IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 11, 2021, accepted July 26, 2021, date of publication July 30, 2021, date of current version August 10, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3101233

Influence of Collaborative Agglomeration Between Logistics Industry and Manufacturing on Green Total Factor Productivity Based on Panel Data of China's 284 Cities

JIN-FENG LI[1,2], (Member, IEEE), HAI-CHENG XU[1], (Member, IEEE), WAN-WAN LIU[3], (Member, IEEE), DONG-FANG WANG[4], (Member, IEEE), AND WEN-LONG ZHENG[1], (Member, IEEE)

[1]School of Economics and Management, Chang'an University, Xi'an 710064, China
[2]School of Logistics and Electronic Commerce, Henan University of Animal Husbandry and Economics, Zhengzhou 450044, China
[3]School of Management, Zhengzhou Institute of Technology, Zhengzhou 450044, China
[4]School of Business, Wuyi University, Wuyishan 354300, China

Corresponding author: Jin-Feng Li (81359@hnuahe.edu.cn)

This work was supported in part by the General Project of Humanities and Social Sciences Research and Planning Fund of Ministry of Education under Grant 19YJA790097, in part by the National Social Science Fund of China under Grant 19XJL004 and Grant 20FJYB009, and in part by the Key Discipline of Henan University of Animal Husbandry Economics ''Business Enterprise Management'' under Grant mxk2016201.

ABSTRACT Improving green total factor productivity (GTFP) is an important theme. Whether collaborative agglomeration between logistics industry and manufacturing (LMCA) can effectively promote GTFP is worth further research. Based on the panel data of 284 cities in China from 2005 to 2018, GTFP is calculated by using the Biennial Malmquist-Luenberger productivity index (BMLPI), and this research investigates the impact of LMCA on GTFP by adopting the spatial Durbin model (SDM) and threshold regressive model (TRM). First, LMCA plays a significant role in promoting the improvement of GTFP in the local and surrounding areas through the knowledge spillover effect, scale economy effect, resource allocation effect and symbiotic economic effect, and the spillover effect is greater than the local effect. Second, the positive direct effect of LMCA on GTFP comes mainly from technological progress, and the positive indirect effect of LMCA on GTFP comes mainly from the positive spillover effect of technological progress and technical efficiency improvement. Finally, the Williamson hypothesis exists significantly in the collaborative agglomeration scenario of the logistics industry and manufacturing of China. With the improvement of the level of economic development, the impact of LMCA on GTFP changes from insignificant to promoting. However, when it is further improved, the promoting effect turns into an inhibiting effect, and this change is dominated mainly by the impact of LMCA on technical change.

INDEX TERMS Collaborative agglomeration between logistics industry and manufacturing, green total factor productivity, Biennial Malmquist Luenberger productivity index, spatial Durbin model, threshold regressive model.

I. INTRODUCTION

The report of the 19th National Congress of the Communist Party of China pointed out that China's economic development must adhere to the principle of quality and efficiency priority and improve total factor productivity (TFP) by promoting quality reform, efficiency reform and dynamic changes in economic development. Green total factor productivity (GTFP) which fully considers energy consumption and negative environmental output has gradually become a key indicator to evaluate the economic quality and the level of green development and an important issue in the context of high-quality economy under the ''new normal'' and the current grim ecological environment [1]. Industrial agglomeration is one of the factors which affect the promotion of GTFP. Industrial collaborative agglomeration is the

The associate editor coordinating the review of this manuscript and approving it for publication was Baozhen Yao.

advanced stage of industrial agglomeration. The specialized agglomeration of a single industry cannot meet the demand of differentiated intermediate products. Industrial collaborative agglomeration, as an important form of spatial organization and a vital force to promote the development of the regional economy, has gradually featured the new economic era and become the means of industrial upgrading and shifting, optimizing spatial layout and improving urban efficiency by sharing infrastructure, information exchange and dissemination, technology spillover, and division of labor brought by scale economy benefits [2].

Manufacturing is an indispensable industry in almost every country. In particular, China is called the world factory, and its manufacturing has a great impact on China and even the world economy. In 2020, China's manufacturing added value accounted for nearly 30% of the global total, maintaining its position as the world's largest manufacturing country for 11 years. China is the only country in the world with all the industrial categories listed in the United Nations Industrial Classification. Agglomeration is an important organizational form of modern manufacturing that plays an important role in promoting the efficiency of the green economy. Therefore, there are an increasing number of studies on the collaborative agglomeration between producer services and manufacturing, which can improve GTFP through the innovation effect [3], pollution emission reduction effect [4], industrial structure optimization and upgrading effect [5], economic growth effect [6] and other ways. The logistics industry, as the producer service industry most closely related to manufacturing, plays a significant role in promoting the production efficiency of manufacturing and presents a spatial geographical proximity to the distribution of manufacturing, showing an increasingly obvious trend of collaborative agglomeration with manufacturing [7]. However, the logistics industry does not completely follow the rule of collaborative agglomeration between producer services and manufacturing. In different spatial ranges, the logistics industry may show that some enterprises cluster to the regional center, and some enterprises will migrate to the periphery of the region along with the manufacturing [8]. The unique phenomenon of the coexistence of "complementarity" and "extrusion" characteristics of collaborative agglomeration between logistics industry and manufacturing (LMCA) has attracted increasing attention [9]. Whether this unique form of agglomeration can effectively improve GTFP is worthy of further study. Therefore, the logistics industry cannot be generalized to the financial, business consulting and other producer services industries. A more targeted theoretical framework needs to be built to analyze the impact of LMCA on GTFP.

The marginal contribution of this paper is as follows: First, from the perspective of spatial spillover, this paper constructs a theoretical model between LMCA and GTFP for the first time, which provides a theoretical analysis framework for revealing the impact mechanism of industrial collaborative agglomeration on GTFP. Second, considering both the spatial spillover effect and threshold effect, based on panel data of 284 cities in China from 2005 to 2018, this paper builds a spatial Durbin model (SDM) and threshold regression model (TRM) respectively, which provides more robust empirical evidence for the relationship between industrial agglomeration and GTFP. Finally, this paper uses data envelopment analysis (DEA) and the Biennial Malmquist Luenberger productivity index (BMLPI) to measure and decompose GTFP of 284 cities in China from 2005 to 2018. BMLPI has the advantages of no linear programming unsolvable, more flexible, considering the technological regression, and relatively simple calculation, which makes the measurement results of GTFP more accurate.

The other sections are organized as follows: Section II shows a literature review; Section III constructs the mechanism analysis framework; Section IV introduces the research design, which includes data, methods and variable selection; Section V gives empirical analysis results and discussion; and Section VI draws research conclusions and policy implications.

II. RELATED LITERATURE REVIEW

Since Ellison and Glaeser (1997) first defined spatial agglomeration among heterogeneous related industries as industrial collaborative agglomeration from the perspective of manufacturing [10], research on collaborative agglomeration between the producer services industry and manufacturing has gradually become a hot issue. GTFP not only includes economic growth but also considers the impact on the environment. Therefore, this paper reviews the related literature from the following three aspects.

A. INDUSTRIAL COLLABORATIVE AGGLOMERATION AND ECONOMIC GROWTH

On the one hand, industrial collaborative agglomeration can promote economic development through positive externalities such as the agglomeration effect, scale economy effect, synergy effect and innovation effect. Chen and Chen [11] proposed that collaborative agglomeration between producer services and manufacturing can generate an economic growth effect (scale and efficiency) by exerting an agglomeration effect and synergy effect. Li and Li [12] empirically found that the collaborative agglomeration between high-tech manufacturing and knowledge-intensive service industries promotes economic development by promoting innovation with a mediating effect model. Based on the spatial econometric model, Li and Feng [13] argued that the collaborative agglomeration between high-tech manufacturing and high-tech service industries can improve production efficiency by industrial collaborative division of labor, realize the free flow of factors, increase the efficiency of resource allocation, form the spatial spillover effect of knowledge, technology and innovation, and drive the economic development of surrounding areas. Hu and Zhu [14] demonstrated that the reasonable spatial layout of producer services and manufacturing helps reduce the production cost of enterprises, improve product quality and competitiveness, enhance factor productivity and promote economic growth.

On the other hand, the impact of industrial collaborative agglomeration on economic growth is also limited by urban population size, economic development level and other factors, which may lead to a nonlinear relationship between them. Chen [15], Peng and Xiao [16], and Zhou and Chen [17] put forward that there is an inverted U-shaped curve between industrial collaborative agglomeration and economic development, that is, industrial collaborative agglomeration can promote economic growth at the early stage, but when the agglomeration reaches a certain level, economic growth will be inhibited due to the existence of negative externalities such as the crowding effect of agglomeration. Dou and Liu [6], Li and Feng [13], and Zhou and Chen [17] believed that there is a threshold effect on the impact of industrial collaborative agglomeration on economic development. When the threshold variable is between the first and second thresholds, the promotion effect of collaborative agglomeration on economic growth is the most significant; when the threshold variable is lower than the first threshold or higher than the second threshold, industrial collaborative agglomeration may hinder economic growth.

B. INDUSTRIAL COLLABORATIVE AGGLOMERATION AND ENVIRONMENTAL POLLUTION

Industrial collaborative agglomeration reduces environmental pollution through the spatial spillover effect, complementary effect and innovation effect. Cai and Xu [18] believed that industrial collaborative agglomeration is conducive to exerting the spatial spillover effect of knowledge and technology, decreasing the enterprise factor cost and transaction cost, and improving the industrial production efficiency and management level to reduce the pollution emissions per unit output and promote the improvement of haze pollution. Miao and Guo [19] analyzed externalities, industrial ecology and specialization, and they believed that industrial collaborative agglomeration could effectively improve environmental pollution by using the synergy between complementary industries, improving the level of specialization, promoting technological innovation and building an industrial symbiosis network. Shen *et al.* [4] established that collaborative agglomeration is conducive to the reduction of industrial sulfur dioxide intensity, and this pollution reduction effect can produce a spatial spillover effect through an economic network. Cai and Xu [20] showed that collaborative agglomeration between the producer service industry and manufacturing can promote the efficiency of manufacturing through the scale economy effect, competition effect, specialization effect and learning effect to reduce environmental pollution.

In addition, the impact of industrial collaborative agglomeration on environmental pollution is also affected by the level of industrial agglomeration, resource allocation and other factors, and there may be a nonlinear relationship between them. Huang and Wang [21] and Lu and Yang [22] indicated that the relationship between industrial collaborative agglomeration and environmental pollution is the inverted U-shape. When the level of industrial agglomeration is low, collaborative agglomeration aggravates pollution; with the continuous development of the agglomeration level, the level of industrial agglomeration across the "inflection point" can reduce pollution emissions. Li *et al.* [23] presented that the effect of industrial collaborative agglomeration on promoting carbon emission reduction is significantly limited by the degree of improper resource allocation, and there is a double threshold effect: in areas with reasonable resource allocation, industrial collaborative agglomeration can produce a significant agglomeration effect and promote the reduction of carbon intensity. Once the degree of improper resource allocation exceeds a critical value, the agglomeration effect will be transformed into a crowding effect, leading to the failure to reduce carbon intensity.

C. INDUSTRIAL COLLABORATIVE AGGLOMERATION AND TFP/GTFP

There is no consensus on the impact of industrial agglomeration on TFP/GTFP, and there are three main viewpoints.

First, industrial collaborative agglomeration promotes TFP/GTFP. Wang *et al.* [9] measured the TFP of 27 cities in the Yangtze River Delta Urban Agglomeration with the Malmquist-Luenberger productivity index (MLPI), applied the system generalized method of moments (GMM) model of a dynamic panel and pointed out that the collaborative agglomeration of the manufacturing and producer services industry has a positive effect on TFP. Yu *et al.* [24] estimated the economic efficiency of 285 Chinese cities based on the stochastic frontier approach (SFA) and concluded that the collaborative agglomeration between manufacturing and producer services has a significant role in promoting the economic efficiency of cities in central and western China. Zhang and Zhao [25] researched the internal relationships between the collaborative agglomeration of the Internet and manufacturing and GTFP based on more than 283 cities in China using a slack-based measure (SBM)-undesirable model and a spatial econometric panel mode. Collaborative agglomeration can significantly improve GTFP and has both significant direct and indirect effect. Moreover, the indirect effect is higher than the direct effect.

Second, industrial collaborative agglomeration restrains TFP/GTFP. Wu [26] proposed that collaborative agglomeration between the service industry and strategic emerging industry has a significant negative effect on TFP because excessive agglomeration produces a negative externality—continuous improvement of the agglomeration level will lead to an increase in sunk costs such as land price, wages, traffic congestion, etc., in the agglomeration area, and it is difficult for enterprises with large fixed capital to exit the agglomeration area. The enterprises with low production efficiency may become zombie enterprises, and reduce the overall supply chain production efficiency. However, Yu *et al.* [24] believed that the industrial collaborative agglomeration between manufacturing and producer service industries hinders urban economic efficiency due to the congestion effect of manufacturing agglomeration and the lack of positive interaction between manufacturing and producer services.

Finally, the impact of industrial collaborative agglomeration on TFP/GTFP is uncertain. Wu [27] and Wu [28] estimated the TFP of 246 cities in China with the Global Malmquist-Luenberger productivity index (GMLPI) and proposed that the impact between the collaborative agglomeration of manufacturing and producer services on TFP presents a nonlinear feature based on TRM. Specifically, with the increase of industrial specialization agglomeration, the impact of collaborative agglomeration between producer services and manufacturing on TFP growth tends to change from negative to positive. When manufacturing specialization agglomeration is a threshold variable, collaborative agglomeration has a threshold effect on TFP and its decomposition items. Wang and Sun [29], Chen *et al.* [30], based on TRM and SDM, demonstrated that the influence of industrial collaborative agglomeration on GTFP is an inverted U-shape, taking the collaborative agglomeration of manufacturing and producer services as the research object. In the initial stage of collaborative agglomeration, there is no strategic cooperative relationship among enterprises, with weak correlation between upstream and downstream and low efficiency of resource utilization. In addition, the migration of diversified enterprises brings more pollutant emissions, and centralized pollution control is more efficient than specialized pollution control. As a result, the effect of pollution reduction gradually appears. Knowledge and technology cooperation among enterprises promotes the spillover of clean technology. The effective division of labor and cooperation further improves production efficiency. Technological progress and large-scale pollution control reduce pollutant emissions.

In conclusion, although many scholars have discussed the impact of industrial collaborative agglomeration on economic growth, environmental pollution and TFP from various aspects, there are a few studies on the impact of the collaborative agglomeration between manufacturing and producer services on GTFP, and the literature often ignores the spatial spillover effect or nonlinear effect. In particular, it lacks the research on the relationship between LMCA and GTFP. Moreover, the literature uses MLPI and GMLPI mainly to caculate urban GTFP, but these measurement methods have some problems, such as infeasible solutions and complex calculations, which cannot accurately measure urban GTFP.

III. THEORETICAL ANALYSIS AND RESEARCH HYPOTHESIS

A. DIRECT PATH FOR LMCA TO INFLUENCE GTFP

The agglomeration of manufacturing or logistics industry reflects the economic phenomenon that enterprises in the same industry choose to cluster to each other because of the constraints of factors such as production elements, transaction costs and location advantages, while the reason of the collaborative agglomeration between them in space is the complementary differences and the mutual needs of the final and intermediate production department. Industrial collaborative agglomeration is a higher stage of industrial agglomeration, which not only enlarges the knowledge spillover effect and crowding effect of a single industrial agglomeration but also produces economic, technological and knowledge linkages due to vertical or vertical linkages among heterogeneous industries. The three kinds of correlation effects produce different positive and negative effects to influence local city GTFP (as shown in the right half of Figure 1).

Theoretically, LMCA may have four positive effects on GTFP. First, LMCA brings more interdisciplinary collision and integration than specialized agglomeration. LMCA can provide technical support for green development and generate greater and more effective innovation results by realizing the sharing and dissemination of complementary knowledge and technology among different industries, forming collaborative innovation consortia, promoting technological innovation and spillover, and improving the innovation performance of the subject and the ability of imitation, digestion, absorption and transformation. Second, with the continuous expansion of manufacturing, the logistics industry is gradually separated from manufacturing. In the development process, manufacturing and logistics promote and depend on each other, and the cooperation division system is gradually improved. The regional GTFP is consequently enhanced through the forward and backward correlation of input and output, reducing the logistics cost, facilitating enterprise communication, division and cooperation, continuous improving the scale effect of economic development, and producing the spillover effect in the surrounding areas. Third, LMCA is conducive to sharing resources, improving the utilization efficiency of infrastructure, public service platforms and human resources, promoting the coordinated development of logistics industry and manufacturing and enhancing the efficiency of urban resource allocation. Finally, LMCA is convenient for the centralized consumption of resources and treatment of pollutants and makes the vertical connection between heterogeneous industries closer, which is more beneficial to the construction of a circular economy system.

Corresponding to the positive effect, LMCA has three negative effects on GTFP. Although LMCA saves transaction costs and talent search costs, when LMCA in a region is excessive, the local land rent, transportation, time and other costs will increase correspondingly, which is not conducive to the improvement of enterprise productivity. Intensive economic activity will also lead to traffic, public infrastructure congestion and environmental degradation, and the scale effect is no longer significant, resulting in a crowding effect, which will challenge the carrying capacity of local resources and the environment and hinder the promotion of GTFP. Moreover, LMCA will attract numerous production factors to gather rapidly and simultaneously, forming a lock-in effect. This path lock-in not only hinders the transformation and technology diffusion of new emission reduction technologies but also crowds out the resources of other regions, which is not conducive to the improvement of GTFP in other regions.

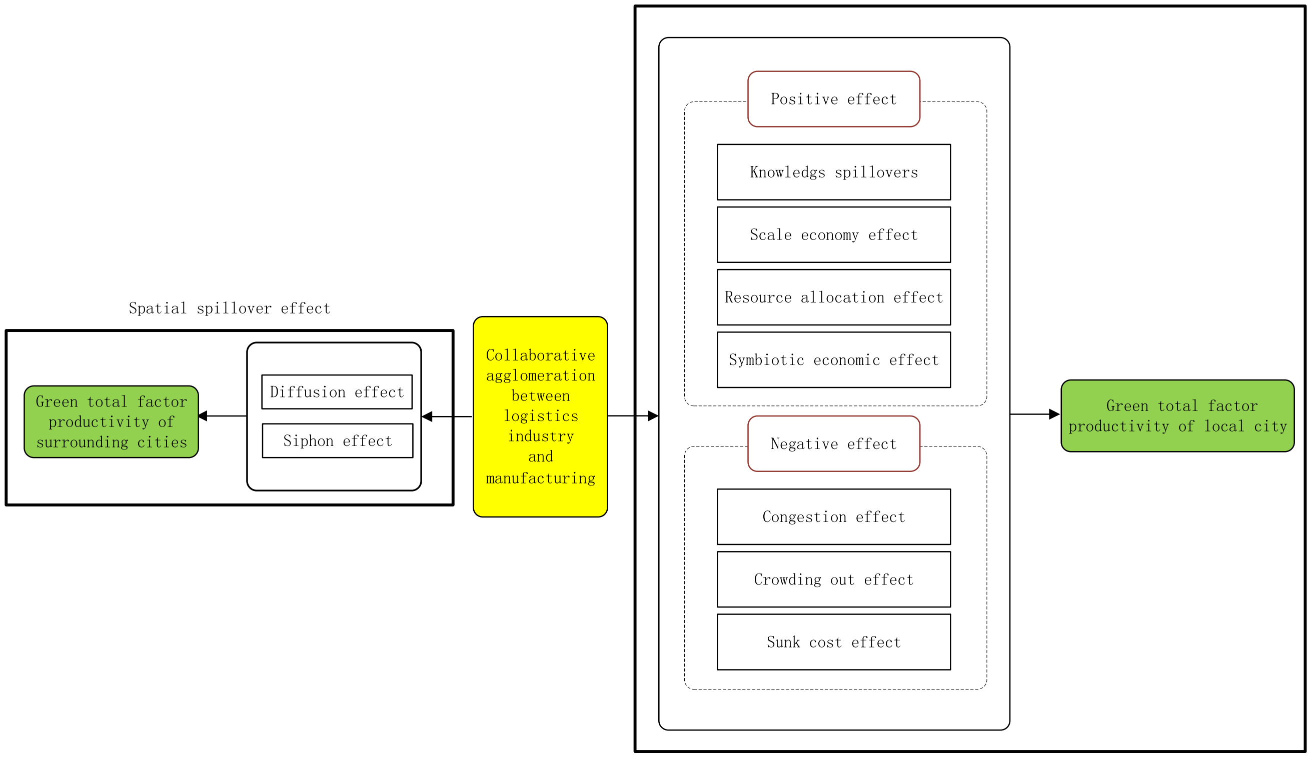

FIGURE 1. **The influence mechanism diagram of LMCA on GTFP.**

Finally, due to the existence of sunk costs, logistics enterprises, especially manufacturing enterprises cannot easily exit a certain region, resulting in relatively low productivity enterprises staying in the industrial agglomeration area for a long time or even evolving into "zombie enterprises", which will reduce the production or service efficiency of related enterprises.

In addition, GTFP can be divided into technical efficiency change (TEC) and technical change (TC), in which TEC refers to the production efficiency affected by management, system, enterprise scale and other factors, and TC refers to the production efficiency affected by technological change or the matching of technological progress with economic scale. In theory, LMCA can effectively promote TEC and TC, but LMCA increases the government regulatory investment, which is not conducive to the improvement of local TEC. The influence direction of LMCA on GTFP and its decomposition depends on the positive and negative effects. Based on the above analysis, we propose Hypothesis 1.

Hypothesis 1. Under the dual influence of positive and negative effects, LMCA has a certain correspondence to the local urban GTFP and its decomposition term, but the influence directions are uncertain.

Williamson [31] proposed the "Williamson hypothesis": spatial agglomeration can effectively promote efficiency in the early stage of economic development, but after reaching a certain threshold value, the impact of spatial agglomeration on economic growth decreases and is not conducive to economic growth, and crowding externalities make agglomeration tend to be a more decentralized geographical spatial structure. According to the hypothesis, the influence of LMCA on GTFP may be discrepant in different stages of economic development. Based on the above analysis, we propose Hypothesis 2.

Hypothesis 2. The impact of LMCA on local urban GTFP and its decomposition items is affected by the level of economic development, and there may be threshold effects with different characteristics in different stages of economic development.

B. INDIRECT PATH OF LMCA AFFECTING GTFP

LMCA affects GTFP of surrounding cities through spatial spillover effects such as diffusion effects and siphon effects (as shown in the left half of Figure 1). In the process of continuous collaborative agglomeration of logistics industry and manufacturing, logistics and manufacturing facilities and other related infrastructure will be continuously improved. Through the diffusion effect, this improvement will bring capital, talent, technology and other resources to the surrounding cities and promote the economic development of the surrounding cities. However, if a city forms a manufacturing growth pole or a logistics growth pole, this pole will have a siphon effect on the surrounding cities, continuously attract the resources of surrounding cities to gather in the logistics industry and manufacturing and hinder the economic growth of surrounding cities. Based on the above analysis, the following research hypotheses are proposed.

Hypothesis 3. LMCA affects GTFP and decomposition items of surrounding cities by exerting diffusion effects and siphon effects.

IV. RESEARCH DESIGN

A. MODEL DESIGN

1) SPATIAL ECONOMETRIC MODEL

To systematically investigate the impact of LMCA on GTFP, the following benchmark model was constructed based on Wu [27]'s econometric model:

$$\ln GTFP_{it} = \alpha + \beta_1 \ln LMCA_{it} + \varphi_1 \sum_{i=1}^{N} X_{it} + \mu_i + v_t + \varepsilon_{it} \tag{1}$$

where i is the city; t is the year; the explained variable *GTFP* is the green total factor productivity; the core explanatory variable *LMCA* is the collaborative agglomeration index between logistics industry and manufacturing; X is a series of control variables, including *INT*, *GOV*, *T*, *ROAD*, *INN*; β_1, φ_1 are the regression coefficients with estimation of the core explanatory variable and a series of control variables; μ_i is the spatial trait effect; v_t is the temporal trait effect; ε_{it} is the random disturbance term; and α is the constant.

LMCA can affect GTFP of local and neighboring areas. There is obvious spatial correlation of GTFP. This paper further constructs a spatial econometric model with a spatial weighting term to test the impact of LMCA of a certain region on GTFP of neighboring regions. SDM is set up as follows:

$$\begin{aligned} \ln GTFP_{it} = {} & \alpha + \rho \sum_{j=1, j\neq i}^{N} W_{ij} \ln GTFP_{it} + \beta_1 \ln LMCA_{it} \\ & + \beta_2 \sum_{j=1, j\neq i}^{N} W_{ij} \ln LMCA_{it} + \varphi_1 \sum_{i=1}^{N} X_{it} \\ & + \varphi_2 \sum_{j=1, j\neq i}^{N} W_{ij} X_{it} + \mu_i + v_t + \varepsilon_{it} \end{aligned} \tag{2}$$

where ρ is the spatial autocorrelation effect of GTFP; W_{ij} is the spatial weight matrix; and β_2, φ_2 are the influence coefficients of the core explanatory variable and control variables on GTFP of adjacent areas, respectively.

Spatial weight matrix is the core of SDM. According to the first law of geography, the closer the spatial units are, the stronger the spatial spillover effect which attenuates with increasing distance will be. Therefore, this paper adopts the inverse distance square spatial weight matrix W_1, and the specific form is shown in formula (3):

$$W_1 = \begin{cases} 1/\mathrm{d}_{ij}^2, & i \neq j \\ 0, & i = j \end{cases} \tag{3}$$

2) THRESHOLD MODEL

To investigate the threshold characteristics of LMCA on GTFP in the process of economic growth, using Hansen's panel threshold model as reference [32], a panel threshold model with *PGDP* as the threshold variable and LMCA as the threshold dependent variable is constructed:

$$\begin{aligned} \ln GTFP_{it} = {} & \alpha + \lambda_1 \ln LMCA_{it} I(PGDP_{it} \leq \tau_1) \\ & + \lambda_2 \ln LMCA_{it} I(\tau_1 < PGDP_{it} \leq \tau_2) + \cdots \\ & + \lambda_n \ln LMCA_{it} I(PGDP_{it} > \tau_{n-1}) \\ & + \beta X_{it} + \mu_i + v_t + \varepsilon_{it} \end{aligned} \tag{4}$$

where $PGDP_{it}$ is the threshold variable; $\tau_1, \tau_2, \ldots, \tau_n$ are the threshold values; $\lambda_1, \lambda_2, \ldots, \lambda_n$ are the estimation parameters of different threshold intervals; and $I(\cdot)$ is the indicative function. When the threshold variable meets the conditions in brackets, it is 1; otherwise, it is 0. Other symbols have the same meanings as above.

B. VARIABLE SELECTION AND CALCULATION

1) EXPLAINED VARIABLES

The traditional accounting method, stochastic frontier analysis (SFA) and data envelopment analysis (DEA) are generally used in academic circles to measure TFP. Compared with the other two methods, DEA has the following advantages. First, DEA does not need to set a specific function form. As a result, DEA avoids the result deviation caused by the wrong setting of the production function in the traditional accounting method and SFA. Second, DEA can decompose TFP into a technical efficiency index and technological progress index. Third, GTFP is constructed by bringing pollution output into a unified input-output production system [33]. Chung *et al.* [34] proposed MLPI based on the directional distance function (DDF), which was used to solve the problem of GTFP measurement, including pollutant emissions as undesirable output, and real green productivity was obtained for the first time. However, MLPI has a potential linear programming unsolved problem when DDF is measured in a mixed period. To solve the infeasible solution problem, Oh and Heshmati [35] constructed a sequential environmental technology set including not only the current year but also all years before the current year, based on the assumption that there will be no technological regression, and proposed the Sequential Malmquist-Luenberger productivity index (SMLPI). This method can only reduce but not completely avoid infeasible solutions and ignores the situation of technical retrogression. In addition, SMLPI represented by the geometric average is not cyclic or transitive. To overcome these shortcomings, Oh and Lee [36] established the Global Malmquist-Luenberger productivity index (GMLPI). Nevertheless, GMLPI also has defects: if the data change, for example, when the data set is added in the new period, the whole frontier of GMLPI needs to be reconstructed, and the whole technology would change. The index needs to be recalculated, and the calculation is very complex and lacks stability. To overcome this problem, Pastor *et al.* [37]

introduced the Biennial Malmquist productivity index (BMPI), which is used as a production technology to calculate the efficiency and productivity index every two periods. BMPI not only avoids the infeasible solution of linear programming when MLPI is decomposed but also avoids recalculation when adding a data set in the new period compared with GMLPI. In the meantime, BMPI can avoid the situation in which sequential DEA does not have technical retrogression but does not consider unexpected output. To overcome the shortcomings of traditional MLPI, SMLPI and GMLPI, based on BMPI and considering unexpected output, Wang *et al.* [38] constructed Biennial Malmquist Luenberger productivity index (BMLPI) to measure and decompose traditional energy productivity under carbon emission constraint, and the calculation formula of the new productivity index is:

$$
\begin{aligned}
BMLPI_t^{t+1} &= \frac{1+\vec{D}_o^B(x^t, y^t, b^t; y^t, -b^t)}{1+\vec{D}_o^B(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})} \\
&= \left[\frac{1+\vec{D}_o^t(x^t, y^t, b^t; y^t, -b^t)}{1+\vec{D}_o^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}\right] \\
&\quad \times \left[\frac{1+\vec{D}_o^B(x^t, y^t, b^t; y^t, -b^t)}{1+\vec{D}_o^t(x^t, y^t, b^t; y^t, -b^t)} \times \frac{1+\vec{D}_o^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}{1+\vec{D}_o^B(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}\right] \\
&= TEC \times TC
\end{aligned} \tag{5}
$$

where TEC is the technical efficiency change; TC is the technical change; and $\vec{D}_o^t(x^t, y^t, b^t; y^t, -b^t)$ represents the directional distance function of the t-phase evaluation object under t-phase technology.

This paper uses BMLPI and Stata16 software to measure GTFP, TEC and TC of 284 cities in China from 2005 to 2018. A GTFP greater than 1 (less than 1) indicates GTFP growth (decline); a TEC greater than 1 (less than 1) suggests a change in green production efficiency caused by an improvement (decline) at the management and system levels; and a TC greater than 1 (less than 1) implies that a change in green production efficiency is caused by technological progress (retrogression).

Since the BMLPI reflects the change rate of GTFP of the current year compared with the previous year, referring to Shen *et al.* [39] and Cheng and Lu [40], this paper adopts the cumulative GTFP as the explained variable. The calculation method of cumulative GTFP is as follows: GTFP value of the base period (2004) is set to 1, the cumulative GTFP in the second year is the cumulative GTFP of the previous year multiplied by the BMLPI of the current year, and the cumulative TEC and cumulative TC are calculated according to the above method. The input-output variables in BMLPI are displayed in Table 1.

TABLE 1. Input-output factors definition.

Type	Index	Definition	Unit
Inputs	Labor force	The number of employees at the end of a year	Million people
	Capital stock	Total investment in fixed assets	Million yuan
	Energy consumption	Electricity consumption of the whole society	10^4 kilowatt-hour
Desirable output	Economic output	Real gross domestic product	Million yuan
Undesirable outputs	Environmental pollution	Industrial sulfur dioxide emissions	Ton
		Industrial wastewater discharge	10^4 ton
		Industrial smoke emissions	Ton

2) CORE EXPLANATORY VARIABLE

LMCA is the core explanatory variable of this paper. Based on the research purpose and the availability of data, referring to Yang [41], this paper uses location entropy to calculate industrial agglomeration and then measures the collaborative agglomeration between logistics industry and manufacturing through the relative difference of the agglomeration. The specific calculation formula is as follows:

$$LQ_{ji} = \frac{e_{ji}/E_j}{e_i/E} \tag{6}$$

$$LMCA_i = 1 - \frac{|LA_i - MA_i|}{LA_i + MA_i} \tag{7}$$

where LQ_{ji} refers to the location entropy of industry j in city i; e_{ji} refers to the number of employees of industry j in city i; E_j refers to the number of employees of industry j in China; e_i refers to the number of employees of all industries in city i; E refers to the total number of employees in all industries in China; $LMCA_i$ refers to the collaborative agglomeration index of logistics industry and manufacturing in city i; and LA_i and MA_i are the location entropy of logistics industry and manufacturing in city i respectively. According to formula (7), the closer the agglomeration level of logistics industry and manufacturing in city i is, the higher the level of collaborative agglomeration is, and the greater the value of $LMCA_i$ is.

3) THRESHOLD VARIABLE

According to the Williamson hypothesis, GTFP is closely related to the level of economic development. Therefore, *PGDP* with a constant price in each region in 2004 is taken as an indicator to measure the level of economic development [42]. *PGDP* is selected as the threshold variable in the threshold panel model to test and analyze the impact of LMCA on GTFP in different stages of economic development.

4) CONTROL VARIABLES

There are five control variables. First, government intervention (*GOV*) is characterized by the proportion of government fiscal expenditure in GDP. Under the system of fiscal decentralization, regional economic development is often associated with the promotion of government officials. Local government often uses economic, administrative and legal means to intervene in economic and social development, including environmental governance. Zhang and Li [43] found that the government is inclined to force firms to cut down pollution by administrative means in regions where government intervention is strong, which results in the misallocation of resources and is harmful to the improvement of GTFP. Second, science and technology investment level (T) is measured by the proportion of government science and technology expenditure in GDP. Generally, science and technology investment can stimulate social innovation, advance technological progress, achieve major changes in the production mode and organizational form of enterprises, improve the utilization efficiency of energy resources, and promote energy conservation and emission reduction [44]. Third, infrastructure (*ROAD*) is represented by the road area per capita. The construction of urban infrastructure can not only improve the economic operation environment and reduce the transaction costs between enterprises and the outside but also accelerate the upgrading of traditional industries and promote regional economic growth. However, if we only improve the urban internal infrastructure and do not form a close contact network with the outside of the city, the improvement of urban infrastructure cannot effectively promote urban efficiency [45]. Fourth, the innovation level (*INN*) is expressed by the total number of patents granted. In theory, innovation can effectively reduce energy consumption and environmental pollution and promote economic growth [29]. However, if innovation fails to effectively transform achievements, innovation may not promote the improvement of GTFP. Finally, population density (*POP*) is estimated by the ratio of the population of municipal districts to the built-up area of municipal districts at the end of the year. Population density reflects the degree of urban sprawl and population spatial agglomeration [46]. The increase in population spatial density may promote the effective use of resources, produce the scale agglomeration effect, and promote GTFP. However, the increase in population spatial density will make the demand for resources and energy grow correspondingly, strengthen the carrying capacity of resources and the environment, and may produce crowding externalities, which will cause further environmental damage due to unreasonable development modes and is not conducive to the improvement of GTFP [47].

C. DATA DESCRIPTION

At present, the logistics industry is not listed as an independent industry in China's national industry classification. Instead, the transportation, warehousing and postal industries are regarded as statistical industries, which can basically represent the development of the modern logistics industry. Therefore, this paper selects transportation, warehousing and postal industry data to replace the logistics industry data [48]. In 2003, China made a great adjustment in the scope of industrial statistics, while the statistical data of ''China Urban Statistical Yearbook'' only separated the telecommunication industry from transportation, storage and post and telecommunications industry in 2005 and began to count the data of urban transportation, warehousing and postal industry. Therefore, the time span of measuring GTFP is 2004-2018; the time span of LMCA and control variables is 2005–2018. To ensure the unity of the sample and the integrity of the data, Lhasa, Chaohu, Bijie, Tongren, Laiwu and other cities were excluded. Finally, 284 cities at the prefecture level and above were selected as the research objects. As the logistics industry and manufacturing are concentrated mainly in municipal districts, the main indicators are the data of municipal districts rather than the whole city, and some missing data are supplemented by the interpolation method. The data are mainly from the China Urban Statistical Yearbook (2005-2019), China Statistical Yearbooks (2005-2019), statistical yearbooks of 31 provinces, autonomous regions, and municipalities (2005-2019), statistical yearbooks of 284 cities (2005–2019), and National Economic and Social Development Statistics Bulletin of 284 cities (2004–2018). The longitude and latitude of each city are from the National Geographic Information Center. This paper uses 2004 as the base period to adjust the price of all data expressed in monetary value. To reduce heteroscedasticity, the related data except threshold variable are also logarithmically processed. Table 2 shows the descriptive statistical results for each variable.

V. EMPIRICAL RESULTS AND DISCUSSION ANALYSIS

A. SPATIAL CHARACTERISTICS OF IMPACT OF LMCA ON GTFP

1) SPATIAL AUTOCORRELATION TEST

Before estimation, the spatial autocorrelation of the main variables was tested by the global Moran index. Table 3 shows that ln*GTFP* passes the significance test of 10% in most years, ln*TC* passes the significance test of 5% in most years, while ln*TEC* passes the significance test of 10% in only 4 years; the core explanatory variable ln*LMCA* passes the significance test of 10% in 7 years. Except ln*POP*, which passes the

TABLE 2. Variables descriptive statistics.

Types	Variables Name	Symbol	N	Sd	Min	Max
Explained Variables	Green total factor productivity	ln*GTFP*	3,976	0.290	–1.421	1.331
	Technical efficiency change	ln*TEC*	3,976	0.200	–0.687	0.673
	Technical change	ln*TC*	3,976	0.258	–1.421	1.498
Core Explanatory Variable	Collaborative agglomeration level between logistics industry and manufacturing	ln*LMCA*	3,976	0.568	–4.756	0.000
Threshold Variable	GDP per capita	*PGDP*	3,976	4.618	0.207	38.378
Control Variables	Government intervention	ln*GOV*	3,976	0.489	–4.584	1.007
	Technology input	ln*T*	3,976	0.326	–5.300	0.523
	Infrastructure level	ln*ROAD*	3,976	0.621	–3.912	4.686
	Innovation level	ln*INN*	3,976	1.827	–8.517	2.637
	Population density	ln*POP*	3,976	1.172	–3.719	4.187

TABLE 3. Spatial autocorrelation test.

Year	ln*GTFP*	ln*TEC*	ln*TC*	ln*LMCA*	ln*GOV*	ln*T*	ln*ROAD*	ln*INN*	ln*POP*
2005	0.070***	0.019	0.097***	0.014	0.062***	0.057***	0.197***	0.283***	0.080***
2006	0.022	0.010	0.064***	0.025	0.062***	0.095***	0.202***	0.290***	0.089***
2007	0.034***	0.019	0.025	0.031*	0.069***	0.120***	0.167***	0.297***	0.077***
2008	0.040**	0.059***	0.046***	–0.006	0.083***	0.125***	0.207***	0.297***	0.078***
2009	0.027*	0.028*	0.051***	–0.007	0.088***	0.127***	0.180***	0.315***	0.060***
2010	0.028*	0.007	0.038**	–0.003	0.084***	0.141***	0.202***	0.335***	0.073***
2011	0.007	–0.012	0.043**	0.003	0.076***	0.194***	0.214***	0.346***	0.035**
2012	0.018	0.016	0.045***	0.042**	0.079***	0.113***	0.152***	0.350***	0.069***
2013	0.037**	0.014	0.025	0.005	0.090***	0.214***	0.188***	0.351***	0.065***
2014	0.033**	0.041**	0.021	0.051***	0.096***	0.201***	0.181***	0.354***	0.089***
2015	0.043**	0.014	0.042**	0.056***	0.101***	0.191***	0.162***	0.357***	0.095***
2016	0.049***	0.025	0.037**	0.075***	0.104***	0.233***	0.171***	0.349***	0.101***
2017	0.038**	0.009	0.042**	0.073***	0.099***	0.280***	0.180***	0.343***	0.100***
2018	0.042**	0.044**	0.042**	0.070***	0.077***	0.213***	0.176***	0.358***	0.043**

significance test of 5% in one year, the other control variables all pass the 1% significance level test.

To further study the correlation between different cities, local indicators of spatial association (LISA) maps of LMCA and GTFP of 284 cities in China from 2005 to 2018 were drawn based on the inverse distance square spatial weight matrix W_1 (Figure 2-Figure 3).

Figure 2 shows that there is a certain local spatial autocorrelation in LMCA, and the agglomeration trend is increasingly obvious. The ''High-High'' cluster area is concentrated mainly in the northeast and central regions in China, and the scope of clusters in the central region is expanding. The ''Low-High'' cluster area is adjacent to the ''High-High'' cluster areas. The ''High-Low'' cluster area is located mainly in the western region, and the surrounding area is mostly the ''Low-Low'' cluster area.

Figure 3 shows that there is a certain local spatial autocorrelation in the growth of urban GTFP, and the agglomeration trend is increasingly obvious but unstable. The ''High-High'' cluster area has changed from ''three core'' to ''one core and many spots''. In 2005, the ''High-High'' cluster area was concentrated mainly at the junction of Henan, Shanxi and Shaanxi, the junction of Yunnan, Guizhou and Guangxi, and the junction of Fujian and Guangdong. By 2018, the ''High-High'' cluster area was concentrated mainly in the Bohai Rim Economic Zone, which included Deyang, Guangyuan, Suining, Neijiang, Ziyang, Lanzhou, Baoji and other cities. The ''Low-Low'' cluster area has

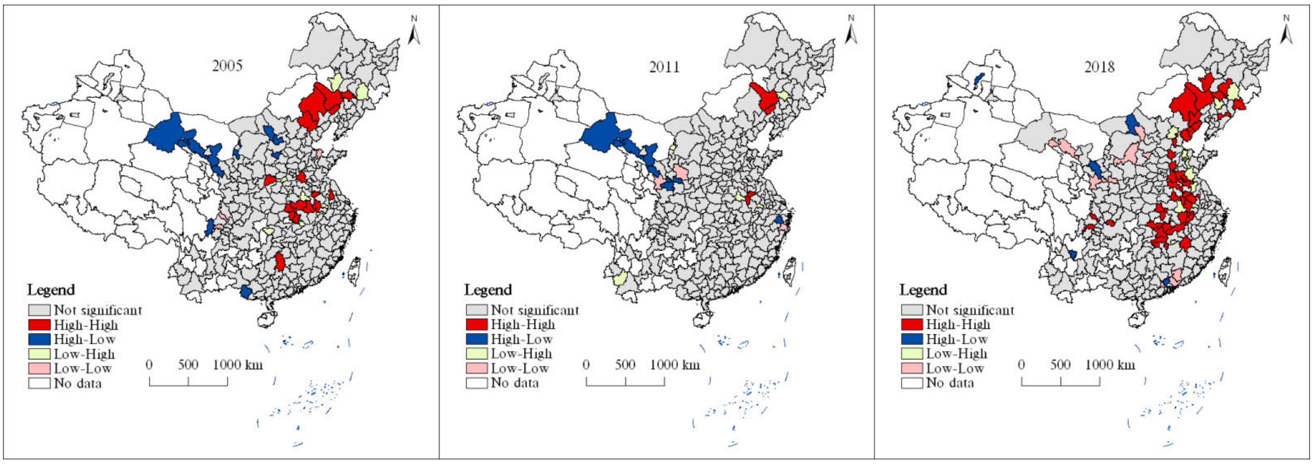

FIGURE 2. Local indicators of spatial association (LISA) map of ln*LMCA* in 2005, 2011 and 2018. High-high and low-low represent statistically significant clusters of high and low ln*LMCA*, whereas high-low and low-high are outliers representing either high ln*LMCA* surrounded by ln*LMCA*, or vice versa.

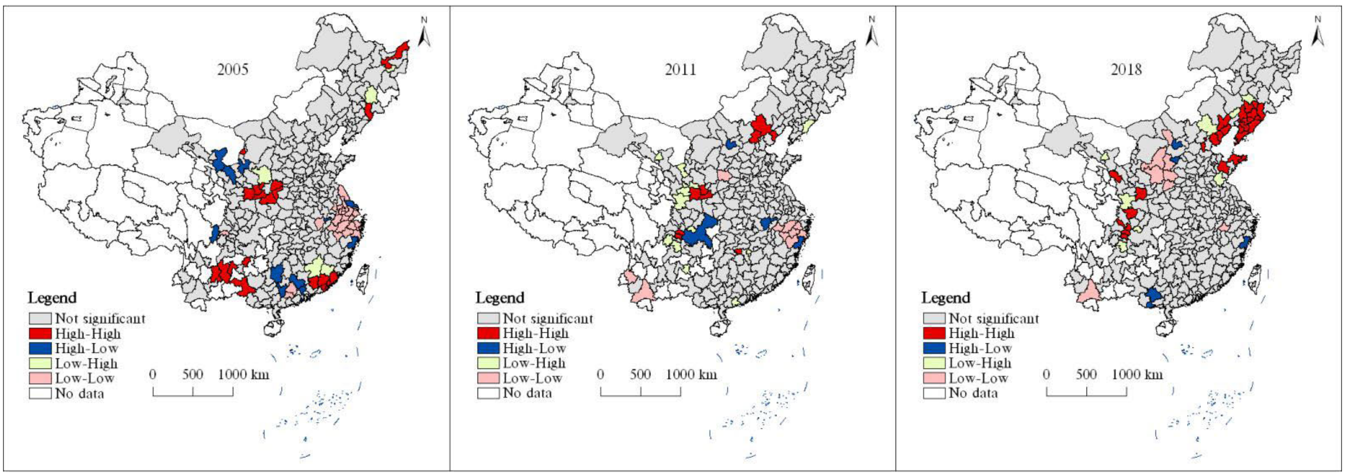

FIGURE 3. Local indicators of spatial association (LISA) map of ln*GTFP* in 2005, 2011 and 2018.

gradually transferred from the eastern Yangtze River Delta to the western Mongolia-Shanxi-Shaanxi junction, including mainly Hohhot, Luliang, Linfen, Yuncheng, Yulin, Yan'an and other cities. The ''High-Low'' cluster area is scattered in Guangzhou, Zhuhai, Wenzhou, Nantong, Guilin, Ya'an and other cities. The ''Low-High'' cluster area is located near the ''High-High'' cluster area.

In conclusion, the significant spatial autocorrelation means that the spatial econometric model can be used to study the effect of LMCA on GTFP.

2) SELECTION OF SPATIAL ECONOMETRIC MODEL

The Lagrange multiplier (LM) test, Hausman test, likelihood ratio (LR) test, and Wald test were used to determine the specific form of the spatial econometric model (Table 4). First, LM and its robust statistics (R-LM) were obtained by OLS estimation for the model without spatial effects, and the choice of spatial autoregressive (SAR) model or spatial error model (SEM) was tested. Second, if the LM test shows that spatial effects are included in the panel econometric model, according to the research of Elhorst [49], SDM can be used directly for spatial econometric estimation. Third, the Hausman test was carried out on SDM to determine whether the model selected fixed effects or random effects. Fourth, the LR test was used to test the fixed effects of SDM to determine whether SDM includes spatial fixed effects or time fixed effects. Fifth, Wald and LR tests are performed to determine whether SDM is weakened in the SAR or SEM model. The test results show that the SDM with double fixed effects is more suitable for spatial econometric estimation in this paper.

3) SPATIAL REGRESSION RESULTS

Based on SDM, the maximum likelihood estimation (MLE) is used for parameter estimation, and the regression results are obtained (Table 5). Table 5 shows that the regression coefficient ρ of the spatial lag term of the SDM regression shows positive results, except that models (3) and (4) are

TABLE 4. Identification test of the spatial panel econometrics model.

Test	Statistic	P-value
LM (error) test	276.668	0.000
Robust LM (error) test	4.895	0.027
LM (lag) test	278.612	0.000
Robust LM (lag) test	6.839	0.009
Wald test spatial lag	20.940	0.002
LR test spatial lag	20.910	0.002
Wald test spatial error	22.950	0.001
LR test spatial error	22.930	0.001
Hausman test	25.980	0.000
LR test SDM with spatial fixed effects	98.790	0.000
LR test SDM with time fixed effects	4665.940	0.000

significant at the 10% level, and model (1) is significant at the 5% level. Other models are significant at the 1% level, indicating that local GTFP, TEC and TC have significant positive spatial spillover effects on surrounding cities.

Due to the spatial lag of the explained variable in SDM, the regression coefficient cannot accurately reflect the real marginal effect of the variable. Based on the method of Lesage and Pace [50], this paper further decomposes the direct (local) effect and indirect (spillover) effect of SDM under the spatial weight matrix.

The influence of LMCA on GTFP and its decomposition term was analyzed. According to model (1) in Table 6, the direct effect coefficient and indirect effect coefficient of ln*LMCA* on ln*GTFP* are 0.014 and 0.086 respectively, which are significant at the levels of 5% and 1% respectively, showing that LMCA has a positive promoting effect on GTFP of local and adjacent regions, and the spillover effect is greater than the local effect. On the one hand, LMCA is conducive to deepening the industrial division of labor. The logistics industry provides more specialized logistics services for manufacturing, and GTFP is boosted by improving production efficiency with the division of labor and cooperation among industries. On the other hand, LMCA can realize the free flow of factor resources among industries, reduce the barriers to the acquisition of factor resources, promote industrial integration and innovation, form complementary industrial advantages, and then improve the efficiency of resource allocation. The free flow of talent, technology and other innovation elements among regions by the diffusion effect is conducive to strengthening interregional talent exchange and technology interaction, forming the spillover of knowledge, technology and innovation space and driving the economic development of surrounding areas. According to model (3) in Table 6, the direct effect coefficient of ln*LMCA* on ln*TEC* is 0.002, but it is not significant, which means that LMCA has no impact on local TEC. The indirect effect coefficient of ln*LMCA* on ln*TEC* is 0.101, and it is significant at the level of 1%, which implies that LMCA has a significant promotion effect on TEC of neighboring areas, possibly because LMCA has a competitive effect on the surrounding areas, forcing the surrounding areas to upgrade the management and system level. According to model (5) in Table 6, the direct effect coefficient and indirect effect coefficient of ln*LMCA* on ln*TC* are 0.011 and 0.004 respectively, which are significant at the 5% and 10% levels respectively, showing that LMCA has a positive effect on local and adjacent regional TC, mainly because LMCA is conducive to the exchange of knowledge and technology among heterogeneous industries, thus promoting local and adjacent technological progress. In other words, LMCA has a promoting effect on local and neighboring GTFP. The positive direct effect of LMCA on GTFP comes mainly from the promoting effect of technological progress. The positive indirect effect of LMCA on GTFP comes mainly from the positive spillover effect of technological progress and technical efficiency improvement, which basically verifies Hypothesis 1 and Hypothesis 3.

The following results can be obtained from the coefficients of the control variables, and most regression coefficients of the control variables are negative and statistically significant at the 1% level.

First, the coefficients of the direct and indirect effects of ln*GOV* are both negative. Except for ln*TEC*, the others are significant at the 1% level, which suggests that government intervention has a negative impact on GTFP and TC of local and adjacent areas but has no effect on TEC, primarily because, under the system of resource allocation by market means, repeated investment and construction, homogeneous competition and other market failure problems caused by government intervention in the economy worsen the efficiency of urban resource allocation and result in serious negative environmental externalities. In the meantime, the performance evaluation mechanism with economic

TABLE 5. Regression results of SDM with spatial and time fixed effects.

Variables	ln*GTFP* (1) W_1	ln*GTFP* (2) W_2	ln*TEC* (3) W_1	ln*TEC* (4) W_2	ln*TC* (5) W_1	ln*TC* (6) W_2
ln*LMCA*	0.013**	0.013**	0.002	0.003	0.011**	0.011**
	(2.231)	(2.215)	(0.398)	(0.647)	(2.135)	(2.117)
ln*GOV*	−0.052***	−0.055***	−0.009	−0.008	−0.045***	−0.045***
	(−4.891)	(−5.187)	(−0.981)	(−0.947)	(−4.918)	(−4.913)
ln*T*	0.040***	0.044***	0.026**	0.025**	0.019*	0.021**
	(3.319)	(3.635)	(2.565)	(2.514)	(1.851)	(2.019)
ln*ROAD*	−0.043***	−0.043***	−0.023***	−0.023***	−0.019**	−0.020**
	(−4.359)	(−4.349)	(−2.802)	(−2.853)	(−2.254)	(−2.314)
ln*INN*	−0.028***	−0.029***	−0.006	−0.007	−0.013*	−0.011*
	(−4.453)	(−4.525)	(−1.198)	(−1.265)	(−1.937)	(−1.719)
ln*POP*	−0.006*	−0.006**	−0.004	−0.004	−0.002	−0.002
	(−1.898)	(−1.996)	(−1.429)	(−1.445)	(−0.853)	(−0.644)
ρ	0.119**	0.097***	0.079*	0.222*	0.258***	0.483***
	(2.538)	(4.544)	(1.698)	(1.770)	(5.854)	(4.771)
*W*ln*LMCA*	0.074***	0.024**	0.093***	0.359***		
	(2.920)	(2.185)	(4.443)	(4.677)		
*W*ln*GOV*	−0.098**					
	(−2.456)					
*W*ln*INN*					−0.032**	−0.102***
					(−2.236)	(−3.008)
*W*ln*POP*	0.027*	0.011*			0.024**	0.111**
	(1.950)	(1.739)			(2.041)	(2.481)

Note: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; t statistics in parentheses. Since the spatial lag items of ln*T* and ln*Road* are not significant, they were removed from the table.

growth as the core makes local officials pay attention to short-term growth and ignore the sustainable development of the economy. This extensive economic growth mode is likely to lead to energy waste and ecological environment deterioration and ultimately is not conducive to the improvement of GTFP and technological progress in the local and adjacent areas. This conclusion is basically consistent with the viewpoints of Chen and Tang [51] and Hu and Chen [52].

Second, the direct and indirect effect coefficients of ln*ROAD* are both negative. Except for the indirect impact on ln*TEC*, the others are significant at least at the 10% level, which means that upgrading the infrastructure level reduces the local and adjacent GTFP, TC, and local TEC, due mainly to the significant network externality of infrastructure between cities. Only networks with effective connections between cities can effectively act as network externalities. However, at this stage, the problems of investment and construction independence in the infrastructure construction of cities make the externalities not play effectively. This viewpoint is coherent with the argument of Chen and Tang [45].

Third, the coefficients of the direct effect and indirect effect of ln*INN* are both negative. Except for ln*TE*, there is a negative impact on ln*GTFP* and ln*TC* in the local and adjacent areas. The most likely cause is that technological innovation aims only at expanding production scale and increasing economic aggregate, and there may be a "siphon effect" on the periphery, leading to a negative impact on the periphery GTFP and TC.

Fourth, the regression coefficient of population density (ln*POP*) to local ln*GTFP* is –0.005, which is significant at the 10% level, but it is negative and not significant to the local ln*TEC* and ln*TC,* indicating that excessive population agglomeration will produce considerable resource demand, cause traffic congestion and be unfavorable to the improvement of local GTFP. The regression coefficient of lnPOP on ln*GTFP* and ln*TC* of neighboring areas is positive, and

TABLE 6. Regression results of SDM with spatial and time fixed effects.

Spatial Effects	Variables	lnGTFP		lnTEC		lnTC	
		(1)	(2)	(3)	(4)	(5)	(6)
		W_1	W_2	W_1	W_2	W_1	W_2
Direct Effects	lnLMCA	0.014**	0.014**	0.002	0.004	0.011**	0.011**
		(2.294)	(2.275)	(0.502)	(0.807)	(2.115)	(2.097)
	lnGOV	−0.053***	−0.056***	−0.009	−0.009	−0.046***	−0.046***
		(−5.189)	(−5.419)	(−1.059)	(−1.024)	(−5.140)	(−5.133)
	lnT	0.041***	0.045***	0.026***	0.026***	0.020**	0.022**
		(3.554)	(3.884)	(2.764)	(2.711)	(2.015)	(2.191)
	lnROAD	−0.043***	−0.043***	−0.023***	−0.023***	−0.019**	−0.020**
		(−4.428)	(−4.421)	(−2.847)	(−2.898)	(−2.289)	(−2.351)
	lnINN	−0.028***	−0.029***	−0.006	−0.007	−0.013**	−0.012*
		(−4.658)	(−4.732)	(−1.250)	(−1.320)	(−2.120)	(−1.901)
	lnPOP	−0.005*	−0.006*	−0.003	−0.004	−0.002	−0.001
		(−1.806)	(−1.885)	(−1.395)	(−1.412)	(−0.669)	(−0.349)
Indirect Effects	lnLMCA	0.086***	0.027**	0.101***	0.469***	0.004*	0.012
		(2.894)	(2.226)	(4.212)	(3.690)	(1.807)	(1.291)
	lnGOV	−0.119***	−0.006***	−0.001	−0.003	−0.016***	−0.048*
		(−2.765)	(−3.289)	(−0.774)	(−0.712)	(−3.255)	(−1.773)
	lnT	0.006*	0.005***	0.002	0.008	0.007*	0.023
		(1.883)	(2.881)	(1.398)	(1.282)	(1.799)	(1.481)
	lnROAD	−0.006*	−0.005***	−0.002	−0.007	−0.007**	−0.021
		(−1.927)	(−3.057)	(−1.272)	(−1.149)	(−1.979)	(−1.439)
	lnINN	−0.004**	−0.003***	−0.001	−0.002	−0.048***	−0.219***
		(−2.006)	(−3.291)	(−0.934)	(−0.904)	(−2.626)	(−2.784)
	lnPOP	0.031**	0.011*	−0.000	−0.001	0.032**	0.223**
		(2.017)	(1.672)	(−0.968)	(−0.918)	(2.065)	(2.162)

it is significant at the level of 5%, which shows that local population agglomeration is conducive to the improvement of technology progress and GTFP in neighboring areas, mainly because population agglomeration in local areas can provide a labor supply for neighboring areas and promote GTFP of surrounding areas.

Finally, the regression coefficients of technology input ($\ln T$) are all positive. Except for the ln*TEC* of neighboring regions, $\ln T$ has a significant effect on other explained variables, which signifies that increasing science and technology investment can improve GTFP and technological progress of local and adjacent regions, which is consistent with the research conclusion of Ji and Li [44]. Thanks to the adoption of more efficient production technology, the recombination of labor, capital, energy and other elements, the consumption of energy and resources drops effectively. Meanwhile, the development of more convenient and economic pollution control facilities is beneficial to reduce the emission of pollutants. GTFP of the local and surrounding areas improves correspondingly.

4) ROBUSTNESS TEST

The spatial econometric model is sensitive to the spatial weight matrix. To further ensure the reliability of the research conclusion, referring to Yuan *et al.* [53], this paper analyzes the robustness of the above main results by using the adjacent spatial weight matrix (W2):

$$W_2 = \begin{cases} 1 & \text{(if region } i \text{ is adjacent to region } j) \\ 0 & \text{(if region } i \text{ is not adjacent to region } j) \end{cases} \quad (8)$$

According to models (2), (4), and (6) in Table 5 and Table 6, the regression coefficients and significance of the core explanatory variable and control variables are consistent with the previous research results, which can fully demonstrate that the regression results are relatively robust.

TABLE 7. Panel threshold effect test.

Explained Variables	Model	F value	P value	Threshold value	95% confidence interval
ln*GTFP*	single threshold	34.42	0.012	0.949	[0.847,0.966]
	double threshold	45.83	0.022	8.112	[7.445,8.164]
	triple threshold	6.35	0.786	——	——
ln*TEC*	single threshold	26.53	0.008	2.214	[2.164,2.230]
	double threshold	30.46	0.008	11.466	[10.978,11.608]
	triple threshold	8.43	0.678	——	——
ln*TC*	single threshold	98.86	0.002	10.709	[10.540,10.816]
	double threshold	15.43	0.318	——	——

B. THRESHOLD CHARACTERISTICS OF IMPACT OF LMCA ON GTFP

1) THRESHOLD EFFECT TEST

To test whether the Williamson hypothesis still holds in the case of industrial collaborative agglomeration, *PGDP* was selected as the threshold variable. Because the technology of spatial threshold regression model is not mature at present, only the local influence from LMCA on GTFP is analyzed in this part. According to Hansen's idea, the number and size of the threshold should be determined before the panel threshold is estimated. The threshold effect test was conducted by using Stata software and the bootstrap method 500 times. The test results are shown in Table 7. Table 7 shows that the F values of the single threshold and double threshold of the model with ln*GTFP* and ln*TEC* as explained variables are significant at least at the 5% level, while the F value of the triple threshold is not significant, indicating that the model has double thresholds. Threshold 1 and threshold 2 of the former are 0.949 and 8.112, respectively, while thresholds 1 and 2 of the latter are 2.214 and 11.466, respectively, both within the 95% confidence interval, which shows the recognition efficiency of threshold values. For the model with ln*TC* as the explained variable, the single threshold is significant at the 1% level and the F value of the double threshold is not significant, indicating that there is a single threshold, and the estimated value of the ln*TC* threshold is 10.709.

2) THRESHOLD REGRESSION RESULTS

Based on the results of the threshold effect test, this paper constructed a double threshold regression model and a single threshold regression model for empirical analysis. The parameter estimation of threshold regression is shown in Table 8.

First, the threshold effect of LMCA on GTFP was analyzed. When *PGDP* was not more than 9490 yuan per year, the estimated coefficient of ln*LMCA* was −0.054, but it is not significant, which denotes that LMCA has no impact on GTFP when LMCA is lower than the first threshold, possibly because when the economic development level is low, the degree of industrial specialization is low, and the synergy effect is weak, which leads to the failure of the economic growth effect. When *PGDP* is greater than 9490 yuan per year and not more than 81120 yuan per year, the ln*LMCA* coefficient is estimated to be 0.031 and significant at the level of 1%, which signifies that LMCA can promote GTFP to a certain extent when crossing the first threshold. The possible reasons are as follows: with the continuous improvement of economic level, the industrial agglomeration in the region has gradually formed a proper scale and its layout has become more and more reasonable, and the interaction and exchange, resource sharing and collaborative innovation between the logistics industry and the manufacturing occurs. In the meantime, the concentration of enterprises is conducive to the sharing of energy-saving and emission reduction treatment facilities, strengthening the centralized supervision of environmental pollution, reducing the unit cost of emission reduction, and making the scale effect of energy conservation and emission reduction gradually apparent. When *PGDP* is larger than 81200 yuan per year, the ln*LMCA* coefficient is estimated to be −0.057, which is significant at the 5% level, indicating that when the second threshold value is crossed, the impact of LMCA on GTFP changes from positive to negative. This is possibly because when the economy is relatively developed, and there may be excessive agglomeration of industries, resulting in resource mismatch, industrial structure imbalance, environmental pollution and other problems, which aggravate regional competition. The increasingly obvious crowding effect counteracts the economic growth effect of collaborative agglomeration and suppresses GTFP. In summary, when the level of economic development is low, the impact of LMCA on GTFP is not significant. When the level of economic development exceeds a certain threshold, LMCA will significantly promote the improvement of GTFP. With the further development of the economy, the impact of LMCA on GTFP changes from promotion to hindrance.

Moreover, the threshold effect of LMCA on TEC and TC was analyzed, showing opposite threshold characteristics. For TEC, when *PGDP* is not more than 22140 yuan per year, the ln*LMCA* coefficient is estimated to be −0.031 and significant at the 5% level, showing that LMCA has a significant inhibitory effect on TEC when it is lower than the first threshold value. The main reason may be that when the economic level is low, the development of the logistics industry is also lagging behind, and it is difficult to effectively embed into the value chain of manufacturing, which limits the collaborative agglomeration effect. In addition, local market

TABLE 8. Regression estimation results of the panel threshold model.

Variables	(1) lnGTFP	Variables	(2) lnTEC	Variables	(3) lnTC
ln*GOV*	−0.013 (−0.710)	ln*GOV*	−0.013 (−0.957)	ln*GOV*	0.004 (0.204)
ln*T*	0.063*** (3.410)	ln*T*	0.030*** (2.814)	ln*T*	0.038* (1.950)
ln*ROAD*	0.007 (0.340)	ln*ROAD*	−0.038*** (−3.562)	ln*ROAD*	0.043** (2.152)
ln*INN*	0.064*** (8.590)	ln*INN*	−0.026*** (−5.828)	ln*INN*	0.092*** (13.498)
ln*POP*	−0.004 (−0.980)	ln*POP*	−0.005 (−1.638)	ln*POP*	0.001 (0.194)
ln*LMCA*(*PGDP*≤0.949)	−0.054 (−1.350)	ln*LMCA*(PGDP≤2.214)	−0.031** (−1.978)	ln*LMCA*(*PGDP*≤10.709)	0.018* (1.944)
ln*LMCA*(0.949<*PGDP*≤8.112)	0.031*** (3.480)	ln*LMCA*(2.214<*PGDP*≤11.466)	0.010 (1.304)	ln*LMCA*(*PGDP*>10.709)	−0.117*** (−3.479)
ln*LMCA*(*PGDP*>8.112)	−0.057** (−2.370)	ln*LMCA*(*PGDP*>11.466)	0.078*** (3.464)		

segmentation and the existence of local protectionism cause the development demand of logistics industry and manufacturing to be out of touch, and local government competition makes the logistics industry appear to be strongly homogenized, resulting in a resource mismatch between the regional logistics industry and manufacturing. Enterprises have no motivation to improve technical efficiency through institutional innovation. When *PGDP* is larger than 22140 yuan per year and not more than 114660 yuan per year, the estimated coefficient of ln*LMCA* is 0.010, but it is not significant, which implies that LMCA has no impact on TEC when crossing the first threshold, possibly because with the enhancement of the economic level and the continuous improvement of the logistics service level, the proportion of logistics outsourcing in manufacturing will continue to increase, which makes manufacturing enterprises focus more on the core competitiveness of enterprises. There is a driving force for organizational change and institutional innovation. The positive effects of collaborative agglomeration may counteract the negative effects of agglomeration and become insignificant in general. When *PGDP* is larger than 114660 yuan per year, the estimated value of the ln*LMCA* coefficient is 0.078, and it is significant at the 1% level, which suggests that LMCA can significantly promote technical efficiency when crossing the second threshold value. With the improvement of the resource allocation efficiency of the logistics industry and manufacturing and the deregulation of enterprises, technical efficiency consequently rises. For TC, when *PGDP* is not more than 107090 yuan per year, the estimated coefficient of ln*LMCA* is 0.018, and it is significant at the 10% level, which indicates that LMCA can promote TC when it is lower than the threshold value. When *PGDP* is larger than 107090 yuan per year, the estimated coefficient of ln*LMCA* is −0.117 and is significant at the level of 1%, which signifies that the influence of LMCA on TC changes from positive to negative when the threshold value is crossed, possibly because the leap forward growth of per capita GDP is often accompanied by excessive agglomeration of manufacturing. The congestion effect is produced by the excessive development of specialized agglomeration that hinders technological progress, rather than the result of collaborative agglomeration itself.

In other words, when *PGDP* is taken as the threshold variable, LMCA has a nonlinear effect on GTFP and its decomposition terms, and there are different threshold characteristics. The impact of LMCA on GTFP and TC tends to change from positive to negative, while the impact of LMCA on TEC tends to change from negative to positive. These conclusions basically verify Hypothesis 2.

VI. CONCLUSION AND POLICY IMPLICATIONS

From the perspective of spatial spillover, this paper constructs a theoretical model that can describe the relationship between

LMCA and GTFP and proposes three theoretical hypotheses. Based on BLMPI, which has the advantages of transitivity and multiplicity, no different results due to different base period selections, no unsolvable linear programming, more flexibility, technical retrogression and a relatively simple calculation, this paper makes a more accurate measurement of GTFP. Then, panel data of 284 prefecture-level and above cities in China from 2005 to 2018 were selected as the research sample. Based on SDM and TRM, this paper makes a systematic and robust empirical test of the theoretical hypothesis and obtains the following main conclusions.

First, LMCA has a positive effect on GTFP of local and surrounding areas, and the spillover effect is larger than the local effect. This conclusion is consistent with Zhang and Zhao [54], showing that in the process of collaborative agglomeration between logistics industry and manufacturing, urban GTFP has also been improved. Industrial collaborative agglomeration has become a new way to enhance GTFP of the city.

Second, LMCA can promote TC of the local city and TC and TEC of the surrounding areas, but the local effect of LMCA affecting TC is larger than the spillover effect. In the surrounding areas, the coefficient of LMCA affecting TEC is higher than the coefficient of TC. These results indicate that LMCA affects urban GTFP by promoting technological progress for local cities and that LMCA affects GTFP of neighboring cities mainly by improving the technical efficiency of neighboring cities.

Finally, there is a double threshold effect between LMCA and GTFP based on the level of economic development. With the per capita GDP crossing a certain threshold, the effect of LMCA on GTFP changes from insignificant to promoting, but when the per capita GDP increases further, this promoting effect turns into an inhibiting effect. This result confirms the existence of the Williamson hypothesis in the field of collaborative agglomeration of the manufacturing and logistics industry in China. From the specific path of action, with the improvement of the level of economic development, the positive effect of LMCA on TEC gradually appears, while the positive effect on TC gradually weakens. Generally, the impact of LMCA on TC dominates its overall impact on GTFP.

Through the above conclusions, the following policy implications are drawn.

First, the deep integration of the logistics industry and manufacturing should be promoted by supporting the integrated development of enterprises, integrating and linking facilities and equipment, guiding the integration and collaboration of business processes, strengthening the integration and convergence of standards and specifications and the integration and sharing of information resources. The government should encourage the integration, expansion and extension of the value chain of the logistics industry and manufacturing to realize the infiltration of the logistics industry into manufacturing from the aspects of procurement, manufacturing and sales. The government should actively and simultaneously build a cooperation platform and launch relevant preferential policies to dredge the integration channels of the logistics industry and manufacturing and tear down the industry barriers between logistics industry and manufacturing.

Second, coordination and cooperation between cities should be proposed. In the case of the city crowding effect, the coordinated development of industry should break through the restriction of administrative division, strengthen the connection and cooperation between cities, fully tap the regional advantages of talent, science and technology and the industry of each city, avoid industrial homogenization between cities, reasonably distribute industrial elements with the development of urbanization, and strengthen infrastructure construction. While improving the carrying capacity of urban infrastructure, the construction of transportation infrastructure among regional cities should be given special attention. We should accelerate the free flow of elements in a larger space, improve the pattern of economic spatial connection, and use the positive externalities (scale economy and knowledge spillover) generated by urbanization to alleviate the negative externality (congestion effect) of a single city.

Finally, the spatial collaborative agglomeration pattern of the logistics industry and manufacturing should be continuously optimized. According to the research conclusion, LMCA has a spatial effect on urban green efficiency, and the indirect effect has a greater impact and is also affected by the level of economic development. On the one hand, collaborative agglomeration is not synchronous agglomeration and symmetric agglomeration, but it needs to promote reasonable spatial LMCA to achieve complementary agglomeration. On the other hand, LMCA to improve urban green efficiency depends on effectively exerting spatial effects. The impact of LMCA on GTFP is distinct in different stages of economic development. Therefore, the spatial pattern of spatial synergy agglomeration should be adjusted in different stages of economic development.

REFERENCES

[1] R. Jia, M. Fan, S. Shao, and Y. Yu, "Urbanization and haze-governance performance: Evidence from China's 248 cities," *J. Environ. Manage.*, vol. 288, Jun. 2021, Art. no. 112436.

[2] X. Qu, Y. Hu, and Y. Zhao, "The influence of industrial agglomeration on manufacturing green total factor productivity: Empirical analysis based on short and long term industrial heterogeneity," *J. Beijing Inst. Technol.*, vol. 21, no. 1, pp. 27–36, 2019.

[3] X. Ji and N. Gu, "Is there innovation-driven effect in the co-agglomeration of producer services and manufacturing industries," *J. Shanxi Univ. Finance Econ.*, vol. 42, no. 7, pp. 57–70, 2020.

[4] W. Shen, Z. Chai, and S. Zhang, "The effect of industrial synergistic agglomeration on industrial pollution reduction: Based on the Yangtze River Delta Urban Agglomeration," *East China Econ. Manage.*, vol. 34, no. 8, pp. 84–94, 2020.

[5] X. Zhou and L. Song, "Influence of coagglomeration of producer service and manufacturing on optimizing and upgrading of industrial structure," *J. Capital Univ. Econ. Bus.*, vol. 21, no. 4, pp. 53–64, 2019.

[6] J. Dou and Y. Liu, "Can co-agglomeration between producer services and manufacturing promote the urban economic growth: Based on the panel data of China's 285 cities," *Mod. Finance Econ.-J. Tianjin Univ. Finance Econ.*, vol. 36, no. 4, pp. 92–102, 2016.

[7] P. Feng and Y. Shen, "Co-agglomeration of producer services and manufacturing industry in Beijing," *J. Capital Univ. Econ. Bus.*, vol. 19, no. 2, pp. 49–59, 2017.

[8] H. Ma and F. Zhao, "Review of researches on collaboration and aggregation of manufacturing and logistics industries: An empirical study on connotation, characteristics and mechanism," *Logistics Technol.*, vol. 35, no. 12, pp. 1–5, 2016.
[9] J. Wang, B. Zhang, and X. Fu, "Research on the influence of industrial coagglomeration on urban TFP," *Stud. Sci. Sci.*, vol. 39, no. 5, p. 842, 2020.
[10] G. Ellison and E. L. Glaeser, "Geographic concentration in US manufacturing industries: A dartboard approach," *J. Political Econ.*, vol. 105, no. 5, pp. 889–927, Oct. 1997.
[11] X. Chen and Z. Chen, "Level and effect on co-agglomeration of producer service and manufacturing industry: Empirical evidence from the eastern area of China," *Finance Trade Res.*, vol. 25, no. 2, pp. 49–57, 2014.
[12] F. Li and Q. Li, "The innovation driving effect of knowledge-intensive business service agglomeration, high-tech manufacturing and co-agglomeration of the two," *Sci. Technol. Prog. Policy*, vol. 36, no. 17, pp. 57–65, 2019.
[13] J. Li and H. Feng, "The economic growth effect of the high-tech manufacturing industry and high-tech service industry co-agglomeration," *Sci. Technol. Prog. Policy*, vol. 37, no. 17, pp. 54–62, 2020.
[14] Y. Hu and W. Zhu, "Study on the effect of the co-agglomeration of producer services," *Ind. Econ. Rev.*, vol. 6, no. 14, pp. 5–14, 2015.
[15] X. Chen, "Study on the co-agglomeration effect of producer service and manufacturing: A case of the Yangtze River Delta," *J. Urban Problems*, vol. 5, no. 12, pp. 63–70, 2016.
[16] L. Peng and M. Xiao, "Multipoint-multipole support effect of the co-agglomeration between producer service and manufacturing: Based on panel data model of the 21 cities and prefectures in Sichuan province," *Enterprise Econ.*, vol. 36, no. 9, pp. 140–146, 2017.
[17] M. Zhou and W. Chen, "Study on the growth effect of synergistic agglomeration of producer services and manufacturing: Taking Changzhutan urban agglomeration as an example," *Mod. Econ. Res.*, vol. 1, no. 6, pp. 69–78, 2018.
[18] H. Cai and Y. Xu, "Co-agglomeration, trade openness and haze pollution," *China Population, Resour. Environ.*, vol. 28, no. 6, pp. 93–102, 2018.
[19] J. Miao and H. Guo, "Influence mechanism of industrial collaborative agglomeration on environmental pollution: An empirical analysis based on the panel data of Yangtze River Delta Urban Agglomeration," *Mod. Manage.*, vol. 39, no. 3, pp. 70–76, 2019.
[20] H. Cai and Y. Xu, "Co-agglomeration, manufacturing efficiency and haze pollution," *J. China Univ. Geosci.*, vol. 20, no. 2, pp. 60–73, 2020.
[21] J. Huang and M. Wang, "Co-agglomeration of manufacturing and producer services industry: A panel data analysis of China's 285 cities," *China Bus. Market*, vol. 31, no. 8, pp. 116–128, 2017.
[22] F. Lu and H. Yang, "Industrial co-agglomeration and environmental pollution control: Impetus or resistance," *J. Guangdong Univ. Finance Econ.*, vol. 35, no. 1, pp. 16–29, 2020.
[23] T. Li, D. Han, S. Feng, and L. Liang, "Can industrial co-agglomeration between producer services and manufacturing reduce carbon intensity in China?" *Sustainability*, vol. 11, no. 15, p. 4024, Jul. 2019.
[24] B. Yu, H. Yang, and G. Jin, "Can industrial agglomeration improve regional economic efficiency?—Spatial econometric analysis based on Chinese urban data," *J. Zhongnan Univ. Econ. Law*, vol. 4, no. 3, pp. 121–130, 2015.
[25] Z. Zhang and B. Zhao, "Can the collaborative agglomeration of internet and manufacturing industry improve the urban green efficiency: Based on the experience of 283 cities in China," *East China Econ. Manage.*, vol. 4, no. 10, pp. 1–9, 2020.
[26] Z. Wu, "The service industry, collaborative agglomeration of strategic emerging industries and high-quality economic growth? Empirical analysis based on provincial panel data from 2005-2018," *J. Henan Normal Univ.*, vol. 47, no. 4, pp. 44–50, 2020.
[27] X. Wu, "Have producer services and manufacturing industry co-agglomeration promoted total factor productivity," *Collected Essays Finance Econ.*, vol. 1, no. 12, pp. 13–20, 2018.
[28] X. Wu, "Research on threshold effect of industrial co-agglomeration's impact on total factor productivity: Based on the empirical test of 246 cities in China," *Econ. Surv.*, vol. 36, no. 2, pp. 72–78, 2019.
[29] Y. Wang and C. Sun, "Research on the impact of industrial coagglomeration on green total factor productivity: From the perspective of the coagglomeration between high-tech industry and producer services," *Econ. Rev. J.*, no. 3, pp. 67–77, 2020.
[30] C. Chen, Y. Sun, Q. Lan, and F. Jiang, "Impacts of industrial agglomeration on pollution and ecological efficiency—A spatial econometric analysis based on a big panel dataset of China's 259 cities," *J. Cleaner Prod.*, vol. 258, Jun. 2020, Art. no. 120721.
[31] J. G. Williamson, "Regional inequality and the process of national development: A description of the patterns," *Econ. Develop. Cultural Change*, vol. 4, no. 13, pp. 3–47, Jul. 1965.
[32] B. E. Hansen, "Threshold effects in non-dynamic panels: Estimation, testing, and inference," *J. Econ.*, vol. 93, no. 2, pp. 345–368, 1999.
[33] Q. Huang, P. Shi, and J. Hu, "Industrial agglomeration and high-quality economic development: Examples of 107 prefecture-level cities in the Yangtze River Economic Belt," *Reform*, no. 1, pp. 87–99, 2020.
[34] Y. H. Chung, R. Färe, and S. Grosskopf, "Productivity and undesirable outputs: A directional distance function approach," *J. Environ. Manage.*, vol. 51, no. 3, pp. 229–240, Nov. 1997.
[35] D.-H. Oh and A. Heshmati, "A sequential Malmquist–Luenberger productivity index: Environmentally sensitive productivity growth considering the progressive nature of technology," *Energy Econ.*, vol. 32, no. 6, pp. 1345–1355, Nov. 2010.
[36] D.-H. Oh and J.-D. Lee, "A metafrontier approach for measuring Malmquist productivity index," *Empirical Econ.*, vol. 38, no. 1, pp. 47–64, Feb. 2010.
[37] J. T. Pastor, M. Asmild, and C. A. K. Lovell, "The biennial Malmquist productivity change index," *Socio-Econ. Planning Sci.*, vol. 45, no. 1, pp. 10–15, Mar. 2011.
[38] B. Wang, L. Yu, and Y. Yang, "Measuring and decomposing energy productivity of China's industries under carbon emission constraints," *J. Financial Res.*, vol. 10, pp. 128–141, Oct. 2013.
[39] N. Shen, H. Liao, R. Deng, and Q. Wang, "Different types of environmental regulations and the heterogeneous influence on the environmental total factor productivity: Empirical analysis of China's industry," *J. Cleaner Prod.*, vol. 211, pp. 171–184, Feb. 2019.
[40] H. Cheng and J. Lu, "The empirical analysis of knowledge capital impact on total factor productivity of industry enterprises," *Econ. Res. J.*, vol. 49, no. 5, pp. 174–187, 2014.
[41] R. Yang, "Industrial agglomeration and regional wage gap: An empirical study based on 269 cities in China," *Manage. World*, vol. 8, pp. 41–52, Oct. 2013.
[42] S. Li and Y. Ma, "The impact of producer services agglomeration on green TFP: An empirical analysis of panel threshold model based on different agglomeration perspectives," *Commercial Res.*, vol. 10, no. 4, pp. 40–48, Apr. 2020.
[43] J. Zhang and X. Li, "Government intervention, environmental regulation and green total factor productivity: The empirical evidence from China's 30 provinces, municipalities and autonomous regions," *Commercial Res.*, vol. 59, no. 10, pp. 162–170, Oct. 2017.
[44] Y. Ji and Z. Li, "Threshold effect of manufacturing agglomeration affecting green total factor productivity of the city," *J. China Univ. Petroleum*, vol. 36, no. 1, pp. 25–33, 2020.
[45] Y. Chen and X. Tang, "Spillover effects of manufacturing agglomeration on urban green total factor productivity: Based on the perspective of urban grade," *Finance Trade Res.*, vol. 29, no. 1, pp. 1–15, 2018.
[46] S. Wei, Y. Chen, and S. Lu, "Urban sprawl, multi-center agglomeration and productivity," *China Ind. Econ.*, vol. 8, pp. 58–75, Jun. 2016.
[47] H. Yuan, Y. Feng, C. Lee, and Y. Cen, "How does manufacturing agglomeration affect green economic efficiency," *Energy Econ.*, vol. 92, Oct. 2020, Art. no. 104944.
[48] Z. Zhong, "Research on logistics industry agglomeration and its determinants based on spatial economics–empirical evidence from 31 Chinese provinces," *J. Shanxi Univ. Finance Econ.*, vol. 33, no. 11, pp. 55–62, 2011.
[49] J. P. Elhorst, "MATLAB software for spatial panels," *Int. Regional Sci. Rev.*, vol. 37, no. 3, pp. 389–405, Jul. 2014.
[50] J. P. Lesage and R. K. Pace, *Introduction to Spatial Econometrics*. Boca Raton, FL, USA: CRC Press, 2009.
[51] Y. Chen and X. Tang, "Study on the synergistic effect of manufacturing agglomeration and urban size on urban green total factor productivity," *South China J. Econ.*, vol. 3, pp. 71–89, Mar. 2019.
[52] X. Hu and M. Chen, "Research on the synergistic effect of manufacturing agglomeration and urbanization development for urban green total factor productivity? Empirical evidence from 261 prefecture-level cities and above in China," *Sci. Technol. Prog. Policy*, vol. 36, no. 24, pp. 70–79, 2019.

[53] H. Yuan, Y. Liu, S. Hu, and Y. Feng, "Does industrial agglomeration aggravate environmental pollution: From a perspective of foreign direct investment," *Resour. Environ. Yangtze Basin*, vol. 28, no. 4, pp. 58–68, 2019.

[54] Z. Zhang and B. Zhao, "Can the collaborative agglomeration of internet and manufacturing industry improve the urban green efficiency? Based on the experience of 283 cities in China," *East China Econ. Manage.*, vol. 34, no. 10, pp. 794–804, 2020.

JIN-FENG LI (Member, IEEE) was born in Anyang, Henan, China. He received the bachelor's degree in economics from Zhengzhou University of Light Industry, in 2008, and the master's degree in industrial economics from Henan University of Technology, in 2012. He is currently pursuing the Ph.D. degree in logistics engineering and management with Chang'an University.

Since 2012, he has been working with Henan University of Animal Husbandry and Economy, where he became a Lecturer, in 2016. He has published ten academic articles, presides over and participated in 19 national, provincial, and department level projects, and participated in the compilation of four books. His research interests include logistics economy, cold logistics, collaborative agglomeration between logistics industry and manufacturing, spatial pattern evolution of logistics, and green total factor productivity.

Dr. Li has been a member of China Logistics Society. His article "Spatial Pattern Evolution and Influencing Factors of Cold Storage in China" won the Excellence Award of the 19th China Logistics Academic Annual Meeting, in November 2020.

HAI-CHENG XU (Member, IEEE) was born in Jingyang, Shaanxi, China. He received the Ph.D. degree in transportation planning and management from Chang'an University, Xi'an, China, in 1999.

He is currently a Professor and the Ph.D. Supervisor with Chang'an University, the Dean of the Highway Infrastructure Economy and Management Research Center, Shaanxi Key Social Science Research Base, the Director of Institute of Transportation Economy, Chang'an University, and the Head of The Academic Team of Transportation Economy and Management. He is also an Expert in the communication appraisal of the degree with the Graduate Education Development Center, Ministry of Education and the industry think tank of the Ministry of Communications. His research interests include highway investment and financing, government regulation, and industrial policy. He has published more than 120 academic articles, presides over 40 national, provincial, and department level projects, and published 14 books. He is the Vice President of the Shaanxi Provincial Assets Appraisal Association, the Chairman of the Professional Technical Committee, and a member of the Standing Committee of the Tourism and Transportation Committee of the Highway Society of China.

WAN-WAN LIU (Member, IEEE) was born in Zhengzhou, Henan, China. She received the bachelor's degree in engineering from Zhengzhou University of Light Industry, in 2009, and the master's degree in economics from Zhengzhou University, in 2013.

Since 2015, she has been working with Zhengzhou University of Technology, where she became a Lecturer, in 2017. She has published five academic articles and presides over and participated in eight department level projects. Her research interests include economic statistics and econometrics.

DONG-FANG WANG (Member, IEEE) was born in Shenqiu, Henan, China. He received the Ph.D. degree in transportation engineering from Chang'an University, Xi'an, China, in 2019.

Since 2011, he has been working with Wuyi University, where he became an Associate Professor, in 2020. He has published 20 academic articles, six of them are cited by SCI/SSCI and CSSCI. He presides over ten national, provincial, and department level projects, and published two books. His research interest includes industrial economics, logistics, and supply chain management. He has been a member of China Logistics Society.

WEN-LONG ZHENG (Member, IEEE) was born in Zhengzhou, Henan, China. He received the bachelor's degree in economics, in 2011, and the master's degree in management from Chang'an University, in 2015, where he is currently pursuing the Ph.D. degree in logistics engineering and management.

Since 2015, he has been an Assistant Researcher of the Regional and Urban Transportation Economics Research Institute, Chang'an University. He is the author of three books and six articles. His research interests include logistics economy, linkage development of logistics industry and manufacturing industry, strategic alliance consulting of logistics enterprises, research on monitoring system of highway freight industry based on big data mining technology, and monitoring of pilot operation of vehicle less carriers.