Does Pollution Levy Standards Reform Promotes Green Innovation? Evidence From China

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Evidence from China

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Abstract

Taking advantage of the quasi-natural experiment generated by the adjustment of pollution levy standards in different Chinese provinces and utilizing detailed prefecture-level data from 2004 to 2014, we rigorously examine the effect of the increase in pollution charges on green innovation by adopting the difference-in-differences method. We find that the increase in the pollution levy standards can significantly promote regional green innovation, with the magnitude of being nearly 10%, as compared with their control group. Additionally, we further find that the positive effects tend to be reinforced by financial development and stringent environmental regulations. Particularly, the stimulating effects are mainly reflected in green invention patents, rather than utility model patents. Finally, this reform promotes green innovation in the central region, but has no effect on the eastern and western regions. Our study suggests that Chinese government should set different pollution levy standards for enterprises in different regions, rather than a one-size-fits-all standard.

Keywords Green innovation; Pollution levy standards; China

JEL classification H23; O31; Q52; Q58

1. Introduction

Since the reform and opening up in 1978, China's economy has achieved world-renowned achievements, however, China has also entered a peak of environmental pressure. China adopting extensive development of "high energy consumption, high pollution, low innovation and low efficiency" is constantly approaching the limit value of environmental bearing capacity. Nowadays, how to achieve a win-win situation between economic growth and environmental improvement becomes one of the challenges facing the Chinese government (EPI, 2019; IPE, 2020), and green innovation provides a feasible path to achieve sustainable growth (Ghisetti and Pontoni, 2015). Theoretically, green innovation can reduce the consumption of materials and energy, and the emissions of exhaust gas and wastewater in the production process. However, China's green innovation is not optimistic, especially when compared with developed countries. Additionally, up to now, research on green innovation has been mainly limited to developed countries, and there are very few literatures focusing on China's green innovation. As the most important environmental policy in China, the impact of pollution levy system on green innovation has not yet been analyzed in depth. Can the pollution levy system enhance China's green innovation performance? What is

the effect heterogeneity? This is what we aim to explore.

In May 2007, the State Council issued the *Comprehensive Work Plan for Energy Conservation and Emission Reduction*, which stipulated that all provinces should follow the principle of compensating pollution control costs, the sulfur dioxide levy standards will be increased from the original 0.63 yuan per kilogram to 1.26 yuan per kilogram in three years. Since then, some provinces have successively increased their pollution levy standards. In July 2007, Jiangsu province took the lead in raising pollution levy standards. After that, 15 provinces including Anhui, Hebei, Shandong, Inner Mongolia, Guangxi, Shanghai, Yunnan, Guangdong, Liaoning, Tianjin, Xinjiang, Beijing, Ningxia, and Zhejiang all raised their pollution levy standards. In 2015, the pollution levy standards were adjusted nationwide. After the adjustment in pollution levy standards, the pollution expenditure that enterprises need to pay increases, and their revenue will also decrease correspondingly, which may affect their green innovation behavior.

In our studies, we rigorously explore how pollution levy standards, the key elements of pollution levy system in China, have influenced regional green innovation. The first problem we encountered was how to identify the green innovation effect of the pollution levy standards policy from other environmental regulations policies. Because, in practice, multiple environmental policies are often used in combination, not just pollution levy standards policy. To do so, we resorted to the exogenous variations generated by the adjustment of pollution levy standards in different Chinese provinces, and adopted difference-in-differences (DID) method by comparing the green innovation changes of the treatment group and control group, and examined the effects that the policy of such a levy change exerts on green innovation. This allows us to exclude the interference of endogenous problem and the confounding factors. We found that the green innovation in the pilot regions has been significantly improved, with the magnitude of being nearly 10%, as compared with their control group. Meanwhile, our results are still robust after controlling other reform and conducting the placebo tests. Simultaneously, our DID strategy satisfies the common trend assumption. Besides, we found that the positive effects are inclined to be reinforced by financial development and stringent environmental regulations. Finally, the pollution levy standards reform only promotes green invention patents, but has no effect on utility model patents; this reform promotes green innovation in the central region, but has no effect on the eastern and western regions.

Our studies build on and contribute to several strands of literature. First, our studies are related to the literature of green innovation. Green innovation refers to innovation that are committed to improving environmental performance in corporate emission reduction, recycling, and the substitution of environmentally friendly materials (Rennings, 2000; Rennings and Rammer, 2011), and mainly includes pollution management, clean technologies and products, natural resource management, and eco-friendly products (OECD, 2011). Previous literature has aimed to shed light on the driving forces of green innovation (Triguero et al., 2013; Ghisetti et al., 2015; Zubeltzu-Jaka et al., 2018). Specifically, Zubeltzu-Jaka et al. (2018) classified the influencing factors into technology push, market pull, regulatory push/pull, and firm specific factors, while Del Río González (2009) and Horbach (2008) categorized the factors of green innovation as internal and external factors. Besides, other scholars emphasize the importance of environmental regulations (Wang et al., 2018; Popp, 2002; Wagne, 2008; Johnstone et al., 2010; Berrone et al., 2013; Lim and Prakash, 2014), environmental policies (Newell, 2011; Nesta et al., 2014), market liberalization (Jamasp and Pollitt, 2008; Sanyal and Ghosh, 2014) in green innovation. However, existing studies

on green innovation are mainly concentrated in developed countries (Berrone et al., 2013; Ghisetti et al., 2015). To bridge this gap, we focused on China, the largest developing country, who is currently concerned about the construction of ecological civilization.

Second, we make contributions to the literature of pollution levy or pollution taxes. Although pollution levy or pollution tax systems have achieved significant positive effects in developed countries (Brown and Johnson, 1984), there is a widespread problem of “endogenous enforcement” in developing countries (Pargal and Wheeler, 1996; Hartman et al., 1997). Under the promotion incentives of local officials, economic development is the most important goal, which results in the actual collection rate of pollution levy being affected by economic development (Wang and Wheeler, 2000; Chen et al., 2014). However, up to now, previous literature mainly focused on the impact of the pollution levy system on pollutant emissions (Harford, 1978; Wang and Wheeler, 2005; Lin, 2013; Jin and Lin, 2014). Nevertheless, studies addressing the impact of pollution levy on green innovation are relatively scarce. And this is what we aim to explore. Theoretically, the pollution levy is an important tax burden for enterprises. When pollution levy has a sufficient impact on the business performance, it can change their innovation behavior and encourage the enterprises to carry out green innovation.

Finally, our research has strong policy significance. Taking advantage of a quasi-natural experiment of the adjustment in China’s pollution levy standards policy, we can more accurately identify the impact of pollution levy standards on green innovation. Our results show that when the pollution levy standards are lower than the marginal cost of corporate pollution abatement, increasing the pollution levy standards can achieve significant green innovation performance. Furthermore, our studies demonstrate that when developing the pollution levy standards, it is necessary to take regional differences into account, and set the pollution levy standards for enterprises in different regions, rather than a one-size-fits-all standard.

The rest of our article is arranged as follows. Section 2 depicts the institutional background and research hypotheses. Section 3 is the data and research design. Section 4 is the empirical results and robustness test. Section 5 is the effect heterogeneity and Section 6 provides the conclusions and policy recommendations.

2. Institutional background and hypothesis proposal

2.1 Institutional background

The pollution levy system was first introduced in OECD countries in the early 1970s. Learning from the experience of environmental management in developed countries, China first proposed the concept of pollution levy system in 1978. Subsequently, in 1979, the “Environmental Protection Law of the People’s Republic of China (Trial)” stipulated that pollutant emissions exceeding the nationally prescribed standards shall be charged according to their quantity and concentration. It further provides a relevant legal basis for pollution levy system. In February 1982, the State Council made detailed regulations on the purpose, scope, standards, additional and reduced conditions, and fee management of the pollution levy. The pollution levy system was formally established and implemented nationwide in July 1982. In 2003, the pollution levy system began to levy based on the total pollutant emission. Then, on July 1, 2005, the pollution levy standards for SO₂ were increased to 0.63 yuan per kilogram. Facing with severe environmental situation, in May 2007,

Chinese central government has clearly proposed a binding target of 10% reduction in the total emissions of major pollutants during the 11th Five-Year Plan period, and stipulated that the pollution levy standards for SO₂ should be increased from 0.63 yuan per kilogram to 1.26 yuan per kilogram. In response to this policy, various provinces in China have successively adjusted their pollution levy standards (see Table 1 for more details). Jiangsu province took the lead on July 1, 2007. Subsequently, Anhui province, Hebei province, Shandong province, and Inner Mongolia Autonomous increased their pollution levy standards in 2008. As of the end of 2014, 15 provinces in China have increased their pollution levy standards to 1.26 yuan per kilogram, except for Beijing, that raised the pollution levy standards to 10 yuan per kilogram.

Table 1 Pilot Provinces for China's SO₂ Pollution Levy Standards

Pilot provinces	Policy time	Pollution levy standards
Jiangsu	2007. 7. 1	1.26 yuan/ton
Anhui	2008. 1. 1	1.26 yuan/ton
Hebei	2008. 7. 1	1.26 yuan/ton
Shandong	2008. 7. 1	1.26 yuan/ton
Inner Mongolia	2008. 7. 10	1.26 yuan/ton
Guangxi	2009. 1. 1	1.26 yuan/ton
Shanghai	2009. 1. 1	1.26 yuan/ton
Yunnan	2009. 1. 1	1.26 yuan/ton
Guangdong	2010. 4. 1	1.26 yuan/ton
Liaoning	2010. 8. 1	1.26 yuan/ton
Tianjin	2010. 12. 20	1.26 yuan/ton
Xinjiang	2012. 8. 1	1.26 yuan/ton
Beijing	2014. 1. 1	10 yuan/ton
Ningxia	2014. 3. 1	1.26 yuan/ton
Ningxia	2014. 4. 1	1.26 yuan/ton

2.1 Research hypothesis

Environmental pollution has negative externalities, resulting in inefficient and unfair resource allocation. To correct the pollution behavior of enterprises, Pigou (1920) proposed to tax the pollution behavior, and the tax should be equal to the marginal external cost of pollutant emissions. This tax is hence known as the "Pigovian tax", and it is also the source of the pollution levy system. The pollution levy system is that the government levies a fee based on the external environmental losses caused by pollutant emissions, and then internalizes the external cost of pollution behavior. The profit of an enterprise is equal to the income (including the income obtained by maintaining the current pollution level, the income obtained by green innovation, etc.) minus the cost (including the pollution fee paid for maintaining the current pollution level, the cost of green innovation, etc.). After the adjustment of pollution levy standards, companies need to pay more pollution fee to the governments. Driven by profit maximization, polluters will comprehensively weigh the pollution fee paid to maintain the current pollution level and the cost of green innovation. If the pollution fee is too high, for cost minimization considerations, polluters are likely to carry out green innovation. Based on this, we propose the Hypothesis 1:

Hypothesis 1: The increase in pollution levy standards can promote green innovation.

However, green innovation activities have the characteristics of long-term, uncertainty, high adjustment costs, high failure rate (Hsu et al., 2015), and need a large amount of financial support (Chemmanur et al., 2014), which makes corporate green innovation face financing constraints (Hall et al., 2016). Meanwhile, previous studies have widely shown that R&D activities to a large extent depend on whether the company can obtain sufficient external financing (Brown et al., 2009; Brown and Petersen, 2011; Ang et al., 2014). Good financial development can effectively solve the information asymmetry in enterprise green innovation, guide investment, improve the efficiency of green innovation investment and capital matching (King and Levine, 1993; Chowdhury and Maung, 2012). Recently, Zhou and Du (2021) found evidence that financial development is conducive to the environmental-biased technological progress. Overall, financial development is a prerequisite for green innovation, which can affect the success and failure of green innovation (Pellegrino and Savona, 2017; Zhou and Du, 2021). Previous studies also extensively recognized that financial development is a dominant factor of innovation (King and Levine, 1973). Based on this, we propose the hypothesis 2:

Hypothesis 2: Financial development can reinforce the positive effect of the increase in pollution levy standards on green innovation.

Besides, due to differences in local economic development and environmental quality, the actual pollution levy rate in different regions varies significantly (Wang and Wheeler, 2005; Chen et al., 2014; Maung et al., 2016). That is to say, there will be endogenous enforcement problems in the pollution levy, and enforcement of environmental regulations can affect the actual pollution levy rate. Moreover, large number of previous studies on driving factors of green innovation have emphasized the importance of environmental regulations, especially mandatory environmental regulations (Dechezleprêtre et al., 2015; Dechezlepretre and Sato, 2017; Wang et al., 2018). The enforcement of environmental regulations can affect the company's expenditure on pollution levy. When local government relax their environmental regulations, enterprises are less likely to be punished for emitting pollutants, and at this time, the pollution fee that companies need to pay is reduced, the optimal policy for the enterprises is to pay pollution fees, rather than green innovations. Especially, when environmental regulations enforcement increases to the extent that the pollution fee paid by the company to maintain the existing pollution level is equal to or more than the cost of green innovation, the enterprises will carry out green innovation. Then, we propose the Hypothesis 3:

Hypothesis 3: Stringent environmental regulations can strengthen the relationship between pollution levy standards reform and green innovation.

3. Data and Research Design

3.1 Data and Summary Statistics

Since July 2003, China began to implement a total pollutant emissions levy system, and the levy standards was 0.63 yuan per kilogram. During 2007 to 2014, several Chinese provinces increased the SO₂ emissions levy standards to 1.26 yuan per kilogram. Therefore, taking advantage of the quasi-natural experiment that adjusts the levy standards of SO₂ emissions in different Chinese provinces, we constructed the panel data at the prefecture-level city from 2004 to 2014, and rigorously examined how the increase in pollution levy standards (hereafter, PLS) influenced

regional green innovation. Learning from the existing literature (Carrion-Flores and Innes, 2010; Johnstone et al., 2010; Nesta et al., 2014), we used patent data to measure green innovation. The World Intellectual Property Organization (WIPO) launched a green list of international patent classifications (IPC) in 2010, which classified green patents into seven major categories: transportation, waste management, and energy conservation, alternative energy production, administrative regulatory or design aspects, agriculture or forestry, and nuclear power generation. In addition, the IPC classification number corresponding to each category is also given. We collected patent information from the State Intellectual Property Office of China from 2004 to 2014. Based on this list and IPC classification number of each patent, we identified the annual number of green patents including green invention patent application, green invention patent authorization, green utility model patent in each prefecture-level city. Here, we used the number of green invention patent applications (log) as an indicator of green innovation. Apart from patent data, the data on the economic characteristics of prefecture-level cities were derived from the China Regional Economic Statistical Yearbook and the China City Statistical Yearbook. Table 2 lists the definitions and summary statistics for each variable. Finally, we also manually collected government work reports of 31 provinces from 2004 to 2014, and the financial branches data were collected from China Banking and Insurance Regulatory Commission website^①.

Table 2 Definitions and Summary Statistics.

Variables	Definition	N	Mean	SD	Min	Max
Lngreen	the logarithm of the number of green invention patent applications in city <i>i</i> at year <i>t</i>	3135	2.84	1.74	0.00	9.41
PLS	=1 if a city increased the pollution levy standards in year <i>t</i> and afterwards; =0 otherwise	3135	0.24	0.43	0.00	1.00
Fix	Fixed asset investment/ GDP	3135	0.58	0.23	0.00	2.16
Lnfdi	Ln(fdi)	3124	9.18	2.22	0.00	14.34
Lnrgdp	Ln(real GDP per capita)	3135	9.94	0.75	4.64	12.95
Lnpopden	Ln(population density)	3135	1.84	0.63	0.20	3.68
Gdpg	GDP growth rate	3135	13.31	3.95	-19.38	108.80
Indus	Value added of the tertiary industry/value added of the secondary industry	3135	1.51	0.83	0.28	10.61

3.2 Research Design

To explore whether the increase in pollution levy standards influenced regional green innovation, we resorted to the quasi-natural experiment that adjusted the levy standards of SO₂ emissions, and used DID method to compare the variations of green innovation in PLS cities before and after the PLS reform with that of prefecture-level cities which had not yet implemented the PLS reform during the sample period. Specifically, the benchmark DID model was set as follows:

$$Lngreen_{it} = \alpha + \beta PLS_{it} + X + \varepsilon_i + \varepsilon_t + \varepsilon_{it} \quad (1)$$

where *i* and *t* indicate city and year, respectively. $Lngreen_{it}$ is the outcome variables we are interested in (the logarithm of invention patent applications number in city *i* at year *t*).

^① <http://xkz.cbirc.gov.cn/jtr/>.

PLS_{it} indicates whether city i implemented the PLS policy in year t , and takes a value of 1 if $t \geq t_{p0}$, and 0 otherwise, where t_{p0} is the policy year; if the reform occurred after July, t_{p0} represents the next year of the reform. Moreover, ε_i is the city-specific fixed effects, capturing the regional characteristics that may affect the dependent variable which not changes with time; ε_t is the year-specific fixed effects, capturing the impact of certain shocks that occur across the country in a fixed year; ε_{it} is the error term. In addition, X represents a series of control variables that may affect regional green innovation. Here, X includes GDP growth rate (Gdp_g), the logarithm of real per capita GDP ($Lnrgdp$), industrial structure (measured by the ratio of the value added of the tertiary industry to the value added of the secondary industry, $Indus$), the logarithm of population density ($Lnpopden$), logarithm of foreign direct investment ($Lnfdi$), and the proportion of fixed asset investment in GDP (Fix).

3.3 Identifying assumption and checks

A main threat to our above research design is that the PLS cities are not randomly selected, so the regional green innovation differences between the PLS cities and non-PLS cities may be caused by pre-existing factors, then our DID method may be biased. To deal with this concern, we adopted the methods proposed by Gentzkow (2006). We first identified the key selection criteria of PLS cities, and flexibly controlled for the key selection variables in our regression. Specifically, those provinces that emit more pollution, and that are economically developed are more likely to raise pollution levy standards. So, we used the SO₂ emissions, GDP growth rate, real per capita GDP, population density, foreign direct investment, fixed asset investment and industrial structure as the key selection variables (Li et al., 2016; Liu and Mao, 2019). Then, we interacted these key selection variables with a third-order polynomial function of time trend in Eq. (2), controlling for the specific time trend in selection variables and excluding the potential confounding factors which may affect both the implementation of the PLS reform and green innovation. Lastly, we interacted the key selection variables with year dummies in Eq. (3), capturing the time effect of key selection variables on our dependent variable.

$$Lngreen_{it} = \alpha + \beta PLS_{it} + \theta(s \times f(t)) + X + \varepsilon_i + \varepsilon_t + \varepsilon_{it} \quad (2)$$

$$Lngreen_{it} = \alpha + \beta PLS_{it} + \gamma(s \times \varepsilon_t) + X + \varepsilon_i + \varepsilon_t + \varepsilon_{it} \quad (3)$$

4. Empirical results

4.1 Baseline results

Table 3 displays the benchmark empirical results of PLS reform on green innovation. In column (1), we only controlled for the city fixed effects, year fixed effects, and the core explanatory variables. On the basis of column (1), we further added the control variables of GDP growth rate and real per capita GDP in column (2). In column (3), we added the logarithm of population density. In column (4), we also introduced the proportion of fixed asset investment in GDP. In column (5), we further added industrial structure. In column (6), we introduced the logarithm of foreign direct investment. It can be found that the coefficients of PLS were all significantly and economically positive, indicating that when the pollution levy standards were increased in the pilot areas, the green innovation has been greatly improved after the PLS reform, as compared with the non-PLS cities. And in terms of the estimated magnitude, compared with non-PLS cities, green innovation in the pilot areas has increased by about 10% ($e^{0.0955} - 1$) after the PLS reform.

Table 3 Baseline estimates.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
PLS	0.1035*** (0.0345)	0.0980*** (0.0348)	0.0974*** (0.0348)	0.0956*** (0.0349)	0.1006*** (0.0354)	0.0955*** (0.0355)
Lnrpgdp		-0.0547 (0.0604)	-0.0544 (0.0604)	-0.0557 (0.0608)	-0.0787 (0.0601)	-0.0520 (0.0629)
Gdpg		-0.0030 (0.0031)	-0.0030 (0.0031)	-0.0026 (0.0031)	-0.0031 (0.0032)	-0.0025 (0.0032)
Lnpopden			-0.1047 (0.2904)	-0.1080 (0.2921)	-0.0970 (0.2861)	-0.1077 (0.2879)
Fix				-0.0471 (0.0751)	-0.0619 (0.0762)	-0.0674 (0.0773)
Indus					0.0459 (0.0383)	0.0425 (0.0392)
Lnfdi						-0.0274* (0.0153)
Constant	7.0526*** (0.0468)	7.6512*** (0.6319)	7.8214*** (0.7786)	7.8479*** (0.7850)	8.0696*** (0.7661)	8.1393*** (0.7944)
City FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
N	3,135	3,135	3,135	3,135	3,135	3,124
R ²	0.9221	0.9222	0.9222	0.9222	0.9223	0.9221

Note: (1) *** denotes significance at 1%, ** at 5%, and * at 10%. “Control” denotes GDP growth rate, real per capita GDP, industrial structure, population density, foreign direct investment, the proportion of fixed asset investment in GDP. FE stands for “fixed effects.”

4.2 Robustness test

4.2.1 Common trend assumption

The premise of DID method is to satisfy the common trend assumption. Specifically, the PLS cities and non-PLS cities should follow similar trends before the PLS reform. To check whether our study satisfies the common trend assumption, we adopted the event study describes by Jacobson et al. (1993). And the estimation equation is set as follows:

$$Lngreen_{it} = \alpha + \beta_n \sum PLS_{t_{i0}+n} + X + \varepsilon_i + \varepsilon_t + \varepsilon_{it} \quad (4)$$

Where $PLS_{t_{i0}+n}$ is a series of year-wise dummy variables indicating whether $t - t_{i0} = n$, with $n = \leq -3, -2, -1, 1, 2, 3, \geq 4$. And t_{i0} denotes the year in which city i implemented the PLS reform; ≤ -3 is a bin for years -11 to -3; ≥ 4 is a bin for years 4 to 6 (Liu and Mao, 2019). Then, we made the omitted time category is $n = 0$, so the coefficient of β_n measures the effects compared to the current period of the reform. If our DID method satisfies the common trend assumption, the coefficient of $\beta_{\leq -3}, \beta_{-2}, \beta_{-1}$ should not be significant. Fig.1 depicts the estimated coefficients of these dummy variables and their 95% confidence interval. As shown in Fig. 1, the coefficient of $\beta_{\leq -3}, \beta_{-2}, \beta_{-1}$ are not significant, indicating that there was no pre-trend difference between PLS cities and non-PLS cities. So, the common trend assumption was satisfied. Moreover, the coefficient of β_3 and $\beta_{\geq 4}$ are economically and significantly positive, and the estimated

magnitude were gradually increased. Taken these results together, we proposed that with the implementation of the PLS policy, the green innovation differences between PLS cities and non-PLS cities gradually increased.

Fig. 1. The event study estimates. *Notes:* This figure depicts the event study estimates and 95 percent confidence intervals of specification (4). The dependent variable is the logarithm of green invention patent applications number. The horizontal axis measures the number of years since the adjustment in pollution levy standards reform. ≤ -3 is a bin for years -11 to -3; ≥ 4 is a bin for years 4 to 6.

4.2.2 Identifying assumption results

Additionally, a primary concern to our DID strategy is that our PLS cities are not randomly selected. So, the above results would be biased. To address this worries, learning from the method suggested by Gentzkow (2006), we introduced the interaction of the selection variables with a third-order polynomial function of time trend or year dummies. In column (1) and (2), we reported the results of including interaction between a third-order polynomial function of time trend and selection variables with and without the control variables, respectively. It can be found that the coefficient of PLS is still positive, despite a drop in estimated magnitude. Similarly, in column (3) and (4), we further controlled the interaction of selection variables with year dummies, and the results were still robust. Combining the results in Table 4, we believed that the PLS reform has promoted regional green innovation.

Table 4 Identifying assumption results

Variables	(1)	(2)	(3)	(4)
PLS	0.0648* (0.0357)	0.0610* (0.0355)	0.0706** (0.0360)	0.0710** (0.0360)
Control	NO	YES	NO	YES
Control*T	YES	YES	NO	NO
Control*T2	YES	YES	NO	NO
Control*T3	YES	YES	NO	NO
Trend	YES	YES	NO	NO
Control*Year dummy	NO	NO	YES	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

N	3,093	3,093	3,093	3,093
R ²	0.9253	0.9259	0.9266	0.9266

Note: (1) *** denotes significance at 1%, ** at 5%, and * at 10%. “Control” denotes GDP growth rate, real per capita GDP, industrial structure, population density, foreign direct investment, the proportion of fixed asset investment in GDP. FE stands for “fixed effects.” In column (1) and (2), we included the interaction between a third-order polynomial function of time trend and selection variables with and without the control variables, respectively. Beyond that, in column (3) and (4), we controlled the interaction of selection variables with year dummies with and without the control variables, respectively.

4.2.3 Excluding other reform

Another concern about above conclusions is that other policies occurred in China during the sample period may interfere with the reliability of our results. Typically, China has implemented sulfur dioxide emissions trading policy (hereafter, ET) during the sample period. In 2002, Shandong, Shaanxi, Jiangsu and Henan, three cities in Liuzhou has implemented ET policies. In 2007, the scope of ET pilot areas was expanded into Jiangsu, Tianjin, Zhejiang, Hubei, Chongqing, Hunan, Inner Mongolia, Hebei, Shaanxi, Henan, and Shanxi. Theoretically, environmental rights trading policies can have an important impact on green innovation (Jaffe and Palmer, 1997; Lanjouw and Mody, 1997; Calel and Dechezleprêtre, 2016), which eventually biased our results. To eliminate the effect of the ET policy, we added the dummy variable of whether a city is ET policy pilot area in Eq. (1) as an additional control variable. The corresponding results are reported in column (1) and (2) of Table 5, we still found a significantly positive impact of the PLS reform, and estimated magnitudes were also consistent with the results of column (6) of Table 3.

In addition, the two control zones (TCZ) policy is also a typical environmental policy. TCZ refers to acid rain control zones and sulfur dioxide control zones, including 175 cities in 27 provinces. TCZ policy aims to control the deteriorating environment in the form of administrative orders. Generally, SO₂ in the TCZ can only be emitted after reaching certain standards, and the total SO₂ emissions control is implemented in the TCZ. Thus, the environmental regulations in the TCZ are tighter than those in non-TCZ. Environmental regulations have a positive impact on regional technological innovation (Porter and Linde, 1995; Berman and Bui, 2001), which may bias our estimation results. For this reason, interactions of TCZ dummy with year dummies were introduced as the additional control variables. We consistently found that the adjustment in pollution levy standards enhanced regional green innovation.

Table 5 Robustness test: excluding other reform

	(1)	(2)	(3)	(4)
Variables	ET	ET	TCZ	TCZ
PLS	0.1012*** (0.0345)	0.0919*** (0.0354)	0.0935*** (0.0347)	0.0910** (0.0355)
ET dummy	YES	YES	NO	NO
TCZ dummy*Year dummy	NO	NO	YES	YES
Control	NO	YES	NO	YES
City FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	3,135	3,124	3,135	3,124

R^2	0.9222	0.9221	0.9232	0.9230
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Note: (1) *** denotes significance at 1%, ** at 5%, and * at 10%. “Control” denotes GDP growth rate, real per capita GDP, industrial structure, population density, foreign direct investment, the proportion of fixed asset investment in GDP. FE stands for “fixed effects.”

4.2.4 Placebo tests

Finally, another concern is that our results may be influenced by omitted variables which were not controlled in the previous analysis. To increase the validity and reliability of our results, we conducted a placebo test described by Chetty et al. (2009), La Ferrara et al. (2012), Li et al. (2016), and Davide et al. (2017). Specifically, we randomly selected 743 samples out of 3135 and designed them as the false PLS status PLS_i^{false} . Then, in order to increase the power of our placebo test, we repeated the process of random selection 500 times, and obtain 500 PLS_i^{false} regression results. In this case of random selection, PLS_i^{false} should have no impact if our baseline results are credible, so the estimated magnitude of PLS_i^{false} should be close to zero. Fig. 2 shows the distribution of the estimates from 500 runs. It can be found that the distribution of the estimates of PLS_i^{false} is centered around zero. Meanwhile, our baseline result is located out of distribution, suggesting that the nexus between PLS policy and regional green innovation were unlikely driven by omitted variables.

Fig. 2. Placebo test. Note: The vertical line in the figure represents the estimated coefficient of PLS in column (6) of Table 3. The figure is the cumulative distribution density of false PLS variables, which is randomly selected.

5. Effect heterogeneity

Our basic conclusion is that the green innovation in the pilot areas has been significantly improved after the PLS reform. On this basis, we continue to focus on the following two aspects: (1) Is the positive effect of the PLS reform on green innovation varies across regions? (2) Is the positive effect of the PLS reform on green innovation varies across patent types? Next, we attempt to answer these two questions separately.

5.1 Regional heterogeneity

5.1.1 Financial development

Compared with other environmental practices, green innovation is characterized by high risks and

a long return on investment cycle, and is not easy to obtain funds from the open market (Berrone et al., 2010), which eventually leads to the reluctance of enterprises to invest or invest less in green innovation (Nie et al., 2021). In addition, the difficulty of financing and expensive financing restrict China's innovation-driven strategy. Logically, a good financial system can provide more financial support, thereby promoting regional green innovation activities. In this part, we aimed to empirically reveal the role of financial development between PLS reform and regional green innovation. Based on benchmark model (1), we introduced regional financial development and its interaction with the PLS reform. We used the year-end loan balance of financial institutions (log) to measure regional financial development (*Finance*). Columns (1) of Table 6 reported the empirical results. We found that financial development is an important channel that affects the relationship between PLS and green innovation. Additionally, we also used the number of financial branches in prefecture-level cities to measure financial development. And the financial branches data were manually collected from China Banking and Insurance Regulatory Commission website. Logically, larger number of financial branches, better financial development. We consistently found that financial development can reinforce the relationship between PLS policy and green innovation in column (2).

Table 6 Effect heterogeneity: financial development

Variables	(1) Finance	(2) Finance
PLS * <i>finance</i>	0.1070*** (0.0252)	0.1489*** (0.0535)
Control	YES	YES
City FE	YES	YES
Year FE	YES	YES
N	3,124	3,124
R ²	0.9226	0.9229

Note: (1) *** denotes significance at 1%, ** at 5%, and * at 10%. "Control" denotes GDP growth rate, real per capita GDP, industrial structure, population density, foreign direct investment, the proportion of fixed asset investment in GDP. FE stands for "fixed effects." Here, only empirical results of the interactions are reported.

5.1.2 Environmental regulations

To verify Hypothesis 3, learning from Chen et al. (2018), we constructed regional environmental regulations indicator via government work reports^②. We constructed as follows: First, we manually collected the government work reports of 31 provinces from 2004 to 2014; Second, we segmented the text of the government work reports; Finally, we counted the frequency of occurrences of

^② Here, it should be noted that previous literature mainly used the number of environmental protection personnel, pollution abatement costs, pollution control investment, pollution tax rate as alternative indicators of government environmental regulations (Keller and Levison, 2002; Gray and Shadbegian, 2003; Henderson and Millimet, 2007), these indicators often only focus on a certain aspect of the environmental governance and are endogenous to economic development, leading to biases in the estimation results. Our indicators can better meet the exogenous requirements. First, local government work reports generally occur at the beginning of the year, while economic activities run through the whole year, which can effectively avoid the endogenous problems caused by reverse causality. Second, our environmental regulations variables are provincial-level variables, and other related variables are prefecture-level city-level variables, which can alleviate the endogenous problems caused by reverse causality.

environment-related words and calculated their proportion to the total word frequency of the full text of the government work reports. Specifically, vocabulary related to the environment includes: environmental protection, pollution, energy consumption, emission reduction, pollution emission, ecology, green, low carbon, air, chemical oxygen demand, sulfur dioxide, carbon dioxide, PM10 and PM2.5, etc. Chen et al. (2018) used the ratio of the total word count of the five words of environment, energy consumption, pollution, emission reduction and environmental protection to the total word count of the full text as the proxy variable of the government's environmental regulations. Compared with them, we used a richer vocabulary, which can more comprehensively capture the government's environmental regulations. Then, we ranked environmental regulations in ascending order with the mean as the critical point, and regressed the sub-samples, respectively. We found that after the PLS reform, only the regions with stringent environmental regulations have markedly improved green innovation, indicating that only moderate environmental regulations can positively regulate the relationship between PLS reform and green innovation.

Table 7 Effect heterogeneity: environmental regulations

Variables	(1)	(2)
	Non- stringent	Stringent
PLS	0.0936 (0.0583)	0.0946* (0.0533)
Control	YES	YES
City FE	YES	YES
Year FE	YES	YES
N	1,638	1,486
R ²	0.9171	0.9422

Note: (1) *** denotes significance at 1%, ** at 5%, and * at 10%. "Control" denotes GDP growth rate, real per capita GDP, industrial structure, population density, foreign direct investment, the proportion of fixed asset investment in GDP. FE stands for "fixed effects."

5.1.3 Geographical location

Then, we also investigated regional heterogeneity from the perspective of geographical location. Table 8 reported the corresponding results. We found the PLS reform only promoted green innovation in the central region, and had no effect in eastern and western regions. This may be because the economy in eastern region is relatively developed and their pollution treatment technology is more advanced. For these areas, the marginal cost of pollution abatement may be lower, enterprises in these areas would rather control pollution directly instead of green innovation. In western, their economic development is poor, local governments are more likely to endogenously enforce for economic growth, and the environmental regulations enforcement in western region are more likely to be lower than those in eastern and western regions, which is not conducive to green innovation in western region. Simultaneously, the pollution levy standards are high for the enterprises in the western region. While in the central region, the pollution levy standards were closer to the marginal cost of corporate pollution abatement, so the increase in pollution levy standards can promote green innovation. This results show that only when the pollution levy standards are close to the marginal cost of corporate pollution abatement can it promote regional green innovation. Moreover, the formulation of the pollution levy standards needs to take regional heterogeneity into account, and set the pollution levy standards for enterprises in different regions,

rather than a one-size-fits-all standard.

Table 8 Effect heterogeneity: geographical location

	(1)	(2)	(3)
Variables	East	Central	West
PLS	-0.0259 (0.0465)	0.8196*** (0.0999)	-0.1127 (0.0736)
Control	YES	YES	YES
City FE	YES	YES	YES
Year FE	YES	YES	YES
N	1,100	1,100	924
R ²	0.9459	0.8881	0.8957

Note: (1) *** denotes significance at 1%, ** at 5%, and * at 10%. “Control” denotes GDP growth rate, real per capita GDP, industrial structure, population density, foreign direct investment, the proportion of fixed asset investment in GDP. FE stands for “fixed effects.”

5.2 Heterogeneity of patent types

Finally, we further discussed the heterogeneity of patent types. There are three types of patents: inventions, utility models, and design patents. Among them, design patents have a small effect on innovation. For this reason, we didn’t pay attention to them. Compared with green invention patent applications, green invention patent authorization can reflect green innovation quality better. We used the number of green invention patent authorization and the number of green utility model patents as the dependent variables, respectively. As shown in column (1) and (2) of Table 9, we found that the PLS policy promoted the green invention patent authorization, but did not promoted green utility model patents.

Table 9 Effect heterogeneity: patent types

	(1)	(2)
Variables	Invention patent authorization	Utility model patent
PLS	0.1106*** (0.0360)	0.0048 (0.0317)
Control	YES	YES
City FE	YES	YES
Year FE	YES	YES
N	3,124	3,124
R ²	0.9158	0.9356

Note: (1) *** denotes significance at 1%, ** at 5%, and * at 10%. “Control” denotes GDP growth rate, real per capita GDP, industrial structure, population density, foreign direct investment, the proportion of fixed asset investment in GDP. FE stands for “fixed effects.”

6. Conclusion and policy recommendations

In this paper, we took advantage of the quasi-natural experiment that adjusts the levy standards of sulfur dioxide emissions in different Chinese provinces, and used the green patent data at the prefecture-level city level, and employed difference-in- difference estimation to identify the impact of the adjustment in pollution levy standards on regional green innovation. The main conclusions

are as follows. First, the increase in pollution charges significantly promoted regional green innovation, and the results were still valid after a series of robustness tests. Subsequently, we found that the adjustment in the pollution levy standards mainly played a role in green invention patents, but had no impact on green utility model patents. Furthermore, the positive effects are mainly reflected in central regions, but not in eastern and west regions. Finally, the positive effect tends to be reinforced by financial development and stringent environmental regulations.

Based on the above conclusions, this article draws the following policy implications. First, as the core of the pollution levy system, the increase in pollution levy standards means that local governments would impose high fees for environmental external losses, and the pollution expenditure that enterprises need to pay increases. Given the income, the revenue of the enterprises will also be correspondingly reduced, which eventually encourage enterprises to carry green innovation. It is foreseeable that when an environmental policy has a sufficient impact on the business performance of enterprises, it can change their behavior. Second, the formulation of the pollution levy standards is the key whether the pollution levy system can play a role. Only when the pollution levy standards are close to the marginal cost of corporate pollution abatement can it promote regional green innovation. However, existing pollution levy standards in China is measured based on the average pollutant abatement cost in the 1990s. Due to inflation, the average pollutant abatement cost has changed significantly today. For this reason, local governments should first calculate the marginal pollution abatement costs of enterprises, set reasonable pollution levy standards. Furthermore, when formulating the pollution levy standards, it is also necessary to take enterprise's regional differences into account, and set the pollution levy standards for enterprises in different regions, rather than a one-size-fits-all standard.

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Declarations

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