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Quantifying the Green Gains: A Difference-in-Differences Analysis of Low-Carbon City Pilot Policies and Green Total Factor Productivity

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Abstract:

In the past decade, China has enhanced its efforts to achieve sustainable and low-carbon development as a strategic response to climate change. According to their respective development stages and resource characteristics, cities in different regions have explored practical paths of carbon transformation through low-carbon city pilots. These pilots are designed to scale up nationwide low-carbon programs, focusing on embracing the challenge of peaking and neutrality carbon targets in China. This paper examines the performance of the low-carbon city pilot policy in China by analyzing panel data of prefecture-level cities from 2007 to 2020. Qualitatively, the paper estimates the impact of policies on GTFP and environmental innovation by incorporating a DID framework. These policies have had a positive impact on GTFP and innovation, but there is still potential for technological advancement. By incorporating the SBM-GML model, this study identifies further refinement areas for policy that would more firmly establish sustainable growth mechanisms within China's evolving green development paradigm.

Keywords: Difference-in-differences model, low-carbon city pilot policy, green total factor productivity (GTFP)

1. Introduction

In this day and age of rapidly accelerating globalization, the phenomenon of ever-worsening climate change is turning into one of humanity's greatest challenges: Whether natural ecosystems are being razed or the sustainable development of humankind and social stability on planet Earth is concerned, it has been destroying it. The country has, therefore, created a development model that looks to innovation, regional balance, ecological coordination, and inclusiveness for the future. Green development, at the core of this model, is gradually but surely embraced as part of the underlying pillars for China's modernization and strategies of ecological civilization. Green development is the one that reduces the impact on the environment by the sustainable economic behavior of giving top priority to resource conservation, pollution control, and ecosystem restoration.

Backing this green vision, China has launched a string of pioneering low-carbon city pilot drives across different cities and regions to meet local resources, industrial structure, and development stages. By doing so, these pilot cities also serve as a testbed for insight generation and frameworks that could be copied to help China contribute to the general goals of peaking and carbon neutrality. These programs are indispensable in the exploration of feasible pathways toward a low-carbon transition and in enabling cities to raise their energy efficiency, reduce emissions, and foster green industries.

However, significant questions remain to how well those pilot programs have delivered tangible environmental and economic outcomes. Based on China's evolving green development paradigm, this paper will empirically investigate the actual impacts of low-carbon city pilot policy on green total factor productivity and green innovation. As such, employing a DID approach based on data from Chinese prefecture-level cities from 2007 to 2020, this paper tries to find out how these policies influence the twofold goals of economic and ecological development. Besides, regional management efficiency and technological progress as factors affecting GTFP in this paper are estimated by using the SBM-GML model. Finally, this study aims to find the achievements and areas that need to be improved and provide input of value for better policy design to be more integrated with sustainable behavior into the economic tissue of China.

2. Problem Formulation and Literature Review

Different studies have been conducted concerning the role of low-carbon city pilot policy in developing green economic productivity and ensuring environmental stewardship in light of an increasing priority given to sustainable growth by urban centers. Such policies have so far provided systematic mechanisms that are focused on ensuring resource efficiency as well as environmental sustainability, primarily through the adoption of targeted measures by cities to integrate green technology into strategies that guide urban development. The training courses represent the knowledge base of theoretical and practical lessons garnered from the implementation of these initiatives in diverse urban contexts. They represent the foundational basis on which cities can make a transition toward low-carbon pathways, balancing economic growth with ecological preservation.

Much attention has been directed toward the role that technological advancement and green innovation might play in supporting low-carbon city transformations. By providing such incentives and supportive policies, allowing initiatives on low-carbon pilots increases the incentives for the adoption of green technologies and provides an enabling environment for continued innovation for sustainable development. Growing pressure on achieving targets accrued from regional emissions and multi-dimensional performance evaluation has demonstrated how local governments are upping their interactions with the green technology sectors to ensure better urban management with reduced carbon footprints. This also reflects the larger trend in sustainable policy design, namely the alignment of urban development with ambitious environmental goals.

Companies, as key agents in the low-carbon city, are adjusting business practices and investment decisions in response to these policies. For instance, empirical analysis by Jahangir et al. (2023) indicates that regulatory policies forced high-emission industries under the pilot policy to reallocate more resources toward the environmental technology upgrading, which fast-tracks compliance and diminishes environmental impact. Besides, Wan and Zhang (2024) indicate that the trend for corporate investment to head toward sustainable and eco-friendly projects depends a lot on economic conditions and resources available in that particular region. At the same time, Hou Xinshuo and He Yan provide evidence showing these policy impacts differ significantly across different cities; hence, it is urgent for regional adjustment so as to make low-carbon initiatives optimal and effective in applying to more settings.

Beyond that, success in low-carbon policies also depends on the public's perception and support of such policies, since the level of policy adoption and sustainability is greatly influenced by the public. For example, Aasen and Vatn (2018) argue that public support for environmental policy is not only related to the extent to which people are engaged in social activities. But is also closely related to the level of political interest in environmental issues. This shows that inclusive communication strategies are important in raising policy acceptance. Albrizio et al. (2017) further state that stringent environmental regulations can lead to increased investment in research and development for environmentally friendly production, with firms adopting cleaner production methods and increasing productivity through improved production methods.

This finding has particular relevance for low-carbon city policy, given its demonstration of exactly how supportive regulatory environments facilitate technological advancement in support of both economic and environmental sides.

From the review, it is shown that on one side, the low-carbon city pilot policy promotes the obvious improvement of GTFP in the green sectors and stimulates green innovation and significant change in corporate behaviors toward sustainability. On the other hand, many problems are to be solved, such as data restraint and the scope of the model applied, consideration of long-term impact, and policy design trade-off problems. From that perspective, it is expected that future research will develop such gaps through more integrated approaches and carry out comprehensive

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long-term valuations that should help enhance the impact of low-carbon policy on urban sustainable development.

3. Empirical Component

3.1 Model Construction

The present study exploits the difference-in-differences approach to deduce the impact of low-carbon city pilot policy implementation on green total factor productivity in urban areas. Estimates from the model are obtained by considering the differential impact of policy implementation in pilot and non-pilot cities, controlling for both time and cross-sectional dimensions.

$$sbm_{it} = \beta_0 + \beta_1 \cdot did_{it} + \gamma X_{it} + \alpha_i + \sigma_t + u_{it}$$

$$ec_{it} = \beta_0 + \beta_1 \cdot did_{it} + \gamma X_{it} + \alpha_i + \sigma_t + u_{it}$$

$$tc_{it} = \beta_0 + \beta_1 \cdot did_{it} + \gamma X_{it} + \alpha_i + \sigma_t + u_{it}$$

Where sbm_{it}, ec_{it}, and tc_{it} represent the three dependent variables: SBM efficiency, regional management efficiency, and technological progress potential, respectively. The policy effect variable, did_{it}, which captures the effect of the low carbon city policy, is obtained by the interaction of two indicators, specifically: $treat_i$, which determines the pilot cities in the program, and $post_t$, that determines the period after the policy implementation. In this setup, $treat_i$ =1 indicates cities within the experimental group (those designated as low-carbon pilots), while $treat_i$ =0 denotes cities in the control group, not participating in the low-carbon initiative. The variable $post_t$ =1 captures periods following policy rollout, with $post_t$ = 0 indicating the pre-policy baseline phase. Similarly, $post_t$ =1 represents the post-policy period (after 2012), and $post_t$ =0 indicates the pre-policy period (before 2012). The term XitX_{it} Xit encompasses various control variables, accounting for factors that may influence the outcomes independently of the policy. Additionally, α_i captures the fixed effects specific to each city, while σ_t adjusts for time-based fixed effects to control for period-specific variations. The random error term is u_{it}.

3.2 Description of Variables

3.2.1 Explained variable: Green total factor productivity

The primary dependent variable in this study is green total factor productivity (GTFP). It is evaluated through an SBM-GML model, which takes into account both beneficial outputs, such as economic gains, and undesirable outputs, like emissions, all within the constraints of available resources and environmental limits. This model defines the production possibility frontier for GTFP based on an environmental technology set, expressed as follows:

$$\{(X,Y,Y^k) \mid X \geqslant \sum_{\substack{j=1 \\ j\neq t}}^{M} \lambda_j x_{sj}, Y \leqslant \sum_{\substack{j=1 \\ j\neq t}}^{M} \lambda_j y_{pj}, Y^k \geqslant \sum_{\substack{j=1 \\ j\neq t}}^{M} \lambda_j y_{qj}^k, M \leqslant e\lambda \leqslant \mu, \lambda_j \geqslant 0 \,\} \quad (4)$$

In this context, undesired outputs include three types of industrial waste: wastewater, sulfur dioxide, and dust emissions. The SBM-GML model is modified to account for these undesirable outputs:

$$\rho = min \frac{\frac{1}{a}\sum_{s=1}^{a} \frac{\bar{x}_s}{x_{st}}}{\frac{1}{b+c}\left(\sum_{p=1}^{b} \frac{\bar{y}_p}{y_{pt}} + \sum_{q=1}^{c} \frac{\bar{y}_q^{\,k}}{y_{qt}^k}\right)}$$

$$s.t.\, \bar{X} \geqslant \sum_{\substack{j=1 \\ j\neq t}}^{M} \lambda_j x_{sj}$$

$$\bar{Y} \leqslant \sum_{\substack{j=1 \\ j\neq t}}^{M} \lambda_j y_{pj}$$

$$\bar{Y}^{\,k} \geqslant \sum_{\substack{j=1 \\ j\neq t}}^{M} \lambda_j y_{qj}^k$$

$$\bar{X} \geqslant x_{st}, \bar{Y} \geqslant y_{pt}, \bar{Y}^{\,k} \geqslant y_{qt}^k$$

$$\bar{X} \geqslant 0, \bar{Y} \geqslant 0, \bar{Y}^{\,k} \geqslant 0, M \leqslant e\lambda \leqslant \mu, \lambda_j \geqslant 0 \quad (5)$$

Where $\bar{x}_s$, $\bar{y}_p$, and $\bar{y}_q^{\,k}$ represent the projected input-output values, while x_{st}, y_{pt}, and y_{qt}^k represent the corresponding original values. GTFP is further decomposed into SBM growth efficiency (ec), which reflects improvements in regional management, and technological progress (tc), which captures the potential for technological advancement.

3.2.2 Key Explanatory Variable: Low-Carbon City Pilot Policies

Given that the low-carbon city pilot initiatives include cities at both the provincial and prefecture levels, with varied timelines for policy rollout, this study takes these complexities into careful consideration. To maintain result accuracy, cities that lacked complete data or were within pilot provinces but did not actively participate in the program were excluded from the analysis. Ultimately, 119 cities that participated across three phases were categorized as the experimental group, while 165 non-participating cities formed the control group. The baseline for policy implementation was set in 2012 to account for any delays in the rollout process.

3.2.3 control variable

Number of public buses and electric buses in operation at the end of the year within city districts (elector). Harmless treatment rate of household waste across the entire city (garbage). Total supply of artificial or natural gas (in 10,000 cubic meters) within city districts (people gas). The Proportion of employment in primary industries across the city (decry people). Household liquefied petroleum gas (LPG) consumption (in tons) within city districts (gas). Road passenger volume (in 10,000 people) across the entire city (road people)Road passenger volume: the number of passengers using the city's road transport system (in 10,000 people).

3.3 Data sources

This study draws on three primary data sources:
1. Low-Carbon City Policy Data: Information on pilot policies for low-carbon cities was sourced from official publications by the National Development and Reform Commission.
2. Macroeconomic Data: City-level economic metrics were extracted primarily from the China Urban Statistical Yearbook, offering detailed insights into economic performance and demographic profiles.
3. Green Total Factor Productivity (GTFP) Metrics: Data measuring GTFP were compiled from several key sources, including the China Urban Statistical Yearbook, China Regional Statistical Yearbook, China Energy Statistical Yearbook, and China Environmental Statistical Yearbook. This comprehensive dataset spans 280 prefecture-level cities and encompasses indicators such as workforce size, the number of large-scale industrial entities, investment in fixed assets, urban development land, R&D expenditures, total water and gas supplies, energy usage, GDP figures, per capita consumption, urban green coverage, and key emissions indicators (industrial wastewater, sulfur dioxide, and particulate emissions).

To model inputs and outputs, labor metrics (such as employee numbers and the presence of large industrial firms) represent labor input; capital input is reflected through fixed asset investments, land allocated for urban development, and R&D spending; and energy input comprises total water, gas, and electricity consumption. Expected outputs are framed by actual GDP, per capita consumption, and urban green space, while undesirable outputs focus on the "three wastes": wastewater, sulfur dioxide, and particulate emissions.

4. Analysis of empirical results

4.1 Benchmark Regression Results

This study employs a two-way fixed-effects DID model to evaluate how low-carbon city pilot policies influence green total factor productivity (GTFP). The regression outcomes, presented in Table 1, reveal that the interaction term (did) yields positive and statistically significant coefficients ($p < 0.05$) in both the sbm and ec models. These findings suggest that the low-carbon initiatives have positively impacted GTFP as well as improved regional management efficiency. On the other hand, the TC model shows a negative sign, indicating that these policies have not significantly driven technological advancement within the region.

Table 1 Benchmark regression results

	(1)	(2)	(3)
VARIABLES	sbm	EC	TC
did	0.00575**	0.00752**	-0.00122
	(0.00285)	(0.00353)	(0.00243)
Control variables	YES	YES	YES
Time fixed effect	YES	YES	YES
City fixed effect	YES	YES	YES
Constant	0.994***	1.011***	0.986***
	(0.0210)	(0.0316)	(0.0226)
Observations	3,151	3,151	3,151

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Note: t statistics in parentheses; *p < 0.1; **p < 0.05; ***p < 0.01

The findings from the benchmark regression indicate that the implementation of low-carbon city pilot policies, with their clear policy orientation and incentive mechanisms, have successfully integrated resource conservation and environmental protection into urban economic development strategies. These policies have ensured significant promotion in GTFP through compelling optimization of the industrial structure, energy efficiency, and technological innovation. The results also showed that the low-carbon pilot city policies are effective in encouraging companies to adopt environmentally friendly technologies and production methods. This shift has been facilitated by some problem-specific measures, such as financial subsidies, tax breaks and green financing, which have contributed to significant reductions in pollution and improvements in resource efficiency.

This transition has equally been made possible with government support—something it can do by increasing funding for research and development in low-carbon technologies. Accelerating the integration of new eco-friendly products and technologies in this way has meant reducing carbon emissions and improving production efficiency that together keeps driving growth in GTFP.

The low-carbon pilot initiatives have also induced industrial transformation, pushing heavily polluting and energy-intensive sectors into sustainability. Regulatory frameworks have been strengthened, legal structures improved, and green performance evaluation systems established, enabling cities to achieve more efficient environmental management and better resource utilization. Such initiatives have successfully reduced resource waste and minimized environmental pollution, establishing a robust basis for the continued expansion of GTFP.

4.2 Parallel Trend Test

An essential assumption in the difference-in-differences (DID) model is that both the treated group (pilot cities) and the control group (non-pilot cities) exhibit parallel trends in green total factor productivity (GTFP) before policy implementation. To verify this, a parallel trend test is conducted. If the GTFP trends between these groups align before the policy, the interaction term should be statistically insignificant. Figures 1a, 1b, and 1c illustrate that the 95% confidence intervals for the coefficients of the interaction terms in the sbm, EC, and tc models intersect with zero, confirming no significant pre-policy differences between treated and control groups. Therefore, the parallel trend assumption is satisfied.

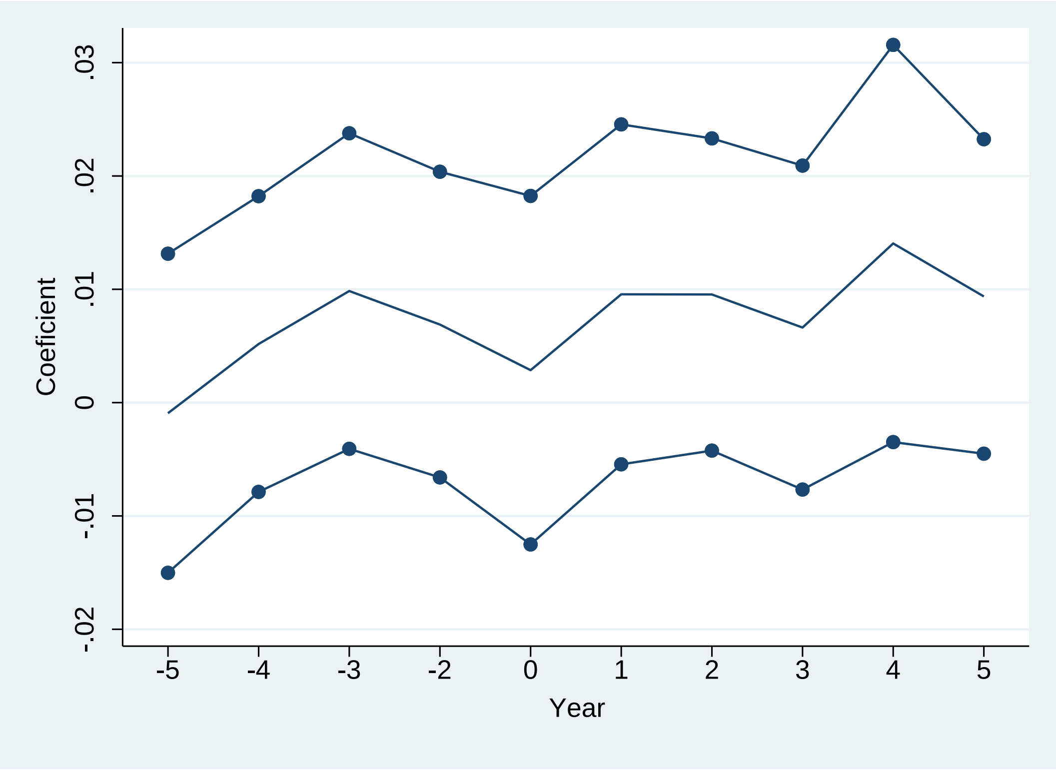

Fig. 1 a sbm parallel trend test

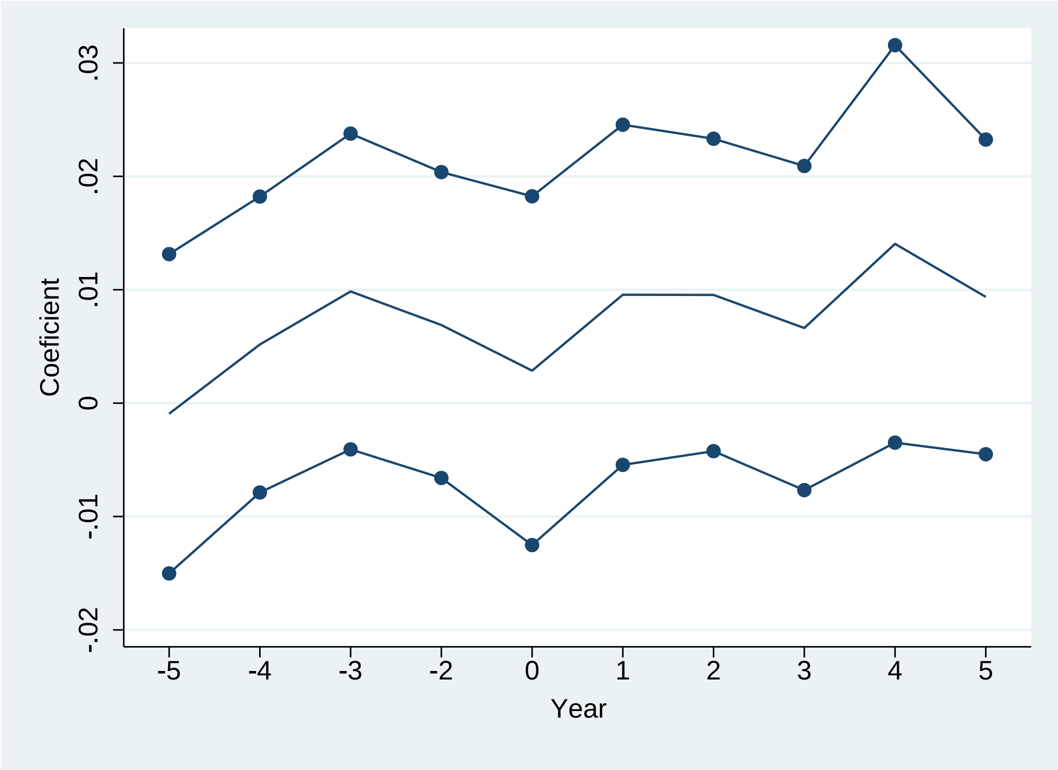

Figure 2 b ec parallel trend test

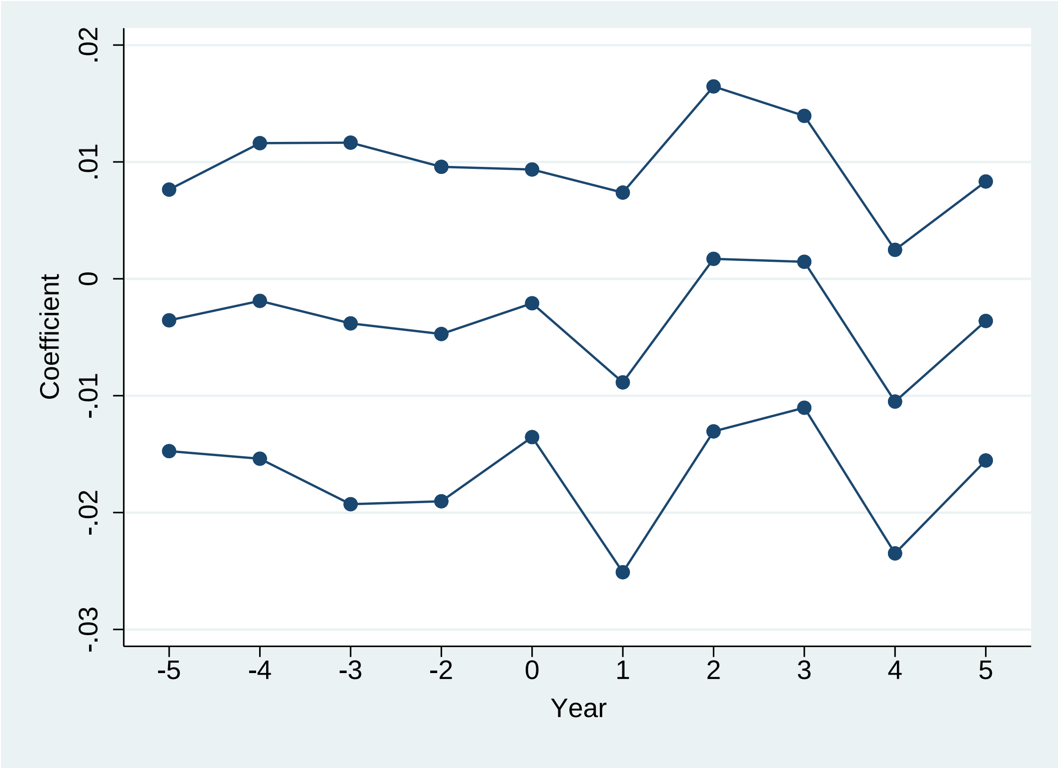

Figure 3 c tc parallel trend test

Note: In the figures, the three dotted lines have distinct interpretations: the upper and lower lines denote the boundaries of the 95% confidence interval, and the middle dotted line represents the estimated coefficients. All par-

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allel trend tests use the pre-policy period (-1) as the base period.

4.3 Placebo Test

To further verify the accuracy of the previous conclusions, a placebo test is conducted. Specifically, the sample data from after the policy implementation (post-2012) is removed, and a hypothetical policy implementation date is set at 2009. The DID model is then re-estimated to observe the coefficients. If the original conclusions hold, the coefficients for the DID variable should be insignificant, as no policy was implemented in 2009. Conversely, if the coefficients are significant, it suggests model specification errors. As shown in Table 2, the coefficients for sbm and ec are both insignificant, confirming that the original results are robust and that the low-carbon city pilot policies have indeed contributed to improvements in GTFP.

Table 2 Placebo test results

	(1)	(2)
VARIABLES	sbm	ec
did	-0.00348	-0.00192
	(0.00388)	(0.00600)
Control variables	YES	YES
Time fixed effect	YES	YES
City fixed effect	YES	YES
Constant	0.951***	0.927***
	(0.0474)	(0.0624)
Observations	1,158	1,158

Note: t statistics in parentheses; *p < 0.1; **p < 0.05; ***p < 0.01.

5. Conclusion

This study examines the real impact of low-carbon city pilot initiatives on green development within China, utilizing a quantitative approach to analyze green total factor productivity (GTFP) across prefecture-level cities from 2007 to 2020. Employing both the difference-in-differences (DID) method and the SBM-GML model, the findings reveal that these pilot policies have contributed significantly to improvements in GTFP and have also fostered advancements in green innovation. Specifically, these policies have promoted progress in regional management efficiency, though they have not fully realized the potential for technological advancement.

Resource optimal allocation, resource consumption constraint, and minimal environmental impact have accordingly enhanced the performance of the urban green economy through the low-carbon city pilot initiatives.

Applied to the above-mentioned results, recommendations have been raised along with arguments for the further development of low-carbon city policies:

1.Innovation to policy-making level: Perfect the institutional structure and give more comprehensive support to pilot policies in empowering them to create green growth in all urban areas.

2.Technology advancement: More investment in R and D of low-carbon technologies would facilitate upgrading of the industrial capability for consideration in large-scale environmental benefits.

3.Regional cooperation: Allow interregional cooperation and sharing of experiences in coherence and harmonious development amongst the low-carbon cities.

Further studies may be done on how different low-carbon city policies affect various regions and industries, and how different mechanisms influence the effectiveness of a policy. In addition, long-term monitoring and evaluation of policy actions facilitate the formulation of policies by decision-makers to ensure the sustainable development of low-carbon cities.

In a word, although the policies of the low-carbon city pilot have played a positive role in green transformation within China, there is still great room for improvement. Through continuous policy innovation and technological advancement in the low-carbon path, China has just moved along the way of meeting targets in peaking carbon and neutrality, creating an environmentally sustainable transition for the economy and society in general.

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