Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-025-04754-7 OPEN

Property rights governance and urban environmental pollution

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Intellectual property rights governance plays a critical role in innovation protection and fosters a stronger connection between government involvement and sustainability. This paper extends property rights governance to environmental areas and uses staggered difference-in-differences to assess its effect on urban environmental pollution, using a pilot policy named National Intellectual Property Rights Demonstration Cities (NIPRDC). Our findings indicate that NIPRDC significantly reduces environmental pollution, confirmed by a set of robust tests. Meanwhile, resource-based cities show a more prominent reduction effect, and cities with higher levels of digital infrastructure and property rights protection perform better in pollution reduction. Then, the influencing mechanisms focus on green innovation and market competition. Notably, besides its macro-effect, NIPRDC also drives an industrial green transition. This study provides valuable insights for governments to utilize the advantages of NIPRDC and adopt more effective measures to balance economy and environment.

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Introduction

Environmental conditions are fundamental to human survival and economic development. Although air quality has been greatly improved in China (Liu et al., 2024; Zhang et al., 2024), environmental pollution continues to manifest in the form of floods, wildfires, and sandstorms, which have shown an upward trend in 2022 and 2023. Meanwhile, rapid economic growth has made China one of the countries with the most severe environmental pollution (Grossman and Krueger, 1994), underscoring the urgent need to address these issues effectively. Therefore, sustainable development has become the social sense. However, many industries, manufacturing especially, continue to exert a persistent influence on environmental pollution (Fan et al., 2023). Agriculture also contributes to air, water, and food pollution due to the extensive use of pesticides, fertilizers, and industrial machinery (Ma et al., 2021). The Kuznets Curve illustrates a direct relationship between economic growth and environmental pollution, suggesting that pollution is an inevitable consequence of economic development in countries.

Undoubtedly, pursuing economic development at the expense of the environment is unsustainable. In modern times, the green economy has become increasingly crucial, with green industries, eco-friendly habits, and even environmental laws becoming more familiar to the public. Currently, China is actively committed to environmental protection and is making resolute efforts to combat pollution through various measures, including green governance.

Property rights governance, including intellectual property protection, plays a crucial role in fostering innovation and ensuring sustainable development (Neves et al., 2021; Geng and Saggi, 2022). Intellectual property protection has been shown to positively influence both export and import volumes, contributing to the advancement of sustainable and circular economic development (Maskus and Ridley, 2016). It is also associated with the business performance of high-tech firms (Lin, 2023) and has a significant impact on the dynamics of research and development (R&D) competition (Chu and Zhou, 2022). Su et al. (2022) observed that intellectual property protection enhances total factor productivity (TFP), especially in developed countries with stronger intellectual property protections. Some studies believed that property rights governance is an effective tool for promoting sustainable development. Therefore, it is urgent for developing countries to increase intellectual property protection. China has made significant efforts in this regard, including the establishment of National Intellectual Property Rights Demonstration Cities (NIPRDC). In 2011, China's intellectual property office issued the Measures for Evaluating NIPRDC and launched the selection of pilot cities. This policy has been piloted in five batches, with approximately 50 demonstration cities established during the sample period. Its implementation highlights both local innovative efforts and the significance of sustainable development.

Sulfur dioxide (SO_2), smoke, and wastewater are primary environmental pollutants that significantly impact urban ecosystems (Fitoussi et al., 2022). The digital economy, energy transformation, and intelligent applications play a key role in reducing urban environmental pollution, thereby promoting sustainable development (Chen et al., 2023). Other studies have found that technological progress and industrial transformation are essential for mitigating air pollution (Ahn and Yoon, 2020; Song et al., 2023). While researches primarily focused on agricultural and industrial wastewater (Kumar et al., 2023); Alan and Köker, 2023), with fewer studies addressing residential wastewater and the land pollution it causes. As we all know, environmental pollution is closely related to human activity. Public infrastructure, particularly high-speed rail, plays a crucial role in mitigating pollution emissions and reducing energy consumption within socio-economic systems (Peng et al., 2021). Additionally, promoting a shift in household consumption patterns toward renewable energy sources represents another effective strategy for achieving environmental sustainability (Chen et al., 2023).

Environmental pollution has become a significant concern, leading to adverse effects in multiple domains, including human health (Joshi et al., 2022), the degradation of water resources (Hou et al., 2021), and the damage to ecosystems (Vezzoni et al., 2023). Consequently, how to manage urban pollution effectively has become a key focus for researchers. Environmental regulations, in nature, can stimulate technological innovation, a concept known as the Porter Hypothesis (Porter, 1991). Extensive research has examined the link between environmental regulation and environment, and found that innovation is a key factor in enhancing environmental quality (Chen et al., 2022). Both market-based and command-based regulations have shown effective positive impacts on reducing environmental pollution (Li et al., 2020). Zhao et al. (2022) have confirmed that the establishment of environmental courts is conducive to reducing pollution. Similarly, both the environmental protection tax (Zhang et al., 2024) and environmental target constraints (Ren et al., 2023; Wang et al., 2023) serve the same function in China.

As noted above, pollution has caused many existing and potential problems that could be solved by some methods, including environmental regulation, environmental tax, punitive measure and technological progress. Dussaux et al. (2022) found that intellectual property protection can improve low-carbon trade and technological innovation. In this context, NIPRDC demonstrates stronger property rights governance through effective regulation. However, few research studied the effect of property rights governance on pollution. Based on above analysis, this paper takes 279 prefecture-level cities as research objects, employing the staggered DID to exploit whether NIPRDC affects environment pollution from 2006 to 2019. Additionally, this study explores the potential mechanisms through which such effects may occur.

This study offers several potential marginal contributions: (1) The use of staggered DID, PSM-DID, and other methods provides a precise estimation of the effect of NIPRDC on urban environmental pollution, offering a new research perspective for assessing the environmental impact of property rights governance. From a research content perspective, it also broadens the scope of studies on property rights governance and environmental issues. (2) Besides, the study makes theoretical contributions regarding the application of property rights policies in urban operations. By examining the effects of green innovation and market competition, it uncovers the potential motivations of local governments or officials to implement NIPRDC. (3) The study analyzes the heterogeneity of NIPRDC's impacts on urban environmental pollution from the perspectives of resource dependence, digital infrastructure, and the foundation of property rights protection. Overall, these findings hold significant practical value for achieving sustainability.

Following sections are as follows. Policy background and the research hypothesis are in Section 2. Section 3 discusses model, variables and data. The empirical results and explanations are shown in the Section 4. Section 5 consists of conclusion and recommendation.

Policy background and research hypothesis

NIPRDC in China. After China's accession to the World Trade Organization (WTO), the country faced increasing pressure from the international community to strengthen its intellectual property protection (Oppenheim, 2005). To fulfill its international commitments and maintain technological relations with other nations, China recognized the necessity of strengthening its intellectual property protection mechanisms. Beyond these international obligations, the significance of intellectual property in fostering technological innovation and driving national prosperity must not be overlooked (Lin, 2023).

In response to these challenges, China has undertaken significant legal and institutional reforms to strengthen intellectual property protection. In 2008, the country enacted the Regulations on the Implementation of the Intellectual Property Law, which further refined and supplemented the existing intellectual property law. Additionally, China established specialized courts and affairs centers to improve the enforcement of intellectual property rights, with the goal of promoting high-quality economic development through innovation. To encourage local governments to actively engage in intellectual property protection, the Chinese government introduced a series of policy measures, including the creation of NIPRDC. These demonstration cities are tasked with setting exemplary standards in intellectual property protection by improving legal frameworks, enhancing law enforcement, and strengthening judicial safeguards.

The impact of these efforts is evident in cities like Wuhan and Shenzhen. For instance, in 2010, Wuhan's high-tech industrial products generated sales revenue of 300.33 billion yuan, accounting for 38.9% of the total sales revenue from industrial enterprises above a designated size. In Shenzhen, high-tech products made up 56.45% of the industrial sales revenue from large enterprises. These figures not only reflect the growing scale of high-tech industries but also demonstrate the continuous improvement in innovation levels in these exemplary cities.

To foster an innovation-driven development model, the NIPRDC initiative is critical for accelerating high-quality economic development. It also plays a crucial role in aligning with international standards, advancing legal and institutional reforms, and promoting an innovation-driven strategy. Among the key components of high-quality economic growth, green development has emerged as a vital focus. However, the relationship between the pilot policy and urban green factors—such as environmental optimization—remains insufficiently explored and is often referred to as a "black box" in the existing literature. Further research is needed to clarify the extent to which intellectual property protection and innovation policies contribute to environmental sustainability in urban settings.

China's status of environmental pollution. Many researchers select SO_2, smoke, and other oxides as indicators of air pollution or environmental pollution in cities (Fitoussi et al., 2022), but environmental pollution also includes water pollution. Based on this comprehensive concept, we used a variety of pollutant perspectives for comprehensive measurement (Cole and Elliott, 2003). We select three types of pollutants to calculate the urban environmental pollution intensity, including wastewater, SO_2 and smoke. After standardizing the above three types of pollutants, we employ the entropy method for analysis and subsequently compute the environmental pollution index for various cities in China from 2011 to 2019. China's status of environmental pollution and NIPRDC location information are shown in Fig. 1. The red nodes are the locations where NIPRDC has been implemented.

Figure 1 illustrates that China's environmental pollution steadily decreased from 2010 to 2019, with notable improvements in the central and eastern regions. However, the environmental pollution levels in most cities remained above the medium level, and some cities in the central region, such as those in Shanxi and Henan provinces, experienced high levels of pollution. This trend is likely closely linked to the regions' abundant natural resources, particularly coal, which has been widely used as an energy source in industrial production.

However, following the implementations of the NIPRDC initiative between 2010 and 2014, environmental pollution levels in most eastern coastal areas declined significantly. Specifically, cities such as Nanyang, Wenzhou, Luoyang, Shijiazhuang, and Yichang, which had high or medium levels of pollution in 2010, saw significant decreasements following the introduction of the policy. Between 2014 and 2018, the NIPRDC pilot program was expanded to include cities like Zhongshan, Foshan, Nanchang, Anyang, Yichang, Changzhou, Panzhihua, Xiangtan, Deyang, Huizhou, Mianyang, Xuzhou, Shantou, Shenyang, Shijiazhuang, and Ma'anshan. As the program developed, significant reductions in environmental pollution were observed in the pilot cities, with Harbin, Nanchang, Shenyang, Xuzhou, Deyang, and Anyang showing the most noticeable improvements. In these cities, pollution levels decreased from high to low, or even to lower levels.

By comparing the trends in the NIPRDC implementations and urban environmental pollution in Fig. 1, it becomes evident that there is a closer correlation between the two factors. The data suggest that environmental pollution in the pilot cities gradually improved over time. Therefore, this paper argues that the implementation of the NIPRDC has had a direct and positive impact on optimizing urban environmental pollution.

Theoretical analysis

NIPRDC and environmental pollution. As China's economy undergoes a comprehensive transformation, the concept of green sustainability has gained increasing attention across various industries (Chen et al., 2023). Green sustainability extends beyond the green economy to encompass environmental protection, green politics, and a green society, all aimed at building a resource-efficient and environmentally friendly nation.

Through the intellectual property system, NIPRDC has emerged as an important driver in reducing environmental pollution, serving as a standard for promoting sustainable and equitable knowledge output. With the implementation of NIPRDC, local governments have gradually introduced stricter intellectual property protection laws and increased penalties for infringement. These measures reduce imitation and protect the legitimate rights of innovators. As a result, entrepreneurs in pilot cities are more motivated to pursue technological innovations under the policy's incentives. As innovation hubs within these cities develop, knowledge output and technology adoption rise, leading to the continued growth of patent-intensive industries. In the future, these industries will play a significant role in transforming China's economic model (Scott and Spadavecchia, 2023). Patent-intensive industries tend to be more sustainable and environmentally friendly than labor- and technology-intensive sectors (Fusillo, 2023). Unlike the previous model of crude economic growth, knowledge-intensive industries are gradually taking the lead, driven by the NIPRDC policy, which contributes to reducing regional environmental pollution. In other words, the pilot cities are transitioning toward greener, low-carbon development.

The establishment of a green and efficient intellectual property management system, tailored to current industrial characteristics, is essential for understanding how intellectual property management departments and markets operate in the digital age. Fully leveraging advanced technology in intellectual property management can contribute to breakthroughs in the intellectual property field, especially as China deepens its reforms, given the sustainable nature of intellectual property (Wang et al., 2021). Under the NIPRDC, it is crucial to utilize government intellectual property protection measures to support urban environmental management. A well-constructed green intellectual property

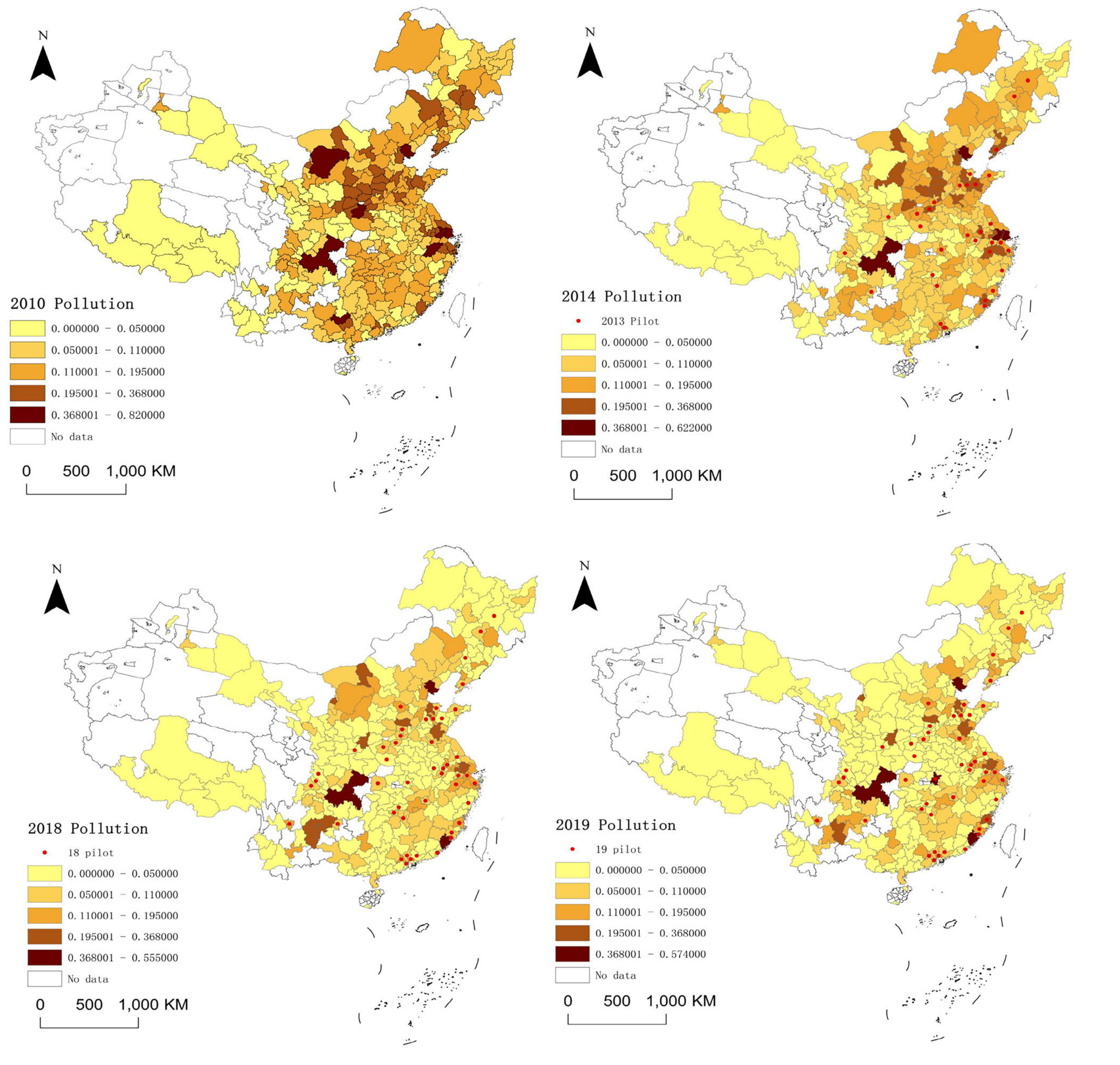

Fig. 1 Evolution trend figure of environmental pollution and NIPRDC in China.

management system can accelerate knowledge spillover and technology application, further expediting urban pollution control and carbon reduction efforts. Ultimately, the idea of "intellectual property for a green future", as articulated during World Intellectual Property Day 2020, emphasizes not only the need to incentivize technological solutions for environmental challenges but also the integral role of property systems, management, and industry in fostering sustainable development.

Based on above contents, this paper introduces this hypothesis:

Hypothesis 1. NIPRDC can reduce urban environmental pollution.

NIPRDC, green innovation and environmental pollution. Intellectual property protection is a key driver of sustainable technology development and its diffusion (Wang et al., 2022; Eppinger et al., 2021). As a core component of China's intellectual property strategy, the NIPRDC program plays a pivotal role in enhancing innovation efficiency and advancing green transformation through both judicial and administrative protections. Local government policies that reinforce property protection help mitigate the risk of technological imitation, thereby reducing sunk costs for innovative enterprises.

As the value of proprietary knowledge and technology continues to rise (Helpman, 1993; Kanwar and Evenson, 2003), businesses are increasingly motivated to innovate, accelerating both the R&D of green technologies and the promotion of their practical applications (Murray and Stern, 2007). This, in turn, drives improvements in the urban green innovation level. It has been demonstrated that technological progress, particularly through cleaner production methods, can significantly reduce emissions of CO_2, haze, and other environmental pollutants (Wang et al., 2012). Furthermore, strengthening property protection to enhance green innovation capabilities is essential for optimizing the environment (Song and Chen, 2023).

Based on above contents, this paper introduces this hypothesis:

Hypothesis 2a. NIPRDC can reduce urban environmental pollution through improving green innovation.

NIPRDC, market competition and environmental pollution. Market competition is a driving force for economic development, and intellectual property protection plays a significant role in fostering fair competition within the market (Yu et al., 2024). However, optimizing market competition presents challenges, particularly in industries where large firms leverage their scale, resources, and market influence to establish monopolies or oligopolies. This creates significant barriers for new entrants, as startups often struggle to protect their technological information and cannot compete on an equal footing with industry giants, resulting in a market environment that lacks fairness and transparency.

In this context, the NIPRDC program plays a crucial role by establishing strong intellectual property protection systems that provide legal and institutional support for innovative companies. These measures not only safeguard corporate innovations but also enhance market confidence in intellectual innovation, thus promoting fair competition. Additionally, NIPRDC strengthens enforcement efforts to combat intellectual property infringements and counterfeit products, ensuring a healthier and more competitive market environment.

When considering the relationship between competition and environmental pollution, NIPRDC has been shown to promote cooperation among different types of enterprises (Telg et al., 2023), which directly contributes to reducing environmental pollution (Lv et al., 2023). While much of the previous research focused on how governments regulate environmental issues (Porter, 1991; Chen et al., 2022; Wang et al., 2022), less attention has been given to the role of market competition in addressing environmental challenges. Market competition is, in fact, a central force in optimizing resource allocation (Zheng et al., 2023), and it significantly impacts industrial pollution emissions (Gong et al., 2017).

Therefore, it is evident that intellectual property protection has the potential to promote the production of high-quality knowledge and innovations, thereby enhancing fair market competition and contributing to environmental sustainability. In other words, market competition serves as a mediating factor for the environmental optimization effects of NIPRDC.

Based on above contents, this paper introduces this hypothesis:

Hypothesis 2b. NIPRDC can reduce urban environmental pollution by optimizing market competition fairly.

Model, variables and data

Empirical model. In this study, we examine the urban environmental optimization deriving from the property rights governance. Considering NIPRDC was piloted in batches, we use the staggered DID model for empirical test. Akin to Beck et al. (2010), we systematically evaluate the impact of NIPRDC on environmental pollution using the following model:

$$EP_{i,t} = \alpha_0 + \alpha_1 IPR_{i,t} + \alpha_2 Control_{i,t} + \gamma_i + \mu_t + \varepsilon_{i,t} \quad (1)$$

Where i and t represent city and year, respectively. $EP_{i,t}$ indicates the environmental pollution of city i in year t. $IPR_{i,t}$ is measureed as the interaction terms of regional grouping dummy variable and policy implementation dummy variable. Specifically, if city i implemented NIPRDC in year t, let the current year and subsequent years of $IPR_{i,t}$ take 1, otherwise 0. To avoid endogenous disturbances caused by unobservable factors, we continue to control for city fixed effects γ_i and year fixed effects μ_t. $\varepsilon_{i,t}$ represents the random error term. The estimated coefficient of α_1 is what we need to focus on in this paper. If α_1 is significantly negative, it indicates that NIPRDC can reduce regional environmental pollution, which is conducive to green sustainability.

Variable description

Explained variable. Most academic studies on pollution have primarily focused on major pollutants, such as SO_2 (Antweiler et al., 2001). Some research has expanded this focus by incorporating multiple pollutant types and adopting a multi-pollutant perspective to provide a more comprehensive assessment of environmental quality (Cole and Elliott, 2003). This multi-pollutant approach offers a clearer representation of regional pollution levels compared to single-pollutant metrics. Building on this, we examine regional pollution intensity by considering three key pollutants: wastewater, SO_2, and smog. After standardizing the pollutant data, we employ the entropy method to assess environmental pollution indicators for Chinese cities over the period from 2011 to 2019 (Yang et al., 2024). The specific steps involved in the calculation are as follows:

Standardize indicators as follows: $\frac{x_{i,j}-\min\{x_{i,j}\}}{\max\{x_{i,j}\}-\min\{x_{i,j}\}}$, $(i = 1, 2,\ldots,m\ ;\ j = 1, 2,\ldots, n)$

Calculate the proportion of i indicator value under j indicator: $q_{i,j}=\frac{y_{i,j}}{\sum_{i=1}^{m} y_{i,j}}$

Calculate the entropy value of j indicator: $e_j = -\frac{1}{lnm}\sum_{i=1}^{m}(p_{i,j}lnp_{i,j}), e_j \in (0, 1]$

Calculate j indicator's coefficient of difference: $g_j = 1 - e_j$

Calculate the weight of j indicator: $w_j = \frac{g_j}{\sum_{j=1}^{n} g_j}$

Calculate the composite score for each indicator: $EP_i = \sum_{j=1}^{n} w_j y_{i,j}$

Explanatory variable. In 2011, the China Intellectual Property Office (CIPO) issued the Measures for the evaluation of NIPRDC, and decided to launch the selection of pilot cities. This policy is not only a concrete practice of intellectual property theory in regions, but also a policy of urban innovation exploration based on China's strategy of strengthening the country with intellectual property rights. NIPRDC is not a pilot work implemented at a single point, but a multi-phase process of expanding the scope of the pilot in batches. Therefore, referring to Pan et al. (2023), we portray the core explanatory variable with the interaction term of the policy implementation dummy variable and area grouping dummy variable. $IPR_{i,t}$ denotes 1 for that year and subsequent years if city i becomes an NIPRDC pilot in year t, and 0 otherwise.

Mechanism variables. Green innovation. This paper uses the number of green patent applications per 10,000 people published by the CIPO to describe the overall green innovation level in each city (*INO*). According to the Patent Law of the People's Republic of China, patents are divided into utility model patents, design patents, and invention patents. The first two are simple improvements to existing technologies, while the last represents a fundamental change to an old technology. We further use green invention patents' quantity per ten thousand people (*INO-B*) to measure substantive green innovation capacity, while utility and new design patents' quantity per ten thousand people (*INO-N*) to portray the city's incremental green innovation capacity.

Market competition. Regional market competition can affect business performance and strategic decisions, which in turn reduce emissions. Akin to Niu et al. (2023), we refer to the algorithm of HHI and calculate the degree of fair competition in the regional market according to the operating income of regional listed companies, denoted as *COM*. The smaller the variable value is, the higher the degree of fair competition in the market is.

Control variables. In order to alleviate the endogeneity problem caused by omitted variables, we introduce control variables related to environmental pollution.

Economic development (*Gdpin*), is measured by the growth rate of regional GDP. The excessive pursuit of regional economic development speed may lead to the aggravation of local environmental pollution problems.

Industrial structure (*Structure*), is measured by the ratio of added value of secondary industry to regional GDP. Industrial development is closely related to environmental pollution, and industrial pollution is an urgent problem in China.

The degree of external linkage (*Fdi*) is measured by the ratio of foreign direct investment (FDI) actually utilized to regional GDP, expressed in ten thousand US dollars. According to the "pollution haven" hypothesis, developed countries are more likely to establish pollution-intensive industries in countries or regions with relatively low environmental standards. In contrast, the "pollution halo" hypothesis posits that multinational enterprises are inclined to transfer green technologies to host countries through industrial investments, thereby promoting emission reductions by aligning with higher environmental standards.

Industrial synergistic agglomeration (*Cag*), is measured by the degree of synergistic agglomeration of manufacturing and productive service industries. Following Yang et al. (2023), we first portray the above industries agglomeration based on the entropy method: $Mag_i = (\frac{q_{i,m}}{q_i})/(\frac{q_m}{q})$, $Sag_i = (\frac{q_{i,s}}{q_i})/(\frac{q_s}{q})$. Then we calculate the industrial agglomeration index by $1 - |\frac{Mag_i - Sag_i}{Mag_i + Sag_i}| + (Mag_i + Sag_i)$.

Technological progress (*TFP*) is measured by total factor productivity using the SFA method, drawing on the model of Battese and Coelli (1992). The input factors are the number of employees and the amount of investment in fixed assets, and the output is the real gross regional product.

Human capital (*Education*) is measured by the ratio of the number of students enrolled in general higher education to the total population. High-end talents pay more attention to the human environment around them, and this kind of labor force may bring knowledge spillover and scientific and technological achievements.

Data sources and descriptive statistics. In this study, we comprehensively examine the environmental optimization effect of NIPRDC. Considering that China's socio-economic data in 2020 may be negatively impacted by the global epidemic, and pollution emission data in 2020 is not reported, our study includes 3680 sample observations during the period of 2006–2019. Urban data are derived from the China City Statistical Yearbook, the China City Construction Statistical Yearbook and the annual statistical bulletin of each city. We use green patent application data from China's national intellectual property rights database and match it with the WIPO International Patent Classification Green List. The intellectual property rights' data of prefecture-level cities are manually collected from the China Law Information Database. Although the database cannot fully cover all cities in China, the intellectual property rights trial cases are very representative. The more cases there are, the stronger the property rights governance in the region. Clean transition data come from CSMAR database and WIND database, and this paper is based on the data of listed enterprises aggregated to the city level. To ensure the persuasiveness of the sample data, we carry out linear interpolation for the missing data in individual years. Meanwhile, we apply a bilateral 1% Winsor tailing process for all continuous variables.

Table 1 presents the key statistical characteristics of the main variables. The explanatory variable shows a minimum value of 0.004 and a maximum of 0.502, indicating substantial regional variation in environmental pollution levels across China. This variation is consistent with the current reality in China, a vast country with a diverse industrial landscape. The geographical and economic characteristics of cities vary significantly, with regions dependent on natural resources often exhibiting poorer industrial structures and lower environmental quality compared to cities that rely more heavily on service-oriented sectors. Additionally, control variables such as the GDP growth rate and industrial structure fall within reasonable ranges, supporting the robustness of the sample in capturing the relationship between the NIPRDC and environmental pollution.

Table 1 Descriptive statistics of variables.

Variable	Obs	Mean	S. D.	Min	Max
EP	3680	0.0908	0.0847	0.0040	0.5020
IPR	3680	0.0736	0.2612	0.0000	1.0000
Gdpin	3680	0.1077	0.0409	−0.0120	0.2070
Structure	3680	0.4809	0.1061	0.1170	0.9097
Fdi	3680	0.0028	0.0027	0.0000	0.0121
Cag	3680	2.3974	0.5409	1.1059	3.7893
TFP	3680	1.4424	0.7466	0.1361	2.8701
Education	3680	0.0175	0.0228	0.0005	0.1147

Empirical analysis

Baseline analysis. Based on model (1), we obtain the baseline regression results presented in Table 2. Column (1) is the results without control variables. The estimated coefficient of *IPR* is −0.0199, which is significantly negative at the statistical level of 1%, indicating that NIPRDC can reduce pilot areas' environmental pollution compared to non-pilot areas. After gradually adding control variables, Column (7) shows that *IPR*'s estimated coefficient is −0.0200, and still has a significant inhibitory effect on the environmental pollution index. **H1** is verified. Our findings are consistent with the existing literature in the field of intellectual property rights governance. Wang et al. (2022) and Eppinger et al. (2021) found that property rights governance is a key element in realizing sustainable technologies' diffusion, which can transfer dirty technology to clean technology, and promote the green transformation and upgrading of polluting industries. These results highlight the fact that intellectual property rights (IPR) protection indeed contributes to clean and sustainable development. However, these studies do not examine the relationship between IPR protection and regional pollution in terms of actual pollutants. Our study enriches and adds to this literature.

Control variables also exhibit a certain degree of confidence in influencing the explained variable. *Gdpin* and *Structure* have a significant positive effect on *EP* in Table 2. This suggests that with the development of regional industry and the over-emphasis local government on economic growth, the regional environment will become a victim of "economic growth". Meanwhile, collaborative industrial agglomeration aggravates the phenomenon of environmental pollution in Chinese cities, which is similar to the findings of Yang et al. (2023). The estimated coefficient of *Fdi* is significantly negative at 1% statistical level. This suggests that current foreign investment plays the "governance" role in addressing environmental pollution in China, aligning with the "Pollution Halo" hypothesis. Multinational corporations, subject to strict environmental standards in their home countries, tend to develop advanced pollution treatment technologies. As a result, when they invest abroad, these clean technologies and environmental management systems are transferred to host countries, fostering the development of environmental protection technology.

Table 2 Baseline regression results.

	(1) EP	(2) EP	(3) EP	(4) EP	(5) EP	(6) EP	(7) EP
IPR	−0.0199***	−0.0209***	−0.0202***	−0.0205***	−0.0201***	−0.0201***	−0.0200***
	(0.0047)	(0.0047)	(0.0046)	(0.0046)	(0.0046)	(0.0046)	(0.0047)
Gdpin		0.1207***	0.1009***	0.1127***	0.1183***	0.1177***	0.1179***
		(0.0288)	(0.0300)	(0.0300)	(0.0302)	(0.0303)	(0.0305)
Structure			0.0418**	0.0463***	0.0399**	0.0396**	0.0394**
			(0.0163)	(0.0164)	(0.0163)	(0.0163)	(0.0164)
Fdi				−2.0546***	−2.1261***	−2.1273***	−2.1327***
				(0.4925)	(0.4934)	(0.4933)	(0.4983)
Cag					0.0110***	0.0110***	0.0109***
					(0.0037)	(0.0037)	(0.0037)
TFP						−0.0018	−0.0018
						(0.0027)	(0.0027)
Education							−0.0249
							(0.1750)
Year FE	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES
N	3680	3680	3680	3680	3680	3680	3680
Adj. R^2	0.7451	0.7462	0.7465	0.7477	0.7483	0.7482	0.7482

Symbols "***, **, and *" indicate significant at the 1%, 5%, and 10% statistical levels, respectively.

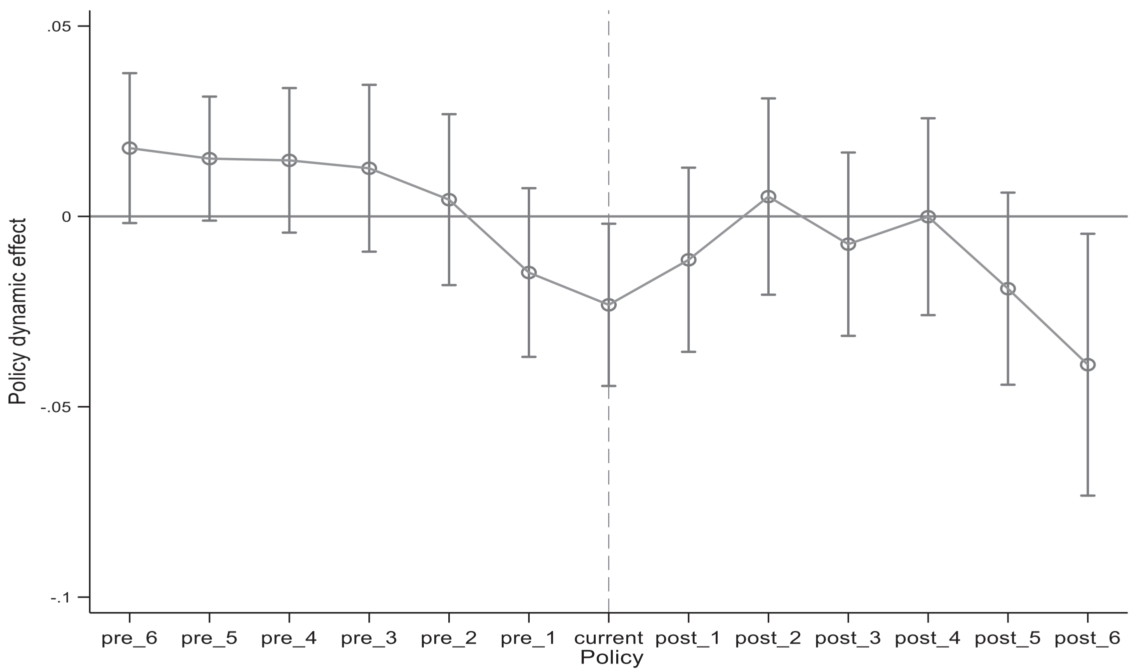

Fig. 2 Parallel trend test.

Robustness tests

Parallel trend test. An essential assumption in the application of the staggered DID model is that there is no significant difference between the treatment and control groups prior to the policy implementations, while a notable divergence occurs after the policy is enacted. To test the parallel trends assumption, we examine data from six periods before and after the policy interventions, using the sixth year prior to the policy as the baseline period. Figure 2 presents the results of this parallel trends test. The estimated coefficients of the interaction terms for the dummy variables are not statistically significant before the pilot program initiated by the CIPO. This suggests that the staggered DID model for the NIPRDC satisfies the parallel trends assumption. Following the implementation of the pilot policy, the estimated coefficients reveal a significant negative relationship between the policy and environmental pollution in both the current period and the sixth year after implementation. This indicates the presence of both immediate and lagged effects of the NIPRDC on regional environmental pollution. Such findings are consistent with the nature of the policy. Unlike other green policies, the NIPRDC places greater emphasis on technological innovation, which typically involves substantial time and financial investment, resulting in a delayed effect on environmental improvements.

Table 3 Robustness test results (1).

	Exclude interference		Remeasure explained variables		
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
	EP	***EP***	***Water***	***SO_2***	***Smoke***
IPR	−0.0177***	−0.0181***	−0.0066*	−0.0111***	−0.0197***
	(0.0046)	(0.0046)	(0.0039)	(0.0038)	(0.0058)
PETP	YES	YES	NO	NO	NO
CETP	NO	YES	NO	NO	NO
Control variables	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES
Constant	0.0435***	0.0415***	0.1594***	0.2533***	0.1813***
	(0.0130)	(0.0130)	(0.0173)	(0.0218)	(0.0388)
N	3680	3680	3680	3680	2314
Adj. R^2	0.7503	0.7508	0.6473	0.7822	0.4601

Symbols "***, **, and *" indicate significant at the 1%, 5%, and 10% statistical levels, respectively.

Table 4 Robustness test results (2).

	PSM-DID	Control omitted variables	Lag1	Excluding special samples	Replacing the tailing method
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
	EP	***EP***	***EP***	***EP***	***EP***
IPR	−0.0182***	−0.0183***		−0.0228***	−0.0123***
	(0.0049)	(0.0047)		(0.0047)	(0.0033)
L.IPR			−0.0129**		
			(0.0052)		
Omitted variables	NO	YES	NO	NO	NO
Control variables	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES
Constant	0.0580**	−0.0541*	0.0432***	0.0438***	0.0530***
	(0.0295)	(0.0288)	(0.0143)	(0.0134)	(0.0104)
N	2200	3672	3313	3267	3680
Adj. R^2	0.7606	0.7464	0.7434	0.7461	0.7678

Symbols "***, **, and *" indicate significant at the 1%, 5%, and 10% statistical levels, respectively.

Exclude policy interference. In order to avoid other policies biasing the benchmark result, we exclude two large-scale pilot policies carried out during the sample period: the pollution emission trading policy (PETP) and carbon emission trading policy (CETP). PETP started at the beginning of the 21st century. After scope promotion and policy improvement, the system for paid use and trading of emission rights had been basically established by 2017. This policy has a good promotion effect on both environmental quality and economic development in China (Chang and Wang, 2010; Wu et al., 2019). CETP began in 2013, followed by successive pilots in 2014 and 2016, is crucial for regional sustainable development and inclusive economic growth (Huang et al., 2019). We further control for PETP and CETP in the baseline model. The regression results are reported in Columns (1) and (2) of Table 3. NIPRDC has a significant dampening effect on local environmental pollution intensity, whether controlling for PETP alone or for both large-scale pilot programs.

Remeasure explained variable. The explained variable of this paper, namely the environmental pollution index, is calculated by the entropy method. In order to make the empirical results more reliable, we change the explained variable's measurement method here. Specifically, we standardize the emissions of wastewater, SO_2, and smoke to portray environmental pollution in turn. Columns (3) to (5) in Table 3 show the regression results after changing the measurement method. The results show that the NIPRDC has a statistically significant negative effect at least at the 10% level.

PSM-DID. The selection of pilot cities for the NIPRDC may not be entirely random, which could introduce selectivity bias. To ensure the robustness of the baseline regression results, we apply year-by-year propensity score matching (PSM) prior to the DID model, following the methodology outlined by Heckman et al. (1997). By employing nearest neighbor matching, we mitigate potential selection bias by matching the pilot cities to the control group on a yearly basis. This approach, commonly used in empirical studies, allows for the optimal utilization of the treatment group data. After removing observations from non-overlapping regions to satisfy the common support assumption, we re-estimate the model. Column (1) of Table 4 demonstrates that the estimated coefficient for IPR remains statistically significant at the 1% level, with the sign and magnitude of the coefficient being largely consistent with those from the baseline regression.

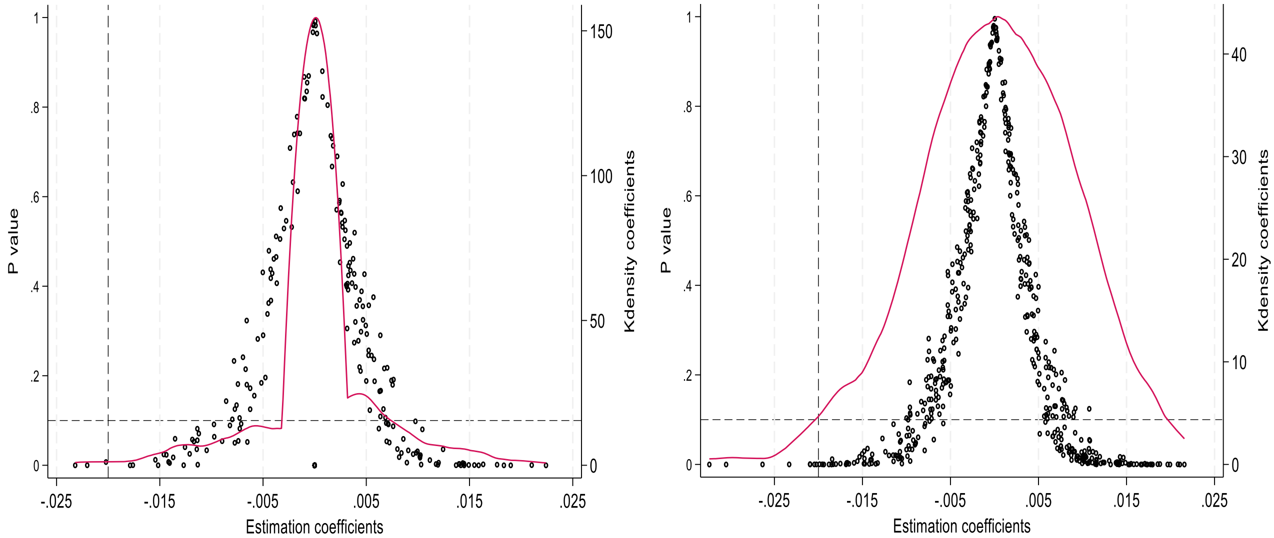

Fig. 3 Placebo test. The circle and line represent the p-value and kernel density distribution, respectively.

Placebo test. Some stochastic factors may play a biasing role in NIPRDC affecting the quality of the urban environment. We first randomly select a sample of cities as new NIPRDC model cities and randomly select new pilot years for them. On this basis, we multiply two dummy variables to obtain a new explanatory variable to re-estimate the baseline model. Second, we repeat the above process 200 and 500 times, obtaining the multiple estimated coefficients and p-values of *EP*, respectively. Figure 3 shows the distribution of randomized means. Whether it is 200 times or 500 times, regression simulation values' distribution is mostly concentrated around 0 and the p-values are mostly larger than 0.1. The true regression coefficient of this paper (−0.0200) is significantly more abnormal than coefficients in the placebo test, which can be regarded as an extreme value. This reaffirms from the counterfactual perspective that NIPRDC reduces environmental pollution emissions in cities. Besides, the estimation result in this paper is unlikely to be caused by other unobservable factors.

Table 5 Mechanism test results.

	(1) *INO*	(2) *INO-B*	(3) *INO-N*	(4) *COM*
IPR	2.2641***	1.1840***	1.0801***	−14.5056**
	(0.1778)	(0.0965)	(0.0931)	(6.1371)
Control variables	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
City FE	YES	YES	YES	YES
Constant	1.1146**	0.8367***	0.2778	1.4357***
	(0.5198)	(0.2571)	(0.2916)	(0.0962)
N	3665	3665	3665	3011
Adj. R^2	0.6758	0.6587	0.6696	0.6919

Symbols "***, **, and *" indicate significant at the 1%, 5%, and 10% statistical levels, respectively.

Other robustness tests. First, the control variables in this paper include economic development rate, industrial structure, etc., which are a more comprehensive considerations of important factors affecting urban pollution. However, we are likely to omit other key variables that affect the explained variable. Here we further control for internet base, technology investment, greening rate and industrial enterprise development. From the urban base perspective, AI and IoT can not only generate technological innovation and information sharing, but also influence regional pollutant emissions through informal environmental regulation such as public opinion campaigns (Liu et al., 2019). Government technology investment is a key factor influencing industrial transformation, which is inextricably linked to regional green and clean upgrading. From the perspective of industrial development, residential consumption and number of industrial enterprises may have a negative impact on environmental pollution (Pan et al., 2023). We use the internet users' number per ten thousand, the ratio of science expenditure to local budget expenditure, the ratio of consumer goods' total retail sales to GDP, and the above-scale industrial enterprises' number to characterize the above variables. Column (2) in Table 4 is the regression results after controlling for the omitted variables. *IPR* remains significantly negative at the 1% statistical level.

Second, the impact of NIPRDC on environmental pollution may have a time lag. To ensure the robustness, we lag the explanatory variable by one period and then regress again. Column (3) in Table 4 shows that the pilot policy still has a significant inhibitory effect on local environmental pollutant emissions.

Finally, China's administrative regions are characterized by diversity, with significant differences in terms of the populations they house and the way they are managed. To avoid the impact of inter-regional political and economic differences, we exclude the four municipalities, as well as the prefectural-level cities covered by the five autonomous regions. Furthermore, we also replace the tailing method, using a bilateral 5% Winsorize tailing process for all continuous variables. Columns (4) and (5) in Table 4 are respectively regression results. The conclusion that NIPRDC can optimize the urban environment remains unchanged.

Mechanism analysis. The regression results of the above benchmark model show that NIPRDC has a significant environmental optimization effect. Based on the previous part of the research hypotheses, we follow Baron and Kenny (1986) and Chen et al. (2020) to test the influencing mechanisms of NIPRDC on urban environmental pollution. The specific model design is as follows:

$$Metavar_{i,t} = w_0 + w_1 IPR_{i,t} + w_2 Control_{i,t} + \gamma_i + \mu_t + \varepsilon_{i,t} \quad (2)$$

$Metavar_{i,t}$ is the mechanism variable, which is used to characterize the green innovation effect and the fair market competition effect. The rest of the variables are consistent with model

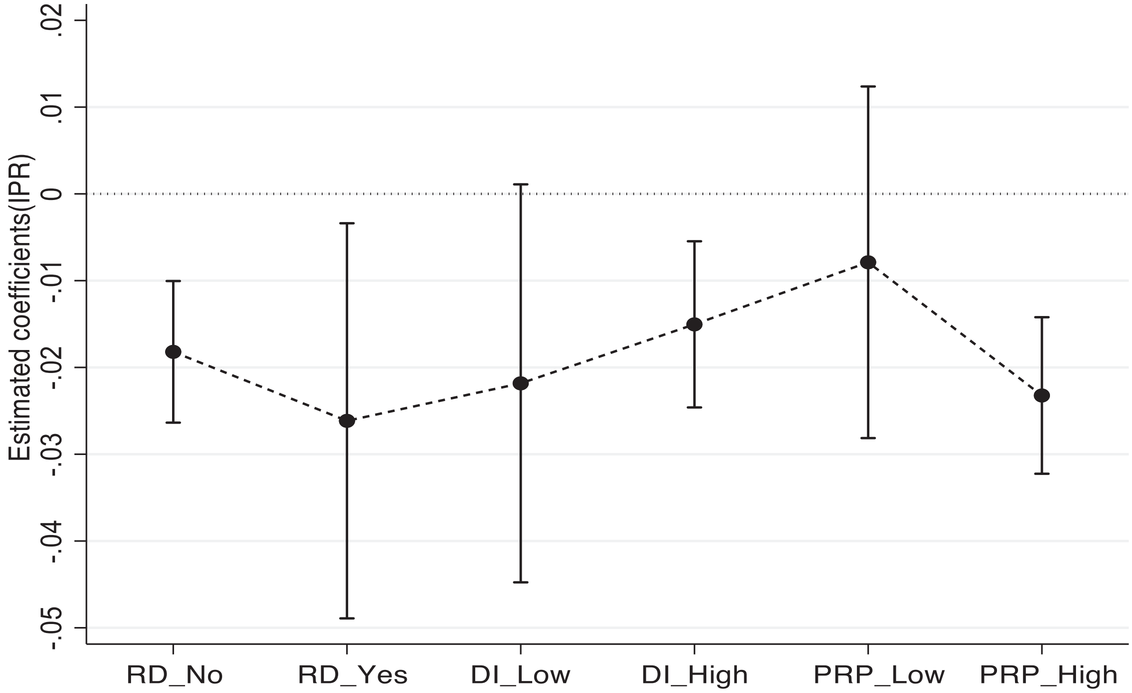

Fig. 4 Heterogeneity analysis results. The dots represent estimates and the vertical lines represent 90% confidence intervals. If the confidence interval does not include the value of 0, then the regression coefficient is significant.

(1). Considering that the model (1) has verified the correlation between explanatory variable and explanatory variable, we focus on w_1 here. If w_1 is significantly positive (negative), it indicates that NIPRDC is able to influence regional environmental pollution through this way.

Green innovation effect. Columns (1) to (3) in Table 5 report the mechanistic regression results based on the green innovation effect. Column (1) shows that *IPR* is significantly positively correlated with *INO*, which suggests that NIPRDC has a significant incentivizing effect on green innovation activities in pilot cities. The estimated coefficients of *IPR* in Columns (2) and (3) are also significantly positive at the 1% statistical level after disaggregating Chinese patent types. Whether it is a simple improvement technology or a substantial change technology, NIPRDC can contribute to its deepening development. Therefore, NIPRDC can reduce the intensity of environmental pollution in the pilot cities and improve the quality of the human environment, by improving green technology innovation.

Market competition effect. Column (4) in Table 5 reports the mechanistic regression results based on the fair market competition effect. The estimated coefficient of *IPR* is significantly negative at the statistical level of 5%. According to the intermediary variable definition, the smaller the index value, the higher the degree of fair competition in the market. So NIPRDC's implementation is conducive to aggravating the degree of local market competition, promoting the transformation and upgrading of enterprises to obtain greater living space. In this context, technological updates can quickly optimize environmental governance and reduce local pollution.

Heterogeneity analysis. To further examine the heterogeneity impacts of pilot policy on environmental pollution, we explore these impacts from the perspective of resource dependence, digital infrastructure and property rights protection.

Resource dependence. Natural resource dependence is closely related to urban industrial development and pollution emissions. The National Sustainable Development Plan for Resource-based Cities (2013–2020) clearly emphasized that resource-based cities are the guarantors of energy security. Resource cities are mainly dominated by natural resource extraction and processing, so their economic structure is relatively homogeneous and pollution is relatively serious. Here, we focus on the role of resource dependence (*RD*) in the impact of NIPRDC on environmental pollution. Figure 4 reports that NIPRDC has significant dampening effects on pollution in both non-resource-based and resource-based cities. However, the empirical p-value between two groups is 0.029, which is significant at the 5% statistical level. So compared to non-resource-based cities, resource-based cities have a more significant effect on environmental management. Hence, the natural resource dependence condition strengthens the environmental optimization effect of NIPRDC.

Digital infrastructure. The application of digital technologies such as big data and artificial intelligence is constantly helping the regional economy enter the digital era. The application of digital tools has a key impact on economic, social and environmental regulation (Ribeiro-Navarrete et al., 2021). For example, digital technology can help local governments build big data environmental supervision platforms. Therefore, we expect that digital infrastructure (*DI*) can strengthen NIPRDC' s pollution reduction effect. In this paper, the overall sample is divided into two groups (*DI_Low* and *DI_High*) and regressed on the median of the indicator. Figure 4 reports that the pilot policy in cities with low digital infrastructure cities does not reduce environmental pollution, while the pilot policy in cities with high digital infrastructure has a significant negative effect.

Property rights protection. NIPRDC's effect is most likely related to the local property rights protection. In areas with low property rights protection, although the pilot policy stimulates local innovation atmosphere, the innovation agents' willingness to engage in R&D activities may be relatively low given the weak regional property rights protection base. In areas with high property rights protection, the crackdown on intellectual property violations is stronger. With the advent of good news on the pilot policy, the local administrative and judicial protection means are continuously strengthened. These measures can effectively safeguard the legitimate rights of innovators and stimulate their willingness of technological innovation (Arza et al., 2023). Therefore, we expect that the foundation of property rights protection (*PRP*) may strengthen the environmental improvement effect of NIPRDC. Regression results are reported in Fig. 4. The policy effects are more pronounced in regions with high property rights protection bases than regions with low property rights protection bases.

Further analysis—industrial transition. The environmental optimization effect of the NIPRDC on Chinese cities may also influence the development of urban industries. Through regulatory suppression, polluting industries face significant challenges compared to cleaner industries, such as non-compliance with emission standards and disruptions in product supply chains, leading to increased pressures on the survival of polluting enterprises. Some heavy polluters, unable to bear the costs of environmental management, may opt to exit the local market. Meanwhile, polluting firms that remain will likely focus on pollution control and strive for a clean transition to sustain their market presence. As a result, the implementation of the NIPRDC is expected to further impact industrial structure development by reinforcing environmental regulations. Specifically, polluting industries may experience local inhibitive effects on their location choices relative to clean industries.

To analyze this, we calculate the number (in logarithmic form) of heavy and non-heavy polluting enterprises in Chinese prefecture-level cities, using firm location data obtained by matching the Listed Company Environmental Verification Industry Classification and Management Directory with data on listed companies in China. Additionally, we use the ratio of heavy-pollution firms to non-heavy-pollution firms as an industrial transition index (*Trans*) (Yu et al., 2020).

Table 6 presents the regression results based on the industrial transition effect. Column (1) reveals that the NIPRDC positively contributes to the development of clean industries (*Fclean*). Furthermore, the estimated coefficient for *IPR* in Column (2) is significantly negative, indicating that the pilot program substantially promotes the transition of heavy-pollution enterprises in the demonstration cities. In other words, the NIPRDC is likely to accelerate the market exit of the most polluting firms, while those that remain will be compelled to adopt cleaner practices in order to survive in the competitive market. This transition can significantly contribute to the shift towards a greener and more low-carbon industrial structure at the local level.

Table 6 Industrial transition results.

	(1) *Fclean*	(2) *Trans*
IPR	0.2513***	−0.0586*
	(0.0284)	(0.0309)
Control variables	YES	YES
Year FE	YES	YES
City FE	YES	YES
Constant	2.3636***	0.4091**
	(0.1419)	(0.1775)
N	2085	1226
Adj. R^2	0.9542	0.7626

Symbols "***, **, and *" indicate significant at the 1%, 5%, and 10% statistical levels, respectively.

Conclusion and discussion

Conclusion. IQAir's World Air Quality Report indicates that only 13 countries meet the recommended PM2.5 concentration levels in 2022. Additionally, a report released by the Organization for Economic Cooperation and Development (OECD) in 2022 highlights that global plastic production surged from 2.34 million tons in 2000 to 460 million tons in 2019, with China accounting for 32% of total production. As a developing country with the largest carbon emissions and plastic producing areas, how China achieves the goal of reducing pollution and carbon in the process of the third world energy transition has the important reference significance for the environmental regulation measures of similar countries. At present, most scholars pay attention to the influencing factors and implementation consequences of environmental regulation. Generally speaking, the green and sustainable research of intellectual property is rarely involved. Therefore, this paper regards the construction of NIPRDC carried out by the China Intellectual Property Office as a quasi-natural experiment. Using the panel data of prefecture-level cities from 2006 to 2019 in China, we explore the impact of China's NIPRDC on environmental pollution through a staggered DID model. In addition, we also open the mechanism "black box" of the pilot policy reducing urban environmental pollution from the perspective of green innovation and market competition, in order to deepen our understanding of NIPRDC and environmental regulation.

Above results show that the construction of NIPRDC has a significant pollution reduction effect, that is, pilot policies can significantly inhibit urban environmental pollution. This conclusion is still valid after multiple robustness tests such as the parallel trend test, exclusion of policy interference, PSM-DID, and placebo test. Mechanism analysis shows that the NIPRDC optimizes urban environmental pollution by stimulating green innovation and fair market competition. The heterogeneity analysis shows that resource dependence, digital infrastructure and property rights protection foundation can significantly enhance the environmental pollution optimization effect of NIPRDC. Furthermore, the pilot policy's sustainable impact accelerates the transition of heavily polluting industries. Overall, this paper offers new empirical evidence for the literature on intellectual property, environmental regulation, and technological innovation.

Discussion. Our findings provide valuable insights for both government policymakers and businesses. Firstly, government should establish a prioritized test mechanism for environmental protection patents and allocate dedicated funds to support sustainable technology research and intellectual property protection projects. This is particularly crucial for resource-based cities, where leveraging intellectual property rights policies to improve local systems and facilitate industrial restructuring is an essential measure for pollution reduction. Furthermore, local governments should enhance digital infrastructure, including the Internet, Big Data, and artificial intelligence, while encouraging financial institutions to actively provide green financing support. These efforts would equip enterprises with the necessary resources for research and pollution reduction. By strengthening property protection at the macro-regional level and promoting sustainable green transition at the micro-enterprise level, the entire industrial chain will move toward higher-end segments, fostering the trend of green industrial relocation. Then, it is imperative for enterprises to enhance internal employee training to raise awareness of IPR and cultivate sustainable innovation capabilities, ensuring long-term market competitiveness. Moreover, firms should strengthen internal environmental and knowledge governance, steering production processes toward green, low-carbon, and circular economy models. Ultimately, these efforts can contribute to the effective optimization of urban industrial structure.

There are still some improvements in this paper. Firstly, there are administrative regions dominated by counties in the pilot lists published by the China Intellectual Property Office, which indicates that different counties and districts within the same city may have different effects under the implementation of the policy. Using county-level data may be more accurate. Secondly, the spillover effects of NIPRDC should not be ignored, and constructing spatial models to study the spatial effects of pilot policies may be the reasonable supplement. Finally, the socio-economic consequences of environmental improvement in China are worth examining in depth.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Received: 3 June 2024; Accepted: 12 March 2025;
Published online: 04 April 2025

References

Ahn S, Yoon HY (2020) Green chasm' in clean-tech for air pollution: Patent evidence of a long innovation cycle and a technological level gap. J. Clean. Prod. 272:122726

Alan H, Köker AR (2023) Analyzing and mapping agricultural waste recycling research: An integrative review for conceptual framework and future directions. Resour. Policy 85:103987

Antweiler W et al. (2001) Is free trade good for the environment? Am. Economic Rev. 91(4):877–908

Arza V et al. (2023) In the name of TRIPS: The impact of IPR harmonisation on patent activity in Latin America. Res. Policy 52(6):104759

Baron RM, Kenny DA (1986) The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. J. Personal. Soc. Psychol. 51(6):1173

Battese GE, Coelli TJ (1992) Frontier production functions, technical efficiency and panel data: with application to paddy farmers in India. J. Product. Anal. 3:153–169

Beck T, Levine R, Levkov A (2010) Big bad banks? The winners and losers from bank deregulation in the United States. J Finance 65(5):1637–1667

Chang YC, Wang N (2010) Environmental regulations and emissions trading in China. Energy Policy 38(7):3356–3364

Chen W, Chen S, Wu T (2022) Research of the Impact of Heterogeneous Environmental Regulation on the Performance of China's Manufacturing Enterprises. Front. Environ. Sci. 10:948611

Chen Y et al. (2020) Arrival of young talent: The send-down movement and rural education in China. Am. Economic Rev. 110(11):3393–3430

Chen S, Yang Y, Wu T (2023) Digital economy and green total factor productivity—based on the empirical research on the resource-based cities. Environ. Sci. Pollut. Res. 30:47394–47407

Chu T, Zhou CW (2022) Complex dynamics of R&D competition with one-way spillover based on intellectual property protection. Chaos Solit Fractals 163:112491

Cole MA, Elliott RJ (2003) Determining the trade–environment composition effect: the role of capital, labor and environmental regulations. J. Environ. Econ. Manag. 46(3):363–383

Dussaux D, Dechezleprêtre A, Glachant M (2022) The impact of intellectual property rights protection on low-carbon trade and foreign direct investments. Energy Policy 171:113269

Eppinger E et al. (2021) Sustainability transitions in manufacturing: the role of intellectual property. Curr. Opin. Environ. Sustainability 49:118–126

Fan W et al. (2023) How does financial and manufacturing co-agglomeration affect environmental pollution? Evidence from China. J. Environ. Manag. 325:116544

Fitoussi R et al. (2022) Human skin responses to environmental pollutants: A review of current scientific models. Environ. Pollut. 306:119316

Fusillo F (2023) Green Technologies and diversity in the knowledge search and output phases: Evidence from European Patents. Res. Policy 52(4):104727

Geng D, Saggi K (2022) Tariff barriers and the protection of intellectual property in the global economy. Eur. Economic Rev. 144:104074

Gong X, Zhang H, Pan M (2017) Market competition, environmental regulation and industrial pollution emission in China. China Popul., Resour. Environ. 27(12):52–58

Grossman G, A Krueger (1994). Environmental Impacts of a North American Free Trade Agreement. The Mexico-U.S. Free Trade Agreement. MIT Press, Cambridge, MA, pp 13–56

Heckman JJ, Ichimura H, Todd PE (1997) Matching as an econometric evaluation estimator: Evidence from evaluating a job training programme. Rev. Economic Stud. 64(4):605–654

Helpman E (1993) Innovation, imitation, and intellectual property rights[J]. Econometrica 61(6):1247–1280

Hou S, Xu J, Yao L (2021) Integrated environmental policy instruments driven river water pollution management decision system. Socio-Economic Plan. Sci. 75:100977

Huang H et al. (2019) Emissions trading systems and social equity: a CGE assessment for China. Appl. Energy 235:1254–1265

Joshi P et al. (2022) Environmental Pollution of Potentially Toxic Elements (PTEs) and its Human Health Risk Assessment in Delhi Urban Environs, India. Urban Clim. 46:101309

Kanwar S, Evenson R (2003) Does intellectual property protection spur technological change? Oxf Econ Pap 55(2):235–264

Kumar SS et al. (2023) Cleaner production of waste-derived alkali activators from industrial and agricultural by-products for sustainable alkali activated binders. Constr. Build. Mater. 391:131824

Li M, Du W, Tang S (2020) Assessing the impact of environmental regulation and environmental co-governance on pollution transfer: Micro-evidence from China. Environ. Impact Assess. Rev. 86:106467

Lin K (2023) The impact of intellectual property protection on business performance of high-tech enterprises: The mediating effect of political-business relations. Finance Res Lett 54:103718

Liu X et al. (2019) How public environmental concern affects the sustainable development of Chinese cities: An empirical study using extended DEA models. J. Environ. Manag. 251:109619

Liu X et al. (2024) Air quality improvements can strengthen China's food security. Nat. Food 5:158–170

Lv K et al. (2023) Can intellectual property rights protection reduce air pollution? A quasi-natural experiment from China. Struct. Change Economic Dyn. 65:210–222

Ma S et al. (2021) An environmental-friendly pesticide-fertilizer combination fabricated by in-situ synthesis of ZIF-8. Sci. Total Environ. 789:147845

Maskus KE, Ridley W (2016) Intellectual Property-Related Preferential Trade Agreements and the Composition of Trade. Robert Schuman Centre for Advanced Studies Research Paper, 2016/35

Murray F, Stern S (2007) Do formal intellectual property rights hinder the free flow of scientific knowledge?: An empirical test of the anti-commons hypothesis. J Econ Behav Organ 63(4):648–687

Neves PC et al. (2021) The link between intellectual property rights, innovation, and growth: a meta-analysis. Economic Model. 97:196–209

Niu Y et al. (2023) Does digital transformation speed up dynamic capital structure adjustment? Evidence from China. Pacific-Basin Finance J 79:102016

Oppenheim C (2005) World Pat. Inf. 27(3):257

Pan M et al. (2023) Can intellectual property rights protection reduce air pollution? A quasi-natural experiment from China. Struct. Change Economic Dyn. 65:210–222

Peng Y et al. (2021) Energy consumption analysis and multiple-criteria evaluation of high-speed trains with different marshaled forms in China. Sci. Total Environ. 759:143678

Porter, ME (1991). America's green strategy. Scientific American

Ren S et al. (2023) Assessing the impact of economic growth target constraints on environmental pollution: Does environmental decentralization matter? J. Environ. Manag. 336:117618

Ribeiro-Navarrete S, Saura JR, Palacios-Marqués D (2021) Towards a new era of mass data collection: Assessing pandemic surveillance technologies to preserve user privacy. Technol. Forecast. Soc. Change 167:120681

Scott P, Spadavecchia A (2023) Patents, industry control, and the rise of the giant American corporation. Res. Policy 52(1):104651

Song H, Chen W (2023) Can two-way foreign direct investment promote green innovation capability in manufacturing? The threshold role of intellectual property protection. J. Clean. Prod. 425:139035

Song Y et al. (2023) Industrial agglomeration, technological innovation and air pollution: Empirical evidence from 277 prefecture-level cities in China. Struct. Change Economic Dyn. 66:240–252

Su Z, Wang C, Peng MW (2022) Intellectual property rights protection and total factor productivity. Int. Bus. Rev. 31(3):101956

Telg N, Lokshin B, Letterie W (2023) How formal and informal intellectual property protection matters for firms' decision to engage in coopetition: The role of environmental dynamism and competition intensity. Technovation 124:102751

Vezzoni R, Sijtsma F, Vihinen H (2023) Designing effective environmental policy mixes in the UN Decade on ecosystem restoration. Ecosyst. Serv. 62:101541
Wu X et al. (2019) Environmental and economic effects of sulfur dioxide emissions trading pilot scheme in China: A quasi-experiment. Energy Environ. 30(7):1255–1274
Wang L et al. (2021) Will researching digital technology really empower green development? Technol. Soc. 66:101638
Wang L, Wang Z, Ma Y (2022) Heterogeneous environmental regulation and industrial structure upgrading: Evidence from China. Environ. Sci. Pollut. Res. 29(9):13369–13385
Wang X, Su Z, Mao J (2023) How does haze pollution affect green technology innovation? A tale of the government economic and environmental target constraints. J. Environ. Manag. 334:117473
Wang Z et al. (2012) Energy technology patents–CO2 emissions nexus: an empirical analysis from China. Energy Policy 42:248–260
Yang R, Hu Z, Hu S (2023) The failure of collaborative agglomeration: From the perspective of industrial pollution emission. J. Clean. Prod. 387:135952
Yang X et al. (2024) Environmental pollution and officials' promotion: How China's green attention matters. J Environ Manag 365:121590
Yu Y, Cheng L, Zhang D (2024) How does market competition affect enterprise cooperative innovation? The moderating role of intellectual property protection and government subsidies. Technovation 137:103102
Yu YZ, Sun PB, Xuan Y (2020) Do Constraints on Local Governments' Environmental Targets Affect Industrial Transformation and Upgrading? Econ Res J 55(08):57–72. (in Chinese)
Zhang P et al. (2024) Estimating the role of air quality improvements in the decline of suicide rates in China. Nat. Sustainability 7:260–269
Zhao Y, Zheng L, Zhu J (2022) Could environmental courts reduce carbon intensity? Evidence from cities of China. J. Clean. Prod. 377:134444
Zheng ZQ, Ma Y, Fan A (2023) Environmental preference, market competition and enterprise green innovation. J. Shandong Univ. (Philos. Soc. Sci.) 4:125–136. (in Chinese)

Author contributions
Shi Chen: formal analysis, writing—review and editing, validation, resources. Jie Peng: writing—original draft, methodology, formal analysis, data curation. Zicheng Zhang: writing—original draft, supervision, project administration, methodology.

Competing interests
The authors declare no competing interests.

Ethical approval
Ethical approval was not required as the study did not involve human participants.

Informed consent
The participant has consented to the submission of the article research to the journal.

Additional information
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