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ANALYSIS OF SPATIAL SPILLOVER EFFECTS OF GREEN TOTAL FACTOR PRODUCTIVITY IN BEIJING-TIANJIN-HEBEI REGION UNDER CARBON NEUTRALITY - BASED ON NIGHTTIME LIGHTING DATA

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ABSTRACT

This study uses panel data of 13 cities in the Beijing-Tianjin-Hebei region from 2003 to 2019 to measure the total GDP output of the Beijing-Tianjin-Hebei region based on the nighttime lighting data; applies DEA estimation method, and adopts the super-efficiency SBM - DDF combined with the Malmquist-Luenberger index for the measurement and assessment of the green total factor productivity index; and uses the spatial Durbin model (SDM) for spatial spillover effect analysis. It was found that: (1) the green total factor productivity in the Beijing-Tianjin-Hebei region in the geographical proximity of the overall positive spillover spatial role; (2) the level of economic development, the structure of the secondary industry, and the strength of governmental governance are the most direct factors affecting the reduction of green total factor productivity in the region, and the Beijing-Tianjin-Hebei region is not well coordinated with the development of the economic development and the green development of the Beijing-Tianjin-Hebei region; (3) the level of the city's economy, education level, industrial structure improvement to other surrounding cities show a negative spatial spillover effect, the polarization effect of Beijing and Tianjin is more obvious; (4) should accelerate the integrated development of Beijing-Tianjin-Hebei, accelerate the industrial revolution of Beijing-Tianjin-Hebei urban agglomeration, eliminating the backward production capacity of the region, improve the consistency of environmental regulations, to avoid the long-term emergence of the "pollution sanctuary The phenomenon of "pollution refuge" should be avoided in the long run.

Keywords: *Beijing-Tianjin-Hebei integration, green total factor productivity, spatial Durbin model, spillover effects.*

INTRODUCTION

At the 75th session of the United Nations General Assembly, the pricident of China made a solemn pledge that China would strive to reach its peak by 2030 and work towards carbon neutrality by 2060. In order to achieve the "3060 goal", China will push ahead with energy conservation, emission reduction and low-carbon development, and decouple economic growth from resource consumption and carbon dioxide emissions. In order to incorporate resource and environmental constraints into the analytical framework of economic growth, the concept of Green Total Factor Productivity (GTFP) has emerged.

Enhancing GTFP and pursuing green development are crucial in China's economic strategy, particularly in the Beijing-Tianjin-Hebei region. To aid carbon neutrality, the government will intensify measures to reduce emissions and boost regional GTFP. This project uses nighttime light remote sensing to evaluate the region's GTFP, examine spatial spillover effects, and analyze influencing factors. It provides policy recommendations to improve green development, lower emissions, and facilitate coordinated green economic growth. These efforts are vital for the regional ecological environment, sustainable development, and achieving the "3060 Goal".

Through the study of domestic and foreign literature and other academic results, foreign countries are more mature in estimating green total factor productivity by DEA method, and a large number of scholars in China also use it in their research. The analysis of the spatial spillover effect of green total factor productivity among regions mainly focuses on the national analysis and the Yangtze River Basin. In this study, the total GDP output of Beijing-Tianjin-Hebei region will be measured based on nighttime lighting data; the DEA estimation method is applied to measure and evaluate the green total factor productivity index by using the super-efficient SBM-DDF combined with the Malmquist-Luenberger index; and spatial autocorrelation is tested based on the spatial weight using the moran's I index, which is a spatial model of total factor productivity in the Beijing-Tianjin-Hebei region, using the Spatial Durbin Model (SDM). Use spatial Durbin model (SDM) spatial spillover effect analysis, construct spatial econometric model to test the spatial spillover effect of green economic development in the Beijing-Tianjin-Hebei region, and explore the inter-regional influencing factors and paths, including positive and negative factors. It provides policy recommendations on how to enhance the interregional positive spillover of green total factor productivity in the Beijing-Tianjin-Hebei region while reducing the negative spillover, promote the coordinated development of green economy in the Beijing-Tianjin-Hebei region, improve the level of green development, and reduce carbon emissions to achieve the goal of carbon neutrality under the new situation.

MATERIALS AND METHODS

Based on the SBM-DDF model under the framework of DEA estimation method, the technology frontier surface is constructed using valid sample data for each prefecture-level city's industry-wide production sector as a decision-making unit (DMU), and then the production effectiveness of the decision-making unit is evaluated, and the results obtained reflect the green total factor production efficiency of each DMU, and at the same time, the slack variables are incorporated into the objective function. The model is as follows:

$$\rho\vec{S}_v^t(x_i^t, y_i^t, b_i^t, g^x, g^y, g^b) = \underset{g^x, g^y, g^b}{MAX} \frac{1}{3}\left[\frac{1}{L}\sum_{l=1}^{L}\frac{S_l^x}{g_l^x} + \frac{1}{M}\sum_{m=1}^{M}\frac{S_m^y}{g_m^y} + \frac{1}{K}\sum_{k=1}^{K}\frac{S_k^b}{g_k^b}\right]$$

$$s.t.\begin{cases} x_{il}^t = \sum_{i=1}^{N} x_{il}^t \cdot \lambda_i^t + S_l^x, l = 1,\cdots, \ L \\ y_{im}^t = \sum_{i}^{N} y_{im}^t \cdot \lambda_i^t - S_m^y, m = 1,\cdots, M \\ b_{ik}^t = \sum_{i}^{N} b_{ik}^t \cdot \lambda_i^t + S_k^b, k = 1,\cdots, K \\ \lambda_i^t \geq 0, \sum_{i=1}^{N}\lambda_i^t = 1 \\ S_l^x \geq 0, l = 1,\cdots, \ L \\ S_m^y \geq 0, m = 1,\cdots, M \\ S_k^b \geq 0, k = 1,\cdots, K \end{cases}$$

The model represents the non-radial, non-directional relaxation-based distance function (SBM-DDF) of decision unit city i in period t, where: L denotes the number of input variables, and x_i^t denotes the inputs of decision unit i in period t. M denotes the number of desired output variables, and y_i^t denotes the desired outputs of decision unit i in period t. K denotes the number of non-desired output variables, and b_i^t denotes the desired outputs of decision unit i in period t. The following is the input-output data (x_i^t, y_i^t, b_i^t) is the input-output data, (g^x, g^y, g^b) is the direction vector, and (s^x, s^y, s^b) is the slack vector of inputs and outputs.

In this project, employment, capital stock, and energy consumption in each region are used as input variables for labor, capital, and energy, respectively, X. GDP and nighttime lighting data constructed by remote sensing estimation are fitted as weighted indicators instead of GDP of 13 cities in Beijing-Tianjin-Hebei as desired outputs, Y. CO2 and SO2 emissions in each region are used as non-desired outputs, b. Solve the above equation as a linear program.

The study uses panel data from 2003-2019 for 13 cities in the Beijing-Tianjin-Hebei region. Data for Beijing and Tianjin is mainly drawn from their respective statistical yearbooks. Hebei's data comes primarily from its statistical yearbook and economic yearbook, with some missing data sourced from prefecture-level publications. The calculation of green total factor productivity (GTFP) requires input of capital, labor, energy, desired outputs (estimated GDP from nighttime lights), and non-desired outputs (CO2 and SO2 emissions).Capital inputs are calculated using capital stock, and since there is no official data on capital stock, this paper uses the method of current physical capital stock = previous period's physical capital stock * (1 - economic depreciation rate) + current period's total fixed asset formation to calculate the formula: $K_{it} = K_{it} - (1 - \delta_{it}) + I_{it}$.

Employment data in Hebei's prefecture-level cities is derived by combining rural and urban numbers from Hebei's Statistical Yearbooks. The resulting data aligns with overall employment trends. Some cities provide employment numbers directly, while others offer unemployment rates, from which employment numbers can be inferred. For energy input data, this study uses total energy consumption. Data for some years in Hebei's cities are incomplete, but the "Hebei Economic Yearbook" provides total energy consumption data for major industrial enterprises in each city. Each city's energy consumption is then estimated proportionally. The resulting data, compared with published province-wide data, has an error within 5%, affirming its accuracy.

CO2 emissions data is sourced from CEADs China Carbon Accounting Database, filled in by interpolation for missing years. SO2 data is from China Urban Statistical Yearbook, with missing values filled from municipal data, ensuring completeness. Nighttime lighting data is from DMSP-OLS and NPP-VIIRS.

Other variables for spatial spillover effects are from the mentioned yearbooks. Green patent data is matched from listed companies to cities, acting as a green innovation indicator. Environmental regulation is measured by the frequency and weight of environment-related terms in city government reports. The science and technology investment intensity, economic development level, industrial structure, education level, and energy structure are represented by respective proxies.

The Spatial Weighting Matrix uses a geographic distance weighting matrix, constructed using the inverse of the highway distance between cities.

RESULTS AND DISCUSSION

1. Green total factor productivity analysis

Statistical data reveals fluctuating GDP values in some years due to statistical changes. To address this, the GDP for Beijing-Tianjin-Hebei is reconstructed using fitted nighttime lighting data and official statistical GDP indicators. Remote sensing operations find primary industry's impact on nighttime lighting weaker than secondary and tertiary industries. Fitting processes use the regional average nighttime lighting DN value to fit with GDP and industry sectors. The fitting results show high conformity with an R2 above 0.8. The fitting graph is shown in the following figure, then the fitted value of nighttime lighting data instead of the output value of the secondary industry, L represents the average DN value, GDP1 and GDP3 represent the primary and tertiary industries, respectively, then the two fitting formulas for the desired output value of city i are as follows:

$$Y_i = 0.0017905 \times L_i^{\,2} - 1.965485 \times L_i + 729.0325 + GDP_{i1} + GDP_{i3} \quad \text{Formula 1}$$

$$Y_i = \exp\left[(-5.06e-16)L_i^{\,2} + (1.12e-7)L_i\right] \quad \text{Formula 2}$$

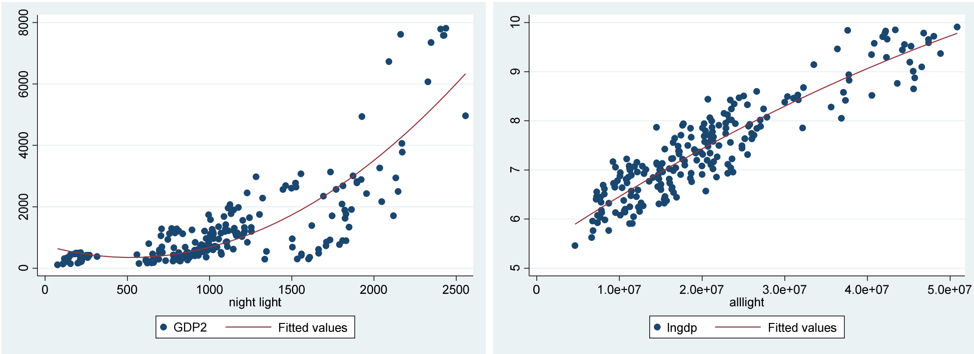

Fig. 1 Fitting of nighttime lighting data

Before the DEA estimation, the production process of the decision unit DMU satisfies the isotonicity assumption is a prerequisite for the efficiency and productivity evaluation using the DEA model [8] . In this paper, the Pearson correlation coefficient test is used, and the results are shown in the table, which shows that the tensorial assumption that as the input variables increase, the output variables also increase is basically met at the 1% significance level. Therefore it can be estimated using the SBM-DDF model under the DEA estimation framework.

Table 1 Results of Pearson's correlation coefficient test

Variables	K	L	E	SO2	CO2	GDP
K	1.000					
L	0.767	1.000				
E	0.708	0.625	1.000			
SO2	0.022	0.108	0.537	1.000		
CO2	0.799	0.652	0.724	0.306	1.000	
GDP	0.849	0.894	0.644	-0.013	0.558	1.000

Equation 2, with a higher goodness of fit and test coefficient, is used to fit desired output values. The DEA estimation method, using the SBM model with non-desired output and directional distance function, measures green total factor productivity (GTFP). Night light-fitted GDP values are used as desired outputs. CO2 and SO2 emissions are considered non-expected outputs for GTFP measurement. Utilizing the Malmquist-Luenberger index, the study conducts a dynamic analysis of GTFP in the Beijing-Tianjin-Hebei region, researching its inter-period change rule.

The global Moran's I index change from 2003-2019 and the Moran's scatterplot for 2019 were plotted to reflect the spatial distribution more clearly, as shown in Figures 2.

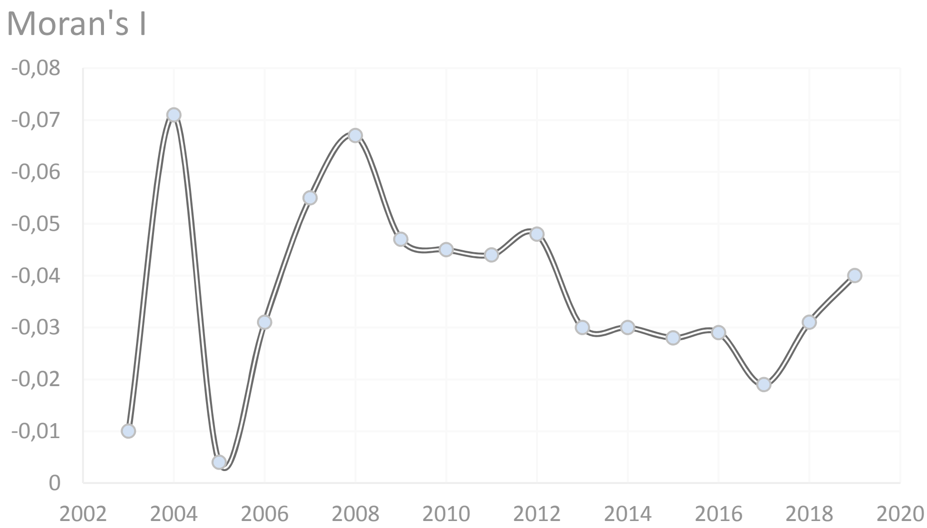

Fig. 2 Map of global Moran index in Beijing-Tianjin-Hebei region

Beijing-Tianjin-Hebei's green productivity (2003-2019) has mild spatial negative correlation with yearly fluctuations and regional variances. Beijing and Tianjin have the highest productivity, with low levels in central-south Hebei. Green development decreases outward from Beijing and Tianjin due to industrial gradient transfer and green technology, with technology playing a larger role after 2012.

Scale efficiency and technological progress are pivotal for green productivity improvement. Cities closer to Beijing, like Langfang, Cangzhou, Tangshan, and Baoding, have experienced slower progress due to the relocation of low-end industries from Beijing since 2015. Technological progress, industrial restructuring, and pollution control are essential for boosting green productivity in the Beijing-Tianjin-Hebei region.

2. Analysis of spatial measurement results

The Spatial Durbin Model (SDM) was chosen to examine the green total factor productivity (GTFP) in Beijing-Tianjin-Hebei. Factors influencing GTFP include economic development level (AGDP), environmental regulation (ENV), industrial structure (SEC), education level (EDL), and clean energy structure (NGP). Other factors like foreign trade level, green innovation technology, and government behavior were also considered. Each factor is measured by relevant metrics like GDP per capita, environmental policy vocabulary, secondary industry output to GDP ratio, higher education enrollees per 10,000 people, natural gas in total energy consumption, and fiscal expenditure to GDP ratio. Spatial econometric analysis was then performed using fixed-effects models.

After determining the spatial econometric model, the spatial econometric analysis was carried out using the stata.17 software.Table 2 reports the results of Durbin model estimation.The ρ values of the two models were significant at the 0.01 level and passed the significance test.In contrast, there were more significant variables in the fixed-effects model and the Log-likelihood value of the fixed-effects model was higher than that of the random-effects model.

Table 2. Estimation results of the spatial panel Durbin model

	fixed effects model		random effects model	
variant	Main	Wx	Main	Wx
AGDP	-0.000*	-0.000*	0	-0.000*
	(-1.771)	(-1.712)	(-1.238)	(-1.885)
ENV	0.159**	-0.281*	0.157*	-0.292*
	(-1.987)	(-1.670)	(-1.907)	(-1.690)
SEC	-0.023***	0.049***	-0.021***	0.045***
	(-4.852)	(-3.841)	(-4.504)	(-3.378)
EDL	0	-0.003**	0	-0.003**
	(-0.62)	(-2.371)	(-0.92)	(-1.995)
NGP	0.045***	0.168***	0.044***	0.168***
	(-5.644)	(-3.684)	(-5.501)	(-3.591)
TP	-0.222*	0.727*	-0.134	0.836**
	(-1.680)	(-1.86)	(-1.105)	(-2.18)
GP	0	0	0	0
	(-0.75)	(-0.321)	(-0.763)	(-0.4)
PB	-1.272**	3.374**	-1.139*	2.694*
	(-1.982)	(-2.247)	(-1.767)	(-1.778)
ρ	0.287***		0.285***	
	(-2.871)		(-2.81)	
lgt_theta			-2.105***	
			(-8.645)	
sigma2_e	0.025***		0.026***	
	(-10.479)		(-10.12)	
Constant			-2.186***	
			(-2.857)	
R-squared	0.245		0.333	
Log-likelihood	95.0838		58.9969	

Note: ***, **, and * indicate that the significance level tests of 1%, 5%, and 10% were passed, respectively.

Based on the results that all ρ values are significant and positive, there is an overall positive spatial spillover of green total factor productivity in the Beijing-Tianjin-Hebei region in the case of geographic proximity, and the estimation results of the variables are also reported, with the β coefficient statistic results in the MAIN of Table 2, and the coefficient statistic results of the WX in the Wx item in the table, which are overall significant in most of the variables.

In order to further explore the influence mechanism of each influencing factor in the spatial spillover effect, this paper reports the average direct effect, average indirect effect and average total effect estimates of the two models in Table

3.Overall, the fixed effect model is a bit better than the random effect estimates. Therefore, we mainly use the fixed effect model for research and analysis.

Table 3. Direct, indirect and total effects of explanatory variables

variant	fixed effects model			stochastic effect		
	direct effect	indirect effect	aggregate effect	direct effect	indirect effect	aggregate effect
AGDP	-0.000*	-0.000*	-0.000**	0	-0.000*	-0.000**
	(-1.853)	(-1.845)	(-2.190)	(-1.345)	(-1.883)	(-2.085)
ENV	0.147*	-0.316	-0.169	0.145*	-0.341	-0.197
	(-1.91)	(-1.362)	(-0.692)	(-1.838)	(-1.474)	(-0.818)
SEC	-0.021***	0.058***	0.038*	-0.019***	0.052***	0.033
	(-4.451)	(-3.068)	(-1.806)	(-4.249)	(-2.748)	(-1.617)
EDL	0	-0.005**	-0.005**	0	-0.004**	-0.004*
	(-0.159)	(-2.253)	(-2.037)	(-0.501)	(-2.003)	(-1.744)
NGP	0.052***	0.250***	0.302***	0.051***	0.247***	0.298***
	(-5.697)	(-3.624)	(-3.95)	(-5.476)	(-3.516)	(-3.83)
TP	-0.185	0.967	0.782	-0.095	1.054*	0.958
	(-1.337)	(-1.625)	(-1.188)	(-0.755)	(-1.916)	(-1.599)
GP	0	0.001	0.001	0	0.001	0.001
	(-0.738)	(-0.441)	(-0.788)	(-0.76)	(-0.483)	(-0.852)
PB	-1.143*	4.098*	2.955	-1.036*	3.26	2.223
	(-1.838)	(-1.901)	(-1.287)	(-1.691)	(-1.576)	(-1.034)

Note: ***, **, and * denote passing the significance level tests of 1, 5, and 10 percent, respectively.

First, economic development negatively affects the green total factor productivity (GTFP) within the region and negatively spills over to other regions, showing a lack of coordination in green and economic development in Beijing-Tianjin-Hebei from 2003-2019. The impact, however, is only significant at the 10% level. A U-shaped relationship exists between economic development level and GTFP, suggesting differences between cities like Beijing and Tianjin and other prefecture-level cities.

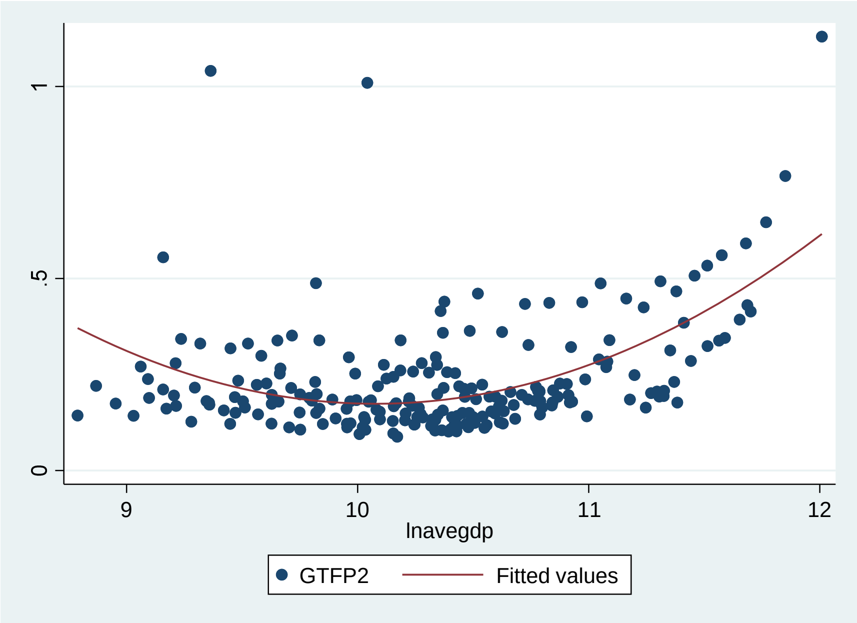

Figure 7 Graph showing the relationship between green TFP and the level of economic development

Second, environmental regulation directly boosts green total factor productivity (GTFP), though its indirect effects are insignificant. Despite Beijing's strong environmental regulation, relocating polluting industries to Tianjin and Hebei erodes their industrial competitiveness. This can cause a "race to the bottom" in environmental standards, leading to ecological disregard. For integrated development in the Beijing-Tianjin-Hebei region, convergence in environmental regulation policies should be pursued to prevent long-term pollution havens.

Besides, the industrial structure in the Beijing-Tianjin-Hebei region, with its high levels of pollutant and carbon dioxide emissions, negatively impacts green total factor productivity (GTFP). Yet, the development of the regional industrial manufacturing industry generates a significant positive spatial spillover effect. Despite the positive coefficient, transferring high-emission secondary industries between cities can lead to a negative spatial spillover effect on other regions' GTFP.

The education level in the Beijing-Tianjin-Hebei region doesn't directly impact green total factor productivity (GTFP) but has a significant negative indirect effect due to talent migration to Beijing and Tianjin. The clean energy structure positively influences GTFP, reducing pollutant emissions significantly. The adoption of clean energy, led by Beijing, is rapidly spreading across the region, creating a positive spatial spillover effect.

Foreign trade levels don't significantly impact green total factor productivity (GTFP), but overall, it should be beneficial for reducing emissions without needing to restrict production. Green innovation technology has no significant direct effect on GTFP, suggesting room for improvement. Government behavior directly affects GTFP negatively, shown by a significant coefficient at the 10% level.In 2012 and before, government performance assessment at all levels is based on GDP, and when some local governments concede environmental protection to economic development out of the pursuit of GDP, it creates the increasingly serious problem of environmental pollution.

And fiscal decentralization allows local governments to share economic gains with the central government, leading to resource mobilization for GDP growth but often neglecting ecological governance. This negatively affects green total factor productivity. The indirect effect is positive, as regional investment in high-energy industries triggers policy diffusion and technological innovation, showing a positive spatial spillover effect.

CONCLUSIONS

In this paper, the DEA estimation method is applied to measure the green total factor productivity by using the SuperSBM model with the GDP fitted by night lights as the desired output and industrial emissions such as carbon dioxide, an environmental factor, as the non-desired output. The spatial spillover effect analysis of green total factor productivity of each city in Beijing-Tianjin-Hebei region from 2003 to 2019 is carried out to explore the influencing factors and paths of green development between regions, and the main results are as follows:

Overall, the green total factor productivity in the Beijing-Tianjin-Hebei region during the period of 2003-2019 generally showed a weak spatial negative correlation and fluctuations from year to year, and the gap in green total factor productivity between the cities in the Beijing-Tianjin-Hebei region was large, and the temporal changes were also more obvious. Beijing-Tianjin-Hebei region by the two cities of Beijing-Tianjin gradually outward green development level shows a decreasing trend. As the city with the highest green total factor productivity in the Beijing-Tianjin-Hebei region, Beijing has been in a steady growth trend, and after 2012, it showed a high rate of growth in green total factor productivity, which was higher than that of other cities. Most of the cities have been experiencing a downward trend for a period of time, and the green total factor productivity has gradually increased since around 2012.

In the Beijing-Tianjin-Hebei region, clean energy use and government policies have positively impacted green total factor productivity, creating a beneficial spillover effect. However, factors like unbalanced economic development, a heavy secondary industry structure, and GDP-focused government behavior have negatively impacted green development. These findings highlight the need for coordinated economic and green growth in the region.And the Beijing-Tianjin-Hebei region's economic and educational levels, as well as its industrial structure, negatively impact surrounding cities due to talent migration and industry relocation. To counter this, talent policies and green technology upgrades should be implemented. Harmonized environmental regulations are also needed across the region to avoid the perpetuation of "pollution shelters."

Relocation of high-energy industries from Beijing to Hebei has slowed technological progress. Improvements to green total factor productivity can come from upgrading technology and merging heavy polluters. Industrial restructuring and elimination of outdated production is necessary for regional industrial integration and overall green productivity.

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