

Article

Environmental Taxes and Corporate Green Transition: Evidence from Chinese Manufacturing Firms

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Abstract

In China, the environmental protection tax constrains and incentivizes firms to cut emissions and lift efficiency. To examine the effect and mechanism of environmental regulation as a driver of corporate green transformation, this study uses data on Chinese listed manufacturing firms from 2011 to 2022. It takes the 2018 environmental fee-to-tax reform as a quasi-natural experiment and employs a difference-in-differences model. The core DID coefficient is 0.0088 ($p < 0.05$). After the reform was implemented, manufacturers in higher-tax regions achieved better green transformation by increasing pollution costs, adjusting investment and improving executives' green awareness. The policy effects were more pronounced for low-profit, non-state-owned, non-patent and labor-intensive firms in regions with higher tax burdens. Additionally, the policy effect exhibited a time lag. The incentive effect was stronger for heavily polluting enterprises, and the policy simultaneously boosted corporate economic performance. Accordingly, we propose broadening the taxable scope, tightening supervision, optimizing tax incentives and adopting targeted policies to support corporate green transformation.

Keywords: cost internalization; environmental protection tax; environmental regulation; green transformation; innovation compensation effect

1. Introduction

Adherence to green development represents a profound revolution in the paradigm of economic development. China prioritizes green and low-carbon development. Transforming traditional industries and fostering green sectors are key strategies to address resource and ecological issues. According to the International Energy Agency's Global CO₂ Emissions Report 2025, global carbon dioxide emissions have risen steadily over the past few years. As the world's three largest emitters, the United States, China, and India account for nearly 40% of total global emissions. Against this backdrop, China is striving to balance economic growth and environmental protection through its commitment to green development. Meanwhile, as the backbone of the real economy, enterprises are key drivers of both economic growth and ecological conservation. However, the interplay between enterprises' profit-maximizing objectives and the non-excludable nature of environmental governance presents formidable challenges to their green transformation. Traditional energy-intensive, high-emission enterprises face pressure to keep pace with technological advances and secure substantial capital investments. Accordingly, many enterprises exhibit limited willingness, insufficient capacity, and inadequate investment in green transformation. In the macro context of environmental regulation reform, enterprises



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must choose between passive compliance and active pursuit of green development. The decisions enterprises make on this front hinge on a critical juncture: they determine their own development trajectory while simultaneously advancing a sustainable green economy. Therefore, this critical juncture urgently warrants an in-depth investigation.

Hence, environmental protection has received increasing attention in China, prompting the government to formulate and implement numerous measures to advance green transformation. For instance, the enactment of the Environmental Protection Tax Law of the People's Republic of China in 2018 marked a pivotal policy shift aimed at curbing enterprises' energy consumption and pollutant emissions. The fundamental principle underlying the law is a direct proportionality: tax liability scales with emissions—rising as emissions increase, falling as they decrease, and ceasing entirely in their absence [1]. This shift from environmental fees to taxes represents a cornerstone of China's environmental regulations and has charted the course of the country's high-quality development. According to Petrik and Runst [2] and Halkos and Papageorgiou [3], environmental regulations, such as environmental taxes, serve as effective instruments for curbing carbon dioxide emissions. Similar tax reforms have been adopted worldwide. For instance, countries such as Sweden and Canada have implemented progressive carbon taxes that effectively promote technological progress and sustainable development [4,5]. Meanwhile, Brazil and South Africa have introduced environmental tax policies that use tax incentives and penalties to foster cleaner industrial processes [6,7]. These global experiences highlight the crucial role of effective environmental tax policies in driving green corporate development and achieving high-quality economic growth. In addition, post-Soviet transition economies, particularly Ukraine, have adopted market-based environmental incentives to advance the energy transition and low-carbon industrial development. Maistrenko argues that implementing environmental regulations in Ukraine is constrained by weak supporting systems, insufficient basic data, and conflicts between environmental goals and industrial growth [8]. In practice, Ukraine's green tariffs—a market-based tool similar to environmental taxes—have been severely undermined by fiscal pressures and payment arrears [9]. Tolstov and Bilan find that many new energy enterprises have voluntarily withdrawn from official green policy frameworks because policy subsidies and market revenues are misaligned. These experiences suggest that fiscal capacity, regulatory systems, and data infrastructure are essential for environmental taxes to work effectively in transition economies. Comparing China's environmental fee-to-tax reform with policy practices in Western countries, developing nations, and post-Soviet economies can provide valuable cross-regional empirical evidence for research on global environmental regulation.

The literature on China's environmental fee-to-tax reform has largely concentrated on its economic and environmental consequences. Regarding the economic benefits of these reforms, Liu et al. [10] showed that the 2018 reform enhanced corporate performance by significantly stimulating firms' environmental investment. Using a difference-in-differences (DID) model and data on listed firms in the Shanghai and Shenzhen A-share markets for 2012–2021, Wang et al. [11] confirmed that higher tax rates under the fee-to-tax reform significantly reduced enterprises' total factor productivity, mainly via strategic greenwashing behaviors in corporate innovation. Using the DID approach [12], Xie et al. [13] found that the implementation of the Environmental Protection Tax Law significantly improved green technology innovation in the advanced manufacturing sector [14]. Moreover, this tax has generated environmental benefits for Chinese enterprises by supporting ecosystem conservation. Gao et al. [15] verified that the Environmental Protection Tax Law reduced pollution and carbon emissions by tightening environmental supervision, reshaping energy structures, and fostering green technologies. Using panel data from 278 Chinese

cities, Kong et al. [16] showed that the environmental tax reform significantly promoted low-carbon total factor productivity and enhanced urban green transformation.

In summary, research findings on the impact of environmental protection taxes on green transformation have been inconsistent. Meanwhile, local governments have the discretion to set environmental taxes and fees. Some provinces have elevated local pollution tax rates by as much as a factor of ten relative to the central benchmark for major pollutants. Against this backdrop, the environmental tax reform constitutes an exogenous event that provides an appropriate setting for applying the DID method.

Accordingly, the present study investigated how China's shift from environmental fees to taxes has affected corporate green transformation at the micro level. Specifically, this study defines the concept of green transformation within the manufacturing sector. In line with China's policy framework, this transformation is both a mandatory element of environmental governance and a vital pillar of the pursuit of high-quality development. Accordingly, green transformation transcends its traditional role as an environmental protection task that conflicts with economic growth, instead serving as a core driver of high-quality development through systematic reform. Green development in the manufacturing industry is defined as the pursuit of resource conservation and environmental sustainability alongside economic growth. Its specific objectives include a substantial increase in the share of green and low-carbon energy, steady improvement in resource utilization efficiency, and a marked reduction in pollutant and carbon emission intensity. Within the context of environmental regulation and corporate green transformation, this study leverages the quasi-natural experiment provided by the fee-to-tax reform to empirically examine the mechanisms underlying environmental regulation and its impact on corporate green transformation, using data from China's listed manufacturing firms for 2011–2022. Finally, this study briefly analyzes the long-term effects and economic consequences of environmental tax policies.

Compared with prior research, this study offers the following marginal contributions: First, it enriches the conceptualization of green transformation for manufacturing enterprises. The economic role of manufacturing as a national pillar industry has largely been absent from research on green transformation. Most previous studies adopt a single environmental perspective, focusing on pollution reduction, cost efficiency, or energy optimization [17,18]. This study examines manufacturing enterprises' green transformation alongside continued economic development, thereby providing a more comprehensive reflection of the level of green development within the manufacturing sector. Furthermore, unlike previous studies that rely on regional- or industry-level data, this study employs firm-level panel data with many observations, thus offering more detailed and robust evidence [12]. As the main market entities and direct targets of environmental taxes, enterprises have made firm-level data particularly suitable for evaluating the policy effects of China's environmental taxes and fees. Additionally, we apply these dimensions to the evaluation of environmental regulation policies. To date, research in this area has been largely short-sighted, prioritizing near-term gains like emissions abatement, environmental quality upgrades [19], and innovation metrics, while overlooking more sustained or systemic impacts. Building on these analyses, we assess how environmental regulations affect the long-term sustainable development of manufacturing enterprises. In doing so, we aim to provide a more holistic reference for both the ongoing refinement and sustained implementation of environmental tax and regulatory frameworks.

2. Institutional Background, Theoretical Analysis, and Research Hypotheses

2.1. Institutional Background

An environmental protection tax is levied on enterprises that directly discharge sewage, waste gas, noise, and other pollutants into the environment. In 2018, China introduced the Environmental Protection Tax Law of the People's Republic of China, marking a pivotal milestone in its environmental taxation framework. The Law guides industrial restructuring and facilitates green development in the manufacturing sector, while also signaling the nascent establishment of China's green tax system [20].

The development of China's environmental tax system can be roughly divided into three stages:

1. The first phase (1979–2002) featured the pollution-discharge fee system, which was initially proposed in 1979 and formally piloted in 1982. During this stage, fees were levied mainly on industrial pollution sources.
2. During the second phase (2003–2017), the Regulations on the Collection and Use of Pollution Discharge Fees further refined the scope and standards of levy, establishing pollution discharge fees as a substantial revenue stream for local governments.
3. Since 2018, the environmental protection tax has been implemented following the enactment of the Environmental Protection Tax Law on 1 January 2018, which replaced the prior fee system. The detailed policy development process is presented in Table 1.

Table 1. Development history of important events of the environmental protection tax.

Time	Environmental Protection Tax Policy
1979	The pollution discharge fee system was first proposed
1982	Interim Measures for the Collection of Pollution Discharge Fees
2003	Regulations on the Collection and Use of Pollution Discharge Fees, which further standardized the collection and use of pollution discharge fees, expanded the collection scope, raised the charging standards, and introduced the concept of green taxation
2007	Comprehensive Work Plan for Energy Conservation and Emission Reduction, which clearly proposed to study and impose an environmental tax
2010	The official proposal to impose an environmental protection tax was put forward; a draft was formulated in 2014, and the draft was solicited for opinions from all sectors of society in 2015
2016	The Environmental Protection Tax Law was legislated and adopted, marking that China's environmental tax officially entered the legislative stage
2018	The Environmental Protection Tax Law was officially implemented

Note: This table presents only the policy development history and does not include any specific numerical units.

In contrast to the original pollution discharge fee regime, the implementation of the Environmental Protection Tax Law demonstrates distinct institutional advantages: First, legal status has been fundamentally strengthened. Environmental regulation has shifted from administrative oversight through fees to mandatory enforcement under the national tax law. The enhanced mandatory nature, standardization, and transparency of tax collection have diminished enterprises' scope to evade environmental costs through negotiation, thereby fostering a pattern of passive compliance. Second, enforcement rigidity has been substantially strengthened. The principle of tax legality has substantially circumscribed local governments' discretionary power, thereby suppressing practices such as "negotiated charging" and "selective law enforcement." Third, the incentive structure has been systematically enhanced. Although tax rates have been increased in certain provinces, the differentiated structure—operating on the principle that emission levels directly determine

tax liabilities—provides enterprises with stable economic incentives to intensify abatement efforts and channel investment toward green technological innovation. Furthermore, all environmental protection tax revenue has been allocated to local governments, which can use these funds. This arrangement has encouraged local authorities to strengthen environmental supervision and protection, further intensifying the green transformation of manufacturing enterprises.

2.2. Theoretical Analysis and Research Hypotheses

Based on the above theoretical elaboration and mechanistic analysis, we formally propose four research hypotheses for subsequent empirical testing.

2.2.1. Theoretical Elaboration and Hypotheses

An environmental protection tax constitutes an environmentally oriented economic policy instrument distinguished by its efficacy, precautionary nature, and long-term sustainability. The instrument's design and operational logic are rooted in Pigouvian tax theory [21] and the Porter hypothesis [22].

Under Pigouvian tax theory, corporate pollution generates negative externalities: the costs of environmental pollution are borne by society rather than by the polluting enterprises, leading to distortions in the allocation of market resources. Relative to traditional fee standards, the shift from pollution discharge fees to environmental protection taxes has standardized tax-collection criteria, substantially reduced local governments' discretion in environmental regulation, and effectively eliminated implicit unfair competition among regions, industries, and enterprises. These mandatory cost constraints, by internalizing externalities, compel manufacturing enterprises to embed pollution abatement in production decision-making, thereby achieving emission reductions through source-level governance.

According to the Porter hypothesis, stringent yet reasonable environmental regulation does not impose a cost burden on enterprise development; rather, it stimulates firms to pursue technological innovation and optimize production processes, thereby engendering an "innovation compensation effect." The environmental protection tax's institutional design—more emissions = higher taxation, fewer emissions = lower taxation, no emissions = no taxation—provides endogenous incentives for manufacturing enterprises to proactively pursue green development. Adopting cleaner production technologies and green environmental protection techniques for full-process emissions control enables enterprises to reduce both emissions and costs while boosting innovation and efficiency. This approach ultimately achieves a synergistic improvement in economic performance and environmental governance, thereby promoting enterprises' green transformation. Appendix A presents a detailed derivation procedure.

Accordingly, this study proposes Hypothesis 1: The fee-to-tax policy shift can foster the green transformation and development of manufacturing enterprises.

2.2.2. Mechanisms Driving Green Transformation and Hypotheses

This study investigates the underlying mechanism by which the environmental fee-to-tax reform influences the green transformation of manufacturing enterprises, examining three distinct dimensions: cost internalization (reflecting passive compliance), investment structure adjustment (representing active optimization), and strategic cognitive upgrading (embodying strategic response) [23].

First, grounded in the external cost internalization logic of Pigouvian tax theory, the implementation of the fee-to-tax reform is expected to encourage enterprises to pursue green transformation more proactively. As an environmental regulatory instrument, the environmental protection tax is enforceable, implementable, and subject to supervision; by internalizing enterprises' environmental pollution costs, it establishes the taxation

principle of “pollution entails payment.” On the one hand, the environmental protection tax burden borne by manufacturing enterprises is directly proportional to both the volume of pollutants they discharge and their pollution control performance [24]. Rising compliance costs incentivize enterprises to reduce tax liabilities by reducing emissions and optimizing production processes, thereby strengthening their willingness to adopt green production and emission-reduction practices and driving green transformation. On the other hand, the rigid enforcement of the “pollution entails payment” principle curbs the speculative notion that external costs will be socialized, thereby prompting enterprises to adopt a long-term cost-accounting perspective. Consequently, manufacturing enterprises incorporate environmental tax liabilities into their budgeting and planning [25]. This transition steers enterprises away from the short-term cost-reduction paradigm that prioritizes pollution, toward a framework of securing long-term efficiency gains through green development, thereby bolstering the momentum of green transformation.

Accordingly, this study proposes Hypothesis 2: The environmental fee-to-tax reform promotes enterprises’ green transformation by strengthening cost constraints.

Second, based on the innovation compensation effect of the Porter hypothesis, the introduction and implementation of the environmental fee-to-tax reform guides enterprises to adjust their investment structures and promote their production models’ green transformation [26]. The core principle of the environmental protection tax policy—more emissions = more taxation, fewer emissions = less taxation, no emissions = no taxation—helps steer enterprises toward market-oriented green investment. For manufacturing enterprises, an environmental protection tax increases the tax burden on traditional high-pollution, high-energy-consumption sectors, which gradually lose their competitive advantage. By contrast, green sectors—such as clean production equipment and green technology research and development (R&D)—can directly reduce enterprises’ environmental expenditures while enabling firms to benefit from preferential tax reductions based on their emission reduction performance [27]. This mechanism is consistent with the Porter hypothesis’s “innovation compensation” effect and engenders a virtuous cycle of emission reductions, tax reductions, and efficiency improvements. Such structural adjustments encourage enterprises to allocate more resources to the green sectors.

Accordingly, this study proposes Hypothesis 3: The environmental fee-to-tax reform promotes enterprises’ green transformation by optimizing their investment structure.

Finally, from the long-term dynamic perspective of Porter’s hypothesis, the enactment of the environmental fee-to-tax reform is anticipated to prompt senior executives to recalibrate their enterprises’ green transformation strategies, given the expected enduring effects of environmental regulation [28]. According to strategic cognition theory, as the core decision-makers of corporate strategy, executives’ level of green strategic cognition determines both the speed and quality of enterprise development. The rigid policy signals of the environmental fee-to-tax reform compel executives to transcend the limitations of traditional cognition. Based on the upper echelons theory, executives possess individual characteristics—such as age, educational background, and risk appetite—that significantly influence their cognitive abilities and decision-making. Further, variations in green cognition shape enterprises’ assessment of the external environment and ultimately determine their environmental strategy. Upon recognizing the persistence of the environmental protection tax policy and the emerging opportunities within the green market, executives are inclined to establish or enhance internal environmental governance systems and green supply chains, thereby ultimately achieving the comprehensive green transformation of manufacturing enterprises [29].

Accordingly, this study proposes Hypothesis 4: The environmental fee-to-tax reform promotes enterprises' green transformation by transmitting policy signals to enhance executives' green cognition.

3. Materials and Methods

3.1. Model Specifications and Variable Declaration

Using a sample of Shanghai- and Shenzhen-listed A-share manufacturing firms in China for 2011–2022, this study uses the 2018 implementation of the Environmental Protection Tax Law as a quasi-natural experiment to examine the impact of the fee-to-tax reform on the green transformation of China's manufacturing enterprises. The DID model used is specified in Equation (1).

$$M_green_{i,t} = \gamma_0 + \gamma_1 Treat_{i,t} + \gamma_2 Post_{i,t} + \gamma_3 Treat_{i,t} \times Post_{i,t} + \sum Controls_{i,t} + \delta_j + \delta_t + \delta_s + \varepsilon_{i,t} \quad (1)$$

where $M_green_{i,t}$ represents manufacturing firms' green development level. Following the literature and the measurement indicators for corporate green transformation proposed by Peng et al. [30]. This study constructs an evaluation index system for the green development level of China's manufacturing industry, comprising two dimensions: comprehensive performance and green development. The comprehensive performance dimension encompasses the economic and social performance of manufacturing enterprises, whereas the green development dimension comprises five indicators: green production, green emissions, green governance, green management, and green culture. This study employs the entropy-weight method to construct a composite green transformation index. Before the weighting calculation, min–max normalization is applied separately to positive and negative indicators to eliminate dimensional discrepancies. Among all sub-indicators, green emissions are defined as a negative indicator, while the rest are positive indicators. As shown in Appendix C, green production has the greatest weight, serving as the core of corporate green transformation. The normalization steps, index calculation procedures, and sensitivity tests are all documented in Appendix C. For sensitivity analysis, we reconstruct the index with an equal-weight scheme. The Pearson correlation coefficient between the entropy-weighted index and the equal-weighted index is 0.9556, indicating that the measurement results are not sensitive to weight settings and that the index is highly stable.

Additionally, $Treat_{i,t}$ is the policy dummy variable. Grouping is based on tax adjustment: the treatment group (Provinces with increased tax burdens: Hebei, Jiangsu, Shandong, Henan, Hunan, Sichuan, Chongqing, Guizhou, Hainan, Guangxi, Shanxi, and Beijing) consists of firms facing an increased tax burden (coded 1), whereas the control group with an unchanged tax burden is coded 0. Given that Yunnan, Liaoning, and Inner Mongolia maintained their original tax rates in 2018 and raised their standards within two years, observations from these three provinces were excluded from the sample. $Post_{i,t}$ is a time dummy variable, taking the value of 0 for the years before 2018 and 1 for 2018 and thereafter. The interaction term between the firm dummy $Treat$ and the time dummy $Post$ serves as the core explanatory variable, capturing the actual effect of the environmental fee-to-tax reform on green development in the manufacturing sector. The specific grouping bases and criteria are presented in Appendix B (Table A1).

$Controls$ represents the control variables in the model, including a series of firm-level characteristic variables such as firm age, leverage ratio, and CEO duality [31]. Furthermore, δ_j denotes industry fixed effects, δ_t denotes year fixed effects, and δ_s denotes firm fixed effects. Additionally, $\varepsilon_{i,t}$ is the random disturbance term, and robust standard errors are clustered at the firm level. This study focuses on the sign and statistical significance of the coefficient γ_3 . A significantly positive γ_3 indicates that environmental regulation promotes

the green transformation of the manufacturing industry. Appendix C presents the variable definitions in the model (Table A2).

3.2. Data Sources and Processing

This study selected A-share-listed manufacturing firms in Shanghai and Shenzhen for 2011–2022 as the research sample. Firm- and industry-level data were mainly obtained from the China Stock Market & Accounting Research (CSMAR) database, and regional data were collected from the China City Statistical Yearbook, the China Industrial Statistics Yearbook, and other official publications. To improve the empirical results' reliability, the raw data were processed as follows: (1) firms designated as ST or *ST during the sample period were excluded, (2) samples of firms listed for less than one year were removed, (3) samples with missing key financial indicators were eliminated, and (4) all continuous variables were winsorized at the 1st and 99th percentiles. After data screening, the final sample comprised 19,686 firm-year observations across 3086 manufacturing enterprises. All data cleaning, descriptive statistics and DID regression analyses were conducted using Stata 18.0 (StataCorp LLC, College Station, TX, USA). Descriptive statistics for the key variables are presented in Table 2.

Table 2. Descriptive Statistics of Variables.

Variable	Symbol	Observed Value	Mean	Standard Deviation	Minimum	Maximum
Green Transformation (index, dimensionless, range: 0–1)	M_green	19,686	0.1453	0.1405	0.00009	0.7561
Policy Dummy Variable (Dummy: 0/1)	Post	19,686	0.5464	0.4979	0	1
Firm Dummy Variable (Dummy: 0/1)	Treat	19,686	0.4072	0.4913	0	1
Firm Size (Natural logarithm of total assets, unit: RMB)	Size	19,686	22.0171	1.1796	17.3882	27.6211
Firm Age (Natural logarithm of operating years, unit: year)	Age	19,686	2.8859	0.3399	1.0986	4.1744
Financial Leverage (Asset-liability ratio, Dimensionless 0–1)	Lev	19,686	0.3662	0.1834	0.0071	0.9853
CEO Duality (Dummy: 0/1)	Dual	19,686	0.3425	0.4746	0	1
Ownership Type (Dummy: 0/1)	Central	19,686	0.2469	0.4312	0	1

Note: The unit and measurement specification of all variables in this table are consistent with the variable definitions in the text.

4. Empirical Findings and Analysis

4.1. Benchmark Result Analysis

DID estimates were performed using the benchmark model (Table 3). Columns (1)–(3) incorporate different combinations of year, industry, and firm fixed effects, and Columns (4)–(6) include additional control variables. The results indicate that the coefficient on the core explanatory variable *Did* was significantly positive at the 5% level across most specifications, regardless of the fixed-effects combination. This finding suggests that China's environmental fee-to-tax reform significantly promoted the green transformation of manufacturing enterprises in regions with increased tax burdens. From an economic perspective, a higher environmental tax burden directly elevates the costs of pollution abatement for enterprises, thereby eliminating the cost advantages of extensive production methods. In response, manufacturing firms often upgrade their green production processes to stabilize long-term operating returns and reduce environmental compliance risks. These empirical results validate the positive effect of the environmental fee-to-tax reform on corporate green transformation, consistent with Hypothesis 1.

Table 3. Benchmark regression results.

Variable	M_Green (1)	M_Green (2)	M_Green (3)	M_Green (4)	M_Green (5)	M_Green (6)
Did (Dummy: 0/1)	0.0084 * (0.0048)	0.0089 ** (0.0043)	0.0086 ** (0.0043)	0.0094 ** (0.0045)	0.0084 ** (0.0043)	0.0088 ** (0.0043)
Post (Dummy: 0/1)	0.1470 *** (0.0280)	0.0591 *** (0.0029)	0.0547 *** (0.0029)	0.1028 *** (0.0243)	0.0210 *** (0.0030)	0.0217 *** (0.0031)
Treat (Dummy: 0/1)	−0.0158 *** (0.0056)	0.0054 (0.0313)	0.0017 (0.0312)	−0.0176 *** (0.0050)	0.0104 (0.0274)	0.0124 (0.0285)
Xit (controls, metrics in Table 2)	No	No	No	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	No	Yes	Yes	No	Yes
Stkcd	No	Yes	Yes	No	Yes	Yes
N_obs	19,686	19,686	19,686	19,686	19,686	19,686
R ²	0.1471	0.0971	0.1237	0.2678	0.1297	0.1488
_cons	0.0928 *** (0.0437)	0.1110 *** (0.0125)	0.0306 (0.0413)	−0.8552 *** (0.0788)	−0.6873 *** (0.0550)	−0.7378 *** (0.0725)

Note: *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$. Robust standard errors are reported in parentheses.

4.2. Robustness Test

4.2.1. Parallel Trend Test

The two-period difference-in-differences model is valid only if the time-series trajectories of the treatment and control groups evolve in parallel before the policy shock; this identifying assumption is validated by the parallel trends test [32]. Therefore, the event study method was used to construct the following model:

$$M_{green_{i,t}} = \delta_0 + \sum_{t=2011}^{2022} \delta_1 Treat_r \times Post_j \times u_t + \sum Controls_{i,t} + \delta_j + \delta_t + \delta_s + \varepsilon_{i,t} \quad (2)$$

For the dynamic effect analysis of the benchmark DID specification, the year preceding tax reform enforcement is designated as the baseline, and all relevant empirical results are illustrated in Figure 1. The difference in green development levels between the treatment and control groups was not statistically significant in the pre-reform period, suggesting that the model satisfies the parallel-trends assumption.

This dynamic pattern suggests a notable lag in corporate responses: in the initial policy stage, firms opted for low-cost, passive compliance measures rather than large-scale green transformation investments, with tangible performance improvements emerging only in the medium- to long-run. This trend also explains why the core Did coefficient turns insignificant when we exclude the 2020–2022 later sample window in robustness checks. The lagged policy effect reflects the inherent characteristics of corporate green transformation. Green technology upgrades, equipment renewal, and production restructuring entail a time-consuming cycle of capital outlays and operational realignment. In the short run, firms mainly adopt low-cost passive compliance, while substantial green improvements appear in the medium and long term.

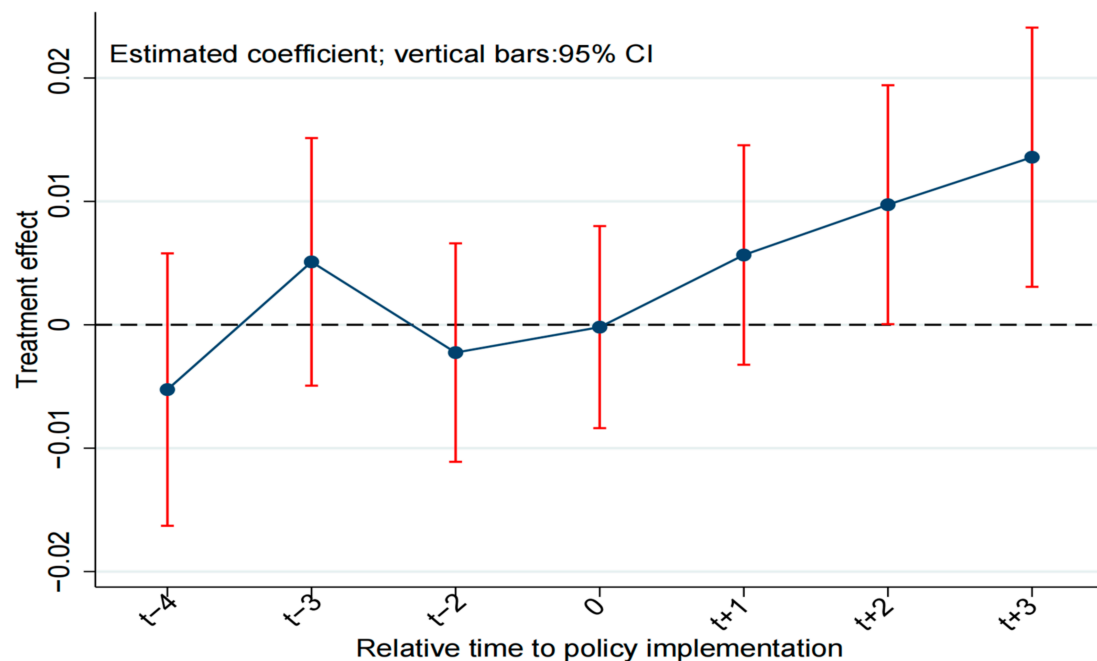


Figure 1. Parallel trend test. Note: X-axis: Relative Time to the Implementation of Environmental Protection Tax Reform. Y-axis: Estimated Coefficient of DID Term. Blue solid dots: Estimated coefficient for each relative period; Vertical red bars: 95% confidence intervals (95% CI); Horizontal dashed line at $y = 0$: Benchmark of zero policy effect.

4.2.2. Placebo Test

To rule out potential bias from omitted or uncontrollable factors in our baseline model results on the environmental “fee-to-tax” reform’s effect on the green development of China’s manufacturing industry, we conduct a randomization test and a placebo test by altering the policy reform implementation date, confirming the robustness of the tax policy effect.

- (1) Random assignment test. This test randomly assigns a treatment status to the tax policy. The *Treat* variable was randomly allocated, and the model was re-estimated for 1000 simulations. Figure 2 shows the distribution of the estimated coefficients, with the dashed red line representing the baseline regression coefficient for the actual policy effect. After 1000 iterations, the placebo coefficients were concentrated around zero and approximately followed a normal distribution. By contrast, the true policy coefficient lay in the extreme tail of the placebo distribution, outside the 95% confidence interval. This indicates that the effect under random assignment differed significantly from the baseline result, thereby passing the placebo test. Additionally, the p -value of the true policy coefficient within the placebo distribution was reported. With a p -value of 0.001, merely 0.1% of permuted coefficients exceed the baseline policy effect in absolute value, much lower than the 0.05 significance level. This further confirms that the policy effect identified by the baseline regression was not due to chance and that the core conclusion is relatively robust.
- (2) Changing the reform’s implementation time. The 2018 policy year was artificially advanced to 2016. Specifically, the *Post* dummy was set to 0 for years before 2016 and 1 for 2016 and subsequent years. A new DID interaction term was then constructed and re-estimated (Column (1) of Table 4). The DID term’s coefficient was positive but statistically insignificant within the confidence interval. This indicates that, in the absence of the reform, China’s manufacturing industry’s green development would not have improved significantly, thereby supporting the baseline regression findings.

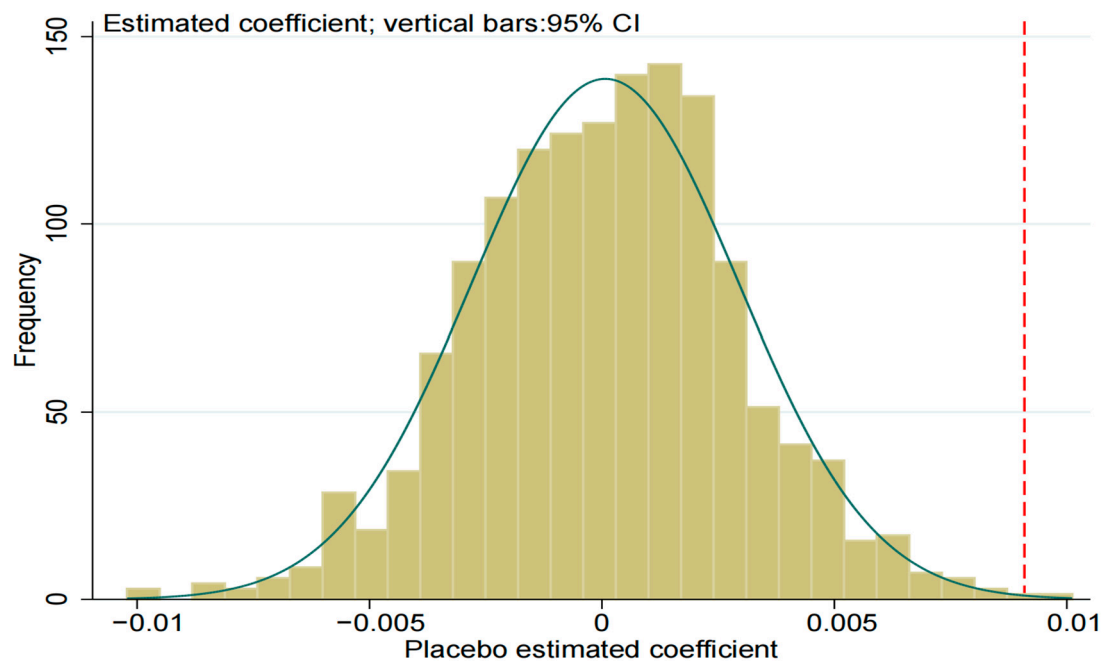


Figure 2. Placebo test coefficient distribution (1000 random repetitions). Note: X-axis: Placebo Estimated Coefficient. Y-axis: Frequency. Red dashed vertical line: True baseline estimated policy coefficient; Yellow histogram bars: Frequency distribution of 1000 simulated placebo coefficients; Green solid curve: Fitted normal distribution curve.

Table 4. Robustness tests ¹.

Variable	(1) Placebo Test	(2) Excluding Environmental Inspections	(3) Excluding Carbon Emission Trading Markets	(4)	(5)	(6)	(7)	(8)	(9) Controlling for Time-Varying Industrial Dynamics
				Excluding the COVID-19 Pandemic Shock		SBM-ML		Equal	
Did (Dummy: 0/1)	0.0064 (0.0047)	0.0081 * (0.0043)	0.0105 ** (0.0054)	0.0162 *** (0.0037)	0.0230 *** (0.0038)	0.0009 * (0.0005)	0.0031 ** (0.0015)	0.0084 ** (0.0043)	0.0104 * (0.0044)
X _{it} (controls, metrics in Table 2)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Industry * Year interactive FE
N_obs	19,686	19,686	10,677	19,686	12,584	16,650	24,302	19,686	19,686
R ²	0.1427	0.1488	0.1400	0.1456	0.1216	0.9086	0.1641	0.1663	0.1758
_cons	−0.9077 *** (0.0736)	−0.7351 *** (0.0733)	−0.4826 *** (0.1022)	−0.8316 *** (0.0725)	−0.5589 *** (0.0819)	0.8540 *** (0.0082)	0.1357 (0.0346)	−0.5779 *** (0.0748)	−0.502 *** (0.0908)

Note: ¹ Owing to space limitations, Table 4 reports only the regression results after including the control variables. Regressions for models without control variables were also conducted, all of which passed robustness tests. *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$. Robust standard errors are reported in parentheses.

The two placebo test methods rule out the interference of random factors. This further indicates that the improvement in firms' green performance is indeed driven by the environmental "fee-to-tax" reform, rather than by unobserved shocks.

4.2.3. Additional Robustness Checks

- (1) To validate our core findings, we conducted a series of complementary robustness checks. First, we excluded competing hypotheses. Environmental inspections were implemented in batches across China's regions in accordance with the Environmental Protection Inspection Plan (Trial) adopted at the 14th meeting of the Central Leading Group for Deepening Overall Reform in 2015. The interaction term between the

environmental inspection dummy and firm fixed effects was added to the regression model to control for the impact of environmental inspections on manufacturing enterprises' green development. The dummy variable was assigned a value of 1 for regions where environmental inspections were implemented in period t and 0 otherwise (The central environmental protection inspection pilot was launched in Hebei in 2015. The regions inspected in 2016 included the Inner Mongolia Autonomous Region, Heilongjiang Province, Jiangsu Province, Jiangxi Province, Henan Province, Guangxi Zhuang Autonomous Region, Yunnan Province, Ningxia Hui Autonomous Region, Beijing, Shanghai, Hubei Province, Guangdong Province, Chongqing, Shaanxi Province, and Gansu Province. The remaining regions were examined in 2017). The corresponding results are reported in Column (2) of Table 4.

- (2) To mitigate the potential interference of other concurrent policies on the green development of the manufacturing sector, the regression was re-estimated after excluding pilot regions of the carbon emissions trading market (The first batch of carbon emission trading pilots in 2011 included Beijing, Tianjin, Shanghai, Chongqing, Guangdong Province, Hubei Province, and Shenzhen. The second batch in 2016 included Sichuan and Fujian provinces. The national carbon emissions trading market was established in 2021), thereby reducing potential biases in the baseline results. The results (Column (3) of Table 4) showed that the coefficient of the core policy variable remained significantly positive. These findings indicate that neither the environmental inspection policy nor the carbon emissions trading policy had a material effect on the baseline results, thereby further supporting the robustness of the baseline model.
- (3) To rule out the interference of the COVID-19 pandemic shock on corporate green transformation, this paper further conducts two robustness tests. On the one hand, a pandemic dummy variable is introduced into the baseline model, taking the value 1 for 2020 and thereafter, and 0 otherwise. The pandemic dummy variable and its interaction term with the DID estimator are incorporated into the model. The regression results are shown in Column (4) of Table 4. The core policy coefficient remains significantly positive, showing that the overall positive policy effect remains robust after accounting for pandemic-wide macro shocks. On the other hand, we exclude observations from the pandemic period 2020 to 2022 and re-run the regression, reporting the results in Column (5) of Table 4. The core coefficient remains significantly positive in this subsample, and the model's statistical power improves accordingly. The results indicate that the coefficient remains significant in the full-sample model with the pandemic dummy variable (Column 4), providing robustness to the policy effect after directly controlling for COVID-19 shocks.
- (4) We replaced the dependent variable and re-estimated the regression model. On the one hand, green total factor productivity was calculated using the non-radial, slack-based Malmquist-Leuenberger index. The input factors primarily included the number of employees, net fixed assets, and industrial electricity consumption in the city where each enterprise was located. Desirable output was measured by corporate operating revenue, whereas undesirable outputs were measured by the proportion of corporate employees and by emissions of industrial wastewater, waste gas, and smoke dust. The regression results presented in Column (6) of Table 4 indicate that the environmental tax policy continued to significantly positively affect the green development of manufacturing enterprises, regardless of whether control variables were included, thereby supporting the baseline regression findings. In addition, we extend the sample period of this alternative dependent variable to 2024 for the robustness test. The extended panel spans a substantial number of years, both before and after the 2018 policy shock, eliminating potential perfect collinearity with the

DID interaction term. The regression results are consistent with those of the baseline regression, indicating that our core conclusions are not sensitive to adjustments in the sample period. On the other hand, we adopt the equal-weighted variable derived from sensitivity analysis as the dependent variable for robustness testing, and the corresponding results are presented in Column (8) in Table 4. That the core explanatory variable retains a significantly positive coefficient of similar magnitude to that in the baseline model further demonstrates the robustness of the empirical conclusions to alternative indicator-weighting structures.

- (5) To control for dynamic changes in industry structure and to mitigate estimation biases arising from manufacturing industry restructuring and industry policy changes during the sample period, this paper further adopts industry-year interactive fixed effects. The regression results are shown in Column (9) of Table 4. The core coefficient remains significantly positive, reinforcing the reliability of the empirical results. Controlling for industry-year fixed effects eliminates interference from structural shifts in industry and periodic sector policies, thereby strengthening the causal link between tax reform and green transformation.

4.3. Pathways to Green Transformation

4.3.1. Cost Internalization

The essence of the environmental protection tax is to internalize the negative externalities of corporate environmental pollution. Accordingly, when regional environmental protection tax rates increase, enterprises' pollution discharge costs rise correspondingly. To manage these compliance costs, some enterprises voluntarily increase their environmental investments. Accordingly, this study constructs a dummy variable, *Cost*, and groups observations based on the one-period lagged median of operating costs. The dummy variable equals 1 if the enterprise's operating costs exceed the median and 0 otherwise. The interaction term between *Cost* and the baseline policy dummy was included in the model to test the underlying mechanism. The results, presented in Column (1) of Table 5, show that the coefficient of the interaction term is significantly positive at the 1% level, indicating that the reform promotes the green development of the manufacturing sector by increasing pollution discharge costs. It proves the first transmission path of the policy. Rising pollution costs force firms to incorporate environmental governance into daily production decisions, a typical embodiment of the internalization of negative externalities in Pigouvian tax theory.

Table 5. Mechanism testing.

Variable	(1) Pollution Discharge Cost	(2) Corporate Investment	(3) Green Cognition of Executives
Did (Dummy: 0/1)	0.0185 *** (0.0051)	0.0028 * (0.0014)	0.0901 *** (0.0242)
X _{it} (controls, metrics in Table 2)	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes
N_obs	14,421	18,580	18,580
R ²	0.1135	0.1076	0.0226
_cons	−0.8161 *** (0.0994)	0.1599 *** (0.0051)	−0.2312 (0.3775)

Note: *** $p < 0.01$, and * $p < 0.1$. Robust standard errors are reported in parentheses.

4.3.2. Investment Structure Adjustment

The environmental protection tax operates on the principle of encouraging manufacturing enterprises to voluntarily restructure their internal investment toward green fixed and intangible assets, thereby driving green transformation and upgrading. The investment expenditure ratio, defined as the proportion of cash paid for the purchase of fixed, intangible, and other long-term assets to total assets, was adopted as the corporate investment

variable. The results are reported in Column (2) of Table 5. The coefficient on the policy variable was significantly positive at the 10% level, thereby confirming the mechanistic effect of corporate investment on the process by which environmental tax policy influences green development. Increased corporate investment in green fixed assets (e.g., cleaner production equipment) effectively offsets the cost pressure from the environmental protection tax through technological innovation, consistent with the “innovation compensation effect” in Porter’s hypothesis. Moreover, firms in less competitive industries are more likely to achieve such compensation through green investments, as they possess greater tax-shifting capacity and sufficient profit margins to support long-term investments. Environmental taxes guide firms in reallocating capital resources. Enterprises gradually reduce investment in high-pollution projects and increase capital input in clean production and green R&D, thereby forming a positive cycle of emission reduction and efficiency improvement.

4.3.3. Strategic Cognitive Upgrading

According to strategic cognition theory, executives’ subjective cognition is a key determinant in the formulation of corporate green strategies. Higher levels of green executive cognition are associated with improved environmental performance. This study constructs the indicator by analyzing the Management Discussion and Analysis (MD&A) sections of listed firms’ annual reports. Environmental keywords are screened across three dimensions: cognition of green competitive advantage, cognition of corporate social responsibility, and perception of external environmental pressure. We quantify the variable by calculating the natural logarithm of total keyword frequency. Full text screening criteria, complete keyword inventory, calculation steps, and detailed explanations of indicator representativeness and reliability are documented in Appendix D. Column (3) of Table 5 reports a significantly positive coefficient at the 1% level, indicating that the environmental protection tax reform promotes green development in manufacturing enterprises through corporate executives’ green cognition, thereby validating the mediating mechanism. Higher levels of green cognition among executives prompt firms to shift away from mere passive regulatory compliance and toward proactive green development strategies. Moreover, top management’s perception of policy trends directly determines the long-term development direction of enterprises.

4.4. Heterogeneity Analysis

4.4.1. Firm Heterogeneity

- (1) **Corporate Profitability.** All sample observations were grouped by firms’ operating profit margins to examine the heterogeneous effects of corporate profitability. Specifically, firms with operating profit margins above the industry-year mean were classified as high-profitability firms, whereas those below the mean were classified as low-profitability firms. Separate regressions were conducted for each group to estimate the impact of the environmental protection tax reform on green development in the manufacturing sector. The results show that, after the environmental fee-to-tax reform, low-profitability firms in regions with higher tax burdens achieved better green development performance. For these firms, higher environmental tax costs directly erode profit margins. Under substantial survival pressure, such enterprises face stronger incentives to curb pollution and reduce costs by pursuing green transformation.
- (2) **Corporate Ownership.** For the regression analysis, all sample firms were categorized as state-owned or non-state-owned based on corporate property rights. Columns (3) and (4) of Table 6 present these results. The comparison of policy-effect coefficients reveals that the reform exerted a stronger effect on the green transformation of non-state-

owned enterprises. Whereas state-owned enterprises enjoy flexible enforcement discretion and implicit policy support, non-state-owned enterprises operate under stricter budget constraints, rendering them more responsive to environmental regulation.

Table 6. Heterogeneity analysis results—firm.

Firm Level	Corporate Profitability		Corporate Ownership		Green Patent Applications	
	(1) High Profitability	(2) Low Profitability	(3) State-Owned	(4) Non-State-Owned	(5) With Patents	(6) Without Patents
Did (Dummy: 0/1)	0.0089 (0.0063)	0.0107 * (0.0060)	0.0102 (0.0092)	0.0081 * (0.0049)	0.0005 (0.0085)	0.0139 *** (0.0049)
X _{it} (controls, metrics in Table 2)	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N_obs	9843	9843	4861	14,825	6133	13,553
R ²	0.1581	0.1495	0.1515	0.1576	0.1428	0.1561
_cons	−0.6717 *** (0.0784)	−0.7085 *** (0.0849)	−0.5690 *** (0.1568)	−0.6701 *** (0.0811)	−0.9166 *** (0.0647)	−0.6526 *** (0.0795)

Note: *** $p < 0.01$, and * $p < 0.1$. Robust standard errors are reported in parentheses.

- (3) Green Patent Applications. To account for potential heterogeneity in the policy's effects on manufacturing firms with varying levels of technological innovation during the green transformation, the full sample was divided into patent and non-patent groups based on whether each firm filed green patent applications in a given year, and separate regressions were estimated for each group. A comparison of the coefficients in Columns (5) and (6) of Table 6 shows that the policy effect variable was positively associated with both groups. This indicates that the environmental protection tax policy promoted green development in the manufacturing sector, with the effect especially pronounced among non-patent firms in regions with higher tax burdens. Unable to rely on innovation-related preferential policies to offset tax pressure due to the absence of green patents, these firms are more dependent on basic green renovations to manage rising environmental costs.

4.4.2. Industry Heterogeneity

- (1) Industry Competition. The Herfindahl–Hirschman Index was employed to classify manufacturing industries into high- and low-competition groups. Industries with an index value exceeding the industry-year average were categorized as the low-competition group, whereas those with values below the average were classified as the high-competition group. A higher index value indicated lower industry competition and greater potential for tax burden shifting. The heterogeneity results are presented in Columns (1) and (2) of Table 7. The low-competition group contained relatively few firms; meanwhile, local governments may provide fiscal support or exercise flexible tax enforcement to ensure the stable operation of these firms. Additionally, firms in less-competitive industries can more easily shift the tax burden to consumers, thereby making their profit margins less sensitive to tax pressure and enabling more effective in-house green transformation.
- (2) Factor Intensity. Manufacturing industries were categorized into labor-, capital-, and technology-intensive sectors to examine the impact of environmental tax policies on green development. Columns (3)–(5) of Table 7 reveal that the reform's positive effect on green development was most pronounced in labor-intensive industries, moderately so in capital-intensive industries, and least evident in technology-intensive industries. Labor-intensive industries encounter relatively low technical barriers to green retrofitting. By optimizing production processes and raw material inputs, these industries can achieve rapid reductions in emissions; consequently, the policy's effect is more evident in the short run.

Table 7. Heterogeneity analysis results—industry.

Industry Level	Industry Competition			Factor Intensity	
	(1) High-Competition Group	(2) Low-Competition Group	(3) Labor-Intensive	(4) Capital-Intensive	(5) Technology- Intensive
Did (Dummy: 0/1)	0.0087 (0.0055)	0.0112 ** (0.0057)	0.0199 * (0.0106)	0.0092 (0.0068)	0.0083 (0.0068)
Post (Dummy: 0/1)	0.0177 *** (0.0042)	0.0242 *** (0.0045)	0.1821 *** (0.0184)	0.0857 *** (0.0264)	0.1385 *** (0.0161)
Treat (Dummy: 0/1)	−0.0131 (0.0249)	0.0011 (0.0459)	−0.0249 ** (0.0117)	−0.0208 *** (0.0080)	−0.0119 ** (0.0060)
X _{it} (controls, metrics in Table 2)	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes
N_obs	10,090	9473	3174	9202	7310
R ²	0.1526	0.1537	0.2089	0.2370	0.2933
_cons	−0.8045 *** (0.0884)	−0.6650 *** (0.1013)	−0.8731 *** (0.1265)	−0.6710 *** (0.0774)	−0.9575 *** (0.0921)

Note: *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$. Robust standard errors are reported in parentheses.

4.5. Multi-Dimensional Effects of Green Transformation

4.5.1. Long-Term Dynamic Effects

As revealed by the parallel trend test (Figure 1), the reform's positive impact on green development in the manufacturing sector exhibited a time lag. Furthermore, this study explored the moderating role of short-term policy fluctuations. The dynamic effect results presented in Table 8 indicate that the reform's impact on the green transformation of manufacturing enterprises was characterized by modest short-term fluctuations alongside a stable long-term trajectory. The baseline regression results based on the full sample demonstrate that environmental regulation policies effectively facilitated the long-term green transformation of the manufacturing sector. Nevertheless, the phased dynamic effect results indicated that the magnitude of the policy effect varied across periods.

Table 8. Multiple effects analysis.

Variable	Long-Term Dynamic Effects			Industry Pollution Attributes	Economic Consequences	
	(1) 2018–2019	(2) 2020–2022	(3) 2011–2022		(5) TFP_OP	(6) TFP_LP
	Short-Term Adaptation Stage	Medium-Term Deepening Stage	Full Sample	(4)		
Did (Dummy: 0/1)	0.0016 (−) ¹	−0.0703 (0.0768)	0.0088 ** (0.0043)			
Did * pollution (Dummy: 0/1)				0.0123 ** (0.0056)		
Did * M _{green} (index. dimensionless, range: 0–1)					0.2320 *** (0.0473)	0.1941 *** (0.0477)
X _{it} (controls, metrics in Table 2)	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N_obs	3655	7102	19,686	19,686	17,087	17,087
R ²	0.0248	0.0837	0.1488	0.1430	0.5459	0.6663
_cons	−0.9251 (−)	−1.8927 *** (0.1544)	−0.7378 *** (0.0725)	−0.8795 *** (0.0724)	−1.6861 *** (0.5628)	−3.2719 *** (0.5038)

Note: ¹ For the 2018–2019 subsample, standard errors were not fully calculated because of the short observation period and limited sample size within clusters; however, this did not affect the analysis of the conclusions in this section. *** $p < 0.01$, and ** $p < 0.05$. Robust standard errors are reported in parentheses.

As shown in Table 8, the environmental protection tax reform induced compliance adaptation with a positive short-term trend, specifically during 2018–2019. During the initial phase of policy implementation, some sample enterprises merely adopted passive

compliance measures and refrained from undertaking source-based green transformation, including research and development of green production technologies or the overhaul of production processes. Furthermore, during the initial implementation phase, enterprise compliance behaviors had not yet reached a scale effect. The interaction between modest progress in transformation and prevailing wait-and-see attitudes may have partially dampened the policy's impact, resulting in outcomes that fell short of expectations. This observation was consistent with the parallel trend plot, which showed that the coefficient at period $t + 1$ remained within the pre-policy fluctuation range. However, this insignificant short-term effect does not signify policy failure. Instead, it captures manufacturing enterprises' necessary adaptation to rigid tax constraints, establishing the foundation for their subsequent long-term transition from passive compliance to proactive green transformation. In the early implementation stage, enterprises largely adopt a wait-and-see attitude and engage in passive compliance, meaning the policy's effects have not yet fully manifested.

The phased results indicated that during the policy's medium-term stable period (2020–2022), the DID policy coefficient was insignificantly negative. Although it did not pass the significance test, this finding closely tracked the coefficient trajectory depicted in the parallel trend plot, maintaining an overall upward trend and therefore not compromising the policy's long-term effectiveness. Specifically, the tax reform exerted a short-term inhibitory effect on high-quality development in the manufacturing sector. In 2020, the COVID-19 pandemic outbreak in China led to a substantial decline in operating income for the sample manufacturing firms, forcing them to reduce nonessential expenditures. It is noteworthy that many traditional, labor-intensive enterprises delayed their green transformation efforts to maintain ongoing production and operations, leading to temporary fluctuations in the negative coefficient. Nevertheless, this observation does not invalidate the underlying logic of green transformation. This stage essentially reflected a temporary equilibrium between the tax reform's long-term positive driving force and short-term external shocks. Although the COVID-19 outbreak forced firms to cut nonessential investment, thereby temporarily restraining progress in green transformation, it did not reverse the policy's long-term positive trend.

Considering the full sample's coefficient effect for the study period (2011–2022), the DID policy coefficient was significantly positive, corroborating the core logic of the Pigouvian tax—internalizing costs to correct environmental externalities—and the innovation compensation effect proposed by the Porter hypothesis. The short-term phased results reflect the green transformation's inherent characteristics in manufacturing enterprises, namely, high investment, long cycle, and multiple constraints. The policy effect exhibited a time lag: Following an initial short-term adaptation, it steadily promoted long-term green development, thereby confirming the robustness of the baseline results. These findings also provide empirical support for the policy optimization recommendations proposed in this study.

4.5.2. Industry Pollution Attributes

Following the approach of prior studies [33,34], this study introduced industry pollution as the third dimension of differencing and adopted the triple-difference (DDD) method to enhance analytical accuracy. Following Deschênes et al. [35], the baseline model was specified as follows:

$$M_green_{i,t} = \gamma_0 + \gamma_1 Treat_{i,t} \times Post_{i,t} \times Pollution_{i,t} + \sum Controls_{i,t} + \delta_j + \delta_t + \delta_s + \varepsilon_{i,t} \quad (3)$$

where $Pollution_{i,t}$ is an industry pollution attribute variable that takes the value of 1 if the manufacturing industry is a heavy-pollution industry (Industry pollution characteristics are

determined according to the List of Heavy Pollution Industries issued by the former State Environmental Protection Administration in the “Circular on Environmental Protection Verification for Enterprises Applying for Listing and Listed Companies Applying for Refinancing” (Huanfa [2003] No. 101) and relevant provisions on heavy pollution industries in the “Circular on Further Regulating Environmental Protection Verification for Heavy Pollution Industry Companies Applying for Listing or Refinancing” (Huanban [2007] No. 105)), and 0 otherwise; γ_1 is the coefficient of the core explanatory variable, which primarily identifies the differential effects of the fee-to-tax reform on the green transformation of manufacturing firms—both between regions that experienced tax rate increases and those that did not, and between heavy-pollution industries and clean industries. The definitions of the other variables are the same as those described above. As presented in Column (4) of Table 8, the triple-difference coefficient is 0.0123 and significantly positive at the 1% level, suggesting that the tax reform significantly incentivized green transformation for highly polluting enterprises in regions with raised taxable pollutant levy standards. Heavily polluting enterprises bear higher marginal emission costs. An environmental tax exerts a stronger binding force on them, so the incentive effect of green transformation is more pronounced.

4.5.3. Economic Consequence Tests

Total factor productivity is an important indicator for enterprises to allocate resources and improve production efficiency [36]. To explore whether the reform had a positive impact on the corporate economy and to avoid selection bias arising from sample continuity issues, this study adopted a change model [37]. It further employed both the Olley-Pakes and Levinsohn-Petrin methods to calculate enterprises’ total factor productivity, thereby measuring the level of corporate economic development. The formula used is presented below:

$$TFP_{i,t} = \gamma_0 + \gamma_1 Treat_{i,t} \times Post_{i,t} \times M_{green_{i,t}} + \sum Controls_{i,t} + \delta_j + \delta_t + \delta_s + \varepsilon_{i,t} \quad (4)$$

where $TFP_{i,t}$ represents the economic consequences for enterprises measured by the total factor productivity indicator. The definitions of the other variables are the same as those described above. As shown in Column (6) of Table 8, whether measured by the Olley-Pakes method or the Levinsohn-Petrin method, the coefficient of the interaction term $Treat_{i,t} \times Post_{i,t} \times M_{green_{i,t}}$ was significantly positive at the 1% level, indicating that the fee-to-tax reform’s driving effect on manufacturing enterprises’ green transformation was also conducive to improving their economic performance. Driven by environmental regulation, green transformation ultimately delivers simultaneous gains in environmental and economic benefits, fully reflecting the innovation compensation effect of the Porter hypothesis.

5. Discussion

5.1. Main Findings and Underlying Causes

According to the main effects test, higher tax rates increase compliance costs and internalize corporate environmental externalities. The mandatory nature of taxation forces polluting enterprises to bear the costs of environmental governance. Second, unified collection standards foster fair competition and eliminate implicit fee cuts and rent-seeking behaviors. Third, the environmental tax’s emission-reduction mandates and resource-use incentives directly reduce firms’ operating costs and enhance efficiency, thereby motivating enterprises to move beyond passive compliance and embrace proactive green transformation. This finding differs from the conclusions of some scholars [38] but is supported by

most studies [15]. This discrepancy can be attributed to differences in variable selection and sample periods across the literature.

The environmental tax internalizes the negative externalities of corporate pollution. It raises emissions costs and compliance pressures, and motivates firms to expand environmental investment in green transformation. Moreover, the core tax rule guides enterprises to adjust their investment structure. Firms allocate more funds to clean facilities and green R&D. They use the innovation compensation effect to offset additional environmental costs. In addition, strict policy signals strengthen executives' green strategic thinking, prompting enterprises to shift from passive compliance to proactive green strategies, thereby enabling a systematic green transformation.

Tax hikes put survival pressure on low-profit firms and impose stricter green requirements. Such enterprises mainly rely on end-of-pipe treatment rather than source control, enabling them to respond to regulations efficiently. Enterprises without green patents cannot enjoy relevant preferential policies, making them more sensitive to rising tax burdens. Restricted by their prevailing production modes and technological capabilities, labor-intensive industries depend heavily on end-of-pipe pollution control, which enables them to achieve rapid short-run emission reductions.

The policy is characterized by a clear time lag: enterprises tend to go through an initial adaptation period, after which the long-term driving force for green transformation gradually stabilizes. The policy plays a more prominent role in promoting upgrades by heavily polluting enterprises and also helps improve overall corporate economic performance.

5.2. Critical Comparison with International Research

The paper's findings align with mainstream international research. Globally, environmental taxes internalize pollution externalities and drive corporate green upgrading. Policy effects typically show time lags. Heavily polluting firms are more responsive to tax changes—a common feature of green transformation worldwide. There are notable discrepancies between China's research conclusions and those of developed Western economies.

Empirical studies of developed European countries reveal that environmental taxes generally restrain economic growth, and the adverse impacts are more pronounced in low-income regions with fragile economic foundations [39]. Meanwhile, environmental taxes yield the greatest benefits for technology-intensive industries, which contrasts with the findings of this study [40]. This divergence stems from differences in industrial structures and corporate profit characteristics between China and Western economies. Furthermore, this paper explores the mediating role of executives' green cognition, a perspective rarely adopted in Western literature. This distinctive feature reflects China's unique policy transmission mechanism. All the above evidence suggests that the effectiveness of environmental taxes is highly contingent on a country's stage of development and industrial structure, implying that a one-size-fits-all tax regime is not applicable across all economies.

Compared with those of typical developing countries such as Brazil and South Africa, China's environmental tax policy yields more stable outcomes. In these countries, inadequate law enforcement and fragmented regulatory systems greatly weaken policy implementation. As typical research subjects in this field, transition economies, such as Ukraine, also attract considerable attention. Relevant studies confirm that environmental taxes exert a U-shaped effect on the competitiveness of local pollution-intensive industries. In the short term, they raise operating costs and weaken industrial performance; in the long term, however, green technological upgrading progressively enhances competitiveness [41]. Under fiscal pressure and imperfect regulation, such economies experience slower policy responses. By contrast, China has put in place robust supporting mechanisms, and all proceeds from environmental taxes are specifically allocated to ecological governance. Such

an arrangement fosters a virtuous cycle and underpins the policy's sustained effectiveness. The view that environmental tax reform should be tailored to national conditions also supports our judgment that extrapolating research findings is limited.

6. Conclusions and Limitations

A total of 19,686 firm-year observations from 3086 manufacturing enterprises listed on China's Shanghai and Shenzhen A-shares for 2011–2022 were selected as the research sample. Using the DID model, we find that the core policy coefficient is 0.0088 ($p < 0.05$). Using the 2018 environmental fee-to-tax reform as a policy intervention, this study examines its effects on the green transformation and upgrading of Chinese manufacturing enterprises.

6.1. Practical Contributions

This study proposes various policy recommendations, offering practical guidance to the central government, local authorities, and enterprises.

6.1.1. Optimize the Environmental Tax Framework

To strengthen regulatory constraints on heavily polluting industries, the central government could gradually expand the list of taxable pollutants and implement tiered tax rates for highly toxic and refractory pollutants. For local governments, comprehensive deployment of big data- and IoT-based intelligent monitoring systems across polluting enterprises is required. Additionally, a standardized, end-to-end traceability system should be established to cover the generation, storage, transfer, and disposal of pollutants. These measures aim to ensure the authenticity and reliability of emission data. Meanwhile, regular green development seminars and training programs should be held for corporate executives to eliminate their biased perceptions of environmental costs.

6.1.2. Refine Differentiated Tax Relief Mechanisms

A progressive tax reduction mechanism linked to pollutant emission intensity should be implemented, drawing on the seven-tier progressive structure of personal income tax: enterprises with lower pollutant emissions per unit of output can enjoy a higher proportion of tax relief. Meanwhile, special financial subsidies and investment tax credits are encouraged for firms investing in green R&D and clean production equipment. This set of policies can fully exert the innovation compensation effect and push enterprises to shift from end-of-pipe treatment to source-based control.

6.1.3. Heterogeneous Regulatory Policies

Policy design must fully account for differences in profitability, patent endowments, and industrial attributes to improve regulatory accuracy. For low-profit manufacturing firms and enterprises without green innovation patents, launch exclusive support packages that include low-interest green loans and free technical transformation guidance. For labor-intensive industries, prioritize policy resources to support upgrades to end-of-pipe pollution control equipment. For technology-intensive industries, additional R&D bonus incentives should be provided to stimulate innovation in original green technologies and facilitate industrial transformation. Furthermore, local tax collection standards should be publicly available to ensure consistent enforcement and prevent arbitrary levies.

6.2. Limitations and Future Research

6.2.1. Extrapolation Limitations of Research Results

This study is carried out against the backdrop of China's unique institutional background, as reflected in unified national environmental tax legislation, a hierarchical envi-

ronmental supervision system, and a mixed-ownership enterprise structure. Accordingly, the conclusions of this paper have certain limitations when extended to other countries.

First, in developed economies with relatively mature market-based economic systems, environmental taxes primarily guide technology-intensive industries to accelerate the adoption of green technologies, unlike the situation in China. Second, for developing countries and transition economies such as Ukraine, weak environmental law enforcement and limited fiscal capacity may greatly reduce the policy effectiveness of environmental taxes, making China's policy experience difficult to transplant directly. Third, the conclusions of this paper are more applicable to economies dominated by manufacturing industries with strong government supervision capacity and gradually adjusted tax rates.

In general, the policy effectiveness of environmental taxes is constrained by a country's institutional environment, fiscal conditions and industrial characteristics. China's policy practice is not a universal solution, and the relevant research conclusions are mainly applicable to countries with a high manufacturing share and a robust regulatory system.

6.2.2. Future Research

This study had some limitations. First, it did not examine the effects of recent policies. Since the 2018 tax reform, several events have had significant impacts across industries worldwide. These include the COVID-19 pandemic and international economic conditions, which have also made recent data difficult to obtain. Moreover, the economic downturn complicated the accurate assessment of policy effects using available data. Meanwhile, mainstream databases and official statistical yearbooks have not fully released complete data for the last three years due to the inherent publication lag. Therefore, this study focused on 2011–2022. This study employs two approaches—incorporating a pandemic dummy variable and omitting the 2020–2022 sample period—to control for the influence of COVID-19. The choice of data period does not alter the conclusions. The current study's sample was limited to listed companies; accordingly, some heavily polluting small and medium-sized enterprises were excluded. Supervising such unlisted enterprises is more challenging for the government, which may partially limit the generalizability of the present study's findings.

Future research could address these limitations as follows: First, future studies could expand the sample size and extend the research period to re-examine this study's conclusions through empirical analysis. Second, future studies should incorporate more unlisted enterprises if the government implements stricter requirements for corporate environmental performance disclosure.

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Environmental Statistical Yearbook, and other official government statistical publications. All data used in this study are publicly accessible through the abovementioned official channels, with no restrictions on academic research use.

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Abbreviations

Abbreviations	Full name
DID	Difference-in-Differences
R&D	research and development
CSMAR	China Stock Market & Accounting Research
CI	Confidence Interval
DDD	Triple Differences
TFP	Total Factor Productivity
OP	Olley-Pakes
LP	Levinsohn-Petrin
SBM	Slacks-Based Measure
ML	Malmquist-Leuenberger
ROE	Return on Net Assets
ESG	Environmental, Social, and Governance
CEO	Chief Executive Officer
Lev	Asset-Liability Ratio
ST	Special Treatment

Appendix A. Mathematical Model: Formal Derivation Under the Baseline Effect

To quantify the baseline effect of the environmental protection tax on corporate green transformation and to reflect the high, realistic correlation between production and pollution in highly polluting manufacturing, this study incorporated pollution emissions into the Cobb–Douglas production function. Specifically, the production function of the manufacturing firms is presented in the following equation:

$$Y = AK^{\alpha}L^{\beta}E^{\gamma} \quad (\text{A1})$$

where Y denotes the firm's output; A denotes the firm's technology level; K denotes capital input; L denotes labor input; and E denotes pollution emissions. Furthermore, α , β , and γ represent the output elasticities of capital, labor, and pollution emissions, respectively, with their sum equal to 1, implying constant returns to scale in the firm's production function.

Given an environmental tax rate t , the environmental tax burden borne by manufacturing enterprises is $t * E$. Assuming that the product market price is p , the price of capital is r , and the price of labor is w , the profit function can be defined as follows:

$$\Pi = pAK^{\alpha}L^{\beta}E^{\gamma} - rK - wL - tE \quad (\text{A2})$$

As firms aim to maximize profits, taking the partial derivative with respect to pollution emissions E and setting it to zero yields the equilibrium condition:

$$\frac{\partial \Pi}{\partial E} = p\gamma AK^{\alpha}L^{\beta}E^{\gamma-1} - t = 0 \quad (\text{A3})$$

Rearranging Equation (A3) yields the optimal pollution emission level for manufacturing firms under equilibrium conditions, where the marginal revenue from pollution emissions equals the marginal cost:

$$E^* = \left(\frac{p\gamma AK^\alpha L^\beta}{t} \right)^{\frac{1}{1-\gamma}} \quad (\text{A4})$$

According to Equation (A4), the environmental protection tax rate t is negatively correlated with E^* . An increase in the tax rate reduces the optimal level of emissions from manufacturing enterprises.

To further examine the effect of corporate green transformation, pollution emission intensity—defined as the ratio of optimal pollution emissions to output—was used as a measure. A decline in pollution-emission intensity indicates an improvement in the manufacturing industry's level of green development. Substituting Equation (A4) into Equation (A1) and simplifying it yielded the pollution emission intensity:

$$\frac{E^*}{Y^*} = \frac{1}{AK^\alpha L^\beta} \left(\frac{p\gamma AK^\alpha L^\beta}{t} \right)^{\frac{1}{1-\gamma}} \quad (\text{A5})$$

As Equation (A5) shows, when the environmental protection tax rate t increases, the pollution emission intensity ratio decreases. This implies that environmental fee-to-tax reform can not only reduce manufacturing enterprises' pollution emissions but also lower their pollution intensity per unit of output, thereby promoting green transformation.

To more clearly analyze the relationship between the environmental protection tax rate t and pollution emission intensity, this study presents graphical trends for both variables.

As shown in Figure A1, when only pollution emissions are considered (i.e., capital and labor inputs are held constant), an increase in the environmental tax rate from t_1 to t_2 reduces pollution emissions from E_1 to E_2 , and the corresponding output from the production function Y falls from Y_1 to Y_2 . Because the sum of the factor elasticities α , β , and γ in the production function equals 1, the change in pollution emissions E is greater than the change in output Y . Thus, the pollution emission intensity satisfies $\frac{E_1}{Y_1} > \frac{E_2}{Y_2}$. This indicates that a higher environmental tax rate reduces pollution intensity and improves green development, consistent with the theoretical baseline results.

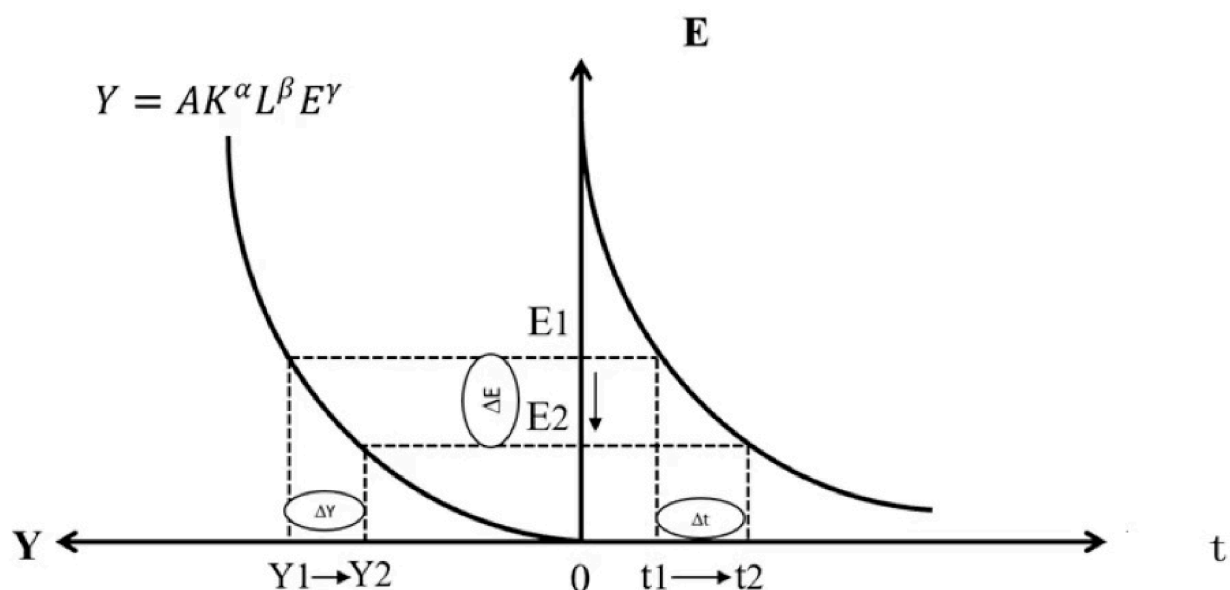


Figure A1. Theoretical model of environmental protection tax and green transformation.

Appendix B. Differentiated Environmental Tax Burden Rules and Regional Sample Classification

Table A1. Environmental tax burden standards and sample grouping by province and municipality.

Group	Type	Region	Tax Burden Standard	
			Pollution Equivalent of Air Pollutants (Yuan)	Pollution Equivalent of Water Pollutants (Yuan)
Control Group	Tax Burden Neutrality (Type 1)	Hubei	SO ₂ and NO _x at 2.4 yuan; other air pollutants at 1.2 yuan	COD, ammonia nitrogen, total phosphorus, and five heavy metals at 2.8 yuan; other water pollutants at 1.4 yuan
		Zhejiang	Four heavy metal pollutants at 1.8 yuan, other pollutants at 1.2 yuan	Five heavy metal pollutants at 1.8 yuan, other pollutants at 1.4 yuan
		Fujian	1.2 yuan	five heavy metals, COD, and ammonia nitrogen at 1.5 yuan, and other pollutants at 1.4 yuan
		Jilin, Anhui, Jiangxi, Shaanxi, Gansu, Xinjiang, Xizang, Ningxia, Qinghai, Inner Mongolia, Heilongjiang	1.2 yuan	1.4 yuan
	Tax Burden Neutrality (Type 2)	Yunnan	1.2 yuan in 2018; 2.8 yuan from 2019 onwards	1.4 yuan in 2018; 3.5 yuan from 2019 onwards
		Liaoning	SO ₂ and NO _x at 2.4 yuan; other air pollutants at 1.2 yuan	COD and ammonia nitrogen at 2.8 yuan; other water pollutants at 1.4 yuan
	Tax Burden Neutrality (Type 3)	Tianjin	NO _x at 8 yuan; SO ₂ , smoke dust and general dust at 6 yuan; other air pollutants at 1.2 yuan	COD and ammonia nitrogen at 7.5 yuan; other water pollutants at 1.4 yuan
		Shanghai	In 2018: SO ₂ at 6.65 yuan, NO _x at 7.6 yuan, other air pollutants at 1.2 yuan; In 2019: SO ₂ at 7.6 yuan, NO _x at 8.55 yuan, other air pollutants at 1.2 yuan	COD at 5 yuan, ammonia nitrogen at 4.8 yuan, and other water pollutants at 1.4 yuan
		Guangdong	1.8 yuan	2.8 yuan
Treatment Group	Increased Tax Burden (Type 1)	Hebei	Graded by region: Tier 1: Key pollutants at 9.6 yuan, other pollutants at 4.8 yuan; Tier 2: Key pollutants at 6 yuan, other pollutants at 4.8 yuan; Tier 3: 4.8 yuan	Graded by region: Tier 1: Key pollutants at 11.2 yuan, other pollutants at 5.6 yuan; Tier 2: Key pollutants at 7 yuan, other pollutants at 5.6 yuan; Tier 3: 5.6 yuan
		Jiangsu	Nanjing: 8.4 yuan; Wuxi, Changzhou, Suzhou, Zhenjiang: 6 yuan; other cities: 4.8 yuan	Nanjing: 8.4 yuan; Wuxi, Changzhou, Suzhou, Zhenjiang: 7 yuan; other cities: 5.6 yuan
		Shandong	SO ₂ and NO _x at 6 yuan, other air pollutants at 1.2 yuan	COD, ammonia nitrogen, and five heavy metals at 3 yuan, other water pollutants at 1.4 yuan
	Increased Tax Burden (Type 2)	Henan, Hunan	4.8 yuan	5.6 yuan
		Sichuan	3.9 yuan	2.8 yuan
		Chongqing	3.5 yuan	3 yuan
		Guizhou, Hainan	2.4 yuan	2.8 yuan
		Guangxi	1.8 yuan	2.8 yuan
		Shanxi	1.8 yuan	2.1 yuan
	Increased Tax Burden (Type 3)	Beijing	12 yuan	12 yuan

Appendix C. Variable Definitions and Variable Calculation

Appendix C.1. Variable Definitions

Table A2. Variable definitions.

Variable Name	Symbol	Definition	
Green Transformation	M_green	Economic Performance	Return on Net Assets (ROE) of the Firm
		Social Performance	Mean ESG Score of the Firm
		Green Production	Implementation of Cleaner Production by the Firm
		Green Emission	Disclosure of Wastewater, Waste Gas, and Solid Waste
		Green Governance	Treatment of Wastewater, Waste Gas, and Solid Waste
		Green Management	Environmental Information, Environmental Management System, Environmental Emergency Mechanism, “Three Simultaneities” System, etc., are disclosed in the annual reports of listed firms
		Green Culture	Corporate Environmental Philosophy, Environmental Guidelines, and Green Development Orientation
Policy Dummy Variable	Post	Taking 2018 as the cutoff year: 0 for years before 2018, 1 for 2018 and thereafter	
Firm Dummy Variable	Treat	Treated group with increased tax burden = 1; control group with unchanged tax burden = 0	
Firm Size	Size	Natural logarithm of total assets	
Firm Age	Age	Natural logarithm of (statistical year minus firm establishment year plus 1)	
Financial Leverage	Lev	Asset-liability ratio	
CEO Duality	Dual	Dummy variable: 1 if the chairman and CEO are the same person, 0 otherwise	
Ownership Type	Central	Dummy variable: 1 for state-owned enterprises, 0 otherwise	

Appendix C.2. Detailed Calculation of the Green Transformation Composite Index

1. Normalize the data to eliminate dimensional effects

This study primarily uses the min–max normalization method. Suppose there are n samples and m evaluation indicators. Let X_{ij} denote each element in the raw data matrix $X_{n \times m}$, X_{min} refers to the minimum value of the j -th indicator, X_{max} denotes the maximum value of the j -th indicator, Z_{ij} represents an element in the normalized matrix, and $Z_{n \times m}$ stands for the full normalized matrix.

When X_{ij} is a positive indicator:

$$Z_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}} \quad (A6)$$

When X_{ij} is a negative indicator:

$$Z_{ij} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}} \quad (A7)$$

Among the seven sub-indicators, the green emissions indicator is the only negative one, while the other six are positive.

2. Stepwise Entropy Weight Calculation

(1) Calculate the proportion of each standardized indicator

$$P_{ij} = \frac{Z_{ij}}{\sum_{i=1}^n Z_{ij}} \quad (A8)$$

(2) Compute information entropy for indicator j

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^n P_{ij} \ln(P_{ij}) \quad (A9)$$

- (3) Calculate the differentiation coefficient

$$d_j = 1 - e_j \quad (\text{A10})$$

- (4) Derive the normalized weight for each sub-indicator

$$W_j = \frac{d_j}{\sum_{j=1}^m d_j} \quad (\text{A11})$$

- (5) Final composite index synthesis

$$M_{\text{green}}_{i,t} = \sum_{j=1}^m Z_{ij} W_j \quad (\text{A12})$$

The detailed entropy values, differentiation coefficients, and final weights for each sub-indicator are presented in Table A3.

Table A3. Calculated Weights of Sub-indicators via the Entropy Weight Method.

Variable	Definition	Indicator Attribute	e_j	d_j	W_j
Economic Performance	Return on Net Assets (ROE) of the Firm	Positive	0.9744136	0.0255864	0.0507116
Social Performance	Mean ESG Score of the Firm	Positive	0.9906396	0.0093604	0.0185522
Green Production	Implementation of Cleaner Production by the Firm	Positive	0.8497077	0.1502923	0.2978757
Green Emission	Disclosure of Wastewater, Waste Gas, and Solid Waste	Negative	0.9184679	0.0815321	0.1615947
Green Governance	Treatment of Wastewater, Waste Gas, and Solid Waste	Positive	0.9300403	0.0699597	0.1386584
Green Management	Environmental Information, Environmental Management System, Environmental Emergency Mechanism, “Three Simultaneities” System, etc., are disclosed in the annual reports of listed firms	Positive	0.9260854	0.0739146	0.1464971
Green Culture	Corporate Environmental Philosophy, Environmental Guidelines, and Green Development Orientation	Positive	0.9060985	0.0939015	0.1861104

Appendix C.3. Sensitivity Test with Equal-Weight Scheme

This study adopts an equal-weight strategy as an alternative weighting scheme to assess the sensitivity of index outcomes to changes in the weighting structure. Each standardized sub-indicator is assigned an equal weight of 1/7, and the calculation is shown in Equation (A13). Table A4 reports a high Pearson correlation of 0.9556 between the two indices, indicating strong consistency in firm-level green transformation rankings across weighting approaches, thereby validating the sensitivity test.

$$M_{\text{green}}_{\text{equal},i,t} = \frac{1}{7} (Z_{\text{Economic Performance}} + Z_{\text{Social Performance}} + Z_{\text{Green Production}} + Z_{\text{Green Emission}} + Z_{\text{Green Governance}} + Z_{\text{Green Management}} + Z_{\text{Green Culture}}) \quad (\text{A13})$$

Table A4. Correlation Between Entropy-Weighted and Equal-Weighted Index.

Index	M_Green	M_Green _{Equal}
M_green	1.0000	-
M_green _{equal}	0.9556	1.0000

Note: N = 19,686

Appendix D. Measurement of Executive Green Cognition

Appendix D.1. Text Source and Screening Criteria

Texts are extracted from the Management Discussion and Analysis (MD&A) sections of annual reports of A-share manufacturing-listed companies from 2011 to 2022. Screening rules:

1. Exclude ST, *ST, delisted, and operationally abnormal enterprises.
2. Remove annual reports that have incomplete, garbled, or blank MD&A content.
3. Only retain full official Chinese annual reports disclosed by stock exchanges.

Appendix D.2. Three-Dimensional Keyword Dictionary

1. Green competitive advantage cognition

Environmental protection strategy, environmental technology development, energy conservation and environmental protection, low-carbon environmental protection, green development, energy saving and emission reduction.

2. Corporate social responsibility cognition

Environmental protection philosophy, environmental education, environmental training, environmental governance, environmental audit, environmental protection work, environmental protection awareness.

3. External environmental pressure perception

Environmental management mechanism, environmental protection policies, environmental protection departments, environmental supervision and inspection, environmental protection laws and regulations.

Appendix D.3. Index Calculation Steps

1. Use the Python Jieba tool (version 0.42.1) to perform word segmentation and stop-word filtering on MD&A texts.
2. Sum the occurrence frequency of all keywords across three dimensions for each firm-year.
3. Take the natural logarithm of total word frequency to obtain the final green cognition proxy and eliminate heteroscedasticity.

This text-based measurement method is widely adopted in existing studies of management and environmental economics, further underscoring its basic representativeness.

Appendix D.4. Representativeness & Reliability Verification

To further validate the representativeness and reliability of the green cognition indicator measured through textual analysis, this study employs corporate environmental investment intensity as an external criterion to assess criterion validity. The environmental investment data are manually compiled from the annual report notes of listed manufacturing firms. Specifically, this study aggregates two categories of environmental expenditures: first, capitalized environmental expenditures disclosed under the construction-in-progress account, including investments in wastewater and waste gas treatment, energy-saving

and environmental protection facilities, desulfurization and denitrification equipment, solid waste disposal, waste heat recovery, and environmental monitoring systems; and second, expensed environmental expenditures recorded under period expenses, including sewage fees and greening costs. To eliminate the confounding effect of firm size, we scale the total environmental investment by year-end total assets to obtain environmental investment intensity.

We regress environmental investment intensity on the green cognition indicator as the core explanatory variable, while controlling for year fixed effects, industry fixed effects, firm fixed effects, and firm-level characteristics, including firm size, leverage ratio, firm age, CEO duality, and ownership type. The regression results are presented in Table A5, which shows that the coefficient for green cognition is significantly negative at the 1% level.

This result draws three key implications. First, executive green cognition and corporate environmental investment are two different constructs: improved strategic awareness does not translate into immediate capital spending. Second, there exists a clear cognition-behavior gap among Chinese manufacturers. Firms with stronger green cognition prefer low-capital approaches, such as process optimization and management improvements, shifting from end-of-pipe treatment to source prevention. Third, cognitive influence has an obvious time lag. Current environmental investment is mainly a passive response to short-term regulation, while green cognition takes effect gradually through long-term strategies and resource allocation.

In summary, the negative correlation between the two does not invalidate the construct validity of the text-based green cognition indicator. On the contrary, this result further demonstrates that, in the context of green transformation in China's manufacturing sector, the transmission mechanism from cognition to action is inherently complex, and that executive green cognition primarily operates by adjusting firms' strategic orientation rather than by directly affecting contemporaneous capital expenditures.

Table A5. List of Abbreviations.

Variable	Environmental Investment
Did (Dummy: 0/1)	−0.0006 *** (0.0002)
Xit (controls, metrics in Table 2)	Yes
Fixed effects	Yes
N_obs	18,580
R ²	0.0130
_cons	−0.0098 (0.0085)

Note: *** $p < 0.01$. Robust standard errors are reported in parentheses.

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