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# Evaluating the Non-linear Interplay and Threshold Dynamics Between Aggregated Industry Synergy and Green Total Factor Productivity

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**Abstract:** Driven by the swift progression of next-generation information technologies, a notable escalation in the synergistic aggregation of productive services and manufacturing industries is recorded. Prior research has primarily concentrated on the implications of standalone industry aggregation. In the current study, the theoretical ramifications of industry synergy aggregation on green total factor productivity have been delineated, with the foundation laid upon Marshall's conceptualization of agglomeration externalities. To empirically validate these theoretical underpinnings, a panel threshold model has been utilized. The data set comprises 92 cities of prefecture-level and above from five significant urban agglomerations: Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Chengdu-Chongqing, and the Middle Yangtze River area, spanning a period of 2010 to 2019. Results unveil a ∽-shaped association between industry synergy aggregation and green total factor productivity. The existence of both agglomeration economies and diseconomies is substantiated in the current phase of industry synergy aggregation. Employing labor force pools and shared intermediate inputs as threshold variables, the initial impact of industry synergy aggregation on green total factor productivity appears to be negative, but after crossing the first threshold, the impact becomes positive, only to revert to negative post traversing the second threshold. Alternatively, when knowledge spillover is taken as the threshold variable, the influence begins as negative, turns positive post the first threshold, and retains the positive influence beyond the second threshold, exhibiting a stronger promoting effect. The findings highlight the recommendation that industry development strategies ought not to be solely centered on the geographical congregation of productive services and manufacturing industries. Instead, a significant emphasis on exploiting the benefits of agglomeration externalities is advised. Specifically, for cities grappling with excessive industry synergy aggregation, strategies should prioritize facilitating industrial relocation as a means to temper the inhibitory effects of agglomeration diseconomies on green total factor productivity.

**Keywords:** Aggregated industry synergy; Green total factor productivity; Marshall externalities; Non-linear dynamics

## 1 Introduction

Over the past four decades, China has achieved remarkable economic growth, a miracle that has attracted worldwide attention. However, this growth has relied on a crude mode characterized by high energy consumption, high pollution, and low output, leading to increasingly severe issues of ecological destruction and environmental degradation. A green growth mode centered on Green Total Factor Productivity (GTFP) could reconcile economic growth with environmental performance. Therefore, enhancing GTFP becomes key in transforming the economic mode under resource and environmental constraints to achieve high-quality economic development. Against the backdrop of high-quality economic development and global industrial modernization, the crux of improving China's GTFP lies in promoting industrial structure optimization and upgrading, enhancing resource allocation efficiency. Following extant economic logic, industrial agglomeration is a significant driver for optimizing and upgrading the industrial structure. With the rapid development of productive services and the permeation and fusion of production elements among industries, the synergistic development of industries has become a critical direction to improve productivity and competitiveness. Thus, the question arises, can the co-agglomeration of productive services and manufacturing industries enhance GTFP? According to the theoretical framework of agglomeration economy externality, if such an effect exists, is there a nonlinear relationship or threshold effect between the two? The explication and empirical study of such questions have significant theoretical and practical implications for scientifically and rationally planning industrial development strategies to promote China's green and efficient economic development.

Research on industrial agglomeration can be traced back to the synthesizer of neoclassical economics. Marshall [1] first conducted a classic economic analysis on the phenomenon of spatial agglomeration of economic activities in 1890 and attributed the formation of industrial agglomeration to three forms of externalities - the effect of labor pools, intermediate input sharing, and knowledge spillover. Many subsequent classic documents on the formation and welfare effects of industrial agglomeration are based on Marshall's agglomeration externality. In current economic literature, these three externalities are more broadly defined as matching, sharing, and learning. Traditional industrial agglomeration mainly focuses on single industries, but real-world industrial activities are more about co-agglomeration of related industries. Ellison and Glaeser [2, 3] first defined the neighboring state of heterogeneous industries in space as ”co-agglomeration” and attributed its cause to the three externalities proposed by Marshall.

Numerous scholars have conducted in-depth studies on the mechanism and welfare effects of industrial co-agglomeration based on the theoretical framework of externality theory and new economic geography. The conclusions of the current theoretical research on the mechanism of industrial co-agglomeration mainly include internal firm transactions and labor sharing [4], input-output associations and scale external economy [5], division of labor [6], institutional policies, and transportation information facilities [7]. The empirical research on the economic effect of industrial co-agglomeration includes urbanization level [8], economic growth [9, 10], urban productivity [11, 12]. In terms of the impact of industrial co-agglomeration on total factor productivity, the conclusions of current empirical research can be summarized into three categories: 1) the impact of industrial co-agglomeration on urban total factor productivity is U-shaped [13, 14]; 2) industrial co-agglomeration will reduce total factor productivity [15]; 3) the impact of heterogeneous industry co-agglomeration on total factor productivity shows an inverted U-shape [16, 17].

Traditional productivity calculations ignore the impact of resource environmental constraints, and evaluations of economic performance are inevitably biased. In the context of intensified resource environmental constraints and high-quality economic development, some scholars have extended the effect of industrial co-agglomeration to green development. Yu et al. [18], taking GTFP as an indicator of high-quality economic development and using a spatial Durbin model for empirical research, found that the agglomeration of productive services promotes the high-quality development of urban economies. Ren et al. [19] used a dynamic spatial econometric model for empirical research and found that the direct impact of industrial co-agglomeration on the green total factor productivity of the city is inverted U-shaped and has a significant positive spillover effect on the green total factor productivity of neighboring cities. Zhang et al. [20] used a spatial econometric model for empirical research and found that there is a significant spatial correlation between industrial co-agglomeration and urban green economic development, and industrial co-agglomeration under various proximity dimensions can effectively promote urban green economic development.

Overall, the current theoretical and empirical research on the effect of industry co-aggregation on GTFP is still in its infancy, presenting opportunities for further expansion in several areas. First, existing theoretical research predominantly centers on the analysis of how industry co-aggregation promotes economic growth and productivity, lacking a comprehensive theoretical analysis framework for the link between industry co-aggregation and green development. Second, both theoretical and empirical research on the effect of industry co-aggregation are founded on Marshall's theory of agglomeration externalities, without taking into account the ineffectiveness of industry co-aggregation. Although some scholars have determined a nonlinear relationship between industry co-aggregation and productivity through empirical research, none have offered a theoretical interpretation from the perspectives of agglomeration economy and agglomeration diseconomy. Third, the focus of existing empirical research is on the relationship between traditional industry agglomeration and three forms of externalities, not touching on industry co-aggregation. In the context of co-development of industries, the traditional externalities of agglomeration require new theoretical elucidation and empirical evidence.

In response to these gaps, this research initiates by drawing on Marshall's theory of agglomeration externalities to theoretically analyze the relationship between industry co-aggregation and GTFP, proposing theoretical research hypotheses. Following this, the DEA model of unexpected output and the GML (Global Malmquist-Luenberger) index method are employed to measure GTFP of all cities in the five major city clusters of Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Chengdu-Chongqing, and Mid-Yangtze. Further, fixed-effect models and panel threshold models are built to empirically test the impact of industry co-aggregation on GTFP. This research's marginal contributions could be identified in the following aspects:

First, regarding the research content, the effect of industry co-aggregation is extended to green development. A comparative analysis is conducted in-depth to explore the nonlinear impact of industry co-aggregation on GTFP in the five major city clusters, thus revealing more comprehensive features of the effect of industry co-aggregation.

Second, in terms of the theoretical framework, both agglomeration economy and agglomeration diseconomy are considered, analyzing the logical mechanism between industry co-aggregation and GTFP, thereby filling the gap where existing literature primarily focuses on the agglomeration economy of industry co-aggregation.

Third, from the research perspective, a panel threshold model is built to empirically test the regulatory effect of Marshall's externalities on the nonlinear relationship between industry co-aggregation and GTFP. This research is thus dedicated to identifying the causal relationship between Marshall's externalities and industry co-aggregation, which is contested within the academic community.

## 2 Theoretical Analysis and Research Hypotheses

Traditional industrial agglomeration effects mainly target manufacturing agglomeration, attributing agglomeration economics to labor pool, intermediate input sharing, and knowledge spillover externalities. Externalities can arise from specialized agglomeration or diversified agglomeration across different industries. Henderson proposed that external economies often arise more from specific industries, while diseconomies of agglomeration originate from the entire city scale in 1974. The externalities that arise solely from manufacturing agglomeration are produced within specific industries. When there is over-agglomeration in the entire region, diseconomies of agglomeration can occur. However, the diversified agglomeration formed by the synergistic agglomeration of productive service industry and manufacturing industry can alleviate the negative externalities of over-agglomeration within the region. The following section examines the mechanisms by which the synergistic agglomeration of productive service industry and manufacturing industry (hereinafter referred to as synergistic industrial agglomeration) influences the green total factor productivity (TFP) through Marshallian externalities.

Firstly, in terms of the labor pool, the labor reservoir constructed by the synergistic agglomeration of productive service industry and manufacturing industry is conducive to the matching between labor and enterprises, and the complementarity of high-skilled and low-skilled labor. This stimulates the optimal allocation of labor factors within the region, thereby enhancing the total factor productivity. Concurrently, the labor reservoir formed by the synergistic agglomeration enables enterprises to flexibly select labor aligned with green development concepts in the labor market, thus considering productivity and environmental performance in development. In summary, the labor pool effect created by the synergistic agglomeration enhances the green TFP in the agglomeration area.

Secondly, from the perspective of intermediate input sharing, the synergistic agglomeration of productive service industry and manufacturing industry provides a market for intermediate inputs to realize economies of scale. The diversified intermediate inputs including productive services and manufacturing expand the types of intermediates faced by enterprises, enhancing not only the productivity but also the flexibility of enterprises to select intermediate goods aligned with green development concepts. This, in turn, considers both productivity and environmental performance in development. Furthermore, synergistic industrial agglomeration facilitates more effective sharing of information, elements, infrastructure, and machinery, which is certainly beneficial for the recycling of corporate resources and energy, as well as centralized emission of homogeneous pollutants in the production process, thereby promoting green city development. To sum up, the shared intermediate input formed by the synergistic agglomeration enhances the green TFP in the agglomeration area.

Thirdly, from the standpoint of knowledge spillover, synergistic agglomeration of productive service industry and manufacturing industry is more likely to form knowledge spillover and learning effects, thereby enhancing the productivity of enterprises in the agglomeration area. On the other hand, the synergistic agglomeration promotes the exchange, learning, and cooperation of complementary knowledge and technology between different industries, thereby facilitating the generation of new technologies, including pollution control technologies. In conclusion, the knowledge spillover effect formed by the synergistic agglomeration enhances the green TFP in the agglomeration area.

The integration and penetration of the productive service industry and the manufacturing industry, under certain circumstances, may also bring diseconomies to urban development: Firstly, the "crowding" effect. When a large number of related industries enter the agglomeration area, exceeding the optimal threshold for agglomeration, it can lead to an increase in the price of production factors, an increase in the cost of living for residents, and insufficient supply of infrastructure. This inevitably disrupts the balance between economic development and ecological carrying capacity, and the direct result of the continuous deterioration of environmental quality is a decrease in the attractiveness of the agglomeration area for labor, the dysfunction of the labor pool effect, thereby adversely affecting the green TFP. Secondly, the sunk cost effect. Some productive service industries and manufacturing companies in the agglomeration area are more prone to low productivity and serious pollution, but due to the large fixed costs such as factory buildings and machinery, many industrial activities cannot easily exit. They can only continue to consume resources and destroy the ecological environment. Based on the above theoretical mechanism analysis, research hypothesis 1 is proposed:

Research Hypothesis 1: Under the interaction of agglomeration economics and diseconomies of agglomeration, there may be an inverted U-shaped or ∽-shaped non-linear relationship between the synergistic agglomeration of productive service industry and manufacturing industry and the green TFP.

Since Marshall proposed agglomeration externalities, this field of study has generally regarded externalities as the cause of industrial agglomeration. However, from the perspective of the actual development of agglomeration economics, although agglomeration is ubiquitous, not all agglomerations can produce externalities. Therefore, externalities should be the result of some specific industrial agglomeration. Simple geographical clustering of some industries also appears as industrial agglomeration but does not produce externalities. If the productive service industry and the manufacturing industry are simply clustered in a certain area, this phenomenon of synergistic industrial agglomeration does not produce Marshallian externalities, nor does it improve the green TFP. Only when the synergistic agglomeration of productive service industry and manufacturing industry can produce Marshallian externalities, does this phenomenon of synergistic industrial agglomeration improve the green TFP. Based on this, research hypothesis 2 is proposed:

Research Hypothesis 2: According to the theory of agglomeration externalities, the impact of the synergistic agglomeration of productive service industry and manufacturing industry on the green TFP has a threshold effect, depending on the labor pool effect, intermediate input sharing, and knowledge spillover produced by synergistic industrial agglomeration.

## 3 Model Setup, Variable Selection, and Data Description

### 3.1 Model Construction

To empirically test the first research hypothesis proposed, the econometric model in the following form is constructed:

$$\ln GTFP_{it} = \alpha + \beta_1 \operatorname{CoAgg}_{it} + \chi X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{1}$$

where, $i$ represents the city, $t$ is the year; the dependent variable GTFP represents the green total factor productivity; $CoAgg$ denotes the synergistic agglomeration of productive service industry and manufacturing industry, which is the core explanatory variable this study focuses on; $X$ represents a series of other control variables that impact the green total factor productivity, including environmental regulation ($evo$), industrial structure ($ind$), resource endowment ($str$), human capital level ($edu$), and the level of foreign direct investment ($fdi$); $u_i$ and $\lambda_t$ respectively represent individual fixed effects and year fixed effects; $\varepsilon_{it}$ denotes the random disturbance term.

Formula (1) is primarily an empirical test of the linear relationship between industrial synergistic agglomeration and green total factor productivity. According to theoretical analysis, there may also exist a non-linear relationship between industrial synergistic agglomeration and green total factor productivity. To empirically test this, the quadratic and cubic terms of the core explanatory variable are added to test the "inverse $U$" or "$N$" shaped relationship between industrial synergistic agglomeration and green total factor productivity:

$$\ln GTFP_{it} = \alpha + \beta_1 \operatorname{CoAgg}_{it} + \beta_2 \operatorname{CoAgg}_{it}{}^2 + \beta_3 \operatorname{CoAgg}_{it}{}^3 + \chi X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{2}$$

To empirically test the second research hypothesis proposed in this study, a panel threshold model proposed by Hansen [21] is adopted, constructing the following panel threshold model:

$$\begin{aligned} \ln GTFP_{it} =& \theta_1 \ln \operatorname{CoAgg}_{it} \cdot I(q_{it} \le \gamma_1) + \theta_2 \ln \operatorname{CoAgg}_{it} \cdot I(\gamma_1 \le q_{it} \le \gamma_2) + \cdots + \\ & \theta_n \ln \operatorname{CoAgg}_{it} \cdot I(\gamma_{n-1} \le q_{it} \le \gamma_n) + \theta_{n+1} \ln \operatorname{CoAgg}_{it} \cdot I(q_{it} > \gamma_n) + \chi X_{it} + \\ & \mu_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{3}$$

where, $q$ denotes the threshold variable, including labor pool ($lab$), shared intermediate inputs ($input$), and knowledge spillover ($spvi$); $\gamma$ denotes the threshold value; $I(\cdot)$ denotes the indicator function; other symbols have the same meanings as mentioned above.

### 3.2 Variable Selection

(1) Dependent variable: GTFP

Based on the conventional Total Factor Productivity (TFP) computation, pollution-related indices are considered as non-desired output. Traditional TFP calculation tends to emphasize economic benefits but neglects environmental protection and sustainable development. The computation of GTFP incorporates the GML index based on the SBM directional distance function, which accounts for the measurement of green total factor productivity under non-desired output constraints and overcomes the infeasible solution issue possibly existing in the traditional ML index.

(2) Core explanatory variable: (CoAgg)

Ellison and Glaeser [2] first constructed the industry co-agglomeration index based on the "dartboard model". However, due to regional segmentation, size, and other factors, the index suffers from boundary identification failure. Duranton and Overman [22] subsequently established the statistically significant DO index using non-parametric kernel density estimation and counterfactual randomization techniques. Chen [23] and Chen et al. [24] modified the EG index and constructed the Gamma index to measure the degree of co-agglomeration of various industries. This study uses this index to measure the co-agglomeration degree of productive service industries and manufacturing industries, first calculating the location entropy of each city's manufacturing and productive service industries [25]:

$$LQ_{ij} = \frac{e_{ij}/E_j}{e_i/E} \tag{4}$$

In the formula, $LQ_{ij}$ represents the industrial agglomeration degree of industry $j$ in region $i$; $e_{ij}$ represents the number of employees in industry $j$ in region $i$; $E_i$ represents the number of employees in industry $j$ nationwide; $e_i$ represents the number of employees in region $i$; and $E$ represents the total number of employees in all industries nationwide. The "year-end number of employees" is uniformly used for industry-specific calculations.

Subsequently, the co-agglomeration degree of productive service industries and manufacturing industries is further calculated based on the calculated location quotient:

$$CoAgg_{ij} = 1 - |LQ_{im} - LQ_{is}| \,/\, (LQ_{im} + LQ_{is}) \tag{5}$$

In the formula, $CoAgg$ represents the co-agglomeration index of productive service industries and manufacturing industries in region $i$. The larger the index value, the higher the co-agglomeration degree between the manufacturing industry and productive service industry in the region; m represents the manufacturing industry, for which two-digit codes 13-43 from the "National Economic Classification (GB/T4754-2017)" are selected; s represents the productive service industries, which include transportation, warehousing, postal services, leasing and commercial services, financial services, information transmission, computer services, software services, scientific research, technical services, and geological exploration as the five major industries following the existing literature's classification criteria.

(3) Threshold Variables

The labor pool ($lab$) is measured by the number of employees in the productive service industry and manufacturing industry at the end of each year across various regions. The more the number of employees in the productive service industry and manufacturing industry, the greater the effect of the labor pool in that region. Given the difficulty in collecting data on industrial added value of prefecture-level cities and the timespan of input-output tables, the shared intermediate inputs ($input$) are indirectly measured by the energy consumption in various regions, reflecting the effect of upstream and downstream industrial relationships. Specifically, the energy consumption of prefecture-level cities is calculated by converting the natural gas, coal gas, and total social electricity consumption into prefecture-level city energy consumption in standard coal tons (10,000 tons). The logic of using this indicator is that the demand for intermediate goods inevitably promotes the development of the corresponding means of production market, with the main sources of means of production being the energy consumption of industries such as mining, power, and gas. Thus, the greater the energy consumption, the larger the scale of the means of production as intermediate goods market. Knowledge spillover ($spvi$) is measured by the number of patent applications in different regions, where a higher number indicates a higher level of local technological innovation and a more significant knowledge spillover effect.

(4) Other Control Variables

In line with existing literature on GTFP, environmental regulation ($evo$), industrial structure ($ind$), resource endowment ($str$), level of human capital ($edu$), and the level of foreign direct investment ($fdi$) are selected as control variables. Environmental regulation ($evo$) is measured by the proportion of environmental pollution control investment in GDP for each region. Industrial structure ($ind$) is measured by the ratio of the value added of the secondary and tertiary industries within the statistical scope of each city. Resource endowment ($str$) is measured by the ratio of capital stock to the number of employees at the end of the year. The level of human capital ($edu$) is measured by the proportion of university students in the total population. The level of foreign direct investment ($fdi$) is measured by the ratio of actual use of foreign capital in each city to GDP.

### 3.3 Data Sources and Statistical Descriptions

A selection has been made of 92 cities of prefecture-level and above within the city clusters of Beijing-Tianjin-Hebei, Cheng-Yu, Yangtze River Delta, Pearl River Delta, and the Mid-Yangtze River City for empirical study. These five national city clusters, occupying $11\%$ of the land area, gather $42\%$ of the nation's population and $54\%$ of GDP, serving as the most crucial growth engines for China's economic development, with a significant agglomeration effect within the city cluster range. With urbanization and industrialization in China entering the phase of mid-industrial agriculture post-2010, the empirical research timeline was chosen as 2010-2019. Measurements of all selected variables are derived from the corresponding years of "China City Statistical Yearbook", "China Statistical Yearbook", "China Energy Statistical Yearbook", patent databases, and statistical yearbooks from across the country. Statistical descriptions of all variables are shown in Table 1.

**Table 1.** Statistical description of variables

| Variables | Sample Value | Mean | Standard Deviation | Minimum Value | Median | Maximum Value |
|---|---|---|---|---|---|---|
| GTFP | 920 | 1.016 | 0.239 | 0.344 | 1 | 2.489 |
| Industrial Agglomeration Degree (*CoAgg*) | 920 | 0.725 | 0.186 | 0.0710 | 0.747 | 1 |
| Labor Pool (*lab*) | 920 | 8445 | 14182 | 106 | 2761 | 70491 |
| Intermediate Input Sharing (*input*) | 920 | 307.8 | 530.9 | 8.252 | 114.1 | 4067 |
| Knowledge Spillover (*spvi*) | 920 | 13134 | 26615 | 39 | 2649 | 236634 |
| Industrial Structure (*evo*) | 920 | 0.149 | 0.0620 | 0.007 | 0.134 | 0.558 |
| Invironmental Regulation (*ind*) | 920 | 49.44 | 8.130 | 16.16 | 49.98 | 74.73 |
| Resource Endowment (*str*) | 920 | 152.2 | 78.71 | 23.80 | 139.2 | 463.9 |
| Foreign Direct Investment (*fdi*) | 920 | 0.0240 | 0.0210 | 0 | 0.0200 | 0.338 |
| Level of Human Capital (*edu*) | 920 | 0.0240 | 0.0270 | 0 | 0.0140 | 0.127 |

## 4 Econometric Test Results and Analysis

### 4.1 Baseline Regression

A two-way fixed effects model is employed for econometric testing of formula (1), the results of which are shown in the first column of Table 2. The regression coefficient of industrial collaborative aggregation ($CoAgg$) appears positive but is not statistically significant, indicating a lack of linear relationship between industrial collaborative aggregation and GTFP due to the interaction of agglomeration economies and dis-economies. The geographical proximity of single or multiple industries doesn't necessarily generate externalities, even those between productive services and manufacturing.

**Table 2.** Baseline regression results

| Variable | Model (1) | Model (2) | Model (3) |
|---|---|---|---|
| *CoAgg* | 0.145 | 0.717 | -2.457 |
| | (1.066) | (0.706) | $(-1.240)$ |
| $CoAgg^2$ | | -0.421 | 5.112* |
| | | $(-0.631)$ | (1.854) |
| $CoAgg^3$ | | 1 | $-2.934$** |
| | | | $(-2.301)$ |
| *evo* | 0.329 | 0.317 | 0.359 |
| | (1.208) | (1.202) | (1.374) |
| *ind* | 0.007*** | 0.007*** | 0.007*** |
| | (2.881) | (2.779) | (2.839) |
| $fdi$ | -0.346 | -0.282 | -0.215 |
| | $(-0.850)$ | $(-0.714)$ | $(-0.548)$ |
| $str$ | 0.001*** | 0.001*** | 0.001*** |
| | (3.829) | (3.915) | (4.160) |
| $edu$ | 2.085*** | 2.138*** | 2.150*** |
| | (2.805) | (3.015) | (3.071) |
| Individual Fixed Effects | Yes | Yes | Yes |
| Year Fixed Effects$R^2$ | Yes 0.130 | Yes 0.134 | Yes 0.197 |
| Observations | 920 | 920 | 920 |

Note: The numbers in brackets below the coefficients are t-statistics calculated using heteroscedasticity-adjusted robust standard errors; *, **, *** denote significance at the 10%, 5%, and 1% levels respectively.

To further verify the nonlinear relationship between industrial collaborative aggregation and green total factor productivity, the second ($CoAgg^2$) and third powers ($CoAgg^3$) of industrial collaborative aggregation are added to the econometric model for regression. The results are displayed in the second and third columns of Table 2. The regression coefficient of $CoAgg$ turns positive after including $CoAgg^2$, but the coefficient of $CoAgg^2$ is negative. Neither shows statistical significance, thus no apparent inverse $U$-shaped relationship between $CoAgg$ and GTFP is discerned. Upon inclusion of $CoAgg^3$, the coefficient of $CoAgg$ turns negative, while the coefficients of $CoAgg^2$ and $CoAgg^3$ become significantly positive at the 10% and 5% levels respectively. Despite the insignificance of the

$CoAgg$ and its first power's coefficients, the t-statistics are close to the $10\%$ significance level. The insignificance could potentially be due to sample size limitations. Consequently, it can be inferred that an S-shaped relationship exists between industrial collaborative aggregation and GTFP. Low levels of aggregation depress GTFP; after reaching a certain inflection point, GTFP improves with increased aggregation. However, when a second inflection point is surpassed, aggregation again impedes GTFP. It suggests that exceeding a certain threshold of collaborative aggregation between productive services and manufacturing can generate agglomeration diseconomies.

The regression results of the control variables are largely consistent with theoretical expectations: the coefficient of environmental regulation ($evo$) is positive but not statistically significant. This could be due to the crowding out effect of environmental governance investment on corporate R&D, thereby negating the enhancement effect of environmental regulation on GTFP. The coefficient of industrial structure ($ind$) is significantly positive at the $1\%$ level, indicating that the increase in secondary and tertiary industry value mainly stems from the growth of the service industry, so optimizing and upgrading the industrial structure can boost GTFP. The coefficient of the level of foreign direct investment ($fdi$) is negative, but not significant, implying that the "pollution heaven hypothesis" may not hold. The coefficient of resource endowment ($str$) is significantly positive at the $1\%$ level, suggesting no "resource curse" in urban development in China. The coefficient of the level of human capital ($edu$) is significantly positive at the $1\%$ level, indicating that human capital has become a crucial determinant in current urban economic development.

On the basis of the regression coefficients of $CoAgg$, $CoAgg^2$ and $CoAgg^3$, the relationship between industrial collaborative aggregation and GTFP has been further plotted, as shown in Figure 1, where, the x-axis represents the level of industrial collaborative aggregation and the y-axis represents its effect on GTFP. A notable insight from Figure 1 is that the absolute value of the slope of the descending parts of the ∽-curve is significantly larger than the absolute value of the slope of the rising part. This geometric feature's economic implication is that, when industrial collaborative aggregation exceeds the threshold value (0.798), appropriate industrial transfers can greatly alleviate the agglomeration diseconomies' inhibitory effect on GTFP. During the study period, the proportion of samples with an industrial collaborative aggregation level exceeding 0.798 is 39.35%, mainly concentrated in the Beijing-Tianjin-Hebei and Middle Yangtze urban clusters. When industrial collaborative aggregation is below the threshold value (0.318), efforts should be made to promote the collaborative aggregation of productive services and manufacturing. During the study period, the proportion of samples with industrial collaborative aggregation levels lower than 0.318 is only 3.7%, indicating that increasing industrial collaborative aggregation is not currently a key approach to promoting GTFP growth.

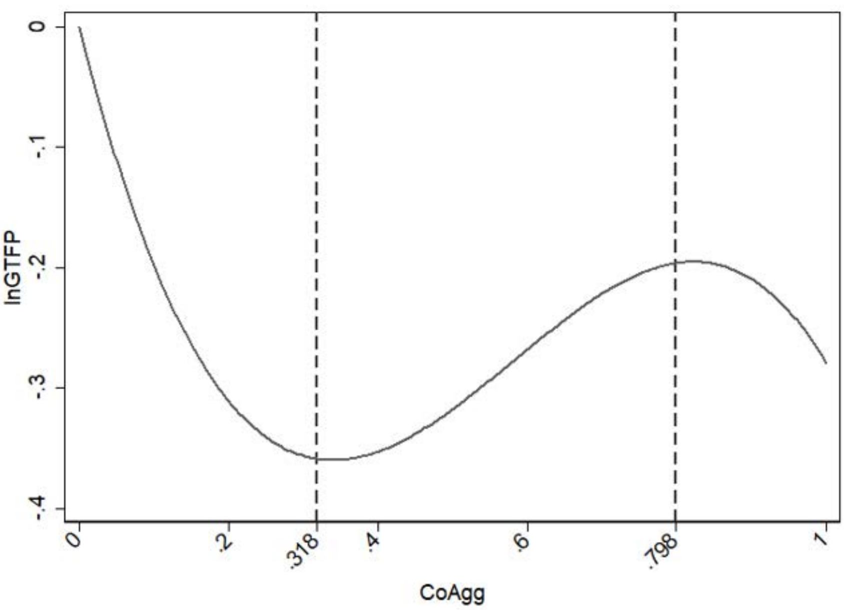


**Figure 1.** Industrial cooperative aggregation and GTFP

### 4.2 Threshold Effect Test

(1) Determination of the Threshold Value

Previous empirical studies suggest a nonlinear relationship between industrial synergy agglomeration and green total factor productivity. The question then arises: does this characteristic persist under various developmental conditions? To further verify Hypothesis 2 proposed in this study, the labor pool ($lab$), input sharing ($input$), and knowledge spillover ($spvi$) were selected as threshold variables to measure Marshall's externalities. Panel threshold models were employed to empirically test the threshold effect of industrial synergy agglomeration on green total factor productivity.

Threshold values were first determined according to the three chosen threshold variables: the labor pool ($lab$), input sharing ($input$), and knowledge spillover ($spvi$). To solve for the threshold values, all samples were divided into 100 grids, with 300 bootstrap samplings conducted. Subsequently, the corresponding P-values and $95\%$ confidence intervals were calculated. Table 3 presents the test results of the threshold effect and the corresponding threshold values. A single threshold F-value of 57.02 was found when using the labor pool ($lab$) as the threshold variable, with a P-value significantly different at the $1\%$ statistical level. A double threshold F-value of 50.07 was found, with a P-value significantly different at the $5\%$ statistical level. The two threshold values were found to be 7.3976 and 10.3348, indicating a nonlinear relationship between industrial synergy agglomeration and green total factor productivity. Two threshold values, 3.1029 and 7.1837, were identified when using input sharing ($input$) as the threshold variable, both of which passed the significance test at the $10\%$ level. A single threshold value of 6.8886 was found when using knowledge spillover ($spvi$) as the threshold variable, with an F-value of 79.9 and a P-value of less than $1\%$. A double threshold value of 8.2433 was identified, with a P-value significant at the $5\%$ level. These findings confirm the presence of a significant threshold characteristic in the effect of industrial synergy agglomeration on green total factor productivity.

**Table 3.** Threshold effect and threshold values

| **Model** | **Threshold type** | **Threshold estimated value** | **Critical value** 1% | 5% | 10% | **F-value** | $95\%$ **Confidence Interval** |
|---|---|---|---|---|---|---|---|
| Labor pool Single threshold | Single threshold | $7.3976^{***}$ (0.0100) | 56.8485 | 36.0049 | 28.9762 | 57.02 | $[7.3502, 7.4152]$ |
| | Double threshold | $10.3348^{***}$ (0.0300) | 65.0362 | 41.8345 | 33.2520 | 50.07 | $[10.243, 10.363]$ |
| Input sharing | Single threshold | $3.1029^{***}$ (0.0033) | 53.0197 | 37.4460 | 30.7615 | 58.74 | $[3.0444, 3.1891]$ |
| | Double threshold | $7.1837^{*}$ (0.0633) | 52.5968 | 35.0586 | 28.9347 | 33.30 | $[5.0169, 7.2543]$ |
| Knowledge spillover | Single threshold | $6.8886^{***}$ (0.0000) | 41.8582 | 30.8370 | 23.2919 | 79.95 | $[6.8240, 6.9127]$ |
| | Double threshold | $8.2433^{**}$ (0.0467) | 36.0529 | 23.4088 | 19.4810 | 23.66 | $[8.0739, 8.2865]$ |

### 4.3 Threshold Regression Result

The regression results with labor supply reservoir ($lab$) as the threshold variable are shown in the first column of Table 4. When the labor supply reservoir is below the first threshold, the impact of industrial cooperative agglomeration on green total factor productivity ($TFP$) is significantly negative. However, when the labor supply reservoir crosses the first threshold, the impact of industrial cooperative agglomeration on green TFP turns significantly positive. This confirms the second research hypothesis previously proposed, asserting that the nature of agglomeration economies depends on whether the agglomeration can create a labor supply reservoir to offset agglomeration diseconomies. Once the labor supply reservoir crosses the second threshold, the impact of industrial cooperative agglomeration on green TFP becomes significantly negative again. This further substantiates the $\backsim$-shaped non-linear relationship between industrial cooperative agglomeration and green TFP derived from the baseline regression.

The regression results with intermediate input sharing ($input$) as the threshold variable are shown in the second column of Table 4. When intermediate input sharing is below the first threshold, the impact of industrial cooperative agglomeration on green TFP is significantly negative. However, once intermediate input sharing crosses the first threshold, the effect of industrial cooperative agglomeration on green TFP becomes significantly positive. This verifies the second research hypothesis, which suggests that the nature of agglomeration economies depends on whether the agglomeration can enable firms in the agglomeration area to gain intermediate input sharing, hence offsetting agglomeration diseconomies. Once intermediate input sharing crosses the second threshold, the impact of industrial cooperative agglomeration on green TFP turns significantly negative again.

The regression results with knowledge spillover ($spvi$) as the threshold variable are shown in the third column of Table 4. When knowledge spillover is below the first threshold, the impact of industrial cooperative agglomeration on green TFP is significantly negative. However, when knowledge spillover crosses the first threshold, the effect of industrial cooperative agglomeration on green TFP becomes significantly positive, and remains significantly positive even after crossing the second threshold. Unlike labor supply reservoir and intermediate input sharing, the externality exerted by knowledge spillover can more effectively offset agglomeration diseconomies in the agglomeration area. Therefore, when the labor supply reservoir and intermediate input sharing in the industrial cooperative agglomeration area reach a certain level, the best way to alleviate agglomeration diseconomies is to promote the exchange, learning, and cooperation of complementary knowledge and technology among different industries in the agglomeration area to fully realize the effect of knowledge spillover.

Further calculations were carried out based on the threshold values of the three threshold variables to determine the distribution of all samples during the period under study in different threshold values. Regarding the labor supply reservoir ($lab$) as the threshold variable, approximately $24\%$ of the samples were below the first threshold value during the study period, with such samples mainly distributed in the Yangtze River Mid-Reach city clusters and Chengdu-Chongqing city clusters. Approximately $66\%$ of the samples were between the first and second threshold values during the study period, indicating that most cities can effectively utilize agglomeration economies in labor supply reservoirs. Approximately $10\%$ of the samples exceeded the second threshold value during the study period, with such samples widely distributed in the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta city clusters. With the knowledge spillover ($spvi$) as the threshold variable, during the period under examination, samples below the first threshold value accounted for approximately $30\%$, mainly distributed in Chengdu-Chongqing and middle Yangtze River urban clusters. Samples that lie between the first and second threshold values accounted for about $28\%$, indicating that while the agglomeration economy of a small number of cities in China can generate knowledge spillover effects, they have not yet reached the optimal level. Samples above the second threshold value accounted for about $42\%$, primarily widely distributed in the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta urban clusters.

**Table 4.** Threshold regression results of the impact of industrial co-agglomeration on green total factor productivity

| Variable | Model (1) | Model (2) | Model (3) |
|---|---|---|---|
| $CoAgg$ | $-0.1071^{***}$ | $-0.1783^{***}$ | $-0.2061^{**}$ |
| (Threshold Variables $\leq \gamma_1$ ) | $(-2.8117)$ | $(-4.3069)$ | $(-5.3885)$ |
| $CoAgg$ | $0.2037^{***}$ | $0.1688^{***}$ | $0.0826^{**}$ |
| ($\gamma_1 <$ Threshold Variables $\leq \gamma_2$) | $(5.3862)$ | $(4.6965)$ | $(2.0139)$ |
| $CoAgg$ | $-0.9323^{***}$ | $-0.7414^{***}$ | $0.2774^{***}$ |
| (Threshold Variables $> \gamma_2$ ) | $(-6.2126)$ | $(-4.4689)$ | $(6.5623)$ |
| $evo$ | 0.0417 | 0.0327 | -0.0049 |
| | $(1.5502)$ | $(1.2041)$ | $(-0.1785)$ |
| $ind$ | $0.2453^{***}$ | $0.2727^{***}$ | $0.1661^{***}$ |
| | $(3.7921)$ | $(4.1964)$ | $(2.5918)$ |
| $fdi$ | 0.0075 | 0.0066 | -0.0054 |
| | $(0.6052)$ | $(0.5301)$ | $(-0.4351)$ |
| $str$ | $0.1565^{***}$ | $0.1583^{***}$ | $0.1607^{***}$ |
| | $(7.9148)$ | $(7.9966)$ | $(8.1097)$ |
| $edu$ | $-0.0851^{***}$ | $-0.0936^{***}$ | $-0.0920^{***}$ |
| | $(-3.5350)$ | $(-3.8904)$ | $(-3.8533)$ |
| Constant Term | $-1.9674^{***}$ | $-2.1173^{***}$ | $-1.8274^{***}$ |
| | $(-6.1413)$ | $(-6.6178)$ | $(-5.7591)$ |
| $R^2$ | 0.105 | 0.091 | 0.102 |
| Observations | 920 | 920 | 920 |

## 5 Conclusion and Implications

With the rapid development of the productive service industry and the penetration and integration of production factors between industries, synergistic industrial development has become an important direction for improving productivity and competitiveness. This study first analyzes the impact of industrial synergy agglomeration on green total factor productivity (TFP) based on Marshall's agglomeration externality theory, and then conducts an empirical study on 92 cities at the prefecture-level and above in the Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Chengdu-Chongqing, and Middle Yangtze River urban agglomerations from 2010 to 2019. The conclusions of this study's theoretical and empirical research are summarized as follows:

(1) There is an inverted U-shaped relationship between industrial synergy agglomeration and green TFP. When the degree of industrial synergy agglomeration is at a low level, it will reduce green TFP; as the degree of industrial

synergy agglomeration increases to a certain inflection point, it will enhance green TFP; however, when the degree of industrial synergy agglomeration crosses the second inflection point, it will have a suppressing effect on green TFP.

(2) The majority of cities have an industrial synergy agglomeration level that lies on the rising segment of the inverted U-shaped curve, while a portion of cities are on the descending part of the curve, and only a few cities are on the left descending part of the curve. Therefore, the current agglomeration diseconomy generated by industrial synergy agglomeration in Chinese cities is more pronounced.

(3) The threshold effect test results show that industrial synergy agglomeration is simply the geographic clustering of different industries, and the essence of agglomeration economy depends on whether agglomeration can generate Marshallian externalities to offset agglomeration diseconomies. This conclusion provides empirical evidence for the academic debate on the causality between agglomeration and externalities, that is, externalities are the cause of agglomeration, but agglomeration does not necessarily produce externalities.

(4) The impact of industrial synergy agglomeration on green TFP is moderated by three types of externalities. With labor pool and intermediate input sharing as threshold variables, industrial synergy agglomeration suppresses green TFP when it is less than the first threshold value and crosses the second threshold value; only when it lies between the first and second threshold values does industrial synergy agglomeration promote green TFP, further corroborating the inverted U-shaped nonlinear relationship between industrial synergy agglomeration and green TFP. With knowledge spillover as the threshold variable, the promoting effect of industrial synergy agglomeration on green TFP is greater when knowledge spillover crosses the first threshold value.

Based on the theoretical and empirical research of this study, the following policy implications can be drawn:

(1) At present, most cities in China have an optimal level of industrial synergy agglomeration, and it is not advisable to blindly promote the geographic clustering of productive service industries and manufacturing. Specifically, cities in the Beijing-Tianjin-Hebei and Middle Yangtze River urban agglomerations generally have an excessive degree of industrial synergy agglomeration. The industrial development strategy should focus on alleviating the suppressing effect of agglomeration diseconomies on green TFP through industrial transfer.

(2) In the Middle Yangtze River and Chengdu-Chongqing urban agglomerations, efforts should be made to improve the labor market and attract skilled labor through various preferential policies, while the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta urban agglomerations can encourage more college graduates or other high-skilled labor to flow to the central and western regions through industrial transfer.

(3) To offset the possible congestion effects of public input sharing, efforts should be made to expand public goods supply, enhance government service capacity, and improve transportation infrastructure in some megacities in the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta urban agglomerations.

(4) The moderating effect of knowledge spillover can most effectively alleviate the diseconomy generated by industrial synergy agglomeration. Therefore, it is crucial to maximize the role of knowledge spillover. Local governments should strengthen knowledge and technology exchange and sharing among different industries and build platforms for promoting technological progress and information exchange. Long-term cooperation in resource information sharing and talent technology should be encouraged among heterogeneous enterprises, and intellectual property protection mechanisms and innovation incentive mechanisms should be improved to create a favorable environment for innovation and exchange.

Future research can proceed in the following directions:

(1) This study measures industrial synergy agglomeration using manufacturing and productive service industries, and future research can construct measurement indicators for industrial synergy agglomeration from more specific industries.

(2) This study mainly uses macro data to measure Marshallian externalities, and future research can use micro data tomeasure Marshallian externalities more accurately and explore the impact of industrial synergy agglomeration on green TFP more comprehensively.

(3) This study examines the impact of industrial synergy agglomeration on green TFP in different urban agglomerations, and future research can compare the impact of industrial synergy agglomeration on green TFP across various regions or countries to provide more generalized conclusions and policy suggestions.

(4) In addition to examining the moderating effects of Marshallian externalities, future research can explore other factors that may moderate the relationship between industrial synergy agglomeration and green TFP, such as environmental policies, institutional quality, and social capital. This will help to better understand the complex relationship between industrial synergy agglomeration and green TFP and provide more targeted policy implications.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The author declares no conflict of interest.

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