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Research on the Impact of Environmental Regulation on Urban Green Total Factor Productivity

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Abstract

Based on the panel data of 285 Chinese cities from 2012 to 2023, this paper constructs linear and nonlinear regression models to empirically analyze the real impact of environmental regulations on the Green Total Factor Productivity (GTFP) of Chinese cities, and conducts heterogeneity analysis. The results show that the impact of environmental regulation on urban GTFP is U-shaped. Currently, China's environmental regulation level is relatively low, which is on the left side of the U-shaped curve, indicating that it inhibits green total factor productivity. Heterogeneity analysis reveals that environmental regulations in small and medium-sized cities and megacities exert a suppressive effect on urban GTFP, while their impact on large cities remains inconspicuous. In service-oriented cities, the regulatory suppression effect is notably pronounced, whereas it is insignificant in industrialized cities. The suppressive effect is particularly evident in cities across central and western regions, but less pronounced in eastern cities.

Keywords

Environmental regulation; Green Total Factor Productivity; U-shaped

1. Introduction

The 14th Five-Year Plan and the 2035 Long-Range Objectives Outline explicitly emphasize the need to strengthen green and low-carbon development while promoting high-quality economic growth. The green development of cities is not only a need for China to cope with climate change, resource pressure and ecological degradation, but also to enhance national economic competitiveness and achieve sustainable development. Urban Green Total Factor Productivity (GTFP) is a core metric for evaluating the effectiveness of urban green transformation and aligning with high-quality development requirements. By coordinating traditional production factors (capital and labor) with green elements (energy and environmental capacity), it enhances overall factor utilization efficiency, ensures

economic growth and industrial upgrading, while achieving resource conservation and pollution reduction. Environmental regulation means that the government restricts or regulates the negative impact on the environment in the process of production and consumption by formulating and implementing a series of laws, standards, policies and other measures. In the past few decades, the acceleration of urbanization in China has gradually increased the pressure on the environment. Cities are not only the engine of economic development, but also the main source of energy consumption, pollution emission and ecological destruction. Therefore, in the process of urban development, how to protect the ecological environment while improving the economic efficiency has become an important issue of urban development. For China's cities and enterprises, environmental regulation is both a constraint and a driving force. It is of great significance to study the relationship between environmental regulation and urban green total factor productivity.

2. Literature Review

The impact of environmental regulation on GTFP is mainly related to "cost effect" and "Porter hypothesis". According to different effects, there are three main views on the relationship between environmental regulation and green total factor productivity. First, it is believed that environmental regulation is not conducive to the improvement of green total factor productivity. In the short term, stricter environmental regulations will increase pollution control costs for businesses, raising production expenses and ultimately hindering sustainable urban development [1]. From the perspective of fiscal decentralization, enterprises may incur higher pollution control costs, potentially reducing their funding for technological innovation and consequently diminishing urban economic efficiency [2]. The second perspective holds that environmental regulation can enhance urban green total factor productivity [3]. Appropriate environmental regulations can offset compliance costs through the compensatory effects of technological innovation pathways [4], while also driving green technological innovation and industrial restructuring, thereby enhancing green total factor productivity [5]. Thirdly, the relationship between environmental regulation and GTFP is uncertain. As environmental regulation intensifies, the impact on corporate and urban GTFP exhibits a U-shaped pattern—initially suppressing then stimulating [6]. Ji Yanli et al. (2022) demonstrated that the relationship between industrial GTFP and environmental regulation follows an inverted 'N' pattern [7]. As governance standards improve, environmental regulation's impact on manufacturing GTFP exhibits a dynamic cycle: initially stimulating growth, then moderating it, and finally reinvigorating the process.

This paper studies the driving effect of environmental regulation on urban GTFP by using linear and nonlinear fixed effect models, and makes heterogeneity analysis according to different city size, industrial structure and regional type,

and explores the path of urban economic green development.

3. Research Design

3.1. Model Construction

This paper uses panel data of 285 prefecture-level cities, sub-provincial cities and municipalities directly under the central government in China from 2012 to 2023 to empirically study the impact of ER on urban GTFP. By analyzing the results of F-test and Hausman test, it was found that both individual effects and time effects exist. Therefore, the fixed effects model was chosen for estimation.This paper mainly studies the impact of environmental regulation on urban GTFP, and sets up the following linear benchmark regression model:

$$GTFP_{it} = \alpha_0 + \alpha_1 ER_{it} + \alpha_2 Control_{it} + \upsilon_i + \lambda_t + \varepsilon_{it}. \quad (1)$$

After the implementation of government environmental regulation policies, enterprises in cities may struggle to meet the regulatory constraints in the short term. They might pay pollution discharge fees or environmental protection taxes, thereby increasing the compliance costs for economic entities and crowding out productive investment, which inhibits GTFP improvement in the short run. In the long run, appropriate environmental regulations can force enterprises to innovate towards low-pollution, high-efficiency directions, generating innovation compensation effects sufficient to cover or even exceed compliance costs, thus enhancing urban GTFP. Therefore, there might be a U-shaped relationship between environmental regulations and urban green total factor productivity. Modifying equation (1) by adding a quadratic term for environmental regulations, the fixed effects model is constructed as follows:

$$GTFP_{it} = \alpha_0 + \alpha_1 ER_{it} + \alpha_2 ER_{it}^2 + \alpha_3 Control_{it} + \upsilon_i + \lambda_t + \varepsilon_{it}. \quad (1)$$

Here, GTFP represents urban green total factor productivity, ER represents environmental regulation intensity, Control represents control variables, i and t denote city and year respectively, μ_i represents city fixed effects, λ_t represents time fixed effects, and ε_{it} is the random disturbance term.

3.2. Variable Selection and Description

1) Explained Variable

Urban Green Total Factor Productivity (GTFP). This paper, referencing the method of Yang Xiang (2015), employs the SBM directional distance function combined with the GML (Global Malmquist-Luenberger) productivity index to measure the green total factor productivity of 285 Chinese cities from 2012 to 2023[8]. Since the GML index represents a dynamic rate of change, this paper uses 2012 as the base year (GTFP value in 2012 set to 1) [9]. The GTFP for 2013 equals the product of the 2012 GTFP and the 2013 GML index. GTFP for subsequent years are obtained by

cumulative multiplication, serving as the explained variable. The measurement of GTFP mainly includes input and output aspects in Table 1. Capital input is measured by the actual capital stock of each city. Academia typically uses the "perpetual inventory method" to estimate actual capital stock. The core formula is: $K_t=I_t+(1-\delta)K_{t-1}$, where K_t is the actual capital stock of the city in year t, I_t is the actual total fixed asset investment in year t (nominal fixed asset investment deflated using a price index), δ is the economic depreciation rate (taken as 9.6%), and K_{t-1} is the actual capital stock in year t-1[10]. Desired output is measured by the Gross Domestic Product (GDP) of each city, deflated to real GDP using 2012 as the base year to eliminate price impacts.

Table 1. Indicators for Measuring Urban GTFP

Primary Indicator	Secondary Indicator	Indicator Description	Data Source
Input Indicators	Capital Input	Actual capital stock (100 million yuan)	China City Statistical Yearbook, China Statistical Yearbook
	Labor Input	Number of employed persons at year-end in each city (10,000 persons)	
	Energy Input	Total social electricity consumption in the city (10,000 kWh)	
Output Indicators	Desired Output	Gross Domestic Product of each city	EDGAR Database, China City Statistical Yearbook, China Environmental Statistical Yearbook
	Undesired Output	CO2 emissions, SO2 emissions	

2) Core Explanatory Variable

ER. This paper adopts the text frequency statistics method, combining content related to ER from various city government work reports. Keywords such as "environmental protection," "environmental conservation," "pollution," "energy consumption," "emission reduction," "sewage discharge," "ecology," "green," "low-carbon," "air," "chemical oxygen demand (COD)," "sulfur dioxide/SO2," "carbon dioxide/CO2," "PM1," "PM2.5" were selected. Python was used to segment the text of government work reports from 2012 to 2023. The sum of the frequencies of 15 environmentally related keywords was calculated and logarithmically transformed to serve as the proxy variable for ER.

3) Control Variables.

Economic Development Level (ECO). Represented by the ratio of year-end deposits and loans of financial institutions to the regional GDP.

Industrial Structure (IS). Represented by the ratio of the tertiary industry's added value to the regional GDP.

Government Intervention Level (GOV). Represented by the ratio of local fiscal general budget expenditures to the regional GDP.

Population Density (POP). Represented by the logarithm of the ratio of the registered population to the administrative land area.

Financial Development Level (FIN). Represented by the ratio of year-end deposits and loans of financial institutions to the regional GDP.
Openness Level (FDI). Represented by the ratio of actual utilized foreign capital to the regional GDP.

3.3. Data Sources and Processing

GTFP data were obtained from the China City Statistical Yearbook, China Statistical Yearbook, and the EDGAR database, and calculated using MAXDEA software. ER data were sourced from government work reports on official government websites. Control variable data were obtained from the China City Statistical Yearbook. Some missing data were imputed using linear interpolation based on the China Statistical Yearbook. Cities with excessive missing data, such as Hami City, were excluded.

4. Empirical Results and Analysis

4.1. Analysis of Linear Model Regression Results

This chapter analyzes the results of the linear regression model from equation (1), and conducts robustness tests, endogeneity tests, and heterogeneity analysis.

4.1.1. Analysis of Linear Model Regression Results

Descriptive statistical analysis was conducted on the main variables involved in the empirical analysis, with results shown in Table 2.

Table 2. Descriptive Statistics

Variable	Sample Size	Mean	Standard Deviation	Minimum	Maximum
GTFP	3420	1.017	0.079	0.687	1.633
ER	3420	3.754	0.447	1.099	4.942
ECO	3420	10.83	0.686	8.927	13.19
IS	3420	0.441	0.100	0.115	0.849
GOV	3420	0.206	0.103	0.0440	0.916
POP	3420	5.739	0.944	1.628	8.176
FIN	3420	2.697	1.214	1.095	7.154
FDI	3420	0.00200	0.00300	0	0.0290

The mean value of GTFP is slightly greater than 1, indicating that, China's urban GTFP shows a slight improvement trend during the sample period. Its minimum and maximum values are 0.687 and 1.633 respectively, indicating significant differences in green total factor productivity among different cities in different years.
The value range of ER spans from 1.099 to 4.942, reflecting differences in environmental regulatory intensity among prefecture-level cities, consistent with the objective reality of uneven economic development and environmental protection pressures across different regions of China.
Regarding control variables, the Economic ECO data indicates that sample cities are

at different stages of development. The mean value of IS is approximately 0.441, with a minimum of 0.115 and a maximum of 0.849, indicating that sample cities are still in the mid-stage of transition from an industrial economy to a service economy, with industrialization characteristics remaining evident, though the degree of industrialization varies across cities. The mean value of GOV is 0.206, implying that local government fiscal expenditures account for about one-fifth of GDP, but this ratio reaches as high as 0.916 in some cities, indicating that economic development in certain cities heavily relies on government investment-driven growth. The mean logarithm of POP is 5.739, and the mean value of FIN is 2.697, both reflecting differences in agglomeration degree and financial deepening among cities. The mean value of FDI is relatively low with a small standard deviation, reflecting that economic growth relies more on endogenous capital and technological.

4.1.2. Correlation and Multicollinearity Tests

Table 3. Correlation Test Results

	GTFP	ER	ECO	IS	GOV	POP	FIN	FDI
GTFP	1							
ER	0.0200	1						
ECO	0.289***	0.150***	1					
IS	0.100***	0.192***	0.341***	1				
GOV	-0.330***	0.048***	-0.578***	0.074***	1			
POP	0.273***	-0.070***	0.215***	0.182***	-0.512***	1		
FIN	0.080***	0.101***	0.289***	0.690***	0.172***	0.045***	1	
FDI	0.150***	-0.029*	0.240***	0.087***	-0.228***	0.296***	0.048***	1

a. * p < 0.1, ** p < 0.05, *** p < 0.01;

The result of Pearson correlation coefficient method to test the correlation among main variables is shown in Table 3. The simple correlation coefficient between ER and GTFP is not significant. This indicates that, without controlling for other factors, there is no significant linear relationship between the two.

To ensure the accuracy and stability of the baseline regression model results, this paper conducted a Variance Inflation Factor (VIF) test on the explanatory variables shown in Table 4 to diagnose potential multicollinearity issues.

Table 4. Multicollinearity Test

Variable	VIF	1/VIF
GOV	2.750	0.364
ECO	2.340	0.427
IS	2.220	0.451
FIN	2.120	0.473
POP	1.670	0.599
FDI	1.140	0.877
ER	1.080	0.927

Variable	VIF	1/VIF
GOV	2.750	0.364
Mean VIF	1.900	

The VIF test results indicate that there's no serious multicollinearity problem in this study model. Although variables such as IS and FIN showed pairwise correlations in Table 3, the VIF test confirm that there's no complex multicollinearity relationship among multiple variables. Therefore, the estimated coefficients obtained from the subsequent baseline regression model can be considered stable and reliable.

4.1.3. Baseline Regression Results

Table 5. Regression Analysis of the Impact of ER on GTFP

	(1)	(2)
	GTFP	GTFP
ER	-0.007**	-0.006**
	(0.003)	(0.003)
ECO		0.123***
		(0.013)
IS		-0.036
		(0.034)
GOV		0.069
		(0.046)
POP		0.052
		(0.039)
FIN		0.003
		(0.004)
FDI		-1.204
		(1.140)
_cons	1.059***	-0.573**
	(0.011)	(0.272)
N	3420	3420
R2	0.736	0.754
CityFE	YES	YES
YearFE	YES	YES
F	5.448	33.552

a. Column (1) presents the two-way fixed effects model with only the core explanatory variable ER; Column (2) presents the full model incorporating all control variables; *p < 0.1, **p < 0.05, ***p < 0.01; values in parentheses indicate t-statistics.

As shown in Table 5, regardless of whether control variables are considered, the coefficient of ER is significantly negative at the 5% level in both sets of regressions. After controlling for city-specific heterogeneity and time trends, strengthening environmental regulations has a significant inhibitory effect on urban GTFP in the current period. This may be because strict environmental policies increase

compliance costs for enterprises in the short term, such as purchasing environmental protection equipment and paying pollution discharge fees, crowding out resources for productive investment and technological research and development, thereby temporarily hindering the improvement of overall green efficiency.

Among control variables, the coefficient of ECO is highly significant at the 1% level, indicating that the level of economic development is a powerful driving force for improving urban GTFP. More economically developed cities typically have stronger financial resources to invest in green technology research and development, more advanced management concepts, and more urgent needs for industrial structure upgrading, effectively promoting GTFP growth. In contrast, the coefficients of other control variables, such as IS, GOV, POP, FIN, and FDI, are not statistically significant. This does not mean these factors are unimportant; rather, it indicates that after controlling for city fixed effects, time effects, economic level, and environmental regulations, the independent direct linear effects of these factors on GTFP are not apparent. They may indirectly influence GTFP through their impact on ECO or ER.

4.1.4. Endogeneity and Robustness Tests

1) Endogeneity Test

To mitigate potential endogeneity issues between ER and urban GTFP, the instrumental variable method (2SLS) was employed for estimation, selecting the lagged term of the core explanatory variable environmental regulation (L.ER) as the instrumental variable.

The instrumental variable was tested for under-identification and weak identification. The Kleibergen-Paap rk LM statistic was 101.682, with a corresponding p-value of 0.0000, strongly rejecting the null hypothesis of "instrumental variable under-identification" at the 1% level. This indicates a significant correlation between the instrumental variable (L.ER) and the endogenous explanatory variable (ER), satisfying the relevance condition. The Cragg-Donald Wald F statistic was 165.239, and the Kleibergen-Paap rk Wald F statistic was 96.261, both far exceeding the Stock-Yogo critical value of 16.38 at the 10% level. This fully demonstrates a strong correlation between the instrumental variable (L.ER) and the endogenous variable, effectively avoiding estimation bias caused by weak instruments. The corresponding estimation results are shown in Table 6.

Table 6. Results of Endogeneity Tests

	(1)	(2)
	ER	GTFP
L.ER	0.225***	
	(0.023)	
ER		-0.039***

		(0.013)
ECO	-0.019	0.123***
	(0.073)	(0.016)
IS	-0.180	-0.049
	(0.168)	(0.037)
GOV	-0.059	0.053
	(0.228)	(0.053)
POP	-0.542***	0.021
	(0.126)	(0.043)
FIN	0.002	0.001
	(0.026)	(0.006)
FDI	7.363	-0.848
	(4.764)	(1.302)
_cons	6.335***	
	(1.251)	
N	3135	3135
R2	0.496	0.033
CityFE	YES	YES
YearFE	YES	YES
F	18.766	29.590

a. * p < 0.1, ** p < 0.05, *** p < 0.01; values in parentheses are t-values.

As can be seen from Table 6, the coefficient of ER is highly significant at the 1% level, indicating that environmental regulation has an inhibitory effect on urban GTFP. After controlling for endogeneity, the magnitude of the inhibitory effect of environmental regulation is much larger in absolute terms than the coefficient in the baseline regression. This result suggests that without controlling for endogeneity, the negative effect of environmental regulation on GTFP would be severely underestimated.

2) Robustness Test

To ensure the reliability of the baseline regression conclusions, this paper conducted robustness tests from the following four dimensions: Excluding municipality samples; Excluding data from 2020 affected by the COVID-19 pandemic; Adding control variables Human Capital (HC) and Urbanization Rate (UR), where HC is represented by the ratio of students enrolled in ordinary institutions of higher learning to the year-end total population, and UR is represented by the ratio of non-agricultural population to registered population; Controlling for provincial fixed effects. The robustness test results are shown in Table 7.

Table 7. Robustness Test Results

	(1)	(2)	(3)	(4)
	Excluding municipalities directly under the central	Exclude the impact of the 2020 pandemic	Add control variables	Add provincial fixed effects

	government			
	GTFP	GTFP	GTFP	GTFP
ER	-0.005*	-0.007**	-0.006**	-0.006**
	(0.003)	(0.003)	(0.003)	(0.003)
ECO	0.117***	0.114***	0.125***	0.123***
	(0.013)	(0.013)	(0.013)	(0.013)
IS	-0.028	-0.037	-0.035	-0.036
	(0.034)	(0.037)	(0.034)	(0.034)
GOV	0.077*	0.029	0.064	0.069
	(0.046)	(0.049)	(0.046)	(0.046)
POP	0.049	0.057	0.045	0.052
	(0.039)	(0.040)	(0.038)	(0.039)
FIN	0.003	0.003	0.003	0.003
	(0.004)	(0.004)	(0.004)	(0.004)
FDI	-1.068	-1.093	-1.370	-1.204
	(1.066)	(1.198)	(1.141)	(1.140)
UR			0.031	
			(0.028)	
HC			-1.003***	
			(0.316)	
_cons	-0.509*	-0.499*	-0.546**	-0.573**
	(0.271)	(0.279)	(0.265)	(0.272)
N	3372	3135	3420	3420
R2	0.764	0.750	0.756	0.754
CityFE	YES	YES	YES	YES
YearFE	YES	YES	YES	YES
F	31.566	29.843	27.899	33.552

a. * p < 0.1, ** p < 0.05, *** p < 0.01; values in parentheses are t-values.

In the four test models shown above, the estimated coefficients of ER remain negative, significantly negative at the 5% level in columns (2), (3), and (4), and significantly negative at the 10% level in column (1) after excluding municipalities. The estimated coefficients of ER fluctuate narrowly between -0.007 and -0.005, closely matching the coefficient from the baseline regression (-0.006). This demonstrates that environmental regulation has an inhibitory effect on urban green total factor productivity, and the baseline regression results are robust.

4.1.5. Heterogeneity Analysis

The impact of environmental regulations on urban GTFP may exhibit heterogeneity across city size, industrial structure, and regions. Heterogeneity test results are presented in Table 8.

Table 8. Heterogeneity Test Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Small and medium-sized	Large cities	Megacities	Industrialization	Service oriented	Eastern	Central and Western Regions
	GTFP	GTFP	GTFP	GTFP	GTFP	GTFP	GTFP
ER	-0.032*	0.002	-0.010***	0.000	-0.009*	-0.007	-0.007**
	(0.018)	(0.005)	(0.004)	(0.003)	(0.005)	(0.005)	(0.004)
ECO	0.101**	0.140***	0.141***	0.109***	0.199***	0.122***	0.137***
	(0.050)	(0.024)	(0.019)	(0.022)	(0.033)	(0.023)	(0.016)
IS	-0.199***	0.023	-0.035	0.009	-0.053	0.062	-0.030
	(0.072)	(0.062)	(0.051)	(0.069)	(0.072)	(0.082)	(0.041)
GOV	0.090	0.117*	0.013	-0.008	0.228***	-0.352***	0.135**
	(0.125)	(0.065)	(0.081)	(0.081)	(0.070)	(0.106)	(0.057)
POP	-0.169*	0.031	0.101**	-0.043	0.204***	0.229***	-0.122***
	(0.099)	(0.081)	(0.049)	(0.043)	(0.066)	(0.059)	(0.041)
FIN	-0.003	0.007	0.002	0.006	0.003	0.016**	-0.002
	(0.016)	(0.007)	(0.006)	(0.006)	(0.009)	(0.008)	(0.006)
FDI	17.003	-1.195	-0.782	2.219	-2.559	-0.598	-0.285
	(11.160)	(0.816)	(1.990)	(2.022)	(2.111)	(2.151)	(0.831)
_cons	0.684	-0.734	-1.036**	0.076	-2.292***	-1.722***	0.247
	(0.770)	(0.508)	(0.415)	(0.328)	(0.581)	(0.500)	(0.276)
N	142	1100	2172	1699	1709	1200	2220
R2	0.946	0.800	0.627	0.804	0.784	0.635	0.802
CityFE	YES	YES	YES	YES	YES	YES	YES
YearFE	YES	YES	YES	YES	YES	YES	YES
F	4.422	13.230	21.210	6.295	9.183	12.646	25.904

a. * p < 0.1, ** p < 0.05, *** p < 0.01; values in parentheses are t-values.

1) Urban Scale Heterogeneity

Following Liang Jinshe (2020), this study uses population size as the criterion for classifying cities: cities with populations under 1 million are categorized as small and medium-sized cities; those with populations between 1 and 3 million are classified as large cities; and those with populations over 3 million are designated as megacities [11]. Regression results indicate that the inhibitory effect of environmental regulations exhibits heterogeneity across city sizes.

ER exerts the strongest suppression on GFTP in small and medium-sized cities. These cities possess relatively weaker economic foundations, smaller enterprise scales, and limited technological capabilities. When confronted with ER, they lack sufficient resources and flexibility to undertake green technological innovation or absorb compliance costs. For large cities, the impact of ER on GTFP is not significant. This may be because large cities typically possess stronger economic strength and greater technological innovation capabilities. They can better absorb the compliance

costs imposed by ER. Simultaneously, their vibrant innovation environment may have already generated an initial innovation compensation effect, offsetting the cost effect of ER. This results in the net effect of ER being statistically insignificant. Megacities similarly face the inhibitory effects of ER. Despite possessing the strongest economic and technological capabilities, they often confront the highest and strictest environmental standards coupled with the most rigorous enforcement. Even with robust innovation capacity, the high compliance costs and complex governance challenges may exceed the compensatory effects of innovation, causing the cost effect to re-emerge as statistically significant.

2) Industrial Structure Heterogeneity

This study uses the ratio of tertiary to secondary industries as the criterion for classifying industrial structure sophistication. Cities with a ratio below 1 are categorized into a subsample representing industrialized stages, while those above 1 form a subsample representing service-oriented stages. Regression results indicate that the inhibitory effect of ER is significant only in service-dominated cities, not in industrialized ones.

This contradicts the conventional view that ER primarily impact industry, likely because the industrial sector has traditionally been the core target of ER. Governments and enterprises in these cities have accumulated experience and technical foundations through long-term interactions with environmental policies. Furthermore, industrial systems serve as primary battlegrounds for technological innovation, possessing the capacity to transform environmental pressures into green technology R&D and application, thereby partially offsetting compliance costs. ER elevates the operational costs of the entire economic system. As integral components of this system, service industries must bear these indirectly transmitted compliance costs. Moreover, for service enterprises, environmental protection is not a core competency. Sudden environmental costs may constitute an unexpected shock that is difficult to absorb or pass on, manifesting as a decline in GTFP.

3) Heterogeneity Among Cities in Different Regional Types

This paper categorizes cities geographically into eastern and central-western cities. Regression results indicate that the inhibitory effect of environmental regulations is significantly present in central-western regions but less pronounced in eastern regions.

Eastern regions boast advanced economies and high technological levels, endowing enterprises with stronger innovation capabilities and risk tolerance. When confronted with environmental regulations, these firms are better equipped to respond through green technological innovation and production process improvements, generating an innovation compensation effect that offsets the cost effect. Consequently, the net impact of environmental regulations becomes negligible. Eastern regions may be at a critical juncture transitioning from cost

effects toward Porter effects. In contrast, cities in the central and western regions remain in accelerated phases of industrialization, facing intense economic growth pressures and relatively backward technological levels. For these areas, the compliance costs imposed by environmental regulations constitute a heavy and difficult-to-shift burden. Consequently, cost effects dominate absolutely, significantly suppressing improvements in GTFP.

4.2. Analysis of Regression Results for Nonlinear Models

To further explore the complex relationship between environmental regulations and green total factor productivity, this study examined the nonlinear relationship in Equation (2) and compared the results of linear regression with those of nonlinear regression, as shown in Table 9.

4.2.1. Benchmark Regression Analysis

Table 9. Linear and Nonlinear Regression Results

	（1）	(2)
	GTFP	GTFP
ER	-0.006**	-0.052**
	(0.003)	(0.026)
ER2		0.008**
		(0.004)
ECO	0.123***	0.017***
	(0.013)	(0.006)
IS	-0.036	-0.064*
	(0.034)	(0.036)
GOV	0.069	-0.175***
	(0.046)	(0.038)
POP	0.052	0.020***
	(0.039)	(0.003)
FIN	0.003	0.005**
	(0.004)	(0.003)
FDI	-1.204	0.610
	(1.140)	(0.666)
_cons	-0.573**	0.858***
	(0.272)	(0.084)
N	3420	3420
R2	0.754	0.200
CityFE	YES	YES
YearFE	YES	YES
F	33.552	51.655

a. * p < 0.1, ** p < 0.05, *** p < 0.01; values in parentheses are t-values.

The coefficient for the first-order term (ER) of environmental regulation is negative,

while the coefficient for the second-order term (ER^2) is positive, both significant at the 5% level. This indicates a U-shaped relationship between environmental regulation and urban GTFP. Specifically, during the initial phase of relatively low environmental regulation intensity, its impact is primarily driven by cost effects. Firms primarily respond by paying fines or implementing end-of-pipe treatments, with compliance costs diverting productive resources and thereby suppressing GTFP. Once environmental regulation intensity crosses a certain inflection point, its impact shifts to being dominated by an innovation compensation effect. Stringent regulations compel firms to undertake fundamental innovations in green technologies and processes. The efficiency gains and product upgrades resulting from these innovations ultimately outweigh initial costs, thereby promoting GTFP growth. The discovery of a "U-shaped" relationship between ER and GTFP unifies the cost hypothesis and the Porter hypothesis within environmental regulation theory, demonstrating they are not mutually exclusive but successively dominate at different stages of environmental regulation development. The establishment of this "U-shaped" relationship indicates that the negative coefficient of ER in baseline linear regression stems from most sample cities likely residing on the left side of the curve, where environmental regulation exerts an inhibiting effect on urban GTFP.

4.2.2. Testing the "U-Shaped" Relationship (SLM Test)

This study follows Lind and Mehlum's methodology for testing the "U-shaped" relationship. The test results are presented in Table 10.

Table 10. Sasabuchi Test and Lind-Mehlum Test

Test		Statistic	T-value	P-value
Sasabuchi Test	Left	3.94	—	0.0473
	Right	3.91	—	0.0480
Lind-Mehlum Test	Left	-0.034	-1.882	—
	Right	0.030	2.413	—

Based on the Sasabuchi test results, the P-values for both the left-tail slope and right-tail slope are less than the 0.05 significance level. This indicates that the slope is significantly negative on the left-falling segment of the "U-shaped" curve and significantly positive on the right-rising segment. The Lind-Mehlum test confirms that within the data range of this study's sample, the effect of environmental regulation on GTFP is significantly negative at lower intensities and significantly positive at higher intensities, satisfying the statistical conditions for a U-shaped relationship.

4.2.3. Robustness Tests

To validate the reliability of the "U-shaped" relationship between ER and urban GTFP, this section conducts robustness tests across four dimensions: (1) excluding municipality-level samples; (2) excluding data affected by the 2020 COVID-19

pandemic; (3) adding control variables for human capital (HC) and urbanization rate (UR); (4) controlling for provincial fixed effects. The results of the robustness tests for the U-shaped relationship are presented in Table 11.

Table 11. Robustness Test Results for the "U"-Shaped Relationship

	(1)	(2)	(3)	(4)
	Excluding municipalities directly under the central government	Exclude the impact of the 2020 pandemic	Add control variables	Add provincial fixed effects
	GTFP	GTFP	GTFP	GTFP
ER	-0.046*	-0.046*	-0.051**	-0.065**
	(0.026)	(0.026)	(0.026)	(0.026)
ER2	0.007*	0.007*	0.008**	0.011***
	(0.004)	(0.004)	(0.004)	(0.004)
ECO	0.011*	0.017***	0.017***	0.022***
	(0.006)	(0.006)	(0.006)	(0.006)
IS	-0.091**	-0.060	-0.065*	-0.032
	(0.036)	(0.038)	(0.037)	(0.038)
GOV	-0.212***	-0.199***	-0.172***	-0.162***
	(0.039)	(0.040)	(0.039)	(0.038)
POP	0.017***	0.019***	0.020***	0.014***
	(0.003)	(0.003)	(0.003)	(0.003)
FIN	0.005**	0.005*	0.005*	0.011***
	(0.003)	(0.003)	(0.003)	(0.003)
FDI	0.468	0.607	0.547	1.587**
	(0.650)	(0.701)	(0.661)	(0.751)
UR			-0.005	
			(0.012)	
HC			0.041	
			(0.134)	
_cons	0.951***	0.863***	0.855***	0.821***
	(0.085)	(0.086)	(0.089)	(0.087)
N	3372	3135	3420	3420
R2	0.189	0.207	0.200	0.346
CityFE	YES	YES	YES	YES
YearFE	YES	YES	YES	YES
F	50.008	50.957	42.895	30.064

a. * p < 0.1, ** p < 0.05, *** p < 0.01; values in parentheses are t-values.

As shown in Table 11, the coefficient of ER remains consistently negative across all four test models, while the coefficient of ER2consistently remains positive. This finding is fully consistent with the benchmark U-shaped relationship model.

Robustness results indicate that the "U-shaped" relationship holds across different

sample ranges (excluding outliers) and time periods (excluding extreme events), demonstrating generalizability. The U-shaped relationship remains robust even after accounting for potential omitted variables, indicating that the benchmark model's estimates are reliable and unbiased, which significantly strengthening the credibility of this research finding and the strength of causal inference. Therefore, the impact of environmental regulations on urban green total factor productivity is nonlinear, exhibiting a "U-shaped" pattern characterized by initial suppression followed by promotion.

5. Research Conclusions and Policy Recommendations

Based on panel data from 285 prefecture-level cities, sub-provincial cities, and municipalities directly under the central government in China from 2012 to 2023, this study examines the mechanism through which ER affect urban GTFP, drawing the following conclusions:

1) Environmental regulations exhibit heterogeneous effects on China's urban GTFP. For cities of varying scales, both small-to-medium-sized cities and megacities face the issue of ER inhibiting urban GTFP; the effect of ER on GTFP in large cities is insignificant. For cities with different industrial structures, the inhibitory effect of ER is significant only in service-dominated cities, while it is insignificant in industrialized cities. For cities in different regional types, the inhibitory effect of ER is significant in central and western regions, but not in eastern regions.

2) The impact of ER on China's urban GTFP exhibits a U-shaped pattern. When regulatory intensity is low, firms primarily respond through passive compliance, generating much cost effects that crowd out productive investment, and then, reducing both firm and city GTFP. As regulations intensify beyond a tipping point, end-of-pipe treatment becomes prohibitively costly, forcing firms to shift from passive compliance to proactive innovation, seeking green technologies or more efficient processes. At high regulatory intensity, innovation compensation effects emerge and outweigh cost burdens. Through resource conservation, efficiency gains, and new product development, these innovations ultimately drive GTFP growth. A linear benchmark regression model confirms that environmental regulations suppress urban GTFP, indicating China's current regulatory intensity remains low-positioned on the left side of the U-curve inflection point.

Empirical results show that China's ER currently reside on the left side of the "U"-shaped curve, primarily exhibiting a suppression effect. Adjustments to regulatory intensity could involve moderate increases. In the short term, for regions with low regulatory intensity—such as Northeast China and major coastal economic provinces—policies like linking environmental inspection frequency to corporate emission reduction outcomes could moderately enhance the enforcement of environmental policy texts, preventing ecological inefficiency caused by weak regulation. For the western ecological barrier regions and central transition

provinces that have already achieved relatively high regulatory intensity, further pressure should be temporarily deferred, with the focus shifted to ensuring the effective implementation of existing policies. In the medium to long term, the government can establish a dynamic evaluation mechanism linking regulatory intensity to GTFP. When a city's GTFP growth rate exceeds the regional average for two consecutive years, policies such as tightening industry emission standards can be implemented to moderately raise regulatory standards. This will drive the city to cross the inflection point of the U-shaped curve and unleash the innovation compensation effect.

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