Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Can Ecological Civilization Construction Alleviate Urban Environmental Pollution? Evidence from a Quasi-Natural Experiment of National Demonstration Zones

Xingcheng Lu
Nanjing University of Finance & Economics
Haowen Jin
Hohai University
Xiaoge Xiong
xiaoge_xiong@163.com

Nanjing University of Finance & Economics

Research Article

Keywords: National Ecological Civilization Demonstration Zones, Urban environmental pollution, Entropy evaluation method, Multi-period DID, Double Machine Learning

Posted Date: June 16th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9586886/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Can Ecological Civilization Construction Alleviate Urban Environmental Pollution? Evidence from a Quasi-Natural Experiment of National Demonstration Zones

Xingcheng Lu [a], Haowen Jin [b], Xiaoge Xiong[c,*]

[a] *Massey Institute, Nanjing University of Finance & Economics, Nanjing 210023, China*
[b] *School of Economics and Finance, Hohai University, Changzhou 213200, China*
[c] *School of Economics, Nanjing University of Finance & Economics, Nanjing 210023, China*
[*] *Correspondence: xiaoge_xiong@163.com*

Abstract: Systematically evaluating the pollution reduction effects of the National Ecological Civilization Construction Demonstration Zone (NECCDZ) policy at a broader pollution level is vital for achieving ecological civilization goals. Treating the NECCDZ policy as a quasi-natural experiment, this study uses 2010–2021 panel data from 213 Chinese cities. By employing a two-way fixed-effects time-varying Difference-in-Differences (DID) model and a Lasso-based Double Machine Learning (DML) model, we empirically examine the policy's impact on urban environmental pollution and its mechanisms. Results indicate that the NECCDZ policy significantly reduces the urban environmental pollution index, passing a series of robustness checks. Mechanism analysis reveals that the policy effectively suppresses pollution and facilitates green, innovative urban development by optimizing energy structures, fostering green technological innovation, and enhancing Green Total Factor Productivity (GTFP). Furthermore, heterogeneity analysis shows the mitigation effect breaks the "large city and industrial stronghold priority" stereotype, proving more pronounced in non-resource-based, small-to-medium-sized cities that have escaped industrial path dependency and possess greater marginal regulatory space. Accordingly, this paper proposes practical recommendations to optimize the NECCDZ policy and promote ecological civilization.

Keywords: National Ecological Civilization Demonstration Zones; Urban environmental pollution; Entropy evaluation method； Multi-period DID; Double Machine Learning

June 16, 2026

1. Introduction

Currently, global environmental challenges are becoming increasingly severe, and sustainable development has become a common pursuit of the international community. As the world's second-largest economy, China faces enormous resource and environmental pressures while experiencing rapid economic development. To actively address this challenge, the government has proposed the national strategy of "ecological civilization construction," aiming to build a modern pattern of harmonious coexistence between humanity and nature. Against this backdrop, the National Ecological Civilization Construction Demonstration Zones (hereinafter referred to as "Demonstration Zones") serve as a testing ground for this policy. Their establishment and construction are not only important measures for my country to promote ecological civilization construction but also provide the academic community with a unique perspective for evaluating the effects of environmental policies.

2. Literature review

2.1 Studies on National Ecological Civilization Demonstration Zones

Ecological civilization demonstration zones are regional pilot projects established by the Chinese government to implement the concept of ecological civilization and promote green development. Since the first guiding opinions were issued in 2016, eight batches of hundreds of national ecological civilization demonstration zones have been named, making it a long-term and routine demonstration creation work. Wang et al. (2022) and Li et al. (2024) believe that this institutional arrangement is often regarded by researchers as a "quasi-natural experiment" to assess its policy effects on environmental protection and sustainable development. The establishment of demonstration zones is not an isolated administrative order, but a systematic development strategy aimed at exploring and promoting an ecological civilization construction model that suits China's national conditions through pilot projects. Meng et al. (2021) and Zhang et al. (2021) found that its core connotations include, but are not limited to: promoting the green transformation of economic development models, optimizing industrial structure, promoting technological innovation, improving energy efficiency, and building a sound ecological environment governance system. Guo et al. (2024) generally believe that the construction of demonstration zones is a comprehensive process that requires the deep integration of ecological and environmental protection into the "five-in-one" development of the economy, politics, culture, and society, and the establishment of a long-term mechanism that combines public participation, corporate responsibility, and government supervision. In practice, demonstration zones are committed to playing a leading role in resource utilization, environmental protection, and green industry development, and promoting the coordinated development of the region's economy and ecological environment through policy incentives, standard guidance, and technical support.

2.2 Studies on the measurement of environmental pollution

As a key indicator for measuring environmental health and policy effectiveness, the environmental pollution index presents diverse measurement perspectives in existing research. Some studies directly focus on concrete pollutant emissions. Lv et al. (2022), in analyzing the impact of multidimensional urbanization on carbon emissions, regarded carbon emissions as the core indicator and explored its spatiotemporal evolution characteristics in depth; Zhang and Fu (2022) and Wang et al. (2022) used carbon dioxide emissions (CDE) or carbon emission intensity as the main indicators for measuring environmental pollution and assessed the emission reduction effectiveness of the demonstration zone construction. At a broader level of environmental quality, researchers have also adopted more comprehensive or specific indicators. Ren et al. (2024) and Guo and Xiong (2023) examined

the contribution of demonstration zone policies to environmental sustainability from the perspectives of "the level of green development of the marine economy" and "green development welfare," respectively. The improvement of these indicators essentially reflects the effective control of environmental pollution. The "urban ecological efficiency" proposed by Liang et al. (2022), the "agricultural green efficiency" adopted by Lu and Xiong (2020), and the "ecological environment quality" focused on by Lan and Hu (2024) are also widely adopted indicators. They reflect resource utilization efficiency, ecosystem health, and pollution prevention and control effectiveness from different dimensions. Guo et al. (2024) even constructed the "Comprehensive Environmental Health Index (CEHI)," which comprehensively assesses the performance of ecological civilization by integrating multiple indicators under the framework of Drivers, Stress, State, Impacts, and Responses (DPSIR), including many environmental factors such as pollutant emissions. These diverse indicator systems together constitute a rich picture of environmental pollution index research, providing a multi-dimensional perspective for a comprehensive understanding of the environmental situation.

2.3 Effects of the Ecological Civilization Demonstration Zone policy on environmental pollution

Regarding the impact of ecological civilization demonstration zones on carbon emissions and environmental pollution, existing studies generally confirm their significant positive effects, but the specific effects exhibit regional heterogeneity and complex mechanisms. Zhang and Fu (2022)'s empirical study shows that the construction of ecological civilization pilot zones can effectively reduce carbon dioxide emissions, but the effect is less significant in provinces such as Fujian, Yunnan, and Guizhou than in Jiangxi and Qinghai. However, Wang et al. (2022) found that the construction of demonstration zones significantly reduced carbon emission intensity, with particularly pronounced effects in provinces such as Fujian, Guizhou, and Yunnan, and also exhibited significant spatial spillover effects. Multiple studies have verified the role of demonstration zone construction in improving environmental pollution from different perspectives: Liang et al. (2022) found that the establishment of demonstration zones significantly improved urban ecological efficiency; Lu and Xiong (2020) proved that it has a significant positive impact on agricultural green efficiency; Ren et al. (2024) pointed out that national marine ecological civilization construction demonstration zones significantly improved the green development level of marine economy; Lan and Hu (2024) also emphasized the significant positive impact of demonstration zone construction on ecological environment quality.

In terms of the mechanisms of action, technological innovation is one of the core driving forces. Empirical studies by Li et al. (2024) and Wang et al. (2022) found that promoting green technology innovation in enterprises and overall regional technological progress can reduce pollution. Industrial structure optimization is another important mechanism. Studies by Guo and Xiong (2023) and Liang et al. (2022) showed that demonstration zones reduce pollution emissions by adjusting industrial structure, eliminating outdated production capacity, and developing green industries. Studies by Lan and Hu (2024) and Wang et al. (2022) found that improvements in government environmental governance, green transformation of industrial enterprises, increased public environmental awareness, the development of green finance, optimization of energy structure, and improvement of market segmentation are also important ways in which demonstration zones influence environmental pollution. The studies also point out that policy effects may have lag and persistence (Lu & Xiong, 2020), and that their spatial proximity effect (Guo & Xiong, 2023) and regional heterogeneity (Lan & Hu, 2024; Zhang & Fu, 2022) need to be fully considered. These findings provide rich theoretical basis and

empirical support for a deeper understanding of the complex role of ecological civilization demonstration zones in environmental pollution control.

Previous literature has largely focused on single environmental dimensions such as carbon emissions or the effects of single regulations, with few systematic assessments of the comprehensive pollution reduction effects and underlying mechanisms of national ecological civilization construction demonstration zones based on a comprehensive indicator system. This paper deeply integrates the multi-period difference-in-differences method with a dual machine learning model, effectively overcoming high-dimensional confounding variables and endogeneity issues, and accurately assesses the impact of demonstration zone construction on urban environmental pollution indices. The marginal contributions of this paper are prominently reflected in: first, a comprehensive and deepened assessment perspective, breaking through the limitations of previous focus on single pollutants, and scientifically measuring and verifying the policy effects of demonstration zone construction on overall urban environmental pollution based on a comprehensive indicator system; second, a systematic revelation of the mechanism of action, by introducing green technology innovation, energy consumption intensity, and green total factor productivity, multidimensionally measuring and empirically verifying the internal transmission path of pollution reduction in demonstration zones; and third, accurate identification of heterogeneous subjects, further distinguishing between resource-based cities, city size, and urban environmental type, clarifying the differentiated directions and subjects of policy promotion for environmental improvement.

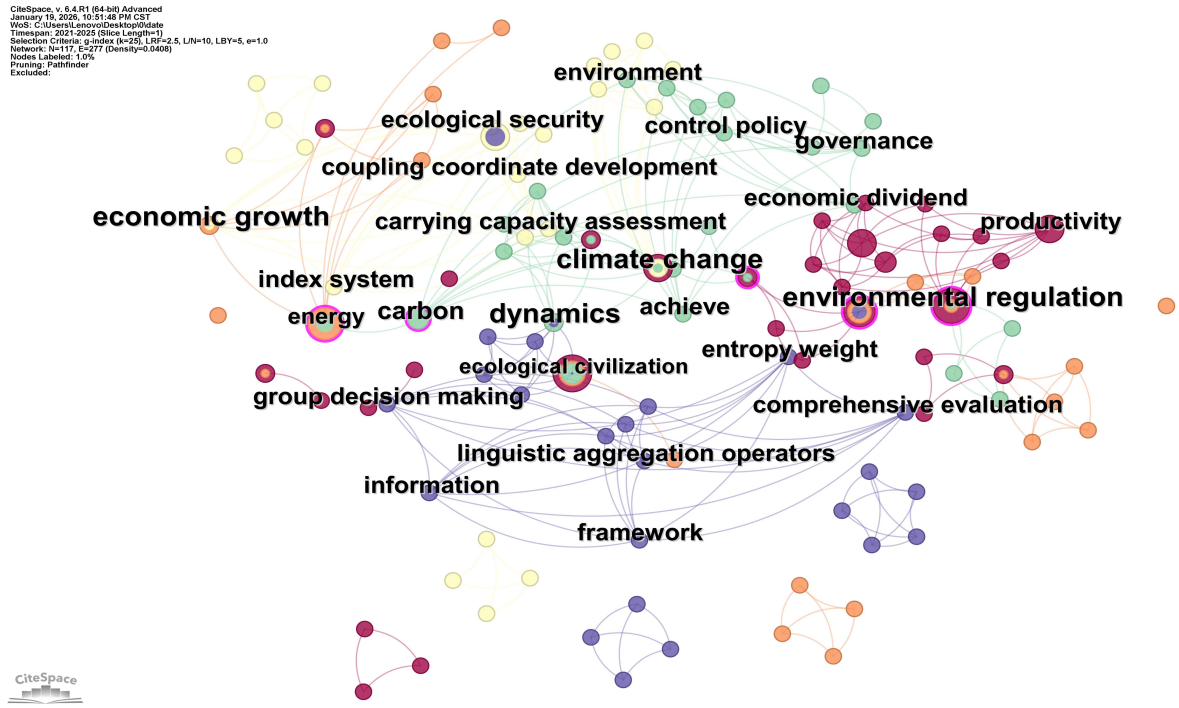


Figure 1 Keyword co-occurrence network

3. Theoretical analysis and research hypotheses

3.1 Effects of National Ecological Civilization Demonstration Zones on Pollution reduction

Environmental pollution, as a typical negative externality, stems from market failure caused by unclear environmental property rights. Ecological civilization demonstration zones are essentially a "quasi-Pigouvian" institutional intervention led by the central government. They include not only

rigid environmental performance indicators (command-control regulations) but also market-based mechanisms such as fiscal subsidies and green finance support. This intervention internalizes environmental externalities by increasing enterprises' pollution discharge costs or reducing their pollution control costs, thereby achieving macro-level pollution reduction. As shown in Figure 1, the comprehensive regulations of the demonstration zones are equivalent to applying an external intervention to the existing supply and demand system (black double-headed arrows in the figure). This forces enterprises' actual production cost curve to shift upwards from MPC, approaching the true marginal social cost curve MSC. Under strict environmental constraints and institutional guidance, the compliance costs of high-pollution, high-energy-consuming ("double-high") enterprises surge, and market factors begin to reallocate. Ultimately, the equilibrium state of the local market converges from the excessive pollution point Em to the socially optimal equilibrium point E∗. During this process, with the exit of inefficient production capacity and the green upgrading of industrial structure, the scale of polluting economic activities has dropped significantly from $Q_m$to Q^*.

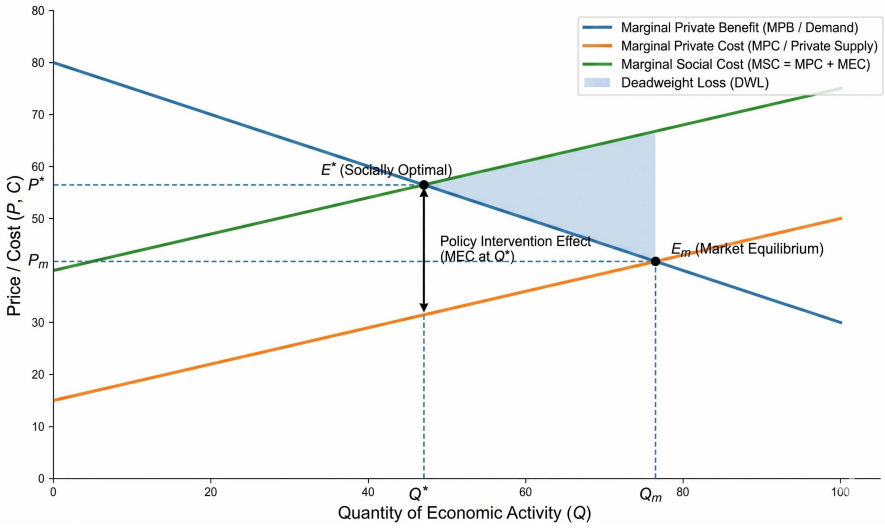


Figure 2 Negative externalities and Pilgrim intervention

From a macro perspective, studies by Li et al. (2025) and Zhang and Wang (2024) found that the ecological civilization construction demonstration zone policy has greatly promoted the comprehensive and in-depth optimization of energy supply structure and technological innovation system, facilitated the coordinated governance of pollutants and ecological environment restoration, improved the efficiency of clean technology transformation and application, and put green and low-carbon development on a new track and at a new level, thereby achieving a significant reduction in environmental pollution and continuous improvement in environmental quality, providing a solid guarantee for the realization of sustainable development goals.

From a micro perspective, the ecological civilization construction policy, by strengthening environmental regulations and incentive mechanisms, has significantly stimulated the green technology innovation vitality of micro-entities in pilot areas. ① On the one hand, the policy's reverse-forcing effect prompts enterprises to increase their R&D investment in green invention patents and utility model patents to achieve a cleaner transformation of production processes; ② On the other hand, government subsidies and policy support alleviate the resource constraints of enterprises in green transformation, thereby improving the overall innovation efficiency of the region. Hu et al. (2023)

found that the demonstration zone policy not only directly promoted the progress of local green technologies but also had a positive impact on the green development of surrounding areas through spatial spillover effects. Therefore, the demonstration zones for ecological civilization construction focus on promoting the green transformation and structural reform of the economy and society, encouraging pilot projects to address pollution and innovate green technologies, and leading the way in sustainable development and the construction of a beautiful China. In other words, only by incorporating pollution control into the demonstration zones for ecological civilization construction, taking green innovation as a breakthrough, and implementing the concept of green and low-carbon development can we achieve systemic changes and high-quality development in the economy and society.

H1: The establishment of National Ecological Civilization Demonstration Zones significantly reduces the urban environmental pollution index.

3.2 The impact mechanism of ecological civilization construction demonstration zones on environmental pollution

National ecological civilization construction demonstration zones primarily achieve significant pollution reduction and emission reduction by strengthening goal-oriented guidance and institutional constraints, deeply implementing energy conservation and emission reduction requirements, and promoting the green transformation of the energy structure. This, in turn, forces industrial structure transformation and upgrading. Specifically, energy is not only the cornerstone of economic growth but also a major source of environmental pollutants. Demonstration zones implement a "dual control" system for energy consumption by improving ecological compensation mechanisms and imposing strict pollution quotas, thus building an energy efficiency management system at the source to curb pollutant emissions (Su et al., 2021). Under this stringent "forcing mechanism," traditional high-energy-consuming industries are forced to transform from extensive growth to intensive models, significantly reducing energy consumption intensity and improving energy utilization efficiency. Simultaneously, under the policy of sustainable development, this transformation demand directly generates tremendous green innovation vitality. Empirical research by Ma and He (2023) shows that enterprises implementing green innovation have a significant positive impact on improving urban environmental pollution. By attracting environmental investment and accumulating human capital, demonstration zones not only promote a positive spatial spillover effect of green utility model patents (Hu et al., 2023), but also significantly enhance the city's green innovation resilience by embedding digital technologies and strengthening green awareness (Li et al., 2024). Furthermore, studies by Jiang et al. (2024) and Kahouli et al. (2022) found that improving green total factor productivity can effectively promote urban environmental restoration and possesses enormous potential for pollution reduction and emission reduction. Demonstration zones have demonstrated significant institutional advantages in regulating environmental governance and formulating pollution prevention laws. Zhang et al. (2022) found that establishing laws to prevent the emission of pollutants from water, air, and solid waste has a significant positive effect on improving green total factor productivity. In addition, research by Yuan et al. (2024) found that new economic development zones have a siphon effect, and ecological civilization demonstration zones significantly improve green total factor productivity in cities with smaller populations, lower human capital, and lower administrative levels. In conclusion, the demonstration zone, through a systematic approach of "reducing energy consumption, innovating, and improving efficiency," provides a lasting driving force for reducing urban environmental pollution.

H2: National ecological civilization construction demonstration zones reduce urban environmental pollution by lowering energy consumption intensity and promoting green innovation and green total factor productivity.

4. Research design

4.1 Model building

4.1.1 Multi-period difference method

The difference-in-differences (DID) method is a commonly used econometric tool for assessing the effects of phased implementation policies. This paper treats the national ecological civilization construction demonstration zone policy as a quasi-natural experiment: different cities are approved to enter the demonstration zone in different years, resulting in a misalignment of the "treatment" over time. Against this backdrop, this paper uses cities that have not yet been approved as a control group. By utilizing the time changes before and after city approval, and combining the differences between the treatment group and the control group during the same period, and controlling for city fixed effects, annual fixed effects, and other relevant control variables, this paper identifies the average impact of the policy on the environmental pollution index.

$$Y_{it} = \beta_0 + \beta_1 treat \times post + \phi X_{it} + \mu_t + \gamma_t + \varepsilon_{it} \quad (1)$$

In the formula, Y_{it} is the environmental pollution index, which is the explained variable; i, t represent the city and time, respectively; X_{it} is the control variable; μ_t, γ_t are the urban solids effect and the individual time effect, respectively; ε_{it} represents the random error term; $treat \times post$ is the dummy variable for the ecological civilization construction demonstration zone; β_1 is the core focus coefficient of this paper, which reflects the pollution reduction effect of the ecological civilization demonstration zone.

4.1.2 Dual machine learning model

Linear regression-based estimation of causal effects struggles to capture the high-dimensional features and nonlinear relationships in economic data. Dual machine learning allows researchers to obtain robust estimates and inferences of causal effects while flexibly controlling for complex high-dimensional covariates (Hu et al., 2022).

Therefore, this paper further adopts the method proposed by Chernozhukov et al. (2018) to construct a dual machine learning model of the partially linear model (PLM) for re-estimation, in order to strengthen the robustness of the baseline conclusions. The specific settings are as follows:

The main regression equation is:

$$Y_{it} = \theta \cdot DID_{it} + g(X_{it}) + \varepsilon_{it} \quad (2)$$

$$E(\varepsilon_{it}|X_{it}, DID_{it}) = 0 \quad (3)$$

The equation for handling variables is set as follows:

$$DID_{it} = m(X_{it}) + v_{it} \quad (4)$$

$$E(v_{it}|X_{it}) = 0 \quad (5)$$

Where Y_{it} is the dependent variable for environmental pollution, DID_{it} is the policy variable for the demonstration zone, and θ is the core net policy effect of concern in this paper. X_{it} is the control variable matrix; $g(X_{it})$ and $m(X_{it})$ are unknown nonlinear disturbance functions, which respectively capture the nonlinear impact of high-dimensional control variables on pollution emissions and policy implementation probabilities; ε_{it} and v_{it} are random disturbance terms. The linear Lasso algorithm is used as the underlying machine learning predictor to fit $g(\cdot)$ and $m(\cdot)$.

Specifically, the estimation of $m(X_{it}) = X_{it}\gamma$ is achieved by solving the following Lasso regression:

$$\hat{\gamma} = arg\ min_{\gamma} \left\{ \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} (DID_{it} - X_{it}\gamma)^2 + \lambda_m \sum_{j=1}^{p} |\gamma_j| \right\} \tag{6}$$

The estimation of $g(X_{it}) = X_{it}\beta$ is similar:

$$\hat{\beta} = arg\ min_{\beta} \left\{ \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} (Y_{it} - X_{it}\beta)^2 + \lambda_g \sum_{j=1}^{p} |\beta_j| \right\} \tag{7}$$

4.2 Variable selection

4.2.1 Dependent Variable: Environmental Pollution Index (EPI)

This paper uses the Environmental Pollution Index (EPI) to measure the degree of environmental pollution in various regions. Following the approach of Deng and Zhang (2022), the construction of this index comprehensively considers multiple pollution sources: on the one hand, it selects the emissions of traditional industrial "three wastes" such as industrial wastewater, industrial sulfur dioxide, and industrial particulate matter as basic indicators; on the other hand, it introduces annual average PM2.5 concentration data for prefecture-level cities in China provided by the Atmospheric Composition Analysis Group of Dalhousie University to reflect air quality. The above data are standardized and weighted using the entropy method to finally derive the comprehensive environmental pollution index for each city.

To avoid estimation bias caused by differences in the dimensions of different pollution indicators, this paper first performs range standardization on the original indicators. Let X_{ijt} represent the original value of the j pollution indicator in city i in year t. Since all the indicators selected in this paper are negative, the standardization formula is as follows:

$$Z_{ijt} = \frac{x_{i\,jt} - \min(x_j)}{max(x_j) - min(x_j)} \tag{8}$$

Where $max(x_j)$ and $min(x_j)$ represent the maximum and minimum values of the j-th pollution indicator in the entire sample, respectively, and Zijt is the standardized pollution indicator. This processing maps the values of each indicator uniformly to the [0,1] interval, with larger values representing higher pollution levels.

Based on this, this paper uses the entropy method to determine the weights of each pollution indicator. Compared to the subjective weighting method, the entropy method can objectively determine the weights based on the information dispersion of the indicator itself. If a pollution indicator shows greater differences between cities and years, it contains more information and thus has a greater weight in the comprehensive index. The specific steps are as follows:

First, calculate the proportion of the j indicator in the city-year observations:

$$p_{ijt} = \frac{z_{ijt}}{\sum_{i=1}^{N} \sum_{t=1}^{T} z_{ijt}} \tag{9}$$

Second, calculate the information entropy of the j indicator:

$$e_j = -k \sum_{i=1}^{N} \sum_{t=1}^{T} p_{ijt}\, ln(p_{ijt}), \quad k = \frac{1}{ln(NT)} \#\ （10）$$

When $p_{ijt} = 0$, let $p_{ijt}\, ln(p_{ijt}) = 0$.

Third, calculate the information utility value of the j indicator:

$$d_j = 1 - e_j \tag{11}$$

Fourth, calculate the weight of the j indicator:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{12}$$

Finally, by weighting and summing the indicators according to their respective weights, the environmental pollution index of city i in year t is obtained:

$$EPI_{it} = \sum_{j=1}^{m} w_j\, z_{ijt} \tag{13}$$

Where m=4, corresponding to industrial wastewater discharge, industrial sulfur dioxide emissions, industrial particulate matter emissions, and annual average PM2.5 concentration, respectively. A larger value indicates a higher degree of comprehensive urban environmental pollution; conversely, a smaller value indicates a lower degree of urban environmental pollution. The EPI constructed in this paper can simultaneously cover water pollution, industrial exhaust gas pollution, particulate matter pollution, and air quality damage. Compared with single pollutant indicators, it can more comprehensively depict the environmental pollution dilemma faced by cities and is more in line with the research theme of this paper, "Can ecological civilization construction alleviate the urban environmental pollution dilemma?"

Table 1 Environmental pollution index measurement

Primary Indicator	**Secondary Indicator**	**Indicator Attribute**	**Information Entropy**	**Information Utility Value**	**Weight**
Industrial water pollution	Total wastewater discharge	Negative	0.9491	0.0509	0.2532
Industrial waste gas pollution	SO_2 emissions in waste gas	Negative	0.9268	0.0732	0.3644
Industrial solid waste pollution	Generation of general industrial solid waste	Negative	0.9403	0.0597	0.2971
Air quality pollution	Annual average concentration of PM2.5	Negative	0.9829	0.0171	0.0853
Composite Index	Environmental Pollution Index (EPI)	Negative	-	-	1.0000

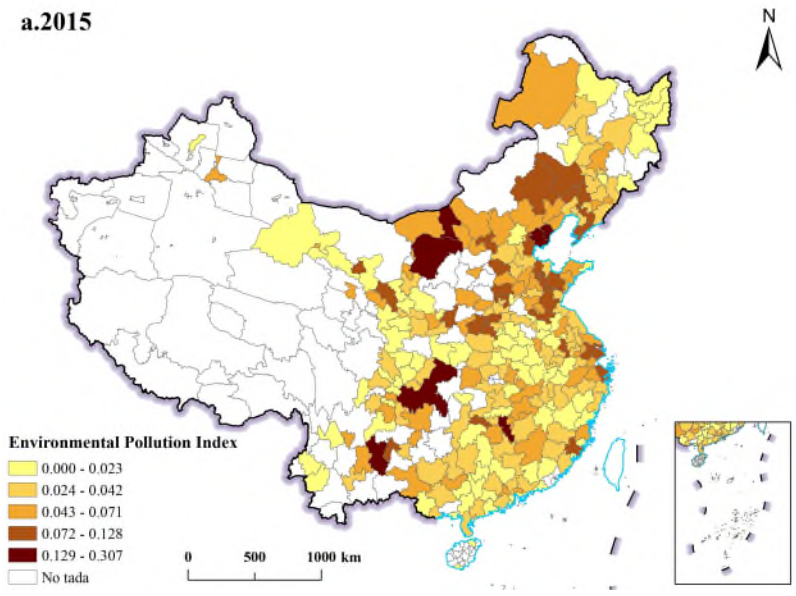


Figure 3 Environmental Pollution Index of Sample Cities (2015)

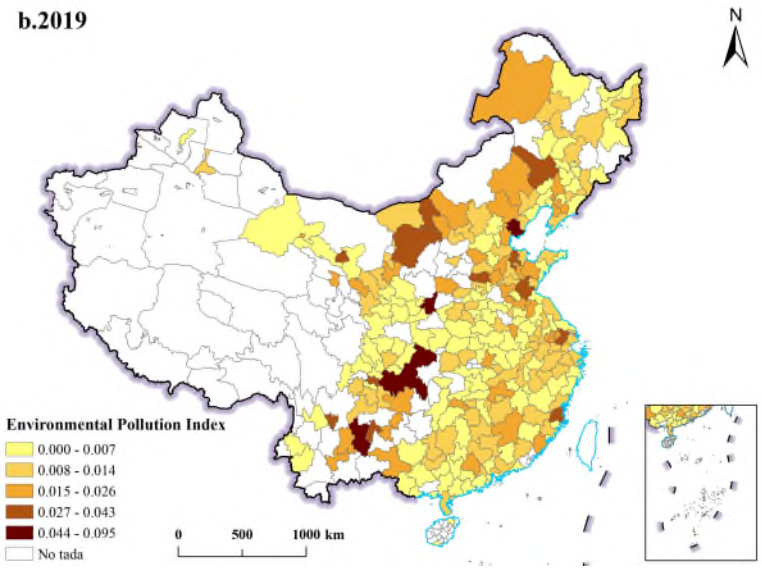


Figure 4 Environmental Pollution Index of Sample Cities (2019)

4.2.2 Core explanatory variable: National Ecological Civilization Demonstration Zone policy

For the national ecological civilization construction demonstration zone policy, if the city is an ecological civilization construction demonstration zone and the observation time is after the policy is implemented, the interaction item between $treat$ and $post$ will be 1; otherwise, it will be 0.

4.2.3 Mechanism variables

For Energy Consumption Intensity (PEC), based on the findings of Wu et al. (2025), which found that digital technology innovation mainly influences urban green development levels through optimizing energy structure, promoting industrial upgrading, and driving urban digital-intelligent integration, energy consumption intensity per unit of GDP is selected.

For Green Technology Innovation (PGT), based on the findings of Tao et al. (2021), which con-

cluded that the implementation of environmental target responsibility system helps promote the expansion of green patent applications, the number of green invention patent applications is selected and logarithmically processed to measure the city's digital technology innovation capability.

For Green Total Factor Productivity (PGE), based on the findings of Liu et al. (2026), which concluded that the "Zero Waste City" pilot policy mainly promotes the improvement of enterprise green total factor productivity through two paths: alleviating financing constraints and enhancing green innovation, the SBM-Malmquist-Luenberger index method is used to calculate the green total factor productivity of each prefecture-level city, referencing the approach of Shi and Li (2020)

4.2.4 Control variables

This study selected economic development level (per capita GDP, logarithmically calculated), financial development level (year-end balance of deposits and loans in financial institutions/GDP), level of foreign investment (actual utilization of foreign capital/GDP), and degree of government intervention (local government general budget expenditure/GDP) as control variables, along with population density, urbanization rate, fiscal investment intensity, and education expenditure level. The aim was to control for potential interference from regional differences on the environmental pollution index and ensure the robustness of the research findings. Sehrawat et al. (2015) found that economic growth and financial development play a key role in predicting changes in environmental quality and emphasized the moderating effect of macroeconomic variables on environmental degradation pathways.

4.3 Data sources and data processing

From 2013 to 2014, six departments, including the National Development and Reform Commission, announced 100 demonstration zones for ecological civilization construction in batches, including 47 prefecture-level cities, 4 provinces, and 49 districts/counties, special areas, or river basins. Considering the different policy effects of the demonstration zone policies on different provincial and municipal divisions, following the approach of Zhang and Wang (2024), city data from the four provinces (including Fujian) in the demonstration zones were removed from the total sample. Simultaneously, to improve the accuracy of the estimation, the prefecture-level cities corresponding to the districts/counties were excluded, with the 47 prefecture-level cities on the list serving as the experimental group and the remaining 166 prefecture-level cities as the control group. Finally, panel data from 213 prefecture-level cities from 2010 to 2021 were selected for analysis. The data came from the China Urban Statistical Yearbook, the China Intellectual Property Database, and statistical yearbooks of various provinces and cities. Missing data were supplemented using the mean method, aiming to capture the long-term relationship between ecological civilization construction demonstration zones and the environmental pollution index.

Table 2 presents the descriptive statistics of the variables.

Table 2 Descriptive statistics

Variable type	Variable name	Symbol	Mean	Std. Dev.	Min	Max
Explanatory variable	Ecological Civilization Zone	did	0.119	0.324	0	1
Dependent variable	Environmental Pollution Index	EPI	0.0303	0.0373	0	0.433
Control variables	Economic development level	EDL	10.72	0.719	8.555	13.19
	Financial development level	FDL	2.506	1.226	0.588	21.30
	Openness	OPN	0.00259	0.00269	0	0.0294
	Government intervention	GID	0.198	0.102	0.0439	0.916

Mediating variables	Energy consumption intensity	PEC	0.0997	0.108	0.00587	1.792
	Green technological innovation	PGT	4.002	1.863	0	10.07
	Green total factor energy efficiency	PGE	0.339	0.132	0.103	1.177
	Observations	**N**	**3132**			

5. Empirical analysis

5.1 Baseline regression results

Table 3 shows the baseline regression results of the impact of the National Ecological Civilization Construction Demonstration Zone policy on the urban environmental pollution index, with column (1) showing the results without control variables. Without any control variables, the difference-in-differences coefficient was significant at the 1% level. After successively adding control variables (economic development level, financial development level, degree of openness to the outside world, and degree of government intervention), the model fit was good, and the difference-in-differences coefficient was significant at the 1%–5% level, indicating that the National Ecological Civilization Construction Demonstration Zone has a significant pollution reduction effect. Column (5) shows that the establishment of the National Ecological Civilization Construction Demonstration Zone reduced the environmental pollution index of the experimental group cities by 0.53% compared to the control group cities, verifying Hypothesis 1 proposed in this paper, indicating that ecological civilization construction has a positive effect on urban environmental improvement and transformation development. However, its effect is lower than that without any control variables, and its effect decreases as the number of control variables increases. This may be because, without controlling for factors such as the level of economic development, the level of financial development, the degree of openness to the outside world, and government intervention, the difference-in-differences coefficient absorbs the environmental pollution improvement effect of these variables to some extent, resulting in a certain overestimation of the baseline regression results. After including relevant control variables, the policy effect is identified more "purified", and its estimation results are closer to the real pollution reduction and emission reduction effect of the national ecological civilization construction demonstration zone policy.

Table 3 Baseline results

	(1)	(2)	(3)	(4)	(5)
	EPI	EPI	EPI	EPI	EPI
did	-0.0292***	-0.00961***	-0.00630**	-0.00528**	-0.00530**
	(-11.22)	(-3.44)	(-2.31)	(-2.09)	(-2.13)
EDL		-0.0445***	-0.0378***	-0.0375***	-0.0379***
		(-11.96)	(-9.18)	(-9.60)	(-9.95)
FDL			-0.0123***	-0.0113***	-0.00877**
			(-3.57)	(-3.43)	(-2.49)
OPN				2.172***	2.251***
				(2.94)	(3.08)
GID					-0.0723**
					(-2.44)
_cons	0.0338***	0.509***	0.468***	0.455***	0.468***
	(109.47)	(12.78)	(11.48)	(11.96)	(12.19)

N	3132	3132	3132	3132	3132
r2	0.0884	0.241	0.315	0.327	0.334
F	125.9	93.56	69.14	56.09	59.03

[1] p < 0.10, ** p < 0.05, *** p < 0.01. Same below.

5.2 Robustness checks

5.2.1 Parallel trend test

Parallel trends are an important prerequisite for multi-period difference-in-differences models, requiring that the environmental pollution indices of the experimental and control cities show a common trend before the implementation of the national ecological civilization construction demonstration zone policy. This paper draws on the relevant research of Beck et al. (2010) to conduct a parallel trend test.

$$y_{it} = \alpha + \sum_{k=-4}^{k=4} \beta_k D_{t_0+k,it} + \rho' X_{it} + \mu_i + \varepsilon_{it} \tag{14}$$

In the formula, $D_{t_0+k,it}$ represents a series of time dummy variables, where t_0 represents the first year of the establishment of the ecological civilization demonstration zone, and k represents the relative time years before or after the year of establishment. Due to the large number of sample periods involved, the data from the four years before and after the policy implementation were shortened and merged with the data from the -4th and 4th periods. To avoid the influence of multicollinearity, the year before the implementation year of the ecological civilization demonstration zone was used as the baseline period, resulting in the results shown in Figure 5. As shown in Figure 5, the regression results for the four years before the establishment of the national ecological civilization demonstration zone were basically insignificant or positively significant, while the coefficients for each period after the establishment of the national ecological civilization demonstration zone were all negatively significant, indicating that the research sample passed the parallel trend test and the policy effect was significant.

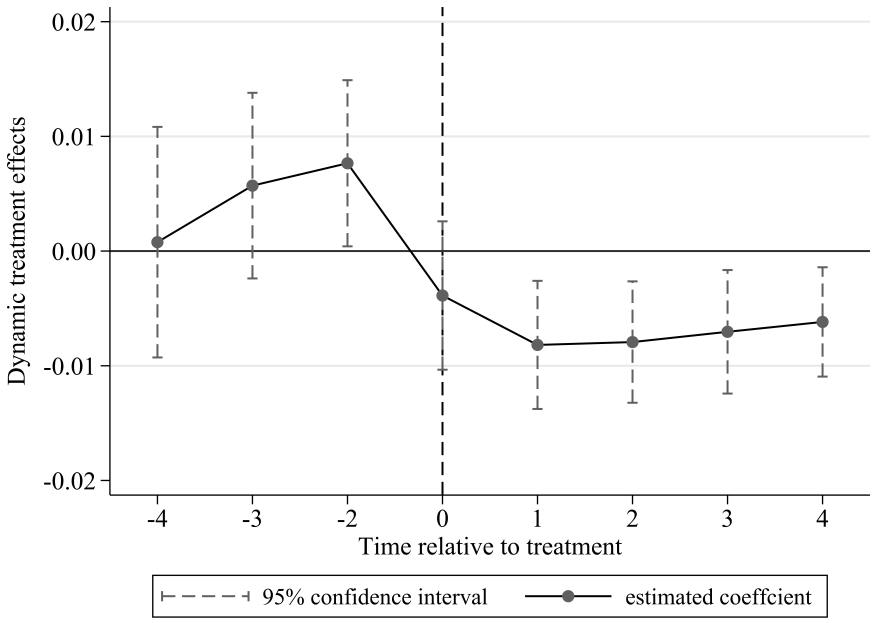


Figure 5 Parallel trend test

Furthermore, to account for potential nonlinear trend deviations, this paper defines the pre-policy linear counterfactual trend as $\hat{\beta}_k^{linear}$, and allows for nonlinear deviations within a certain range:

$$\hat{\beta}_k^{linear} = a + bk \tag{16}$$

$$\hat{\beta}_k^{lower} = \hat{\beta}_k^{linear} - M|k| \tag{17}$$

$$\hat{\beta}_k^{upper} = \hat{\beta}_k^{linear} + M|k| \tag{18}$$

In the figure, the solid black line represents the event study estimate, the dashed line represents the linear counterfactual trend obtained based on the pre-policy implementation sample, and the gray shaded area represents the sensitivity interval formed under the maximum allowable nonlinear deviation magnitude M. Therefore, even considering potential nonlinear parallel trend violations, the core conclusions of this paper still possess strong robustness.

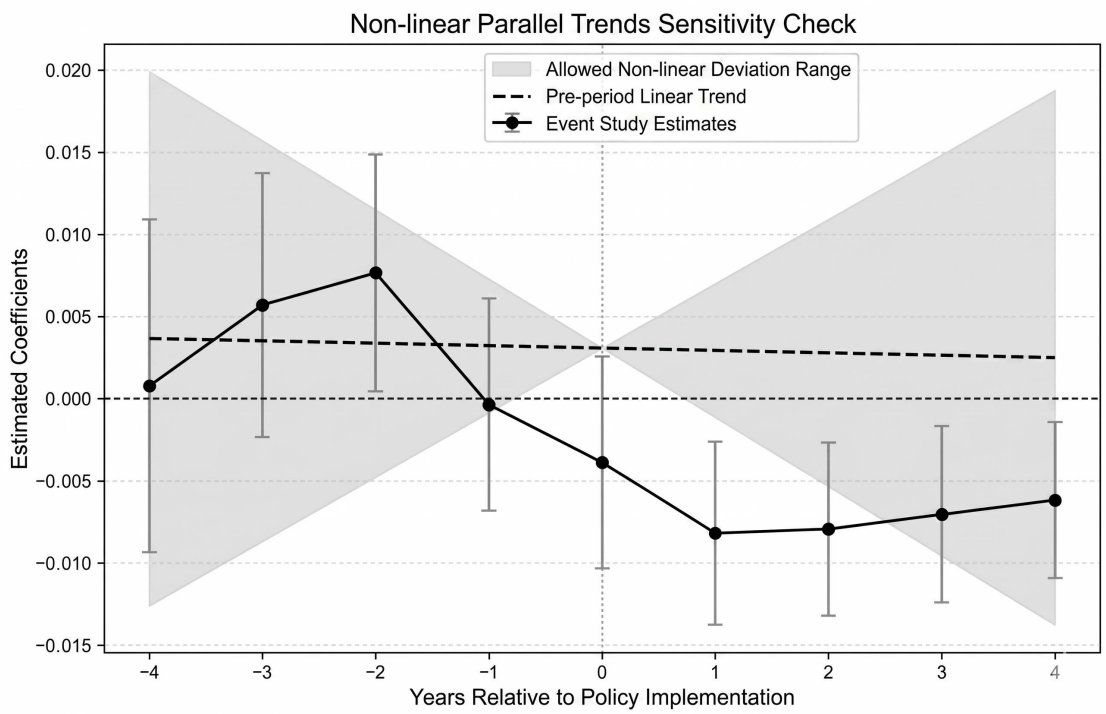


Figure 6 Nonlinear parallel trend sensitivity test

5.2.2 Placebo test

In addition to the factors already controlled for, some unobservable random factors can affect the estimation results. Therefore, this paper further conducts a placebo test. By randomly selecting 261 pseudo-samples from ecological civilization demonstration zones during the sample period of 2007-2021 as a pseudo-treatment group, these samples were substituted into the baseline model for regression analysis. This randomization process was repeated 500 times to obtain the regression equation coefficients, t-values, and p-values of the virtual experimental group. A virtual coefficient distribution map and coefficient probability density were plotted. Figure 5 shows that the mean of the simulated estimated coefficients is close to zero, basically following a normal distribution, and the p-values of most samples exceed 0.10. This indicates that the randomized policy did not affect the environmental pollution index, ruling out the possibility that the pollution reduction and emission reduction effects of the national ecological civilization construction demonstration zones were caused by unobservable factors.

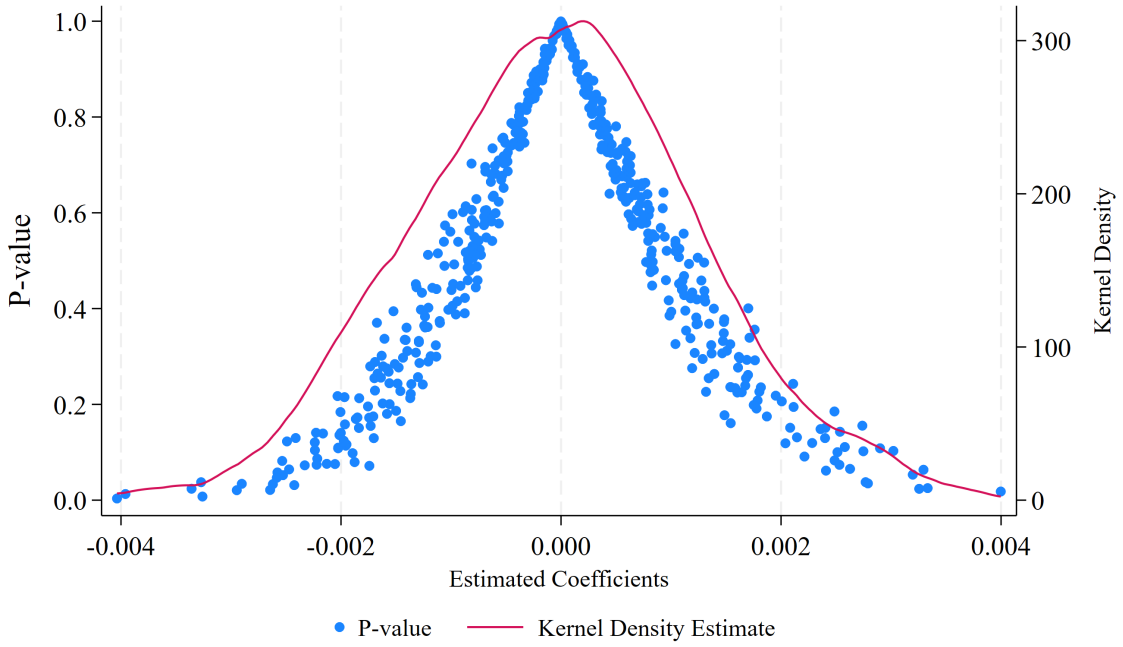


Figure 7 Placebo test

5.2.3 Adding control variables

(1) Adding control variables. To minimize estimation bias caused by omitted variables, this paper re-examines the baseline regression model by adding population density, urbanization rate, fiscal investment intensity, and education expenditure level. As shown in column (1) of Table 4, the effect of `did` on environmental pollution decreases after adding control variables, but remains significant at the 10% level. This indicates that the construction of national ecological civilization demonstration zones can reduce the environmental pollution index, and the regression results have strong robustness.

(2) Tailing. The control variables of the sample are subjected to two-sided 1% tailing to avoid the influence of least significant and most significant outliers. As shown in column (2) of Table 4, the coefficients of the core explanatory variables are significantly negative at the 5% level, which is consistent with the baseline regression results. This indicates that the conclusions of this paper are not affected by extreme outliers and have good robustness.

Table 4 Robustness check results

	(1)	(2)
	Adding control variables	Tailing
did	-0.00486*	-0.00560**
	(-1.83)	(-2.46)
EDL	-0.0316***	-0.0353***
	(-8.00)	(-10.72)
FDL	-0.00783**	-0.00883**
	(-2.37)	(-2.49)
OPN	2.257***	1.861***
	(3.14)	(3.14)

GID	-0.0702**	-0.0726**
	(-2.36)	(-2.58)
POP	-0.0311	
	(-1.54)	
URB	-0.0545**	
	(-2.07)	
FIS	-0.000507	
	(-1.12)	
EDU	0.00857	
	(0.21)	
_cons	0.600***	0.440***
	(5.17)	(13.09)
N	3132	3132
r2	0.344	0.394
F	35.66	71.23

5.3 Mechanism analysis

From the perspective of exploring the internal mechanisms of environmental pollution control, this paper examines the mechanisms by which the construction of national ecological civilization demonstration zones reduces the environmental pollution index (EPI) from three aspects: energy consumption intensity, green innovation technology, and green total factor productivity (PGE).

As shown in Table 4, column (1) shows the regression results of the main model. The estimated coefficient of the core explanatory variable did is significantly negative at the 1% level, indicating that the construction of national ecological civilization demonstration zones has a significant inhibitory effect on the EPI. Regarding the mechanism test, the *did* coefficient in column (2) is significantly negative at the 5% significance level, indicating that the construction of demonstration zones is conducive to significantly reducing energy consumption intensity (PEC). Furthermore, the *did* coefficients in columns (3) and (4) are significantly positive at the 1% significance level, indicating that the construction of demonstration zones can effectively promote the progress of green innovation technology (PGT) and improve green total factor productivity (PGE). Therefore, the construction of national ecological civilization demonstration zones can effectively reduce the urban environmental pollution index by reducing energy consumption intensity, promoting green technology innovation, and improving green total factor productivity, thus verifying the mechanism hypothesis **H2** mentioned above.

Table 5 DID mechanism test

Variable	(1) EPI	(2) PEC	(3) PGT	(4) PGE
DID	-0.004***	-0.011**	0.639***	0.026***
	(-2.97)	(-2.57)	(9.24)	(3.75)
Control Variables	Yes	Yes	Yes	Yes
N	3132	3132	3132	3132

5.4 Dual machine learning results

5.4.1 Baseline regression results

In this study, the impact of national ecological civilization construction demonstration zones on the

environmental pollution index was investigated in depth using a dual machine learning model. In the baseline setting, the model adopted a 1:4 sample split ratio and used the LassoCV algorithm as the prediction basis. The regression analysis in column (1) of Table 6 shows that the regression coefficient of the demonstration zone construction is significantly negative at the 1% significance level, preliminarily verifying the policy's inhibitory effect on pollution emissions. In column (2), a quadratic term of the control variable was introduced to eliminate nonlinear interference, but the coefficient of the core variable remained significantly negative. Secondly, in columns (3) and (4), the sample split ratio was adjusted to 1:2 and 1:7 respectively using K-fold cross-validation to eliminate bias caused by random splitting. Finally, columns (5) and (6) attempted to replace the original partially linear Lasso algorithm with a nonlinear Lasso algorithm. All of the above multi-dimensional tests demonstrate that the construction of national ecological civilization construction demonstration zones can effectively reduce pollution, a conclusion with high robustness, further supporting the **H1** research hypothesis of this paper.

Table 6 DDML Regression Results

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Model Description	Baseline Model	Quadratic Model	K=3	K=8	Alternative Method	Alternative Method
DID	-0.00810***	-0.00794***	-0.00848***	-0.00762***	-0.00782***	-0.00797**
	(0.00145)	(0.00141)	(0.00150)	(0.00142)	(0.00150)	(0.00146)
Linear Controls	Yes	Yes	Yes	Yes	Yes	Yes
Quadratic Controls	No	Yes	Yes	Yes	No	Yes
Individual FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	3132	3132	3132	3132	3132	3132

The baseline regression analysis confirms that the construction of National Ecological Civilization Demonstration Zones (ECDZs) exerts a significant average suppressive effect on environmental pollution. However, given China's vast territory, cities exhibit substantial heterogeneity in terms of resource endowments, population agglomeration, and environmental and geographical conditions. As a result, the effectiveness of policy implementation may vary across different urban contexts. Ignoring such heterogeneity may obscure the true policy effects in specific types of cities.

To address this issue, this study further conducts heterogeneity analysis by dividing the full sample along three dimensions: city size, resource endowment, and urban environmental classification. This subgroup analysis aims to examine whether the environmental effects of the Ecological Civilization Demonstration Zone policy are asymmetric across different urban settings, thereby providing more nuanced empirical evidence to support the formulation and implementation of place-based and differentiated environmental policies.

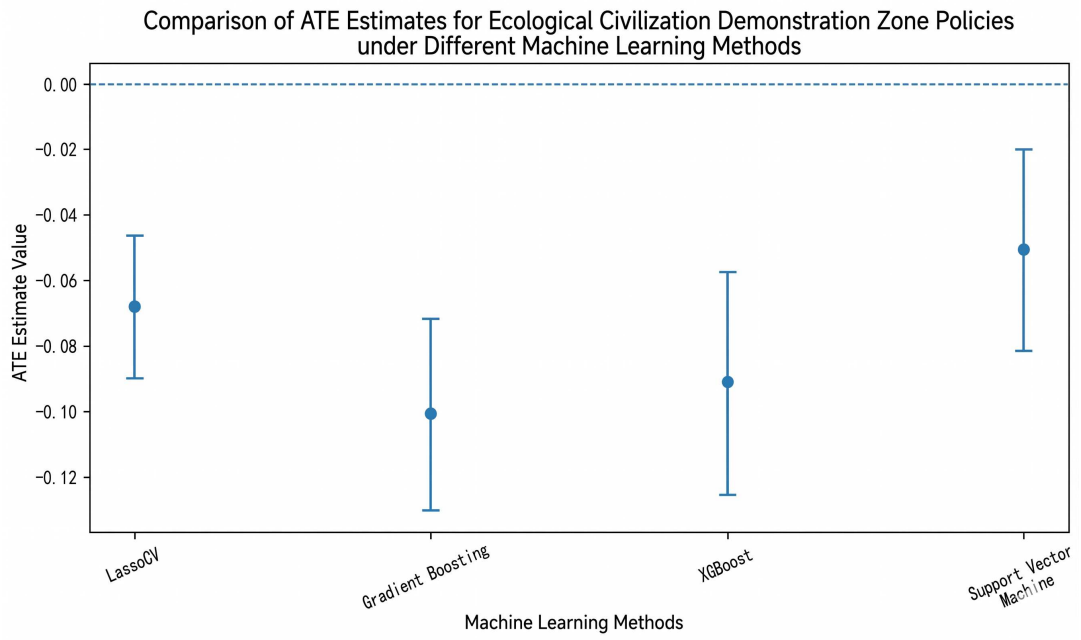


Figure 8 Comparison chart of ATE estimation methods for various machine learning methods

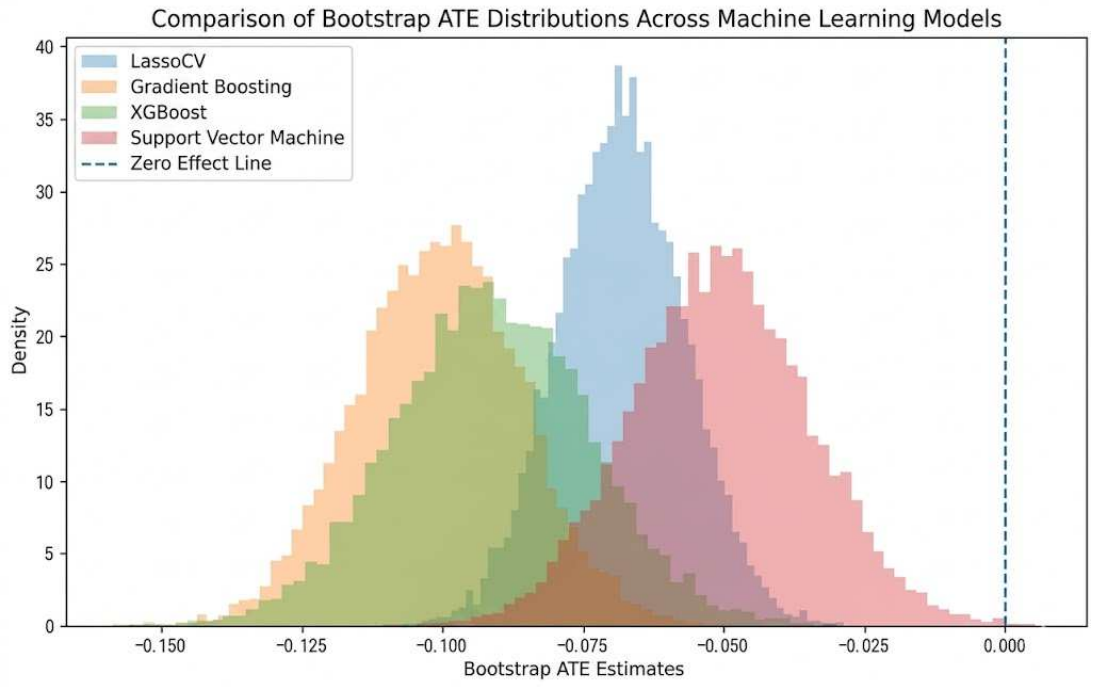


Figure 9 Bootstrap ATE distribution comparison

5.4.2 Mechanism test

To further investigate the mechanism pathways, this section references the research of Farbmacher et al. (2022), in which the mechanism pathways were again tested using dual-mode machine learning (DDML).

The results in Table 7 show that: in column (1), the coefficient of policy effect on energy consumption intensity is significantly negative, indicating that the construction of the demonstration zone has suppressed environmental pollution by reducing energy consumption intensity; in column (2), the

coefficient of demonstration zone construction on green innovation technology is significantly positive, indicating that the policy has generated emission reduction effects by inducing green technology innovation; in column (3), the coefficient of policy on green total factor productivity is significantly positive, confirming that improving energy efficiency is an important tool for the demonstration zone to play a role in environmental governance. These mechanism tests verify research hypothesis H2.

In summary, the impact of the construction of national ecological civilization demonstration zones on the environmental pollution index mainly comes from the following three aspects: First, by reducing energy consumption intensity, pollution emissions from energy input are reduced at the source; second, by inducing the progress of green innovation technology, emission reduction and decarbonization are achieved through technological means; third, by improving green total factor productivity, resource allocation is optimized to reduce environmental load. The combined effect of these mechanisms and pathways ultimately resulted in a significant inhibitory effect of the demonstration zone construction on environmental pollution.

Table 7 DDML mechanism test

	(1)	(2)	(3)
Variables	PEC	PGT	PGE
DID	-0.0281**	0.399***	0.0235*
	(0.0116)	(0.122)	(0.0143)
Linear Terms Controlled	Yes	Yes	Yes
Quadratic Terms Controlled	Yes	Yes	Yes
Individual Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes
N	3132	3132	3132

5.5 Heterogeneity analysis

5.5.1 City size

City size is closely associated with regional resource allocation capacity, the intensity of environmental governance investment, and the degree of industrial agglomeration, all of which may influence policy effectiveness. To more precisely identify differences in policy sensitivity across cities of different sizes, this study follows the classification criteria specified in the *Notice on Adjusting the Standards for City Size Classification* issued by the State Council. Specifically, 106 cities with populations exceeding one million are classified into four categories: megacities, super-large cities, large cities, and small and medium-sized cities, which are coded from 1 to 4, respectively. Separate regressions are conducted for each subgroup to examine heterogeneous policy effects.

Columns (1)–(4) of Table 5 report the regression results for megacities, super-large cities, large cities, and small and medium-sized cities, respectively. The results in column (4) show that the DID coefficient is statistically significant at the 10% level for small and medium-sized cities. This finding may be explained by the relatively late start of environmental governance in these cities, where extensive development patterns have resulted in substantial room for marginal environmental improvement. Once subjected to the stringent constraints and incentives associated with the demonstration zone policy, such cities can achieve rapid emission reductions through measures such as shutting down highly polluting enterprises and upgrading basic pollution control facilities, thereby exhibiting a notable latecomer advantage.

In contrast, although the estimated coefficients for larger cities (megacities, super-large cities, and large cities) are negative, they are not statistically significant. One possible explanation is that large cities have long been the primary targets of national environmental regulation and therefore already operate at relatively high levels of environmental governance. As pollution control deepens, further emission reductions face diminishing marginal returns, making it difficult for the demonstration zone policy alone to generate significant short-term effects. In addition, the large population size and economic scale of these cities create rigid emission demands, which may dilute the net impact of the policy.

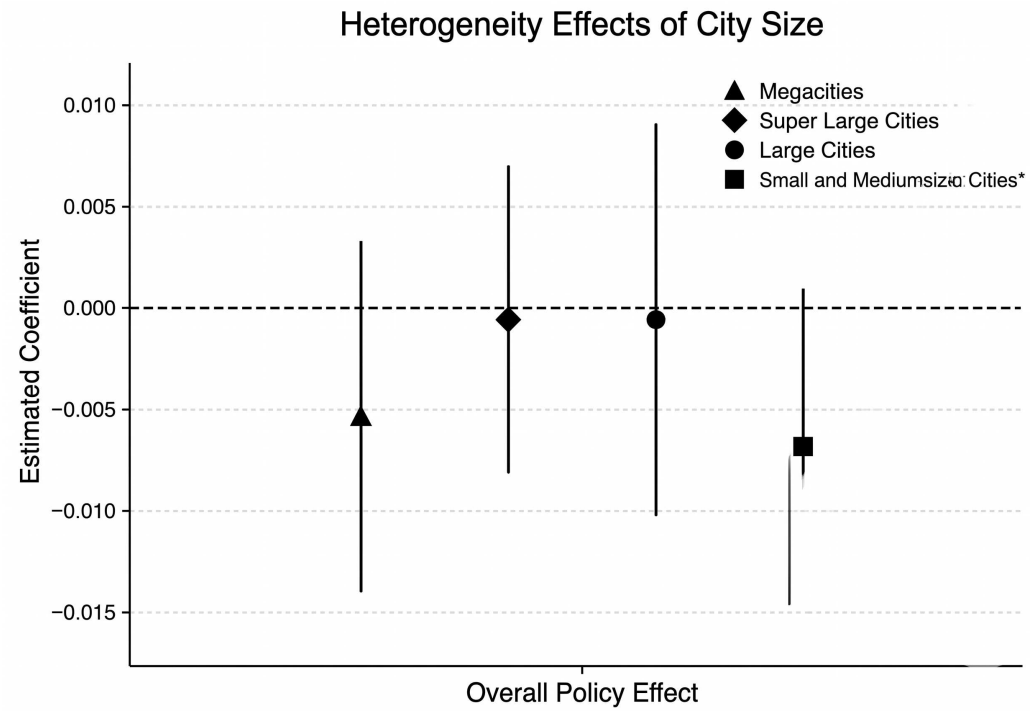


Figure 10 Heterogeneity Effects of City Size

5.5.2 Resource-based cities

Cities differ markedly in resource endowments and development models, which can profoundly shape the effectiveness of environmental policies. Resource-based cities play a strategic role in ensuring national energy security, but long-term overexploitation and the concentration of high-pollution industries often exacerbate conflicts between economic growth and ecological protection, leading to a "resource curse." To examine whether the National Ecological Civilization Demonstration Zone policy can break this path dependence, a dummy variable identifying resource-based cities is constructed based on the *National Plan for Sustainable Development of Resource-Based Cities (2013–2020)*.

Column (5) of Table 5 reports the regression results for resource-based cities. The results show that the effect of the demonstration zone policy on the environmental pollution index is positive and statistically insignificant. This outcome may reflect a green paradox effect: facing expectations of stricter environmental regulation associated with demonstration zone designation, resource-based firms may accelerate extraction and production activities before full policy enforcement to maximize short-term profits. Such strategic "front-loading" behavior can lead to a temporary increase in pollutant emissions, resulting in an insignificant and positive estimated coefficient.

In contrast, the DID coefficient for non-resource-based cities is negative and statistically significant at the 1% level, indicating that the demonstration zone policy effectively suppresses environmental pollution in these cities. Non-resource-based cities are less dependent on energy-intensive industries and typically face lower resistance and compliance costs in environmental governance. Consequently, policy signals can be more smoothly transmitted to firms, inducing cleaner production and resulting in more pronounced pollution reduction effects.

5.5.3 Urban environmental classification

Cities also differ in their baseline environmental governance capacity and historical regulatory intensity, which may affect the marginal impact of demonstration zone policies. Environmentally key cities have long been subject to stringent regulation and generally possess more advanced monitoring systems and pollution control infrastructure, but they also face significant legacy pollution burdens. To assess whether the demonstration zone policy generates additional effects beyond existing regulation, this study classifies cities based on the List of National Key Environmental Protection Cities during the Eleventh Five-Year Plan period.

Column (7) of Table 5 presents the regression results for environmentally key cities. Although the DID coefficient is negative, it is not statistically significant, suggesting that the demonstration zone policy does not generate a significant additional pollution reduction effect in these cities. A plausible explanation is the presence of increasing marginal abatement costs: in cities where low-cost end-of-pipe treatment measures have already been widely adopted, further emission reductions require deep technological innovation or industrial restructuring, both of which entail high marginal costs. During the initial phase of demonstration zone construction, these challenges may offset policy incentives, resulting in insignificant short-term effects.

Column (8) of Table 5 reports the results for non-key environmental cities. In this subgroup, the DID coefficient is negative and statistically significant at the 10% level, indicating that the demonstration zone policy effectively reduces environmental pollution. Non-key cities typically face weaker baseline regulation and therefore possess greater marginal potential for environmental improvement. The introduction of the demonstration zone policy serves as a strong external constraint that fills institutional gaps. Compared with the structural pollution challenges faced by key cities, non-key cities can achieve rapid improvements through relatively low-cost measures, such as upgrading basic pollution control facilities and closing small, highly polluting enterprises, thereby exhibiting a pronounced latecomer effect.

Table 8 Heterogeneity regression results

	City size				Resource-based cities		Urban environmental classification	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	EPI	EPI	EPI	EPI	EPI	EPI	EPI	EPI
did	-0.00534	-0.000581	-0.000592	-0.00685*	0.00409	-0.00901***	-0.00340	-0.00491*
	(-1.21)	(-0.15)	(-0.12)	(-1.72)	(0.99)	(-2.93)	(-0.79)	(-1.97)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	0.486***	0.325***	0.441***	0.0947	0.466***	0.450***	0.759***	0.308***
	(5.88)	(6.89)	(6.40)	(1.20)	(7.63)	(9.99)	(10.45)	(8.94)
N	984	864	912	372	1212	1920	1260	1872

r2	0.405	0.361	0.340	0.421	0.369	0.369	0.410	0.348

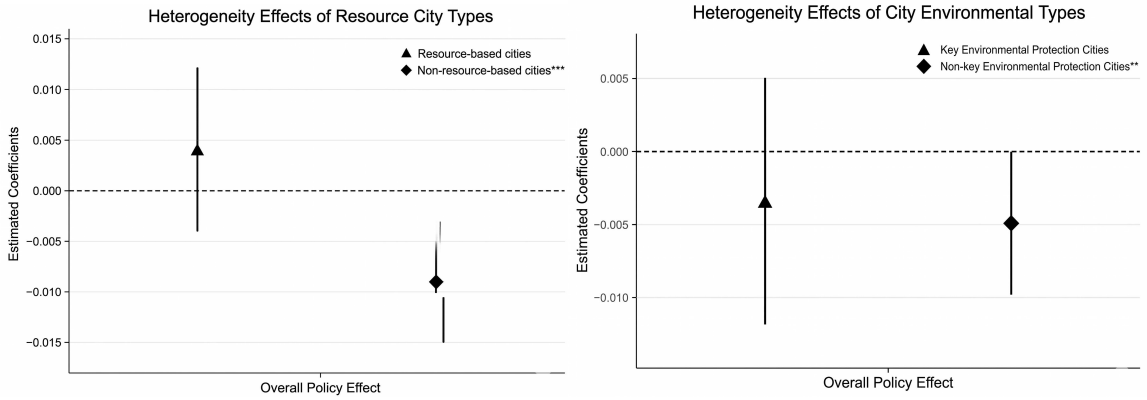


Figure 11 Heterogeneity effects of different city types

5.5.4 Heterogeneity of environmental pollution

To further examine the asymmetric impact of the construction of ecological civilization demonstration zones on regions with different environmental pollution endowments, this paper uses a quantile regression model for parameter estimation. The results show that, in a mean sense, the coefficient of the ecological civilization demonstration zone policy (did) is significantly negative, indicating that the policy has generally effectively reduced the regional environmental pollution index (EPI). As the EPI gradually increases, the absolute value of the estimated did coefficient shows a clear increasing trend. This suggests that the pollution reduction and carbon reduction effect of the ecological civilization demonstration zone policy has a typical "timely help" rather than a "finishing touch" characteristic. In regions with relatively light environmental pollution, the emission reduction effect of the demonstration zone policy is relatively weak.

This may be because: for regions with relatively good environmental quality and light pollution, their environmental governance already has a certain foundation, the marginal technical cost of further emission reduction is high, and the marginal improvement space of the policy is limited; conversely, for heavily polluted regions, their extensive economic characteristics are often more pronounced. The introduction of the ecological civilization demonstration zone policy is usually accompanied by stricter environmental regulations, environmental assessment targets, and strong administrative intervention. This stringent "reverse forcing mechanism" can quickly cut off high-pollution emission sources and significantly reduce the space for pollution emissions, thereby releasing huge environmental governance dividends in the short term, proving the effectiveness of the policy in heavily polluted areas.

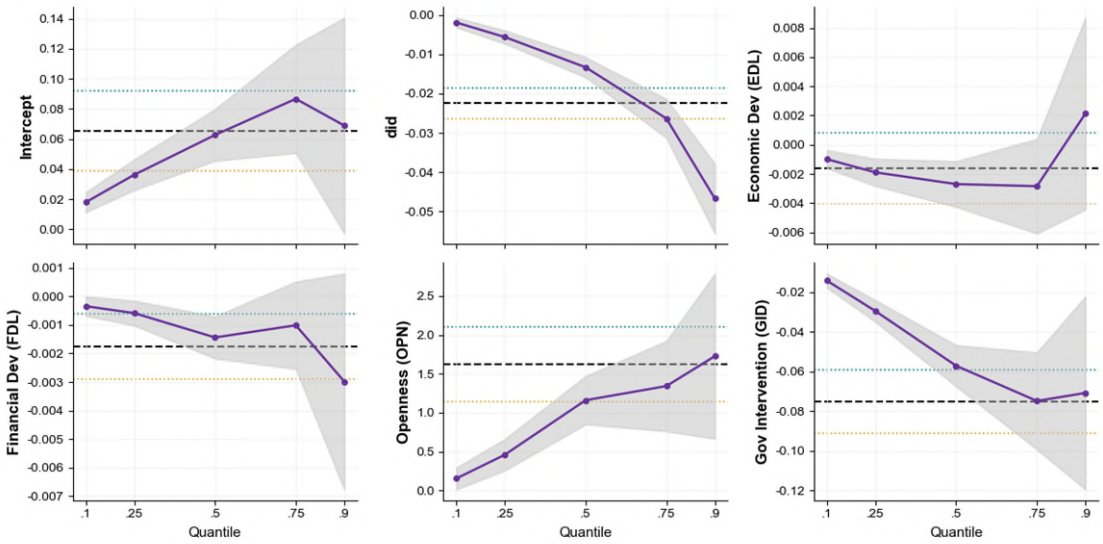


Figure 12 Trend chart of different quantile coefficient values

6. Conclusions and policy implications

6.1 Conclusions

China has steadily progressed towards the goals of high-quality development and ecological civilization construction, and urgently needs to cultivate new drivers of green development through green technology innovation. Accurately assessing the role of ecological civilization demonstration zones in promoting environmental pollution control is of great significance for exploring ecological civilization construction models that suit my country's national conditions and improving the effectiveness of environmental governance. Therefore, this paper uses panel data from 213 prefecture-level cities in my country from 2010 to 2021, and employs a multi-period difference-in-differences and dual machine learning model to empirically examine the impact of the establishment of ecological civilization pilot demonstration zones on environmental pollution levels. The main research conclusions are as follows:

(1) The results of the multi-period difference-in-differences and dual machine learning model show that national ecological civilization construction demonstration zones significantly and effectively alleviate urban environmental pollution. This finding is supported by several robustness tests.

(2) This paper constructs an environmental pollution index at a broader pollution level to comprehensively and accurately reflect the pollution reduction effect of policies. Mechanism testing reveals that national ecological civilization construction demonstration zones effectively suppress urban environmental pollution by promoting energy structure optimization, green technology innovation, and green total factor productivity. (3) Heterogeneity analysis shows that the pollution reduction effect of the demonstration zone construction breaks the stereotype of "prioritizing large cities and major towns", and is more significant in non-resource-based small and medium-sized cities that have broken away from industrial path dependence and have a higher marginal regulatory space. In addition, from the perspective of urban environmental characteristics, compared with key environmental protection cities that already have high environmental protection thresholds, the pollution reduction dividend of the demonstration zone is more fully released in non-key environmental protection cities, and its improvement effect is more obvious.

6.2 Policy implications

Based on the above research findings, the policy implications of this paper are as follows:

(1) Comprehensively refine the pollution reduction experience of demonstration zones and improve the long-term mechanism of "pilot-promotion". Given the significant role of national ecological civilization construction demonstration zones in alleviating urban environmental pollution, the successful models of each pilot project should be systematically summarized and elevated to institutional norms. By steadily expanding the scope of demonstration zones, the local pollution reduction benefits can be transformed into nationwide universal experiences, providing a solid institutional guarantee for achieving high-quality urban development.

(2) Focus on core pollution reduction mechanisms and strengthen green technology empowerment and energy efficiency improvement. Mechanism analysis shows that reducing energy consumption intensity, promoting green technology innovation, and improving green total factor productivity are key paths to pollution reduction. Therefore, policy efforts should focus on: strictly enforcing energy efficiency standards to effectively reduce energy consumption intensity; increasing policy support and funding for green technology innovation; and improving the resource recycling system to comprehensively enhance green total factor productivity, ultimately achieving a win-win situation for economic growth and environmental protection.

(3) Implement differentiated and precise governance to fully unleash the pollution reduction potential of various types of cities. Policy formulation needs to break away from the stereotype of "prioritizing large cities and major towns". On the one hand, non-resource-based small and medium-sized cities should be encouraged to take the lead in exploring new green and low-carbon models by taking advantage of their higher marginal regulatory space, and environmental protection investment in non-key environmental protection cities should be increased to fully release their pollution reduction dividends. On the other hand, large cities need to focus on solving the problem of "agglomeration is not economical", resource-based cities should accelerate the elimination of industrial path dependence, and key environmental protection cities need to deepen institutional and mechanism innovation to overcome the marginal diminishing effect of governance.

CRediT authorship contribution statement

Xingcheng Lu: Conceptualization, Data Curation, Methodology, Validation, Investigation, Formal analysis, Writing-original draft.

Haowen Jin: Conceptualization, Methodology, Validation Formal analysis, Writing-original draft

Xiaoge Xiong: Conceptualization, Methodology, Validation Formal analysis, Writing-original draft

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding Statement

This research received no external funding.

References

Beck, T., Levine, R., & Levkov, A. (2010). Big bad banks? The winners and losers from bank deregulation in the United States. *The Journal of Finance*, 65(5), 1637–1667. https://doi.org/10.1111/j.1540-6261.2010.01589.x

Chernozhukov, V., Chetverikov, D., Demirer, M., et al. (2018). Double/debiased machine learning for treatment and structural parameters. *The Econometrics Journal*, 21(1), C1–C68. https://doi.org/10.1111/ectj.12097

Deng, R., & Zhang, A. (2022). The impact and mechanism of digital economy development on environmental pollution in Chinese cities. *South China Journal of Economics*, (2), 18–37. https://doi.org/10.19592/j.cnki.scje.390724

Farbmacher, H., Huber, M., Laffers, L., Langen, H., & Spindler, M. (2022). Causal mediation analysis with double machine learning. *The Econometrics Journal*, 25(2), 277–300.

Guo, Q., & Xiong, W. (2023). How does the construction of national ecological civilization demonstration zones affect green development welfare? *China Population, Resources and Environment*, (7), 18–29.

Guo, Y., Yu, D., Zou, M., et al. (2024). Assessment of ecological civilization construction from the perspective of environment and health in China. *Eco-Environment & Health*, 3(1), 281–289. https://doi.org/10.1016/j.eehl.2024.02.008

Hu, J., Hu, M., & Zhang, H. (2023). Has the construction of ecological civilization promoted green technology innovation? *Environmental Technology & Innovation*, 29, 102960. https://doi.org/10.1016/j.eti.2022.102960

Hu, S., Jiang, H., & Xie, H. (n.d.). Theory and application of double machine learning: From "black box" to "toolbox".

Jiang, Y., Guo, Y., Bashir, M. F., et al. (2024). Do renewable energy, environmental regulations and green innovation matter for China's zero carbon transition? Evidence from green total factor productivity. *Journal of Environmental Management*, 352, 120030. https://doi.org/10.1016/j.jenvman.2024.120030

Kahouli, B., Hamdi, B., Nafla, A., et al. (2022). Investigating the relationship between ICT, green energy, total factor productivity, and ecological footprint: Evidence from Saudi Arabia. *Energy Strategy Reviews*, 42, 100871. https://doi.org/10.1016/j.esr.2022.100871

Lan, X., & Hu, Z. (2024). The impact effect and mechanism of national ecological civilization demonstration zones on ecological environmental quality. *Journal of Beijing Jiaotong University (Social Sciences Edition)*, (1), 138–154. https://doi.org/10.16797/j.cnki.11-5224/c.20240018.007

Li, C., Zhang, S., & Yan, B. (2024). Impact of ecological civilization demonstration zones on urban green innovation resilience: Evidence from China. *Frontiers in Environmental Science*, 12, 1514582. https://doi.org/10.3389/fenvs.2024.1514582

Li, L., Guo, J., Wu, X., et al. (2025). Does promoting new urbanization help mitigate environmental pollution? Evidence from China's pilot policies. *Journal of Environmental Management*, 388, 125925. https://doi.org/10.1016/j.jenvman.2025.125925

Li, Q., Feng, Y., Wang, R., et al. (2024). Impact of national ecological civilization construction demonstration zones on corporate ESG. *Ecological Indicators*, 166, 112463. https://doi.org/10.1016/j.ecolind.2024.112463

Liang, Q., Xiao, S., & Liu, Y. (2022). The impact and mechanism of environmental policies on urban ecological efficiency: A quasi-natural experiment based on national ecological civilization demonstration zones. *Journal of Xi'an Jiaotong University (Social Sciences Edition)*, (3), 61–70. https://doi.org/10.15896/j.xjtuskxb.202203007

Liu, M., Liang, H., Liu, Y., et al. (2026). The impact of "zero-waste city" pilot policies on firms' green total factor productivity. *Ecological Economy*, (1), 105–114.

Lu, S., & Xiong, J. (2020). Can the establishment of national ecological civilization demonstration zones improve agricultural green efficiency? Evidence from Hunan Province. *Journal of Central South University (Social Sciences)*, (3), 90–101.

Lv, T., Hu, H., Zhang, X., et al. (2022). Impact of multidimensional urbanization on carbon emissions in ecological civilization experimental areas. *Physics and Chemistry of the Earth*, 126, 103120. https://doi.org/10.1016/j.pce.2022.103120

Ma, X., & He, J. (2023). Air pollution and corporate green innovation in China. *Economic Modelling*, 124, 106305. https://doi.org/10.1016/j.econmod.2023.106305

Matraeva, L., Vasiutina, E., Korolkova, N., et al. (2022). Identifying rebound effects and sustainable energy efficiency policy: A global review. *Energy Research & Social Science*, 85, 102402. https://doi.org/10.1016/j.erss.2021.102402

Meng, F., Guo, J., Guo, Z., et al. (2021). Urban ecological transition: Practice of ecological civilization construction in China. *Science of The Total Environment*, 755, 142633. https://doi.org/10.1016/j.scitotenv.2020.142633

Ren, W., Xu, Y., & Xiao, H. (2024). Impact of marine ecological civilization demonstration zone policies on green development of marine economy. *Marine Policy*, 161, 106048. https://doi.org/10.1016/j.marpol.2024.106048

Sehrawat, M., Giri, A. K., & Mohapatra, G. (2015). Financial development, economic growth, and environmental degradation: Evidence from India. *Management of Environmental Quality*, 26(5), 666–682. https://doi.org/10.1108/MEQ-05-2014-0063

Shi, D., & Li, S. (2020). Emissions trading system and energy efficiency: Measurement and evidence from prefecture-level cities and above. *China Industrial Economics*, (9), 5–23. https://doi.org/10.19581/j.cnki.ciejournal.2020.09.001

Su, J., Liang, Y., Ding, L., et al. (2021). China's energy development strategy under the carbon neutrality goal. *Bulletin of Chinese Academy of Sciences*, 36(9), 1001–1009. https://doi.org/10.16418/j.issn.1000-3045.20210727001

Tao, F., Zhao, J., & Zhou, H. (2021). Does environmental regulation promote the "incremental quality improvement" of green technology innovation? *China Industrial Economics*, (2), 136–154. https://doi.org/10.19581/j.cnki.ciejournal.2021.02.016

Wang, K., Xu, R., Zhang, F., et al. (2022). The impact of national ecological civilization demonstration zones on carbon emission intensity. *China Population, Resources and Environment*, (7), 57–70.

Wu, C., Deng, H., & Xia, Q. (2025). The impact of digital technology innovation on green development. *China Soft Science*, (2), 66–80.

Yuan, C., Shang, M., Han, Z., et al. (2024). Impact of national ecological demonstration zones on green total factor productivity. *Journal of Environmental Management*, 356, 120421. https://doi.org/10.1016/j.jenvman.2024.120421

Zhang, B., Yu, L., & Sun, C. (2022). How does urban environmental legislation guide enterprise green transition? *Energy Economics*, 110, 106032. https://doi.org/10.1016/j.eneco.2022.106032

Zhang, J., & Wang, X. (2024). The impact of ecological civilization construction on urban carbon emissions. *Ecological Economy*, (5), 214–222.

Zhang, L., Li, Y., Xu, J. L., et al. (2021). Evaluating hybrid energy systems for ecological civilization construction. *Journal of Cleaner Production*, 278, 123769. https://doi.org/10.1016/j.jclepro.2020.123769

Zhang, Y., & Fu, B. (2022). Impact of ecological civilization pilot zones on carbon emissions. *Journal of Environmental Management*, 324, 116652. https://doi.org/10.1016/j.jenvman.2022.116652

Zhang, Z., Luo, X., Du, J., et al. (2024). Government R&D subsidies and green innovation: Substantive or strategic? *Finance Research Letters*, 67, 105796. https://doi.org/10.1016/j.frl.2024.105796