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How Do Green Finance Reform And Innovation Pilot Zones Promote Pollution-Control Investment? : Evidence from Chinese Provinces

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Abstract: This paper examines whether and how green finance reform and innovation pilot zones increase the implementation intensity of regional pollution-control investment under China's carbon peaking and carbon neutrality (dual-carbon) goals, based on panel data for 30 Chinese provincial-level regions from 2012 to 2024, treating the 2017 establishment of these pilot zones as a quasi-natural experiment and constructing a difference-in-differences model for causal identification. The study finds that green finance pilots significantly increase pollution-control investment intensity, with improving the financing environment and stimulating technological innovation serving as the main mechanisms. The effect is more pronounced in regions with lower digital finance development, weaker innovation foundations, heavier industrial pollution, and lower economic development. The study indicates that green finance is a viable strategy for converting environmental governance requirements into actual investment behavior. It also represents a practical approach to advancing high-quality economic development and ecological governance jointly.

Keywords: green finance; pollution-control investment; financing constraints; green technological innovation; difference-in-differences

1. Introduction

China is one of the economies that has advanced relatively rapidly in building a green finance system, while also facing deep pressures in the green transformation of its development model. In recent years, China has made remarkable progress in ecological civilization construction and environmental protection, but green transformation is long-term, systemic, and structural, and its policy effects are often difficult to observe fully in the short run (Yang, 2013; Fan et al., 2019; Li et al., 2024). In the context of the coordinated advancement of the "dual-carbon" goals and high-quality development, whether environmental governance policies can achieve substantive results depends not only on the intensity of environmental constraints themselves, but also on whether these constraints can be further transformed into sustained governance investment and implementation capacity. For local governments and enterprises, whether environmental pressure can be translated into equipment upgrading, end-of-pipe treatment, cleaner production, and environmental infrastructure construction is usually first reflected in the scale and implementation intensity of pollution-control investment, and not necessarily immediately in final environmental performance indicators. Therefore, pollution-control investment is not only an important intermediate variable for observing the implementation effects of environmental governance policies, but also a key entry point for understanding how green transformation policies are converted from external constraints into actual governance capacity.

At the same time, structural financial reforms represented by green finance provide new institutional instruments for addressing the transformation problem from "environmental constraints" to "governance implementation." Through arrangements such as green credit, green bonds, green funds, green insurance, and environmental information disclosure, green finance incorporates the environmental attributes of projects into the allocation of financial resources and guides capital from high-pollution and high-energy-consumption sectors toward green retrofitting, cleaner production, and pollution-control activities. Existing studies show that green finance can alleviate corporate financing constraints and provide financial support for environmental investment and green technology R&D (Su and Lian, 2018; Yu et al., 2021; Fan et al.,

2021; Wang et al., 2022). However, the policy effects of green finance are not inherently uniform. Some studies point out that financing penalties and investment-suppression effects may weaken firms' environmental governance capacity and even induce a "green paradox" or greenwashing behavior (Nan and Wen, 2019; Yin et al., 2022; Zhao et al., 2026). Therefore, whether green finance can promote the transformation of pollution-control investment from policy requirements into actual implementation remains an empirical question that requires further examination.

In June 2017, China's State Council approved the establishment of green finance reform and innovation pilot zones in selected areas of Zhejiang, Jiangxi, Guangdong, Guizhou, and Xinjiang. The pilot regions were required to conduct institutional exploration in green credit, green bonds, green funds, green insurance, environmental information disclosure, and related fields, and to promote the integration of financial support with industrial green transformation. This policy institutionalizes the capital-allocation logic of green finance. It is not only an important component of China's supply-side structural reform in finance, but also provides a quasi-natural experiment for identifying the impact of green finance on the implementation intensity of pollution-control investment. Unlike the general level of green finance development, green finance reform and innovation pilot zones have a clear policy starting point, institutional boundaries, and regional variation, and therefore provide a relatively clear identification setting for examining whether green finance policies effectively promote the implementation of governance investment.

The existing literature has developed rich discussions on the micro-level effects of environmental policies and the policy effects of green finance. In the field of environmental regulation, scholars have focused on the emission-reduction effects of policy instruments such as low-carbon city pilots, emissions trading, and carbon emissions trading, and generally find that these policies can generate pollution-control and carbon-reduction benefits (Du et al., 2021; Huang et al., 2022; Zeng et al., 2023). In the field of green finance, related studies mainly examine the effects of green finance pilots on outcome variables such as corporate green innovation, debt financing costs, regional green innovation, and low-carbon energy transition (Shi et al., 2022; Zhang et

al., 2022; Liu and Wang, 2023; Cheng and Zhu, 2024; Zhang et al., 2024). These studies lay an important foundation for understanding the policy effects of green finance, but two aspects still require further extension. First, existing studies pay more attention to whether green finance produces higher levels of green output or environmental performance, while paying less attention to the implementation intensity of pollution-control investment as a research object; as a result, they have difficulty answering whether green finance truly promotes the implementation of governance projects and governance capital expenditure. Second, existing studies usually discuss financing improvement and innovation incentives separately, rarely placing the two in a unified framework; thus, explanations remain insufficient regarding how green finance transforms external policy requirements into observable governance investment through the mutual connection between capital supply and technological response.

Based on this, this paper takes the establishment of green finance reform and innovation pilot zones in 2017 as a quasi-natural experiment, uses panel data for 30 provincial-level regions in China from 2012 to 2024, and constructs a two-way fixed-effects difference-in-differences model to systematically test the impact of green finance pilots on the implementation intensity of pollution-control investment. The findings are as follows. First, green finance pilots significantly increase the implementation intensity of regional pollution-control investment, and this conclusion remains valid after parallel-trends tests, placebo tests, and a series of robustness checks. Second, mechanism tests show that green finance pilots operate mainly through two mutually connected pathways, namely improving the financing environment and stimulating technological innovation, thereby promoting the transformation of pollution-control investment from policy pressure into actual implementation. Third, heterogeneity analysis shows that the promotion effect of green finance pilots is more prominent in regions with weaker digital finance foundations, lower innovation foundations, heavier industrial pollution burdens, and lower levels of economic development, indicating that green finance has a more pronounced marginal effect in regions with stronger resource constraints and governance pressure.

The possible marginal contributions of this paper are reflected mainly in the following three aspects. First, this paper extends research on the policy effects of green finance from the perspective of the implementation intensity of pollution-control investment. Existing studies mostly evaluate the effects of green finance pilots from outcome variables such as green innovation, debt financing costs, environmental protection investment, and energy transition (Shi et al., 2022; Zhang et al., 2022; Liu and Wang, 2023; Cheng and Zhu, 2024), while paying insufficient attention to the intermediate link of whether environmental constraints can be translated into actual governance capital expenditure. By incorporating the implementation intensity of pollution-control investment into the analytical framework, this paper helps reveal how green finance promotes the movement of environmental governance from policy requirements toward actual investment. Second, this paper characterizes the mechanism through which green finance pilots affect pollution-control investment from the perspective of the mutual connection between improvement in the financing environment and technological innovation response. Unlike existing studies that discuss financing improvement and technological innovation separately, this paper emphasizes that green finance not only increases the availability of funds for governance projects by alleviating financing constraints, but also strengthens firms' governance capacity by incentivizing green technological innovation, thereby providing new empirical evidence for understanding the composite transmission mechanism of green finance. Third, this paper further identifies the boundaries of the effect of green finance pilots on the implementation intensity of pollution-control investment. Through regional heterogeneity analysis, this paper finds that the policy effect is more significant in regions with weaker digital finance foundations, lower innovation foundations, heavier industrial pollution burdens, and lower levels of economic development. This not only helps deepen the understanding of the differentiated impacts of green finance policies, but also provides policy implications for promoting the coordinated development of green finance and pollution-control investment in accordance with local conditions.

The remainder of this paper is organized as follows. Section II reviews the related literature and proposes the research hypotheses; Section III introduces the model specification and data; Section IV reports the baseline regression results; Sections V and VI discuss the transmission channels and heterogeneity evidence; and Section VII presents the conclusions, policy implications, and limitations.

2. Theoretical analysis and research hypotheses

(1) Green Finance, Improvement in the Financing Environment, and Implementation of Pollution-Control Investment

The insufficient supply of pollution-control investment does not arise from a single market failure, but from the joint effect of environmental externalities and financing constraints. First, the theory of environmental externalities suggests that the social costs generated by firms' pollution emissions are often difficult to internalize fully. In the absence of effective institutional constraints, firms lack intrinsic incentives to allocate resources to pollution-control activities, because the private returns to such investment are often lower than the social returns (Antweiler et al., 2001; Andersen, 2017). Second, theories of information asymmetry and credit rationing indicate that pollution-control projects usually involve large upfront investment, long payback periods, strong asset specificity, and insufficient collateralizable assets; consequently, they are more likely to face higher financing premiums or credit rationing in external financing markets (Stiglitz and Weiss, 1981; Myers and Majluf, 1984). Under such circumstances, even when firms are willing to undertake pollution control, they may delay or abandon the relevant investment because of financial constraints (Nan and Wen, 2019). Therefore, insufficient pollution-control investment essentially reflects a distortion in resource allocation caused by the superposition of inadequate private incentives for environmental governance and external financing frictions.

Green finance can be regarded as an institutional response to the dual market failures of externalities and financing constraints described above. As an important complement to the traditional financial system, green finance embeds the environmental attributes of projects into the allocation process of financial resources

through instruments such as green credit and green bonds. On the one hand, relying on mechanisms such as environmental information disclosure, green project identification, and third-party assessment, green finance reduces information asymmetry between financial institutions and enterprises and alleviates the credit-rationing problems faced by green projects. On the other hand, green finance incorporates environmental risks and green performance into the risk-identification and pricing systems of financial institutions, so that environmental externalities are, to some extent, transformed into differences in financing constraints, financing costs, and capital availability, thereby improving the availability of funds for pollution-control projects (Fan et al., 2021; Wang et al., 2022).

Existing studies provide empirical support for the above logic. The related literature shows that green credit affects the investment and financing behavior of heavily polluting enterprises (Su and Lian, 2018), green finance can alleviate the financing constraints faced by green innovation activities (Yu et al., 2021), green bonds can promote corporate green innovation by relaxing financing constraints (Wang et al., 2022), and inclusive and accessible green financial services also help promote low-carbon green technological innovation (Yang et al., 2025). In the context of China's green finance reform and innovation pilot zones, the significance of the pilot policy lies not only in expanding the supply of green financial instruments, but more importantly in reducing the identification costs of green projects through institutionalized arrangements, improving the ability of financial institutions to identify, screen, and support green projects, and strengthening environmental information disclosure and risk constraints. Existing studies find that green finance reform and innovation pilot zones can reduce the debt financing costs of heavily polluting enterprises (Shi et al., 2022) and significantly promote corporate environmental protection investment (Cheng and Zhu, 2024).

Based on the above analysis, green finance reform and innovation pilot zones may increase the implementation intensity of pollution-control investment through three channels. First is the capital-availability channel. Green finance broadens the financing sources of pollution-control projects and alleviates the underinvestment problem

caused by the large upfront investment and long payback periods of such projects (Andersen, 2017; Fan et al., 2021). Second is the financing-cost channel. Through environmental information disclosure, green project certification, and risk-identification mechanisms, green finance reduces information asymmetry and thereby lowers the debt financing costs of green projects (Shi et al., 2022). Third is the incentive-resetting channel. Green finance incorporates environmental risks, green returns, and corporate environmental performance into financial decision-making, changing firms' cost-benefit expectations regarding pollution-control investment and thus strengthening their incentives to undertake pollution-control investment (Wang et al., 2022). Although the three mechanisms operate through different pathways, all of them help promote the actual implementation of pollution-control investment.

Accordingly, this paper proposes the following hypothesis:

Hypothesis 1: Green finance reform and innovation pilot zones can increase the implementation intensity of regional pollution-control investment.

(2) Improvement in the Financing Environment and Technological Innovation Response Mechanism

On the basis of the above theoretical analysis, whether green finance reform and innovation pilot zones can promote the effective implementation of pollution-control investment depends crucially on whether they can transform external policy constraints into internally executable governance capacity within enterprises. Pollution-control investment depends not only on the external pressure created by environmental regulation, but also on whether firms possess the corresponding financial conditions and technological capabilities. According to externality theory, under market-based environmental regulation instruments such as emissions trading and carbon trading, firms must bear the corresponding costs of pollution emissions and respond to regulatory pressure by reducing emissions, upgrading equipment, or increasing governance investment (Antweiler et al., 2001; Andersen, 2017). Existing studies show that moderate environmental regulation can force heavily polluting enterprises to accelerate technological upgrading (Cai et al., 2020), and that market-based policy instruments such as emissions trading and carbon trading can also guide firms to

conduct green innovation and promote the coordinated governance of pollution reduction and carbon reduction (Du et al., 2021; Yan et al., 2020; Qian et al., 2021). However, regulatory pressure itself does not necessarily translate into actual governance investment. Only when firms have sufficient financing capacity and technological response capacity can external policy constraints be further converted into observable pollution-control investment.

The formation of pollution-control capacity depends on the joint support of capital supply and technology supply. On the one hand, pollution-control projects usually involve large upfront investment, long investment recovery periods, and uncertain short-term returns, and firms are easily constrained by financing limitations when promoting the construction of governance facilities, cleaner-production retrofits, and green technology R&D. Green finance can alleviate the external financing constraints faced by firms' pollution-control and green R&D activities by broadening financing channels for green projects, reducing green project identification costs, and improving risk-pricing mechanisms in financial institutions, thereby increasing the availability of funds for governance projects (Yu et al., 2021; Wang et al., 2022). On the other hand, green technological innovation is an important pathway through which firms achieve pollution reduction and improved governance efficiency. Yet green R&D activities usually have strong uncertainty, long R&D cycles, and relatively low private rates of return, which can easily lead to insufficient innovation incentives among firms; this problem is particularly salient among small and medium-sized enterprises (Zhao et al., 2023; Zhao et al., 2024). According to absorptive capacity theory, firms need continuous knowledge accumulation and technological learning in order to transform external green technology opportunities into internal innovation outputs and improvements in governance capacity (Cohen and Levinthal, 1990). Therefore, the implementation of pollution-control investment depends not only on external regulatory pressure, but also on whether improvement in the financing environment and enhancement of technological innovation capacity can form an effective complement.

Based on the literature on environmental regulation, financing constraints, and green innovation, green finance reform and innovation pilot zones may increase the implementation intensity of pollution-control investment mainly through two transmission mechanisms. The first is the financing-environment improvement mechanism. By improving the system of financial instruments such as green credit and green bonds, the pilot policy broadens financing sources for firms' pollution-control projects and green technology R&D, lowers financing costs, alleviates external financing constraints, and enables governance investments that had originally been delayed or suspended because of insufficient funds to be implemented (Yu et al., 2021; Wang et al., 2022). The second is the technological innovation response mechanism. By strengthening green project identification, environmental information disclosure, and green financial support, the pilot policy guides firms to increase green R&D investment and promotes cleaner production, equipment upgrading, and process transformation, thereby enhancing firms' technological capacity to convert regulatory pressure into governance performance (Zhang et al., 2022; Zhao et al., 2023). These two pathways are not independent of each other: improvement in the financing environment provides financial support for green technology R&D and governance equipment upgrading, while technological innovation response increases the expected returns and financeability of green projects. The two reinforce each other and jointly promote the transformation of external policy constraints into actual pollution-control investment. Accordingly, this paper proposes the following hypothesis:

Hypothesis 2: Green finance reform and innovation pilot zones increase the implementation intensity of regional pollution-control investment mainly by improving the financing environment and stimulating technological innovation responses.

3. Data and Empirical Strategy

(1) Data Sources and Construction of Key Variables

1. Dependent Variable: Implementation Intensity of Pollution-Control Investment

The dependent variable in this paper is the implementation intensity of pollution-control investment, measured by the natural logarithm of the completed investment in industrial pollution control as a share of gross regional product.

Specifically, completed investment in industrial pollution control reflects the capital expenditure actually used by each province in a given year for industrial pollution prevention and control, and can characterize the degree to which environmental constraints are translated into governance projects and governance capital expenditure. Dividing it by gross regional product can, to some extent, remove the influence of interprovincial differences in economic scale when comparing pollution-control investment intensity. The raw data for this indicator come from environmental statistics of the National Bureau of Statistics and province-level data in the China Environmental Statistical Yearbook over the years.

The natural logarithm of the dependent variable is taken mainly for the following reasons. First, logarithmic transformation helps interpret the estimated coefficient as the relative effect of green finance pilots on the implementation intensity of pollution-control investment. Second, the logarithmic form can alleviate the right-skewness of the variable distribution and reduce the influence of extreme values on the estimation results. Third, this specification can, to some extent, capture possible nonlinear relationships between the dependent variable and the core explanatory variable as well as the control variables.

2. Core Explanatory Variable: Green Finance Pilot

The core explanatory variable in this paper is the green finance pilot policy treatment variable($GFPilot_{2017_{it}}$), obtained by multiplying the pilot-province dummy variable by the policy-implementation-period dummy variable. The pilot provinces are the five provinces approved by China's State Council in 2017 to establish green finance reform and innovation pilot zones. The policy implementation period takes the value of 1 for 2017 and subsequent years, and 0 for years before 2017.

3. Control Variables

With respect to control variables, the implementation intensity of provincial pollution-control investment may be affected by macro-level factors such as economic development, population structure, government behavior, and openness. Referring to the studies of Yan et al. (2022), Zhang (2023), and Zhang et al. (2024), this paper selects economic development level, urbanization level, degree of government

intervention, degree of openness, and population size as control variables. Specifically, economic development level ($Econ_{it}$) is measured by the natural logarithm of regional GDP; urbanization level (Urb_{it}) is measured by the share of urban population in the permanent resident population; degree of government intervention (Gov_{it}) is measured by the ratio of general public budget expenditure to GDP; degree of openness ($Open_{it}$) is measured by the ratio of actually utilized foreign direct investment to GDP; and population size ($lnPop_{it}$) is measured by the natural logarithm of the permanent resident population at year-end.

Among these variables, data on GDP, urbanization level, population size, and general public budget expenditure all come from the China Statistical Yearbook. Data on actually utilized foreign direct investment come from provincial statistical yearbooks and statistical bulletins. Variable definitions and descriptive statistics are reported in Table 1.

Table 1 Descriptive Statistics of Main Variables

Variable	Treatment group	Control group	Treatment group	Control group
	pre-policy	pre-policy	post-policy	post-policy
	(2012-2016)	(2012-2016)	(2017-2024)	(2017-2024)
Pollution-control investment implementation intensity				
	-2.299 (0.663)	-2.221 (0.760)	-3.134 (0.610)	-3.347 (1.134)
Green finance pilot	0.000 (0.000)	0.000 (0.000)	1.000 (0.000)	0.000 (0.000)
Economic development level	7.614 (0.843)	7.415 (0.797)	8.172 (0.836)	7.817 (0.860)
Urbanization level	54.430 (11.233)	57.716 (13.221)	63.196 (8.832)	65.011 (10.185)
Degree of government intervention	0.259 (0.112)	0.245 (0.102)	0.233 (0.134)	0.243 (0.114)
Degree of openness	0.019 (0.013)	0.024 (0.020)	0.011 (0.011)	0.011 (0.012)

Population size	8.462 (0.531)	8.160 (0.752)	8.533 (0.566)	8.142 (0.775)
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Note: The numbers outside parentheses are means, and the numbers in parentheses are standard deviations.

(2) Regression Model

To identify the causal effect of green finance pilots on the implementation intensity of pollution-control investment, this paper constructs a difference-in-differences (DID) model based on provincial panel data. The baseline model is specified as follows:

$$Y_{it} = \alpha + \beta GFPilot_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where Y_{it} denotes the implementation intensity of pollution-control investment in province i in year t ; $GFPilot_{it}$ is the interaction term between $Pilot_i$ and $Post2017_t$; X_{it} includes economic development level (Econ), urbanization level (Urb), degree of government intervention (Gov), degree of openness (Open), and population size (lnPop); μ_i and λ_t absorb province-level time-invariant differences and nationwide year-specific common shocks, respectively. ε_{it} is the random disturbance term. This paper clusters standard errors at the province level.

4. Empirical Results

(1) Baseline Regression Results

Table 2 reports the baseline difference-in-differences estimation results. Column (1) controls only for province fixed effects and year fixed effects; columns (2) to (6) sequentially add control variables including economic development level, urbanization level, degree of government intervention, degree of openness, and population size, in order to test the sensitivity of the core estimation results to changes in model specification.

The estimation results show that when only two-way fixed effects are controlled for, the estimated coefficient of the green finance pilot variable ($GFPilot2017$) is significantly positive. As the control variables are gradually included, the sign of the core coefficient remains positive and statistically significant, indicating that the establishment of green finance reform and innovation pilot zones significantly increases the implementation intensity of regional pollution-control investment. This

result suggests that after excluding time-invariant structural differences at the province level, nationwide year-specific common shocks, and the influence of major provincial characteristics, green finance pilots can still effectively promote the implementation of pollution-control investment. The direction and magnitude of the core coefficient are relatively stable across different model specifications, providing preliminary support for the core hypothesis proposed in this paper.

Table 2 Baseline Regression Results

Variable	Investment intensity (1)	Investment intensity (2)	Investment intensity (3)	Investment intensity (4)	Investment intensity (5)	Investment intensity (6)
<i>GFPilot2017</i>	0.313** (2.632)	0.417*** (3.136)	0.393*** (3.193)	0.389*** (3.134)	0.395*** (3.316)	0.358** (2.634)
Economic development level	No	Yes	Yes	Yes	Yes	Yes
Urbanization level	No	No	Yes	Yes	Yes	Yes
Degree of government intervention	No	No	No	Yes	Yes	Yes
Degree of openness	No	No	No	No	Yes	Yes
Population size	No	No	No	No	No	Yes
Province fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	378	378	378	378	378	378
R ²	0.708	0.723	0.724	0.725	0.725	0.726

(2) Robustness Tests

1. Parallel-Trends Test

The key premise for difference-in-differences identification is that the treatment and control groups share a common trend before policy implementation. To test this assumption, this paper constructs an event-study model, taking the year in which the green finance reform and innovation pilot zones were established, 2017, as relative period 0 and using the year before policy implementation, 2016, as the omitted base period. Specifically, this paper defines the relative period as $(rel=year-2017)$ and sets interaction terms year by year according to relative policy time. Considering that estimates for single years at the later end of the sample period may be affected by small-sample fluctuations, this paper combines 2022-2024 into a terminal bin. This specification can test the comparability of trends between the treatment and control groups before policy implementation and also helps characterize the dynamic changes in the policy effect after implementation.

This paper constructs the following event-study model:

$$Y_{it} = \alpha + \sum_{k \neq -1} \delta_k [Pilot_i \times I(RelTime_{it} = k)] + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

In this model, relative period -1, namely 2016, is omitted. The pre-policy dynamic terms are used to test whether the treatment and control groups satisfy the parallel-trends assumption, while the post-policy dynamic terms are used to characterize the dynamic release process of the green finance pilot effect.

Figure 1 reports the event-study results. Before policy implementation, the dynamic coefficients for each period from 2012 to 2015 fluctuate around the zero line, and all 90% confidence intervals cover zero. The joint test for the four pre-policy dynamic terms yields $F(4,29)=0.589$, failing to reject the parallel-trends assumption, which indicates that there is no significant systematic trend difference between the treatment and control groups before policy implementation. After policy implementation, the dynamic coefficients for 2017 and 2018 are small and insignificant; the coefficient for 2019 turns positive but does not reach conventional levels of statistical significance; while the coefficients for 2020-2021 and for the pooled 2022-2024 terminal bin are significantly positive. Overall, the event-study results support the pre-treatment trend comparability required for difference-in-differences

identification and indicate that the effect of green finance pilots on the implementation intensity of pollution-control investment has a certain lag, with the policy effect being gradually released after the policy has been implemented for some time.

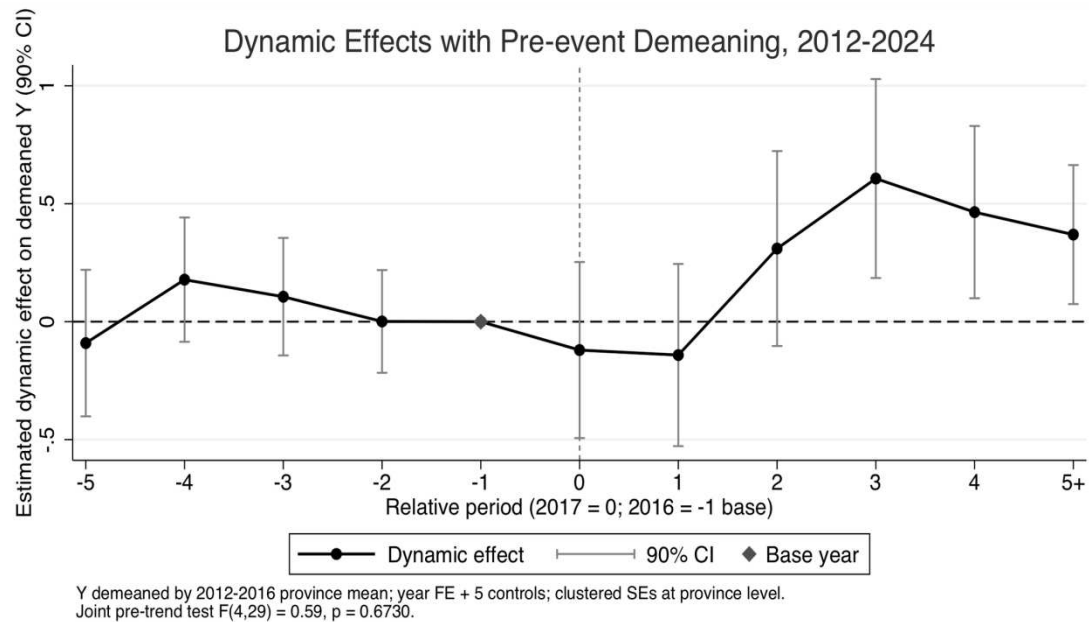


Figure 1 Continuous Dynamic Effects and Parallel Trends

2. Placebo Test

To rule out the possibility that the baseline results are driven by random factors or unobservable province-level shocks, this paper further conducts a random placebo test. Specifically, five pseudo-pilot provinces are randomly selected from the 25 non-pilot provinces and are combined with years 2017 and after to construct a pseudo-policy interaction term. The model is then re-estimated while maintaining the same fixed effects and control-variable settings as in the baseline regression. The above random selection and regression procedure is repeated 500 times, thereby obtaining the empirical distribution of pseudo-treatment effects.

Figure 2 reports the placebo test results. The 500 pseudo-treatment effects are mainly concentrated around zero, with a 90% confidence interval of $[-0.365, 0.311]$. By contrast, the true estimated coefficient in the baseline regression is 0.358, located in the right tail of the pseudo-treatment-effect distribution. This result indicates that the baseline estimation result is difficult to explain by random disturbances or

province-level unobservable shocks, further supporting the robustness of the core conclusion of this paper.

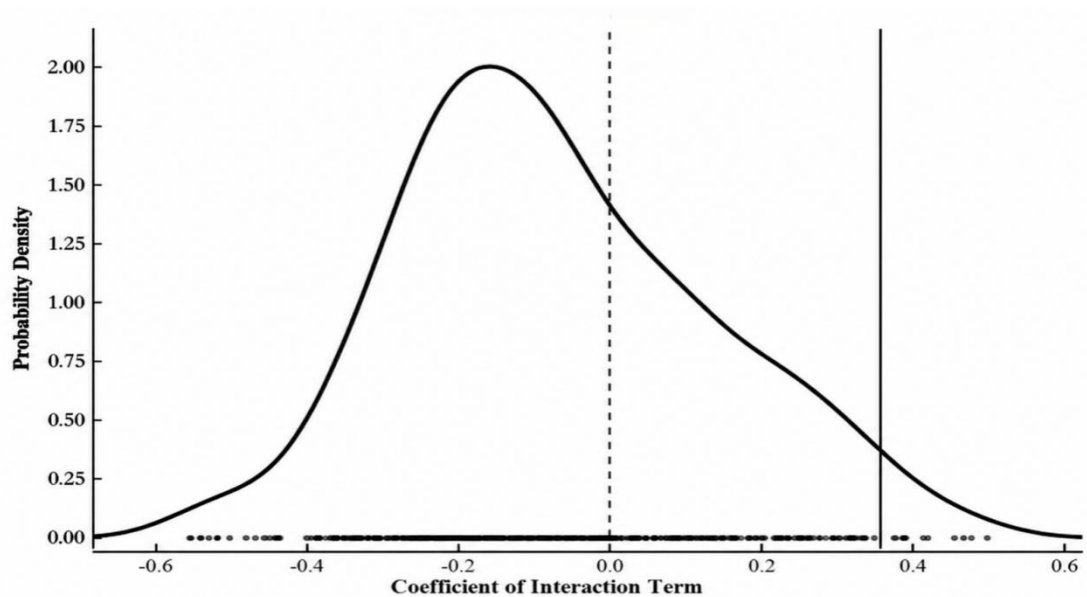


Figure 2 Placebo Test

3. Excluding the Influence of Competing Policies

During the sample period, China also advanced a number of ecology- and environment-related policies, which may affect pollution-control investment. To exclude interference from competing policies, this paper further controls for policy shocks from ecological civilization pilot zones, carbon trading pilots, and central environmental protection inspections. Specifically, the ecological civilization pilot zone variable is set according to relevant national policy documents: Fujian, Jiangxi, and Guizhou take the value of 1 from 2016 onward, and Hainan takes the value of 1 from 2019 onward. The carbon trading pilot variable is set according to the pilot arrangements determined by the National Development and Reform Commission and the actual launch years of local carbon markets. The central environmental protection inspection variable is set according to the first entry year of the first round of inspections in each province and takes the value of 1 in the entry year and thereafter. The pollution discharge permit system was promoted uniformly nationwide around 2017; in a provincial annual model that includes year fixed effects, it is mainly reflected

as a nationwide common shock and is therefore absorbed by year fixed effects rather than included separately in the estimation.

The results in Table 3 show that after separately controlling for ecological civilization pilot zones and carbon trading pilots, the coefficient of the green finance pilot remains significantly positive and is close to the baseline result. After further including the central environmental protection inspection variable, the core coefficient is 0.353 and significant at the 5% level. When ecological civilization pilot zones, carbon trading pilots, and central environmental protection inspections are controlled for simultaneously, the core coefficient is 0.414 and significant at the 1% level. These results indicate that the promoting effect of green finance pilots on the implementation intensity of pollution-control investment is not driven by contemporaneous ecological and environmental policies or environmental regulatory shocks, and that the baseline conclusion has good robustness.

Table 3 Robustness Test Results

Variable	Excluding ecological civilization pilot zone effects (1)	Excluding carbon trading pilot effects (2)	Changing the dependent variable (3)
GFPilot2017	0.484*** (2.797)	0.359** (2.682)	0.358** (2.634)
Ecological civilization pilot zone	-0.539* (-1.853)		
Carbon trading pilot		0.129 (0.697)	
Control variables	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Observations	378	378	378
R ²	0.732	0.726	0.745

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

4. Changing the Measurement of the Dependent Variable

To examine whether the results depend on the specific construction of the dependent variable, this paper further replaces the logarithm of pollution-control investment as a share of GDP with the logarithm of pollution-control input and re-estimates the model. Column (3) of Table 3 shows that after this replacement, the coefficient of GFPilot2017 remains significantly positive at the 5% level, indicating that the baseline conclusion does not depend on the specific measure of GDP-standardized investment intensity. Even when the scale of pollution-control input is examined directly, there remains a significant positive association between green finance pilots and increased pollution-control input. The conclusions under the two measures are highly consistent, further strengthening the robustness of the empirical findings.

5. Double Machine Learning Test Results

To further examine whether the baseline conclusion is affected by the functional-form specification of control variables, this paper introduces double/debiased machine learning (DML) as a supplementary robustness test in addition to the traditional two-way fixed-effects model (Chernozhukov et al., 2018). DML uses machine learning methods to estimate the conditional expectations of the outcome variable and the treatment variable with respect to covariates, and estimates the treatment effect based on orthogonalized residuals, thereby alleviating, to some extent, potential bias arising from insufficient linear control-variable specification, nonlinear relationships, and omitted interaction terms.

Specifically, this paper first residualizes the dependent variable, the policy treatment variable, and the control variables with respect to province fixed effects and year fixed effects. It then uses economic development level, urbanization level, degree of government intervention, degree of openness, population size, their squared terms, and their pairwise interaction terms as machine learning features, applies five-fold cross-fitted LASSO grouped by province to estimate the outcome equation and the treatment equation separately, and finally regresses the outcome residuals on the

treatment residuals to obtain the orthogonalized treatment effect, with standard errors clustered at the province level.

Table 4 reports the DML estimation results. Under the baseline DML specification, the estimated coefficient of the green finance pilot is 0.516 and significant at the 1% level. After further controlling for ecological civilization pilot zones and carbon trading pilots, and after replacing the measure of the dependent variable, the DML estimated coefficients remain significantly positive. This result indicates that after relaxing the linear functional form of the control variables and allowing nonlinear relationships and interaction relationships among covariates, the promoting effect of green finance pilots on the implementation intensity of pollution-control investment remains robust.

Table 4 Double Machine Learning Test Results

Variable	Baseline regression (1)	Excluding ecological civilization pilot zone effects (1)	Excluding carbon trading pilot effects (2)	Changing the dependent variable (3)
GFPIlot2017	0.516*** (3.301)	0.629*** (3.297)	0.415*** (3.069)	0.449*** (3.611)
Control variables	Yes	Yes	Yes	Yes
Residualization of province and year fixed effects	Yes	Yes	Yes	Yes
Five-fold cross-fitted LASSO	Yes	Yes	Yes	Yes
Observations	378	378	378	378
R ²	0.026	0.045	0.017	0.020

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively; the values in parentheses are t-values calculated using province-clustered standard errors. The DML estimation residualizes province and year fixed effects and uses five-fold cross-fitted LASSO grouped by province. The machine learning features include the five conventional control variables, their squared terms, and their pairwise interaction terms.

5. Mechanisms analysis

The preceding results show that green finance reform and innovation pilot zones significantly increase the implementation intensity of regional pollution-control

investment. To further explain the source of this policy effect, this paper tests the transmission channels from two perspectives: improvement in the financing environment and technological innovation response.

(1) Green Finance Pilots Improve the Financing Environment

Pollution-control projects usually involve large upfront investment, long payback periods, and insufficient collateral, and are therefore easily constrained by external financing constraints. Through institutional arrangements such as green credit, green bonds, green funds, and environmental information disclosure, green finance pilots improve the ability of financial institutions to identify and support green projects, and expand the coverage of financial services to entities with governance needs.

To test this channel, this paper uses the ratio of "coverage breadth/use depth" in the Peking University Digital Financial Inclusion Index as a proxy variable for improvement in the financing environment. The results in column (1) of Table 5 show that green finance pilots significantly increase this ratio, indicating that the pilots can promote the expansion of financial accessibility to marginal regions and entities that were originally underserved by financial services, thereby providing financial support for the implementation of pollution-control investment.

(2) Green Finance Pilots Stimulate Technological Innovation Responses

Pollution-control investment requires not only financial support, but also technological capacity. By strengthening green project identification, environmental information disclosure, and green finance incentives, green finance pilots can increase the expected returns to green technology R&D and governance equipment upgrading, and guide regional innovation activities to respond in the direction of green transformation. This paper uses the number of invention patent applications to measure regional technological innovation response. The results in column (2) of Table 5 show that green finance pilots significantly increase the number of invention patent applications, indicating that the pilots can stimulate regional innovation activities and provide a technological foundation for the implementation of pollution-control investment.

Table 5 Transmission Channel Test Results

Variable	Improving the financing environment channel (1)	Stimulating technological innovation response channel (2)
GFPilot2017	0.060* (1.89)	2.884** (2.15)
Control variables	Yes	Yes
Province fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Observations	360	300
R ²	0.933	0.965

6. Heterogeneity Analysis

The mechanism analysis shows that green finance pilots operate mainly by improving the financing environment and stimulating technological innovation responses. If the above mechanisms hold, their promotion effect should be more pronounced in regions with weaker financing foundations, insufficient innovation capacity, stronger demand for pollution control, and relatively lagging economic development, because such regions have greater room for improvement in capital availability, technological support, and governance investment. Based on this, this paper further conducts grouped tests from four dimensions: digital finance foundation, innovation foundation, industrial pollution burden, and economic development level. The results are reported in Table 6.

(1) Heterogeneity by Digital Finance Foundation

The digital finance foundation reflects a region's capacity for financial service coverage and the efficiency of financial resource allocation. Regions with a higher digital finance foundation usually already have better financial accessibility, so the marginal room for improvement brought by green finance pilots is relatively limited. By contrast, regions with a lower digital finance foundation are more likely to face insufficient financial services and financing constraints, and are therefore more likely

to benefit from the pilot policy. The results in columns (1) and (2) of Table 6 show that in regions with a lower digital finance foundation, the green finance pilot coefficient is significantly positive; in regions with a higher digital finance foundation, the coefficient is positive but does not pass the significance test. This result indicates that the promoting effect of green finance pilots is mainly reflected in regions with weaker financial foundations and greater room for financing improvement.

(2) Heterogeneity by Innovation Foundation

The innovation foundation determines the conditions under which a region can transform financial support into governance-related technological capacity. Regions with stronger innovation foundations usually already possess better R&D resources and technological accumulation, whereas regions with weaker innovation foundations need external institutional incentives to make up for technological shortcomings. The results in columns (3) and (4) of Table 6 show that in regions with a lower innovation foundation, the green finance pilot coefficient is significantly positive; in regions with a higher innovation foundation, the coefficient is insignificant. This indicates that the pilot policy is more likely to stimulate technological responses in regions with weak innovation foundations and promote the implementation of pollution-control investment.

(3) Heterogeneity by Industrial Pollution Burden

The heavier the industrial pollution burden, the stronger the environmental governance pressure and demand for pollution-control investment that a region usually faces. For regions with higher pollution burdens, green finance pilots can convert stronger governance demand into actual investment through financial support and technological incentives. The results in columns (5) and (6) of Table 6 show that the coefficient of green finance pilots is significantly positive in regions with higher industrial pollution burdens, but insignificant in regions with lower burdens. This result indicates that green finance pilots are more effective in regions with stronger demand for pollution control.

(4) Heterogeneity by Economic Development Level

The level of economic development affects a region's fiscal capacity, financial supply, and firms' capacity to invest in governance. Regions with higher levels of economic development often already have a stronger foundation for governance investment, whereas regions with lower levels of economic development are more likely to be constrained by capital and technology, and the marginal effect of policy support may be larger. The results in columns (7) and (8) of Table 6 show that in regions with lower levels of economic development, the green finance pilot coefficient is significantly positive; in regions with higher levels of economic development, the coefficient does not pass the significance test. This result indicates that green finance pilots help compensate for the insufficient pollution-control investment capacity of less-developed regions.

Table 6 Heterogeneity Analysis

Variable	Low digital finance (1)	High digital finance (2)	Low innovation foundation (3)	High innovation foundation (4)	Low industrial burden (5)	High industrial burden (6)	Low economic level (7)	High economic level (8)
GFPilot2017	0.361** (2.36)	0.389 (1.42)	0.406* (2.13)	0.281 (0.76)	0.310 (1.58)	0.420* (1.86)	0.348* (1.88)	0.373 (1.17)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	195	183	186	192	186	192	189	189
Number of provinces	15	15	15	15	15	15	15	15
R ²	0.731	0.737	0.731	0.706	0.722	0.775	0.731	0.760

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively; the values in parentheses are t-values calculated based on province-clustered robust standard errors.

7. Conclusions and Policy Implications

Taking the establishment of green finance reform and innovation pilot zones in 2017 as a quasi-natural experiment, this paper uses panel data for 30 provincial-level

regions in China from 2012 to 2024 and applies a difference-in-differences model to examine the impact of green finance pilots on the implementation intensity of pollution-control investment. The study finds that green finance pilots significantly increase the implementation intensity of regional pollution-control investment. This conclusion remains valid after controlling for province fixed effects, year fixed effects, and provincial characteristic variables, and it passes parallel-trends tests, placebo tests, and multiple robustness checks. This indicates that green finance reform and innovation pilot zones are not only an adjustment in the allocation mode of financial resources, but can also promote the transformation of environmental governance requirements into actual governance investment.

The transmission channel tests show that green finance pilots operate mainly through two pathways: improvement in the financing environment and technological innovation response. On the one hand, the pilots help improve the accessibility of financial services and alleviate the financing constraints faced by pollution-control projects and green technology R&D. On the other hand, the pilots can incentivize regional innovation activities to adjust toward a green and low-carbon direction, providing technological support for pollution-control investment. The heterogeneity analysis further finds that the promoting effect of green finance pilots is more pronounced in regions with weaker digital finance foundations, lower innovation foundations, heavier industrial pollution burdens, and lower levels of economic development. This indicates that green finance policies have higher marginal effects in regions with stronger governance demand, more prominent resource constraints, and greater room for improvement.

The above findings have the following policy implications. First, the construction of green finance reform and innovation pilot zones should continue to be deepened, and regional differences should receive greater attention in subsequent policy expansion. For regions with weak digital finance foundations, insufficient innovation capacity, heavy industrial pollution burdens, and low levels of economic development, support from instruments such as green credit, green bonds, green funds, and green guarantees should be appropriately increased, guiding green financial resources toward regions

with strong governance demand and tight financing constraints and avoiding excessive concentration of green finance policies in regions with stronger financial foundations.

Second, the transmission channels through which green finance affects pollution-control investment should be made smoother. On the financing side, the availability and affordability of green financial services should be improved, and coverage should be expanded for small and medium-sized enterprises, green retrofit projects, and the construction of pollution-control facilities. On the technology side, the costs for firms to undertake green R&D and equipment upgrading should be reduced through green technology innovation funds, R&D subsidies, and support for cleaner-production retrofits. At the same time, green project identification, environmental information disclosure, and supervision of the use of funds should be improved to ensure that green financial resources are truly converted into pollution-control capacity.

Third, coordination should be strengthened among green finance policies, environmental regulation, industrial policies, and innovation policies. The implementation of pollution-control investment requires not only financial support, but also stable environmental constraints and technological response mechanisms. Local governments should strengthen firms' governance pressure through environmental regulation, reduce the costs of governance investment through green finance, and enhance technological transformation capacity through innovation policies, thereby forming a policy chain of "environmental constraints-financial support-technological response-governance investment" and improving the overall implementation efficiency of green transformation policies.

This paper still has certain limitations. First, because of data availability constraints, this paper uses provincial annual panel data and cannot further observe the loan terms, use of funds, equipment procurement, and project implementation processes of individual pollution-control projects. Therefore, the mechanism tests mainly provide empirical evidence consistent with the theoretical mechanisms. Future research could use firm-level, bank-credit-level, or project-level data to identify more precisely the specific chain through which green finance affects pollution-control

investment. Second, the green finance pilots cover a limited number of provinces, and the treatment-group sample in the heterogeneity tests is relatively small; the relevant conclusions therefore still need to be further tested as the policy implementation period lengthens and the pilot scope expands. Third, this paper constructs the indicator of pollution-control investment implementation intensity using completed investment in industrial pollution control, but has not yet distinguished among different types of investment such as end-of-pipe treatment, cleaner production, equipment upgrading, and environmental infrastructure construction. Subsequent research could further subdivide the structure of governance investment in order to evaluate more accurately the environmental governance effects of green finance policies.

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Data Availability Statement

The provincial panel data used in this study were compiled from publicly available statistical yearbooks and official statistical bulletins, including the China Statistical Yearbook, the China Environmental Statistical Yearbook, provincial statistical yearbooks, and provincial statistical bulletins. Data used to proxy the financing-environment mechanism were obtained from the Peking University Digital Financial Inclusion Index of China. Patent-application data used to measure technological innovation responses were compiled from China National Intellectual Property Administration patent statistics annual workbooks. The processed dataset used for the empirical analyses, together with variable definitions, coding schemes, transformation records, estimation outputs, logs, and replication code, is provided in the supplementary data and code

package submitted with this revised manuscript for the purposes of peer review. These files can be accessed through the supplementary materials accompanying the revised submission. The original source data remain subject to the access and redistribution terms of the respective data providers.

Ethical Approval

This article does not contain any studies with human participants performed by any of the authors.

Informed Consent

This article does not contain any studies with human participants performed by any of the authors; therefore, informed consent is not applicable.