



# The Impact of the Comprehensive Innovation Reform Pilot Zone on Urban Green Total Factor Productivity: An Empirical Analysis Based on the Difference-in-Differences Approach

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**Abstract.** This paper examines 333 Chinese cities (2009-2023) using the comprehensive innovation reform pilot zones as a quasi-natural experiment and difference-in-differences method to study institutional innovation's impact on urban green total factor productivity (GTFP). Results show the pilot zone policies significantly improve urban GTFP, with robustness confirmed by city/year fixed effects and control variables. Parallel trend tests indicate no pre-policy differences between treatment and control groups, with effects manifesting post-implementation. Further robustness tests (replacing explained variables, removing specific cities) validate core conclusions. Mechanism analysis reveals the policy works through industrial structure upgrading and advancement, enhancing resource allocation efficiency and environmental performance. This research demonstrates pilot zones' dual significance in promoting innovation-driven development and urban green transformation for high-quality growth.

**Keywords:** Comprehensive Innovation Reform Pilot Zone, Green Total Factor Productivity, Difference-in-Differences, Industrial Structure Upgrading, Industrial Structure Sophistication

## 1 Introduction

Since the 21st century, China's rapid growth has come with rising energy use and pollution [1]. To achieve sustainability and the "dual carbon" goals, green total factor productivity (GTFP), which incorporates environmental factors, better reflects development quality [2]. Improving GTFP reduces resource waste and emissions while promoting growth [1, 2]. The National Development and Reform Commission has called for green development and source control [3].

GTFP measures high-quality development and green transformation [4]. It is commonly measured using non-radial SBM with global Malmquist-Luenberger (GML) index [1, 5]. Empirical studies show various policy pilots improve GTFP. Nie et al. (2021) found innovative city construction raised GTFP by ~4.9% [4]. Li et al. (2023) used DID and found big data pilots improved GTFP, especially in coastal re-

gions, via technical efficiency and green innovation [1]. Key pathways include technological innovation and industrial upgrading [1, 4, 6]. On digital economy policy, Wen et al. (2025) used big data pilot zones and multi-period DID, showing digitalization raises firm-level GTFP through green patents and specialization [6]. On green finance, Pang et al. (2024) found that green finance reform pilot zones improved provincial GTFP [7]. Zhang Y. et al. (2025) showed these zones enhanced carbon productivity via green innovation and industrial greening [5]. These studies have practical significance for China's dual carbon goals and provide empirical references for green transition. However, existing research has limitations: most focus on single policies, while comprehensive institutional reform policies are understudied. Transmission channels often examine single mechanisms, lacking multi-level institutional pathways [6].

## 2 Theoretical Basis and Research Hypotheses

As a core policy carrier for China's innovation-driven development strategy, the Comprehensive Innovation Reform Pilot Zone aims to remove institutional barriers constraining innovation, optimize the innovation ecosystem, and improve regional innovation performance [8, 9]. GTFP—a comprehensive efficiency indicator balancing economic growth and environmental protection—depends on technological progress and resource allocation efficiency [7].

### 2.1 Mediating Mechanism of Overall Industrial Structure Upgrading

Overall industrial structure upgrading involves coordinated evolution of primary, secondary, and tertiary sectors, with core in optimal cross-industry resource reallocation. The Comprehensive Innovation Reform Pilot Zone policy attracts innovation resources and lowers entry barriers, guiding capital, talent, and other factors to shift from low-efficiency, high-pollution traditional sectors to high-efficiency, low-energy emerging industries—essentially market-based capital allocation optimization [7]. Based on this, the paper proposes:

Hypothesis 1: The Comprehensive Innovation Reform Pilot Zone policy promotes urban GTFP by facilitating overall industrial structure upgrading.

### 2.2 Mediating Mechanism of Industrial Structure Sophistication

Industrial structure sophistication refers to the industrial system's deep transformation from labor-intensive to technology- and knowledge-intensive development, involving increased industrial value added and inherent requirements for green production transformation. A higher share of modern services reduces urban economic growth's dependence on material resources, lowering environmental burdens and enabling structural carbon reduction [9]. Based on this, the paper proposes:

Hypothesis 2: The Comprehensive Innovation Reform Pilot Zone policy promotes urban GTFP by facilitating industrial structure sophistication.

### 3 Research Design

This study uses the DID method to examine the impact of the Comprehensive Innovation Reform Pilot Zone policy on urban GTFP.

#### 3.1 Model Specification

The model can be represented as:

$$Super\ efficiency\ SBM_{it} = \alpha + \beta DID_{it} + \sum_k \gamma_k X_{kit} + \mu_i + \lambda_t + \varepsilon_{it} \tag{1}$$

The explained variable, "super-efficiency SBM," is a measure of urban green total factor productivity . The GTFP calculated using the super-efficiency SBM model in this paper can be expressed as:

$$\min \rho = \frac{1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 - \frac{1}{s_1 + s_s} \left( \sum_{r=1}^{s_1} \frac{s_r^g}{y_{rk}^g} + \sum_{t=1}^{s_2} \frac{s_t^b}{y_{tk}^b} \right)} \tag{2}$$

Constraints:

$$x_{ik} \geq \sum_{j=1, j \neq k}^n x_{ij} \lambda_j - s_i^-$$

$$y_{rk}^g \leq \sum_{j=1, j \neq k}^n y_{rj}^g \lambda_j + s_r^g$$

$$y_{tk}^b \geq \sum_{j=1, j \neq k}^n y_{tj}^b \lambda_j - s_t^b$$

$$1 - \frac{1}{s_1 + s_2} \left( \sum_{r=1}^{s_1} \frac{s_r^g}{y_{rk}^g} + \sum_{t=1}^{s_2} \frac{s_t^b}{y_{tk}^b} \right) > 0$$

$$s_i^-, s_r^g, s_t^b, \lambda_j \geq 0$$

$DID_{it}$  the core interaction term is the product of city i's reform pilot zone status and post-policy implementation year , capturing policy effects;  $\varepsilon_{it}$  is the random error term. Control variables include: population size, economic development level finan-

cial development level, government intervention level, and fiscal investment intensity.  $X_{kit}$  City fixed effects  $\mu_i$  and year fixed effects  $\lambda_t$  control for unobservable urban heterogeneity and macroeconomic time effects, respectively.

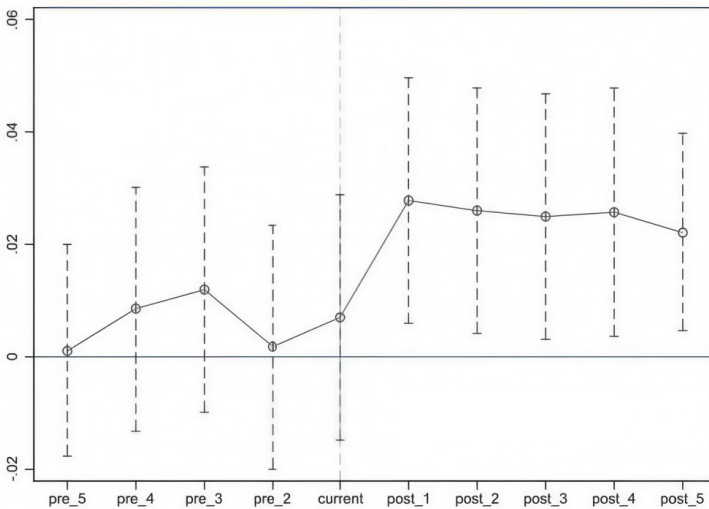
### 3.2 Data Sources and Sample Construction

This study covers 333 Chinese cities from 2009-2023. After removing incomplete records due to missing values, the final sample includes 290 cities with 4225 city-year observations, forming an approximately balanced panel.

GTFP is measured via super-efficient SBM, with inputs and outputs. Data sources: urban and environmental statistical yearbooks. Policy variables: Treat, Post, and interaction term DID; dummy variables generated to test dynamic effects and parallel trends. Control variables: population size, economic development, financial development, government intervention and fiscal input.

## 4 Empirical Analysis

### 4.1 Parallel Trend Test



**Figure 1.** Parallel Trend Test

As shown in Figure 1, the "current" period coefficient is also insignificant, showing no immediate policy effect. Post-implementation, post\_1 to post\_5 coefficients are all significantly positive at the 5% level, demonstrating the policy's sustained positive impact on urban GTFP with gradual and stable effects. These results confirm the parallel trend hypothesis, supporting the reliability of baseline regression conclusions.

**4.2 Benchmark Regression**

**Table 1.** Benchmark Regression Results

Variable	No control variables Super efficient SBM	Add control variables Super efficient SBM
DID	0.018*** (0.004)	0.012*** (0.004)
Population size		0.120*** (0.018)
Economic development level		0.049*** (0.009)
Financial development level		0.007*** (0.003)
Degree of government inter- vention		-0.042 (0.031)
Fiscal investment		-0.004*** (0.000)
Cons	0.330*** (0.001)	-0.885*** (0.155)
Id	Yes	Yes
Year	Yes	Yes
N	4853	4225
R <sup>2</sup> adjusted	0.690	0.697

Note: \*\*\*, \*\* and \* represent significance levels of 0.1 % , 1 % , and 5 % , respectively , and the values in parentheses are standard errors.

As shown in Table 1, after controlling for relevant control variables and individual-year two-way fixed effects, the core explanatory variable DID has an estimated coefficient of 0.012, significantly positive at the 0.1% statistical level. This strongly validates the core hypothesis that the comprehensive innovation reform pilot zone policy significantly improves green total factor productivity, indicating a positive promoting effect.

**4.3 Robustness Test**

**Table 2.** Robustness Test

Variable	Replacement of Explanatory Variable		Exclusion of Special Samples	
	No control variables	Add control variables	No control variables	Add control variables
	Super efficient CCR	Super efficient CCR	Super efficient CCR	Super efficient CCR
DID	0.024*** (0.005)	0.018*** (0.005)	0.019*** (0.005)	0.013** (0.006)
Population size		0.103*** (0.024)		0.096*** (0.024)
Economic development		0.031*** (0.012)		0.033*** (0.012)

Variable	Replacement of Explanatory Variable		Exclusion of Special Samples	
	No control variables	Add control variables	No control variables	Add control variables
	Super efficient CCR	Super efficient CCR	Super efficient CCR	Super efficient CCR
level				
Financial development level		0.005 (0.003)		0.005 (0.003)
Degree of government intervention		-0.091** (0.041)		-0.073* (0.041)
Fiscal investment		-0.005*** (0.001)		-0.005*** (0.001)
Cons	0.566*** (0.001)	-0.338 (0.210)	0.566*** (0.001)	-0.316 (0.208)
Id	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	4853	4225	4793	4165
R <sup>2</sup> adjusted	0.660	0.665	0.660	0.664

Note: \*\*\*, \*\* and \* represent significance levels of 0.1 % , 1 % , and 5 % , respectively , and the values in parentheses are standard errors.

To eliminate the influence of the explained variable's measurement method on estimation results, this paper replaces the original ultra-efficient SBM model-measured green TFP with ultra-efficient CCR model efficiency values for re-regression. As shown in Table 2, the DID coefficient remains 0.018, positive and significant at the 0.1% level, consistent with baseline results, confirming the comprehensive innovation reform pilot zone's robust promoting effect on urban green TFP.

## 5 Mechanism Analysis

**Table 3.** Mechanism of Action Test

	(1)	(2)
	Overall upgrading of industrial structure	Industrial structure upgrading
DID	0.010* (0.006)	0.118** (0.056)
Population size	-0.076** (0.033)	-0.157 (0.467)
Economic development level	0.001 (0.016)	0.078 (0.229)
Financial development level	0.004 (0.005)	-0.225* (0.134)
Degree of government intervention	-0.163*** (0.049)	-0.476 (0.459)
Fiscal investment	0.002** (0.001)	0.002 (0.005)
Cons	2.742***	-0.348

	(1)	(2)
	Overall upgrading of industrial structure	Industrial structure upgrading
	(0.304)	(5.328)
Id	Yes	Yes
Year	Yes	Yes
N	4225	4225
R <sup>2</sup> adjusted	0.924	0.845

Note: \*\*\*, \*\* and \* represent significance levels of 1 % , 5 % , and 10 % , respectively, and the values in parentheses are standard errors.

First, regarding overall industrial structure upgrading, as shown in Table 3, the core explanatory variable (DID) has an estimated coefficient of 0.010 after controlling for city and year fixed effects, significant at the 10% level. This indicates the pilot zone policy significantly promotes overall upgrading of urban industrial structure.

Second, for industrial structure sophistication, as shown in Table 3, the DID coefficient is 0.118, significant at the 5% level. This further shows the policy not only drives overall upgrading but also facilitates the evolution of urban industrial structure toward advancement and rationalization.

## 6 Conclusion

This paper examines the impact and mechanism of the comprehensive innovation reform pilot zone policy on urban green total factor productivity using 333 Chinese cities (2009-2023) and a difference-in-differences method based on a quasi-natural experiment. Results show the policy significantly improves GTFP, with robustness confirmed by city-year fixed effects, parallel trend tests, and robustness checks.

Mechanism analysis reveals two policy paths: (1) optimizing innovation resource allocation to drive industrial structure upgrading, improving resource efficiency and reducing high-energy-consuming sectors; (2) strengthening technological innovation and institutional environments to promote high-tech/modern service industries, enhancing green technology diffusion and production transformation capacity. This validates the pilot zones as dual-function tools balancing economic-ecological efficiency and supporting institutional innovation for GTFP improvement.

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