indicate that the technical efficiency of the logistics industry across China's provinces (municipalities and autonomous regions) is relatively low, with significant regional disparities. The eastern region demonstrates the highest efficiency, followed by the central region, while the western region exhibits the lowest efficiency. In the context of economic belt research, the focus primarily centers on analyzing the logistics efficiency of the Yangtze River Economic Belt [3], the Yellow River Economic Belt [4], and the regions along the Belt and Road [5]. In the context of inter-provincial and urban efficiency research, the primary objective is to enhance the high-quality development level of the regional logistics industry by measuring the logistics efficiency of provinces and cities, thereby driving the advancement of regional economic development [6]. In addition, in the process of constructing a modern logistics system for an enterprise, scientifically evaluating the logistics efficiency of the enterprise can improve the quality of logistics management and service capabilities. Some scholars utilized financial data from 80 listed logistics companies as a sample to investigate logistics efficiency. The study revealed that while the overall development of China's logistics enterprises is trending upward, the technical efficiency remains relatively low, suggesting significant potential for further improvement in industry efficiency [7].

In terms of GTFP research, relevant domestic and foreign research has made some progress, with specific research conducted in different sectors and industries, the digital economy and other fields, mainly including its core connotations, measurement and evaluation, and analysis of the temporal and spatial evolution path [8,9]. In comparison, research on GTFP within the logistics sector remains limited. Accurately measuring and enhancing GTFP is crucial for fostering the harmonious development of the logistics industry and ecological environmental protection during China's high-quality development phase. Two primary methodologies are employed to calculate GTFP: the parametric Stochastic Frontier Analysis (SFA) and the parametric or non-parametric Data Envelopment Analysis (DEA). Utilizing the stochastic frontier approach, which extends beyond the logarithmic production function, a study examining GTFP in China's prefecture-level cities from 2000 to 2019 revealed that the overall level of green logistics development in the country has been steadily increasing. This underscores the importance of continued efforts to integrate sustainability into the logistics industry [10]. Although the SFA can distinguish between the effects of technical inefficiency factors and statistical errors on efficiency, it has the disadvantages of subjectivity in the setting of the production function, higher requirements for the distribution characteristics of the error term and sample size, etc., which may lead to an underestimation of the overall efficiency level of the sample [11]. DEA does not require the production function to be set in advance, and can produce more objective evaluation results [12]. Existing research indicates that the index of change in the GTFP of China's logistics industry is generally increasing, yet the sector remains entrenched in an extensive development mode characterized by high input and low output. This long-standing approach has resulted in issues such as resource waste, environmental pollution, and ecosystem degradation. The level of green development remains low, with significant regional disparities in development progress [13].

After reviewing the existing literature, this paper identifies the need for further deepening, expansion, and innovation in the content and methodologies of research on the Green Total Factor Productivity (GTFP) of the logistics industry. In terms of research content, existing studies primarily focus on measuring the quality of green development and analyzing the driving factors within the logistics industry. Few studies explore the dynamic characteristics of GTFP in the logistics sector, and research on its convergence is even more limited. In terms of research methods, the measurement of GTFP requires consideration of the radial relationship between factor inputs and outputs. However, most existing studies employ either radial or non-radial models. Radial models overlook the impact of non-radial slack variables, while non-radial models fail to capture the proportional information between target and actual values of inputs or outputs. To address these limitations, this paper adopts a combined static and dynamic perspective to resolve the inherent issues of radial and non-radial models. An Epsilon-Based Measure (EBM) model incorporating super-efficiency and undesirable outputs is utilized to measure the technical efficiency of the logistics industry across 30 provinces in China from 2005 to 2021. The Global Malmquist-Luenberger index is employed to assess the GTFP of the logistics industry. Using ArcGIS software, the spatial distribution characteristics of China's green logistics total factor productivity are analyzed and described, and the dynamic evolution of GTFP in the logistics industry is examined. This study aims to provide a theoretical foundation for enhancing GTFP in the logistics industry under environmental constraints and to promote the high-quality development of China's logistics sector.

3. Indicator System Construction

3.1 GTFP Evaluation Indicator System for Logistics Industry

Facing the challenges of limited resources and increasingly severe environmental pollution, the logistics industry must prioritize the principles of green development and sustainability. Resources and the environment are no longer merely endogenous variables influencing the development of the logistics industry but have also become rigid constraints that limit the quality of its growth. This paper constructs an evaluation index system based on the perspectives of "logistics resources input" and "logistics resources output" quality [14-16], as shown in Table 1.

Table 1. GTFP Evaluation Indicator System for Logistics Industry

Variable type	Variable name	Variable Connotation
Input variable	principal	Estimation of fixed capital stock in transportation, storage and postal services using the perpetual inventory method.
	labor force	Number of persons employed in transportation, storage and postal services by province.
	infrastructure	Miles of transportation route network.
	information technology	Number of Internet broadband access ports.
	renewable energy	Consumption of primary energy sources such as coal, crude oil, gasoline, diesel, fuel oil, liquefied petroleum gas (LPG), natural gas, and electricity was selected as the indicator of measurement, converted to energy consumption of standard coal.
Desired output variables	Value added of the logistics industry	2005 as base period, adjusted for tertiary value-added indices.
	Logistics turnover	Cargo turnover and passenger turnover converted to "consolidated turnover".
Non-expected output variables	CO_2 emissions	Calculation of emissions from primary energy consumption by region based on the IPCC.

3.2 Data Sources

This paper focuses on the logistics industry in each province as the research object. Considering data availability and completeness, annual panel data from 30 provinces in China spanning 2005 to 2021 are selected as the research sample. The original data are sourced from the China Statistical Yearbook, China Energy Statistical Yearbook, local statistical yearbooks of various provinces and cities, the National Bureau of Statistics, and other relevant publications. Individual missing data points are supplemented using the exponential smoothing method and interpolation method. To represent the logistics industry, this paper selects transportation, warehousing, and postal services, which collectively account for over 85% of the logistics sector.

3.3 Data Processing

1)Capital stock measurement method. Drawing on the research of some scholars [17], the capital stock of the transportation, storage and postal industry is projected based on the perpetual inventory method:

$$K_{it} = K_{i,t-1}\left(1-\delta_{it}\right)+I_{it} \tag{1}$$

Where I is the real fixed asset investment, in order to minimize the bias, the depreciation rate δ in this paper follows the practice of Shan Haojie [18], taking δ = 10.96%, with 2005 as the base period capital stock $K_0 = I_0 \big/ \left(\delta+g\right)$, I_0 is the base period fixed asset investment, g is the geometric growth rate of fixed asset investment in each province.

2)Energy consumption measurement method. Selection of raw coal, gasoline, natural gas and other eight major energy consumption, converted to standard coal energy consumption as energy inputs, the total energy inputs in the logistics industry accounting formula is as follows:

$$E_{ij} = W_{ij} \times \theta_j \tag{2}$$

where E_{ij} is the standard coal consumption of logistics industry in province i for j types of energy, W_{ij} is the consumption of logistics industry in province i for j types of energy, and θ is the converted standard coal coefficient.

3)Carbon emission measurement methods vary across countries due to differing regulations, and several studies have proposed diverse approaches for calculating carbon emissions [19,20]. Given the absence of standardized statistical methods and comprehensive data on carbon dioxide emissions within China's logistics industry, this paper adopts the IPCC 2006 Carbon Emission Calculation Guidelines to estimate carbon emissions. The calculation is based on the following equation:

$$CO_2 = \sum_{j=1}^{8} CO_{2_j} = \sum_{j=1}^{8} E_{ij} \times \rho_j \tag{3}$$

where ρ_j is the carbon emission factor for energy j.

4. Using the Template

4.1 GTFP Measurement in the Logistics Industry

In this study, the Epsilon-Based Measure (EBM) model is employed, which integrates both radial and non-radial distance functions to account for non-desirable outputs [21]. To enhance the relative comparability of effective decision-making units, the EBM model is further extended to a super-efficient form, constructing a super-efficient EBM model that is non-oriented, incorporates non-desirable outputs, and assumes variable returns to scale, as shown in the equation (4):

$$\gamma^* = \min_{\theta,\phi,\lambda,s^-,s^+} \frac{\theta + \varepsilon_x \sum_{i=1}^{m} \frac{w_i^- s_i^-}{x_{ik}}}{\phi - \varepsilon_y \sum_{r=1}^{s} \frac{w_i^+ s_i^+}{y_{rk}} - \varepsilon_b \sum_{p=1}^{q} \frac{w_p^{b-} s_p^{b-}}{b_{pk}}}$$

$$\begin{aligned}
s.t. &\sum_{t=1}^{T}\sum_{j=1,j\neq 0}^{n} x_{ij}^t \lambda_j^t - s_i^- \le \theta x_k, i=1,\dots,m \\
&\sum_{t=1}^{T}\sum_{j=1,j\neq 0}^{n} y_{rj}^t \lambda_j^t + s_i^+ \ge \phi x_k, r=1,\dots,s \\
&\sum_{t=1}^{T}\sum_{j=1,j\neq 0}^{n} b_{pj}^t \lambda_j^t - s_p^{b-} \le \phi b_{pk}, p=1,\dots,q \\
&\sum_{t=1}^{T}\sum_{j=1,j\neq 0}^{n} \lambda_j^t = 1 \\
&\lambda \ge 0, s_i^- \ge 0, s_r^+ \ge 0, s_p^{b-} \ge 0
\end{aligned} \tag{4}$$

Where γ^* is the technical efficiency value of the EBM model with variable returns to scale and θ is the planning parameter for the radial component; k is the decision unit being evaluated; ε_x is the key parameter after considering radial efficiency values and non-radial relaxation values $0 \le \varepsilon_x \le 1$; w_i^- Indicates the weights of the input indicators, which satisfy $\sum_{i=1}^{m} w_i^- = 1\left(w_i^- \ge 0\right)$; w_i^+ and w_p^{b-} denote the weights of desired and non-desired outputs, respectively; s_i^- is the amount of slack in the non-radial input factor i; s_i^+ and s_p^{b-} denote the deficient variables for desired outputs and the slack for non-desired outputs, respectively; m and s are the quantities of inputs and outputs, respectively; s_{ik} and y_{ik} are the class i inputs and class r outputs of the kth decision cell, respectively; λ_j is the linear combination coefficient of the decision cell; φ is the output expansion ratio;

Since the EBM model is limited to measuring the technical efficiency of a decision-making unit at a specific point in time and cannot capture changes in technological progress and productivity, it is necessary to construct the Global Malmquist-Luenberger (GML) index and decompose it based on technological efficiency. The GML index is used to compare changes in Green Total Factor Productivity (GTFP) over time, analyze shifts in the relative position of each region and the production frontier (efficiency changes), as well as movements of the production frontier itself (technological change). This approach measures the dynamic changes in GTFP and its decomposition terms within the logistics industry across provinces and cities. The GML index is constructed as follows:

$$\begin{aligned} & GML^{t,t+1}\left(x^t, y^t, x^{t+1}, y^{t+1}, b^{t+1}\right) \\ &= \frac{1+D_G^T\left(x^t, y^t, b^t\right)}{1+D_G^T\left(x^{t+1}, y^{t+1}, b^{t+1}\right)} \\ &= \frac{EC^{t+1}}{EC^t} \times \frac{BPG_{t+1}^{t,t+1}}{BPG_t^{t,t+1}} \\ &= \frac{EC^{t+1}}{EC^t} \times TC^{t,t+1} \\ &= EC^{t,t+1} \times TC^{t,t+1} \\ &= PEC^{t,t+1} \times SEC^{t,t+1} \times TC^{t,t+1} \end{aligned} \tag{5}$$

where

$D_G^T\left(x, y, b\right) = \max\left\{\beta \middle| \left(y+\beta y, b-\beta b\right) \in P_G\left(x\right)\right\}$

follows from the global set of production possibilities with reference to set P_G; EC^t denoted as the technical efficiency in period t, representing the change in proximity to the production frontier; $BPG_t^{t,t+1}$ represents the "best-practitioner gap" at the global production frontier in period t; $TC^{t,t+1}$ denotes the effect of a shift in the overall production frontier of the logistics industry, i.e., technological change, over a t to $t+1$ period. In the case of variable returns to scale (VRS), EC can be further decomposed into pure technical efficiency change (PEC) and scale efficiency change (SEC).

where $GML^{t,t+1}$ represents the GTFP change index for the logistics industry for the period t to $t+1$. If $GML>1$, it indicates an increase in desired output, a decrease in undesired output, and GTFP growth; If $GML=1$, it means that GTFP is unchanged; If $GML<1$, it indicates a decrease in GTFP. Similarly, EC, TC, PEC and SEC have similar meanings.

4.2 Methodology for the Study of Spatio-Temporal Convergence

This paper employs the concept of convergence from economic development studies to analyze the evolutionary trends of GTFP in the logistics industry across China's provinces and cities. The convergence of GTFP in the logistics industry is primarily examined at the σ-convergence level.

σ -convergence analysis: σ -convergence describes the trend where the Green Total Factor Productivity (GTFP) of the logistics industry across various regions increasingly aligns with the overall average level over time, indicating a reduction in disparities. This phenomenon is typically measured using the coefficient of variation (CV), which evaluates whether the dispersion of GTFP across regions exhibits a declining trend. A decreasing coefficient of variation over time suggests that regions with lower GTFP are catching up to those with higher GTFP, reflecting σ-convergence. The coefficient of variation is calculated as follows:

$$\sigma_j = \frac{\sqrt{\sum_i^N \frac{\left(Q_i - \overline{Q}\right)^2}{N}}}{\overline{Q}} \tag{6}$$

Where N is the number of provinces in China (N=30), Q_i denotes the GTFP of the logistics industry in province i, and $\overline{Q}$ denotes the mean value of the GTFP of the logistics industry in China. When the coefficient of variation decreases, it indicates the presence of σ-convergence.

5. Results

5.1 Evaluation Results and Analysis of the Efficiency of the Logistics Industry

Based on the Super-EBM model, which incorporates non-desirable outputs, the technical efficiency of China's inter-provincial logistics industry from 2005 to 2021 is measured. This model reflects the distance between the input and output levels of the logistics industry in each province and the production frontier. An efficiency value greater than 1 indicates that the decision-making unit (DMU) is effective, with higher values signifying greater efficiency. The regions are classified according to the National Bureau of Statistics' 2011 division of China's economic regions, which categorizes the country into four major areas: the eastern, central, western, and northeastern regions. Table 2 presents the comprehensive technical efficiency, pure technical efficiency, and scale efficiency of the logistics industry in these four regions and their respective provinces for the years 2005, 2013, and 2021, as well as the 17-year average values.

Table 2. Efficiency Values of the FOUR MAJOR REGIONS and Provinces in China

Area Name	Provinces	Combined technical efficiency				Pure technical efficiency				Scale efficiency			
		2005	2013	2021	average	2005	2013	2021	average	2005	2013	2021	average
Northeast	Liaoning	0.342	0.768	0.501	0.568	0.468	0.768	0.501	0.620	0.730	1.000	1.000	0.905
	Jilin	0.278	0.481	0.434	0.434	0.295	0.502	0.471	0.474	0.946	0.958	0.923	0.924
	Heilongjiang	0.257	0.294	0.259	0.298	0.259	0.306	0.273	0.319	0.992	0.961	0.946	0.937
	average	0.292	0.514	0.398	0.433	0.340	0.525	0.415	0.471	0.889	0.973	0.956	0.922
Eastern	Beijing	0.160	0.438	0.285	0.302	0.213	0.440	0.318	0.330	0.751	0.995	0.898	0.897
	Tianjin	1.234	1.102	1.082	1.141	1.309	1.222	1.228	1.248	0.943	0.902	0.881	0.914
	Hebei	1.019	1.078	1.120	1.094	1.047	1.081	1.170	1.108	0.973	0.997	0.958	0.987
	Shanghai	1.098	1.185	1.323	1.203	1.099	1.222	1.328	1.227	0.999	0.970	0.996	0.980
	Jiangsu	0.361	1.014	1.009	0.780	0.722	1.016	1.013	0.920	0.499	0.999	0.995	0.838
	Zhejiang	0.469	0.708	0.720	0.649	0.566	0.713	0.723	0.672	0.829	0.992	0.995	0.963
	Fujian	0.581	0.549	0.785	0.637	0.629	0.555	0.796	0.658	0.924	0.988	0.986	0.968
	Shandong	1.026	0.662	0.789	0.833	1.038	0.686	1.033	0.981	0.988	0.965	0.764	0.853
	Guangdong	0.296	0.609	0.722	0.594	1.022	0.672	1.066	0.942	0.289	0.905	0.677	0.644
	Hainan	0.498	0.440	1.078	0.532	1.088	1.011	1.115	1.000	0.458	0.435	0.968	0.531
	average	0.674	0.778	0.891	0.777	0.873	0.862	0.979	0.909	0.765	0.915	0.912	0.858
Central region	Shanxi	0.385	0.476	1.004	0.613	0.401	0.478	1.011	0.633	0.959	0.996	0.993	0.969
	Anhui	1.050	1.121	1.005	1.040	1.054	1.122	1.007	1.043	0.996	1.000	0.998	0.997
	Jiangxi	0.362	0.608	0.739	0.599	0.362	0.623	1.004	0.661	0.998	0.977	0.737	0.922
	Henan	0.558	0.734	0.766	0.773	0.701	0.758	0.844	0.846	0.796	0.968	0.908	0.915
	Hubei	0.263	0.653	0.636	0.563	0.355	0.682	0.639	0.622	0.743	0.957	0.996	0.906
	Hunan	0.437	0.615	0.466	0.564	0.474	0.616	0.478	0.579	0.922	0.998	0.975	0.972
	average	0.509	0.701	0.770	0.692	0.558	0.713	0.830	0.731	0.902	0.983	0.935	0.947
Western	Inner Mongolia	1.031	0.630	1.005	0.888	1.036	0.657	1.005	0.939	0.996	0.958	0.999	0.947
	Guangxi	0.308	0.472	0.461	0.439	0.324	0.495	0.501	0.465	0.951	0.953	0.920	0.945
	Chongqing	0.251	0.487	0.491	0.455	0.265	0.490	0.510	0.468	0.947	0.995	0.962	0.973
	Sichuan	0.241	0.313	0.305	0.313	0.303	0.353	0.306	0.334	0.797	0.887	0.997	0.940
	Guizhou	0.310	0.453	0.393	0.403	0.377	0.486	0.398	0.446	0.823	0.933	0.990	0.901
	Yunnan	0.191	0.383	0.419	0.351	0.203	0.395	0.423	0.369	0.939	0.969	0.991	0.956
	Shanxi	0.297	0.506	0.555	0.481	0.298	0.514	0.577	0.499	0.998	0.986	0.962	0.966
	Gansu	0.433	0.553	0.415	0.515	0.501	0.589	0.524	0.598	0.863	0.940	0.791	0.859
	Qinghai	0.390	0.407	0.344	0.392	1.998	1.102	1.036	1.209	0.195	0.370	0.332	0.340
	Ningxia	0.348	0.785	0.518	0.671	1.160	1.297	1.366	1.287	0.300	0.605	0.379	0.519
	average	0.376	0.486	0.479	0.479	0.623	0.614	0.638	0.637	0.788	0.867	0.846	0.842
National average		0.494	0.629	0.666	0.616	0.665	0.707	0.768	0.730	0.813	0.917	0.897	0.876

a. Combined technical efficiency (TE) = pure technical efficiency (PTE) x scale efficiency (SE)

In terms of the comprehensive technical efficiency value, at the national level, the average comprehensive technical efficiency of China's logistics industry is generally low, but it is generally showing an upward trend. From 2005 to 2021, the comprehensive technical efficiency of China's logistics industry increased from 0.494 to 0.666. Among the 30 provinces, except for Tianjin, Shandong, Anhui, and Inner Mongolia, where logistics efficiency has declined, the rest have all increased. Specifically, there are only 4 provinces in China with an average comprehensive technical efficiency of the logistics industry greater than 1, accounting for 13.33%: Tianjin, Hebei, Shanghai, and Anhui. In terms of regional distribution, the comprehensive technical efficiency value of the logistics industry in the eastern region is the highest, with an average value of 0.777, while the comprehensive technical efficiency value in the northeastern region is the lowest, with an average value of only 0.433. It is evident that significant disparities exist in the overall efficiency of regional and provincial logistics in China. The logistics efficiency in the northeastern and western regions is relatively low. This may be attributed to the fact that the development of the logistics industry in these regions remains in an extensive stage, characterized by inefficient resource utilization and suboptimal actual output.

Table 3. Changes in GTFP and Decomposition in Four Major Regions of China, 2005-2021.

Project	Regional	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	average
	Northeast	0.9571	1.0091	1.1237	1.1983	0.7984	0.9906	1.0156	0.9262	1.5329	0.7343	1.0335	1.0726	1.0877	0.9883	0.9193	1.0181	1.0254
	Eastern	0.9993	1.0334	1.0072	1.1747	0.8421	1.0837	0.9918	1.1110	0.9731	0.9371	0.9806	1.0561	1.0424	1.0757	1.0473	1.1715	1.0329
GML	Central region	1.0014	0.9751	1.1514	1.2005	0.7984	1.0482	1.0818	0.9006	1.2962	0.8155	0.9937	1.0537	1.0589	0.9570	0.9424	1.1288	1.0252
	Western	0.9562	0.9502	1.1319	1.3962	0.7003	1.0471	1.0011	0.9476	0.9783	0.9652	1.0026	1.0550	1.0549	1.0308	0.9776	1.0979	1.0129
	National	0.9797	0.9888	1.0934	1.2634	0.7770	1.0539	1.0156	0.9905	1.0956	0.9028	0.9966	1.0569	1.0548	0.9948	0.9879	1.1206	1.0233
	Northeast	1.0712	0.9396	1.7304	0.7605	0.9627	1.0342	1.2177	1.0723	1.2223	0.9292	0.9897	0.9435	1.0278	0.9487	0.9351	0.9476	1.0458
	Eastern	1.0966	0.9916	1.3128	0.8236	1.0788	0.9982	1.1206	1.1699	0.9491	1.0122	1.0095	0.9872	0.9734	1.0270	1.0533	1.0743	1.0424
EC	Central region	1.1719	0.9270	1.3922	0.8840	0.9917	1.0048	1.1723	0.9907	1.2553	0.9342	1.0775	1.0209	1.0154	0.9877	0.9398	1.0462	1.0507
	Western	1.0954	0.8979	1.5520	0.9245	0.9496	1.0398	1.1460	0.9375	0.9888	1.0578	1.0615	0.9692	0.9902	0.9463	0.9465	1.0314	1.0334
	National	1.1087	0.9391	1.4582	0.8663	1.0024	1.0184	1.1499	1.0391	1.0522	1.0050	1.0402	0.9830	0.9934	0.9817	0.9796	1.0403	1.0411
	Northeast	0.8937	1.0781	0.6625	1.5888	0.8307	0.9528	0.8384	0.8797	1.1952	0.7605	1.0460	1.1380	1.0583	1.0428	0.9818	1.0748	1.0014
	Eastern	0.9093	1.0432	0.8379	1.4818	0.7806	1.0933	0.8871	0.9179	1.0067	0.9254	0.9759	1.0697	1.0721	1.0458	1.0057	1.0965	1.0093
TC	Central region	0.8573	1.0687	0.8537	1.3762	0.8064	1.0434	0.9234	0.9101	1.0176	0.8696	0.9236	1.0322	1.0454	0.9670	1.0303	1.0801	0.9878
	Western	0.8695	1.0633	0.7454	1.5135	0.7407	1.0116	0.8906	1.0283	0.9903	0.9133	0.9462	1.0917	1.0670	0.9977	1.0351	1.0643	0.9980
	National	0.8828	1.0591	0.7896	1.4830	0.7762	1.0393	0.8907	0.9530	1.0217	0.8933	0.9616	1.0771	1.0635	1.0121	1.0190	1.0792	1.0001
	Northeast	1.0470	0.9270	1.6908	0.7941	0.9786	1.0080	1.1699	1.0366	1.3102	0.9015	1.0121	0.9737	1.0360	0.9683	0.9357	0.8759	1.0416
	Eastern	1.0526	0.9828	1.1006	0.8849	1.0227	1.0162	1.0453	0.9915	1.0589	1.0207	1.0471	0.9974	0.9680	1.0199	1.0288	1.0106	1.0155
PEC	Central region	1.1415	0.9195	1.3412	0.8980	0.9863	0.9908	1.1470	0.9968	1.3087	0.9197	1.0456	1.0974	0.9695	1.0945	0.9073	1.0509	1.0509
	Western	1.0740	0.9062	1.3393	0.8981	0.9797	0.9821	1.1343	0.9563	1.0281	1.0485	1.0781	1.0038	1.0214	0.9705	0.9450	0.9727	1.0211
	National	1.0777	0.9365	1.2953	0.8833	0.9952	0.9978	1.1108	0.9842	1.1227	0.9988	1.0547	1.0174	0.9947	1.0116	0.9644	0.9913	1.0273
	Northeast	1.0233	1.0135	1.0434	0.9629	0.9846	1.0274	1.0396	1.0291	0.9490	1.0425	0.9770	0.9693	0.9919	0.9795	0.9997	1.0812	1.0071
	Eastern	1.0427	1.0092	1.1768	0.9297	1.0536	0.9852	1.0733	1.1888	0.9068	0.9916	0.9674	0.9899	1.0121	1.0061	1.0232	1.0591	1.0260
SEC	Central region	1.0311	1.0080	1.0439	0.9854	1.0054	1.0147	1.0218	0.9948	0.9602	1.0130	1.0316	0.9420	1.0616	0.9192	1.0610	1.0132	1.0067
	Western	1.0214	0.9940	1.1966	1.0259	0.9701	1.0754	1.0086	0.9787	0.9629	1.0094	0.9893	0.9658	0.9706	0.9757	1.0016	1.0620	1.0130
	National	1.0306	1.0038	1.1441	0.9794	1.0065	1.0284	1.0359	1.0570	0.9423	1.0075	0.9893	0.9694	1.0047	0.9749	1.0205	1.0532	1.0155

b. The northeast includes Liaoning, Jilin, and Heilongjiang; the east includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; the center includes Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan; and the west includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai and Ningxia.

Regarding technical efficiency, China's logistics sector improved from 0.665 to 0.768 between 2005 and 2021. From the perspective of provincial regions, during the research period, Tianjin, Hebei, Shanghai, Jiangsu, Hainan, Anhui, Ningxia, and Qinghai achieved pure technical efficiency at the production frontier in most years, realizing the full utilization of logistics resources. The mean pure technical efficiency (PTE) of the logistics industry across seven provinces exceeded 1, representing 23.33% of the sample, with a predominant geographic distribution in the eastern and western regions. From a regional perspective, PTE values demonstrated consistent improvement across all four major regions, indicative of enhanced management practices and technological advancements within the logistics sector in these areas. Consistent with trends observed in comprehensive technical efficiency, the eastern region exhibited the highest PTE values, while the northeastern region recorded the lowest.

In terms of scale efficiency, the logistics industry in China exhibited consistently high levels from 2005 to 2021, demonstrating a modest upward trend, with values increasing from 0.813 in 2005 to 0.897 in 2021. The mean scale efficiency during this period was 0.876, surpassing both pure technical efficiency and comprehensive technical efficiency. From the perspective of provincial regions, during the research period, except for Guangdong, Hainan, Ningxia, and Qinghai, the scale efficiency values of the logistics industry in each province were relatively high, but no province's scale efficiency mean reached 1, indicating that each province is still facing the obstacle of unreasonable input scale. In terms of region, the economies of scale in the four major regions are all on the rise, and the development trend is that they maintain a high level compared to the comprehensive technical efficiency and pure technical efficiency. Among these regions, the central region exhibits the highest logistics scale efficiency, with an average value of 0.947, while the western region has the lowest logistics scale efficiency, with an average value of 0.842. This disparity may be attributed to the further implementation of the "Rise of the Central Region" strategy, which has driven the logistics industry in the central region to continuously increase investments in infrastructure construction and enhance the level of logistics informatization.

5.2 Analysis of GTFP Change in the Logistics Industry

Using panel data from 2005 to 2021 on the input factors, expected output, and non-expected output of the logistics industry in 30 provinces (municipalities, and autonomous regions, and employing Max DEA software, the Global Malmquist-Luenberger (GML) index of the Green Total Factor Productivity (GTFP) of the logistics industry in each province (municipality, and autonomous region) and its decomposition indicators are calculated. The changes in the GTFP of the logistics industry in the four major regions, derived from the above model, along with the results of its decomposition, are presented in Table 3.

As shown in Table 3, the growth rate of the GTFP of China's logistics industry from 2005 to 2021 was 0.90%, with an average annual change in technical efficiency of -0.42% and an average annual change in technological progress of 1.35%. This indicates that the GTFP of China's logistics industry during this period experienced positive growth, while the decline in the growth rate of technical efficiency had a negative impact on the GTFP of the industry. The growth rate of GTFP is mainly the growth effect brought about by technological progress. Furthermore, technical efficiency is broken down into pure technical efficiency changes and scale efficiency changes, and the growth rates of the two indicators are -0.56% and 0.14% respectively. This indicates that the negative impact of pure technical efficiency on overall technical efficiency is more pronounced, and the trend of changes in pure technical efficiency and GTFP from 2005 to 2021 is similar. It can be concluded that the decline in pure technical efficiency is the fundamental reason for the decrease in the growth rate of GTFP. This may be attributed to issues such as poor management and low efficiency in the utilization of technology in most provinces and cities across China. Figure 1 illustrates the trend of the Green Total Factor Productivity (GTFP) growth index in the logistics industry across the eastern, central, western, and northeastern regions of China from 2005 to 2021. As depicted in the figure, the overall GTFP growth index in the logistics industry for all four regions exhibits a fluctuating upward trend. Among these, the eastern region's logistics industry recorded the highest average growth rate of 1.07% during the observation period, achieving the highest level of green development in 2007, 2011, 2013, 2019, 2020, and 2021. In contrast, the northeastern region's logistics industry had the lowest average growth rate of 0.41% during the same period. This was primarily due to the region's pure technical efficiency growth rate of -1.18%, which was significantly lower than that of the eastern (-0.27%), central (-0.55%), and western (-0.66%) regions, thereby constraining GTFP growth. Consequently, the decline in pure technical efficiency is a critical factor contributing to regional disparities in GTFP changes, highlighting the relatively greater constraints imposed by resources and the environment in the northeastern region.

Table 3 and Figure 2 demonstrate that the change in the Green Total Factor Productivity (GTFP) of China's logistics industry from 2005 to 2021 generally exhibited a fluctuating upward trend. Specifically, the GTFP of the logistics industry showed a rapid increase from 2005 to 2009, rising from -2.03% to 26.34%. During this period, China's logistics industry experienced rapid development, and technological progress achieved an average annual growth rate of 1.35%. This growth can likely be attributed to the rapid economic development following China's reform and opening-up, during which the previously lagging logistics industry no longer aligned with economic activities. Governments at all levels actively drew on the logistics development experiences of Western developed countries, tailored policies to national conditions, intensified urban environmental governance, and guided the logistics industry to further deepen reforms. However, from 2009 to 2010, the GTFP of the logistics industry displayed a clear downward trend. This decline was partly due to the impact of the 2008 financial crisis on the Chinese logistics industry, which faced challenges such as reduced freight transport demand and increased production factor costs, leading to a decline in GTFP. Additionally, the rising marginal abatement costs of the logistics industry further suppressed its green development. From 2010 to 2015, the total factor productivity of China's logistics industry exhibited an "M-shaped" trend. One possible explanation is that during the 12th Five-Year Plan period, China's logistics enterprises integrated and optimized logistics resources through technological innovation, management innovation, and organizational innovation, and new business models emerged continuously. China has vigorously developed new equipment that is energy-efficient, environmentally advanced, and recycles resources, promoting the intelligent and green development. At the same time, China's logistics industry during the 2011-2015 Plan period will face both achievements and problems, as well as challenges and opportunities. For example, there are problems such as the intertwined contradictions of insufficient effective demand and inadequate supply capacity, the coexistence of excess and structural shortages in the total logistics infrastructure, and the slowdown in the growth of logistics demand, as well as operational difficulties for some companies, which have resulted in an “M-shaped” increase in its GTFP. From 2015 to 2021, the change in the GTFP of the logistics industry exhibited a fluctuating upward trend, with an average annual growth rate of 3.67%. This growth was primarily driven by technological progress, which had an average annual growth rate of 3.20%. This shows that the automation, intelligence and informatization of modern logistics management have ushered in opportunities for green development.

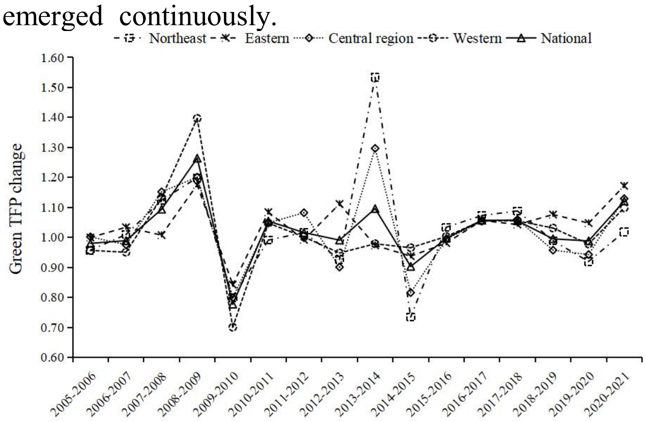


Figure 1. Trends in GTFP Changes in China's Logistics Industry in Four Major Regions, 2005-2021

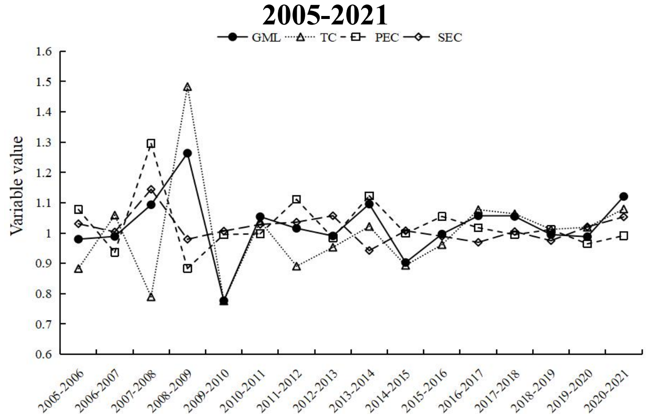
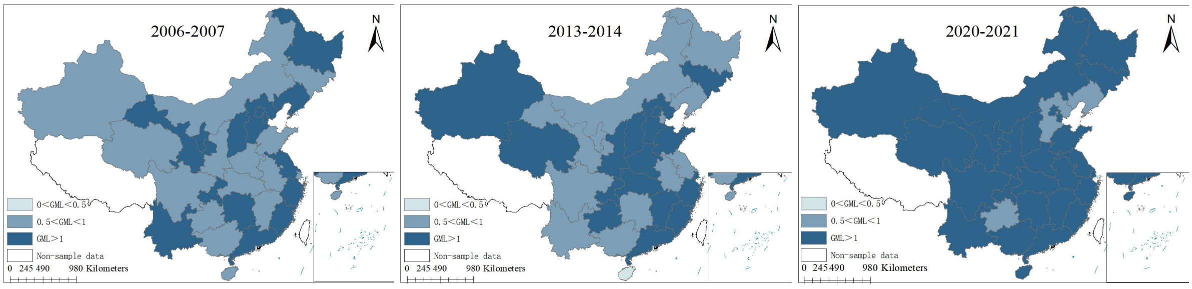
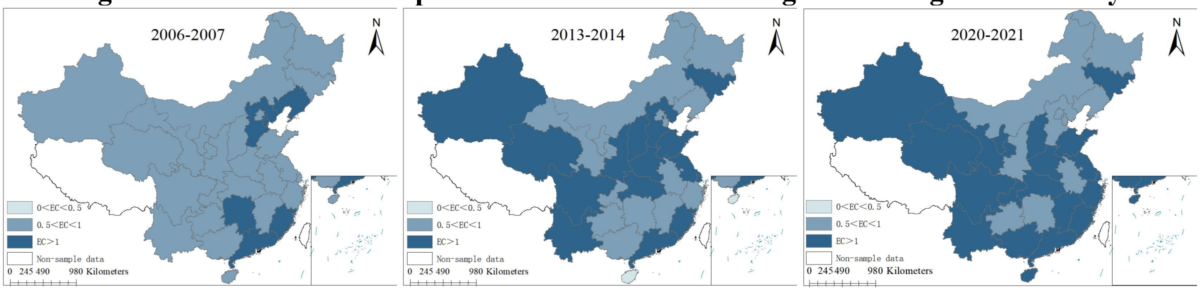


Figure 2. Trends in GTFP and Its Decomposition Index in the Logistics Industry, 2005-2021



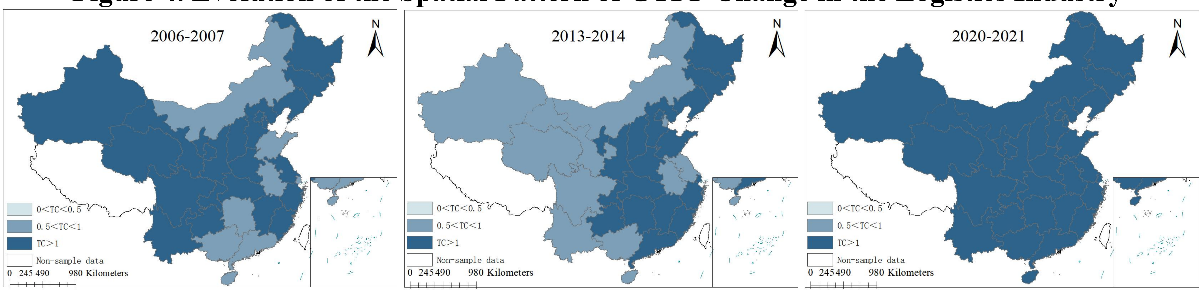
a Movement of the GML 2006-2007 | b Movement of the GML 2013-2014 | c Movement of the GML 2020-2021

Figure 3. Evolution of the Spatial Pattern of GTFP Change in the Logistics Industry



a Movement of the EC 2006-2007 | b Movement of the EC 2013-2014 | c Movement of the EC 2020-2021

Figure 4. Evolution of the Spatial Pattern of GTFP Change in the Logistics Industry



a Movement of the TC 2006-2007 | b Movement of the TC 2013-2014 | c Movement of the TC 2020-2021

Figure 5. Evolution of the Spatial Pattern of Technical Efficiency Changes in the Logistics Industry.

5.3 Spatial Distribution Patterns of GTFP Changes in the Logistics Industry

Using Arcgis 10.8 software, the spatial distribution patterns of changes in GTFP, technical efficiency, and technological progress in the logistics industry for the three time periods 2006-2007, 2013-2014 and 2020-2021 are plotted respectively, as shown in Figure 3, 4 and 5. There are differences in the changes in GTFP and its decomposition between different time periods and provinces. In 2006-2007, the provinces and cities with a change in GTFP of the logistics industry greater than 1 included Beijing, Tianjin, Hebei, Guangdong, Chongqing, and 15 other provinces and cities, and were mainly concentrated in the eastern region and parts of the northeastern region. The GTFP shows obvious spatial non-uniformity characteristics. Overall, it shows a gradual decrease in the efficiency value of “coastal-inland”, and there is a more obvious agglomeration phenomenon in coastal areas. The reason for this is that coastal areas have unique natural and geographical advantages, as well as strong support from national policies. They vigorously develop export-oriented economies, and have sufficient capital, advanced technology, and well-developed transportation. Therefore, coastal areas have taken the lead in improving the efficient use of social and natural resources. In 2013-2014, 60% of the sample provinces and cities showed positive growth in GTFP. The 10 cities that improved significantly were mainly distributed in the central and western regions, and the growth in GTFP was mainly driven by technological efficiency. This shows from another perspective that these provinces and cities take environmental issues into account while promoting the transformation and development of the logistics industry. Environmental governance has achieved the rational allocation of resources in the logistics industry and linked environmental protection, thereby improving the GTFP of the logistics industry. The change in the GTFP of the logistics industry in 2020-2021 shows a further upward trend. Only the GTFP of the logistics industry in Liaoning Province, Hebei Province, and Guizhou Province has not improved, and the technological progress index value in the four major regions during the study period is greater than 1, which shows that technological progress has significantly contributed to improving the GTFP. Under the guidance of the national strategy of “innovation-driven development,” the supporting and leading role of scientific and technological innovation in China's logistics industry has been significantly enhanced. Scientific and technological innovation has gradually broken through the constraints of resource and environmental bottlenecks, and GTFP has continued to improve. During this period, technical efficiency has to some extent constrained the improvement of the GTFP. Possible reasons: on the one hand, there are problems of input redundancy and diseconomies of scale in actual logistics operations, and there is still much room for optimization of the factor allocation structure, which fails to give full play to the role of industrial agglomeration.

6. Convergence Analysis of GTFP in the Logistics Industry

6.1 σ-Convergence Analysis

Figure 6 illustrates the trend of the coefficient of variation (σ) for GTFP at the national level and across the four major regions from 2005 to 2021. As depicted in the figure, China's GTFP in the logistics industry exhibited a slight "serrated" fluctuation pattern over this period. From a national perspective, the absolute gap in GTFP among regions fluctuated modestly, indicating an overall sigma convergence in GTFP growth across China's provinces. In terms of sub-regions, except for the western region, the northeastern, eastern, and central regions experienced significant fluctuations in the σ value from 2011 to 2016, with similar trends, suggesting divergence in GTFP changes within these regions during this period. Overall, the eastern, central, and western regions displayed fluctuating and intermittent slight convergence, reflecting a gradual narrowing of internal disparities within these regions over the research period. In contrast, the northeastern region's σ value generally showed a fluctuating increase, with convergence gradually shifting toward slight divergence.

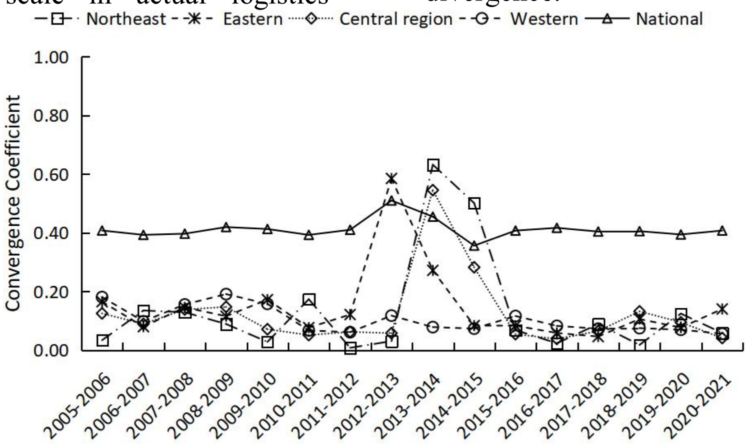


Figure 6. Coefficients of Variation of GTFP of Logistics Industry in Four Major Regions of China

7. Conclusions

This study is based on data related to the GTFP of the logistics industry in 30 provinces in China from 2005 to 2021. Utilizing a Super-EBM model incorporating non-desirable outputs and the Global Malmquist-Luenberger productivity index, the GTFP is measured, and the spatial distribution patterns of GTFP in the logistics industry are comprehensively characterized. Finally, the coefficient of variation is employed to analyze the σ-convergence characteristics of the evolution of disparities in GTFP within the logistics industry. The main conclusions and implications are as follows:

From 2005 to 2021, the growth rates of GTFP in the logistics industry varied across the country and the four major regions, and there were significant spatial differences. The GML index of GTFP generally increased slightly by 0.90%, mainly due to technological changes. Decomposing the GTFP GML index, we find that technological progress grew by 1.35% and technological efficiency fell by 0.42%. This shows that the decline in pure technological efficiency is the main reason hindering the improvement of GTFP. From the perspective of the four major regional divisions, the deterioration of pure technological efficiency is the key factor that has caused the GTFP of the northeast region to lag behind that of other regions. This means that China's logistics industry is constrained by soft factors such as the market environment and management level, and the efficiency of resource factor allocation is significantly lower than the economy of scale and agglomeration efficiency of the logistics industry. There is also the problem of inefficient use of technology, which shows that there is still much room for growth and development potential for the GTFP of China's logistics industry.

Specifically, in the future, it is essential to further enhance the technological and managerial capabilities of the logistics industry, optimize its industrial structure, allocate resource elements more rationally, foster the development of market economies within the logistics sector, and improve resource allocation efficiency. Simultaneously, it is crucial to actively align with promoting the enhancement of logistics quality and efficiency, reduce costs, and strengthen the support of logistics technology innovation and the empowerment of digital technologies in logistics, while encouraging technological progress. Emphasis should be placed on improving the management practices of logistics enterprises, designing effective supply chain strategies, and enhancing the operational efficiency of modern supply chains. Building a professional logistics workforce, advancing the intelligent transformation of logistics, improving the technical efficiency of the industry, and fostering the coordinated improvement of GTFP in regional logistics industries are key priorities. Additionally, efforts should be intensified to promote green logistics development, enhance energy conservation and emission reduction in the logistics sector, encourage logistics enterprises to adopt green energy-saving and low-carbon management practices, popularize energy management contract models, and actively conduct energy conservation diagnostics. Accelerating the development of reverse logistics service systems, establishing integrated online and offline reverse logistics service platforms and networks, innovating service models and scenarios, and promoting product recovery and resource recycling are also critical steps forward.

From 2005 to 2021, the coefficient of variation for the growth index of GTFP and its four major regions exhibited a slight "saw-tooth" fluctuation pattern during the research period. Overall, a sigma convergence trend is observed in the growth of GTFP across Chinese provinces, indicating a reduction in the absolute gap between regions over time. Therefore, to promote the green and high-quality development of the logistics industry in the future, it is essential to first recognize the importance of fostering balanced development in the total factor productivity of green logistics. Building on this understanding, efforts must adhere to the principle of narrowing regional disparities in total factor productivity, coordinating development strategies, and enhancing regional collaboration.

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