



Pollutant reduction effects of vertical environmental reform in China

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Abstract

The vertical environmental reform in China has led to the change of environmental management system from territorial management model to vertical management model. This study uses the data of 263 prefecture-level cities in China to examine the effects of China's vertical environmental reform on pollutant emissions, including industrial sulfur dioxide, wastewater emissions, and industrial fumes emissions. The findings demonstrate that vertical environmental reform resulted in a reduction in industrial sulfur dioxide, wastewater emissions, and industrial fumes emissions. And the governance effects is gradually enhanced with the passage of time, which are long-lasting effects. The above conclusions are still valid after a series of robust estimates including mitigating selection bias, placebo test, changing the dependent variables, and mitigating heterogeneous treatment effects. According to heterogeneity analysis, the vertical environmental reform has reduced the increase of pollutants caused by financial pressure and official associations, and treats border pollution problems more effectively. Under the decentralized governance system, the implementation of vertical environmental management helps to reduce local pollutant emissions. This conclusion provides the latest evidence from China for the academic debate on the advantages and disadvantages of territorial environmental management and vertical environmental management and also provides policy implications for the government's environmental governance.

Keywords Vertical environmental reform · Environmental governance · Sulfur dioxide emissions · Wastewater emissions · Fumes emissions

Abbreviations

SO ₂	Sulfur dioxide emissions
EPBs	Environmental protection bureaus
VER	Vertical environmental reform
MEE	Ministry of Ecology and Environment
gdp	Regional gross domestic product
dens	Population density
ind	Industry structure
fisc	Fiscal pressure
fdi	Foreign investment
acc	Number of environmental emergencies in the previous year

Introduction

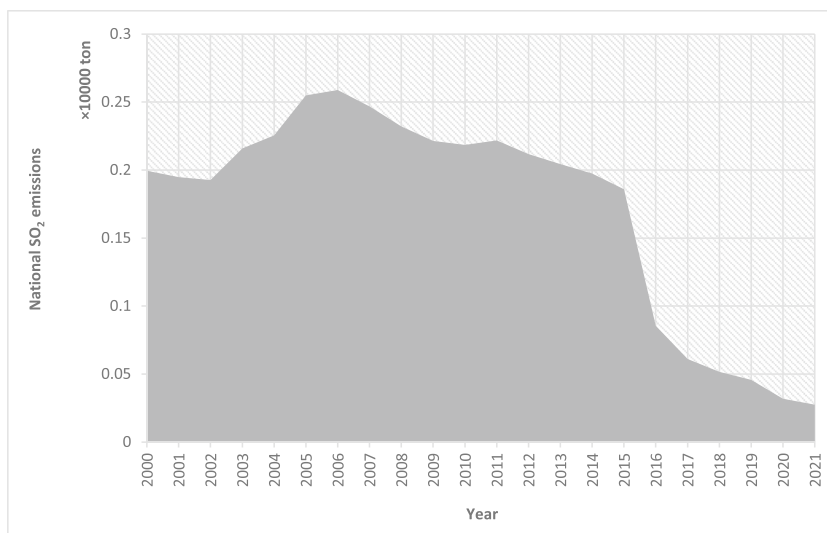
The environment exhibits market failures as a typical public good. Government involvement in the preservation of the environment is important. The key to addressing the problem in the reform of China's environmental management system is how to play the function of the government in the system of environmental governance efficiently. The territorial management model had served as the foundation for China's environmental management system from the 1980s. Although local environmental protection bureaus (EPBs) were operationally supervised by higher-level environmental protection departments. Local governments, which displayed typical decentralization features, were in charge of hiring staff and allocating funds for local EPBs. Following China's reform and openness, local GDP growth and local tax revenues have become the most crucial administration objectives for local governments as a result of fiscal decentralization (Qian and Weingast 1997) and political promotion incentives (Li and Zhou 2005). To boost economic growth and increase the number of taxpayers, local government authorities frequently lowered environmental restrictions on polluting

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Fig. 1 Total national SO₂ emissions, 2000–2021



businesses and even disturbed environmental monitoring and enforcement (Feng, et al. 2023).

The national vertical environmental reform (VER) in EPBs was formally launched by the central government in September 2016 to address the aforementioned environmental governance challenges. Before the VER, local EPBs faced administrative subordination from the local party government and operational guidance from the higher-level EPBs. In this dual management system, the county-level EPBs, as agents who carried out environmental monitoring and enforcement, were both directed by the municipal EPBs and controlled by the county-level governments' personnel and financial controls. The implementation of environmental monitoring and enforcement always needs to get the county-level governments' personnel and financial support (Li et al. 2019), which makes it easy for county-level EPBs to be interfered with by county-level governments when they prioritize economic goals in the governance targets. VER broke the territorial management mode and changed the environmental management system of China from territorial management mode to vertical management mode. Following the VER, the local EPBs' director was appointed and dismissed by the higher-level EPBs rather than local government. And the county-level EPBs adjusted to the dispatched agencies of the municipal EPBs, which means that the personnel appointment and funding of the county-level EPBs are all under the responsibility of the municipal EPBs, rather than the county-level government.

This paper uses the time-varying difference-in-difference (DID) method to test the impact of VER on regional pollutant emissions, including industrial sulfur dioxide, wastewater emissions, and industrial fumes emissions. The reason for using sulfur dioxide as the research object is that coal consumption has long accounted for more than 50% of total energy consumption in China, so that sulfur dioxide from

coal combustion is one of the most important pollutants in China. At the same time, smog caused by industrial smoke and dust discharge and water pollution caused by industrial wastewater discharge are environmental problems that have long plagued China. According to statistics (Fig. 1) published by China's MEE (Ministry of Ecology and Environment), SO₂ emissions have significantly decreased since 2016, which is also the year when VER began. Did China's pollution emissions decrease as a result of the VER?

Examining the effect of VER on the management of environmental pollution has theoretical and practical significance. First, this article contributes to the existing literature on the debate between the strengths and weaknesses of vertical and territorial management, which has long been a hot topic in academia. This study of the governance effects of shifting China's environmental management system from territorial to vertical management provides valuable real-world evidence for this academic debate. Second, we used precise data, prefecture-level official data, and the time-varying DID methodology to conduct a quantitative study of the governance effects of VER. In order to fully reflect the governance effects of VER, the paper not only examined the influence of VER on industrial sulfur dioxide emissions but also examined the influence of VER on industrial wastewater and industrial fumes emissions. The findings of the study can provide policy recommendations for the next step of pollutant emission governance.

Literature review and theoretical hypothesis

Literature review

There has been a broad debate about whether the territorial management model or vertical management model is more

efficient for government in the academic. Tiebout (1956) provided a decentralization theory in which local governments have more local information, are more aware of local people's needs, and can respond more precisely than the central government. The disadvantage of the vertical management model is that the central government is unable to consistently account for the variations in preferences, technical advancements, and cultural elements of inhabitants in various regions (Besley and Coate 2003; Millimet 2003). In the case of free mobility of local citizens, local governments can deliver public goods in a more targeted and effective manner under a territorial management model (Stigler 1957). There is also literature that expresses the other viewpoint. For instance, territorial management model may lead to the free-riding behavior of local governments (Lipscomb and Mobarak 2017). Additionally, it is asserted in the literature that neither territorial nor vertical administration has an absolute advantage and that the merits of both depend on the marginal advantages of differentiated government provision of public goods versus the external marginal costs (Oates and Portney 2003).

In the field of China's environmental governance specifically, the majority of the research contends that the country's long-standing territorial management model of environmental regulation plays a significant role in the environmental governance's failure (Wang et al. 2002; Golding 2011). Local GDP growth goals and environmental governance goals frequently conflict in China as it industrializes (Zhang et al. 2021), which makes local governments less inclined to regulate the environment (Kostka 2013). There are even local protectionist behaviors under the territorial management model, such as local governments tolerating illegal emissions by businesses and lowering environmental standards to entice high-energy and high-polluting businesses to invest and build factories in their jurisdictions (Jia and Nie 2017).

This paper uses the difference-in-differences (DID) method to investigate the changes in SO₂ emissions of local industries after the vertical environment reform in China from 2012 to 2020 with prefecture-level data, and responds to the dispute between vertical management mode and territorial management mode in the field of government environmental protection. A few studies (Han and Tian 2022; Han et al. 2021) conducted some empirical studies for the 2002 sub-municipal vertical environment reform pilot in Shanxi Province.¹ However, since the sub-municipal vertical environment reform pilot in Shanxi Province was implemented by local governments in a special context,² there could be endogeneity between the reason for reform and the result

of vertical reform. Researchers now have a better opportunity to empirically test the differences in governance effects between territorial and vertical management thanks to the central government's implementation of the countrywide vertical environment reform in 2016. This reform is more mandatory, better coordinated, and has better exogeneity. However, due to the short time of the reform and the delay in its actual implementation in the provinces, the empirical literature on this round of reform is still relatively small. Based on the theory of control, this study gives an organizational explanation for the governance effect of vertical reform by describing the shift in the governmental governance model produced by the withdrawal of environmental inspection authority. Additionally, this study tests the mechanism using data from municipal environmental monitoring and enforcement at a more granular level and is able to demonstrate that the impact of vertical reform is primarily due to the regulation of stricter enforcement by the local environmental protection departments.

Theoretical analysis and hypothesis

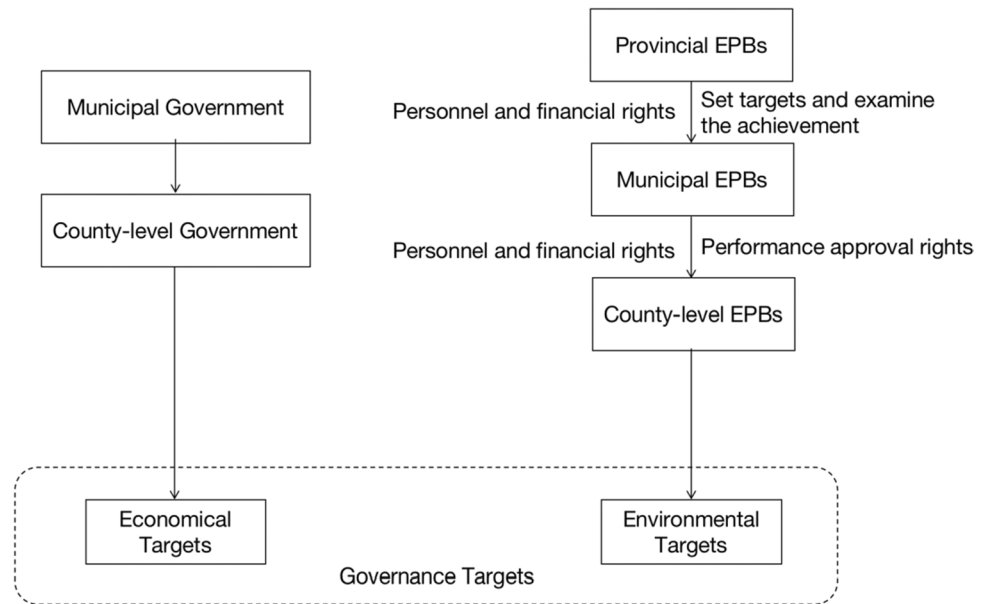
The core of the VER is the change in personnel and financial rights. Following the environmental vertical reform, the provincial EPBs appointed and dismissed the municipal EPBs' director, as well as the party secretary. The appointment and removal of personnel and funding of municipal environmental monitoring agencies are also the responsibility of the provincial EPBs. As shown in Fig. 2, most of the personnel and financial authority of municipal EPBs have been transferred to the provincial EPBs after the VER.

The environmental monitoring and enforcement in environmental governance are carried out by county-level EPBs, and the ability of county-level enforcement parties to effectively implement environmental monitoring and enforcement and resist local protectionist intervention is the key to environmental governance and the focus of institutional reform in the VER. To achieve a separation between county-level party governments and county-level EPBs, county-level EPBs are even administratively subject to the municipal EPBs. It is more challenging for county-level governments to intervene in county-level EPBs' environmental enforcement because they lack formal authority over county-level EPBs based on organizational status or real authority over personnel appointments, dismissals, or financial support. (Wang et al. 2020) A high degree of connection between municipal EPBs and county-level EPBs is

¹ There has been the sub-city environmental protection administrative management system reform viewing in Shanxi Province since 2002.

² An important reason for Shanxi Province's implementation of sub-municipal vertical management reform in 2002 was the Han River water pollution incident in 2001, which sparked great concern in society as well as the central government.

Fig. 2 Distribution of rights between local governments and EPBs after the VER



also achieved through the centralized transfer of power from county-level EPBs to municipal EPBs. Municipal EPBs no longer need to rely on personnel and financial support from county-level party governments to complete grassroots environmental monitoring and enforcement, effectively breaking the political alliance between municipal EPBs and county-level party governments, guaranteeing the independence of environmental monitoring and enforcement, and facilitating strict enforcement by grassroots environmental departments, thereby reducing regional pollutant emissions. Based on this, the research hypothesis of this paper is proposed:

Hypothesis The VER reduces regional pollutant emissions by improving environmental enforcement at the municipal level and below.

Empirical design

Model

Since the implementation time of the VER in each province varies, this paper adopts a time-varying DID model, in which the areas that have implemented the vertical environmental reform in different years of the sample period are used as the treatment group and the areas that have not implemented the vertical environmental reform are used as the control group. This paper uses a time-varying DID model to compare the changes in regional pollutant emissions before and after the implementation of the policy in the two sample groups to estimate the governance effects of the vertical environmental reform. Drawing on

Beck et al. (2010), the following econometric model was designed to test the hypothesis.

$$\text{pollution}_{it} = \alpha + \beta \text{VER}_{it} + \delta \text{control}_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

where pollution_{it} represents the pollutant emission of city i in year t . The dummy variable, VER_{it} , indicates if the city is subject to the vertical environment reform or not in year t . Before the implementation of vertical environmental reform in city i , $\text{VER}_{it} = 0$. After the implementation of vertical environmental reform in city i , $\text{VER}_{it} = 1$. The control_{it} is a set of control variables. μ_i represents city-fixed effects, controlling for time-invariant city characteristics. γ_t represents year-level time fixed effects, controlling for city-invariant year characteristics. ε_{it} is a random disturbance term. The model is estimated using clustered robust standard errors. If the hypothesis holds, the coefficient of VER_{it} should be significantly smaller than 0.

The mediating effect model is designed to test whether the VER reduces regional pollutant emissions by improving environmental enforcement at the municipal level and below. We use the two-step approach to achieve the mediating effect model. The first step is to test the impact of VER on grassroots environmental enforcement:

$$\text{enforcement}_{it} = \alpha + \beta \text{VER}_{it} + \delta \text{control}_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

where enforcement_{it} represents the grassroots environmental enforcement's strength. Other variables and model settings are the same as in (1). The second step is to regress the VER_{it} and enforcement_{it} with pollution_{it} . The other variables and model settings remain the same as in (1).

$$\text{pollution}_{it} = \alpha + \beta \text{VER}_{it} + \phi \text{enforcement}_{it} + \delta \text{control}_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (3)$$

If the mediating effect of environmental enforcement at the grassroots level exists, firstly, the implementation of the vertical environment reform should significantly increase the environmental enforcement at the grassroots level, so that β in Eq. (2) should be significantly greater than 0. Besides, the increase of grassroots environmental enforcement should reduce the regional pollutant emissions; φ in Eq. (3) is significantly less than 0.

Variables

Pollutant emissions

In this paper, industrial sulfur dioxide emissions (SO_2) are selected to construct the regional pollution emission variable. The reason is that China's coal-based energy structure determines that the main form of environmental pollution in China is air pollution (Wang et al. 2019). SO_2 from coal combustion is a serious health hazard to the population and has been one of the main targets of pollution reduction by China's central government since 1998 (Chen et al. 2013; Liu et al. 2022; Zhang et al. 2022). Using industrial SO_2 emissions as the explanatory variable can examine the achievement of environmental emission reduction targets by each local government. Also, SO_2 is a common indicator choice for scholars to explore environmental pollution problems (Antweiler et al. 2001; Sultani et al. 2021). In addition, the other pollutants, industrial wastewater emissions (effluents), and industrial smoke emissions (fumes) are also selected for robustness testing based on data availability. These three pollutants are the main targets of China's central government's emission reduction efforts from the Eleventh Five-Year Plan to the Fourteenth Five-Year Plan.

Grassroots environmental enforcement efforts

This paper measures regional grassroots environmental enforcement efforts by enforcement_{it} using the number of environmental protection administrative penalty decisions made by EPBs at the municipal and county levels in a single year. Compared to the existing literature (Han et al. 2021; Han and Tian 2022; Jin et al. 2023) which uses the frequency of environmental inspections and the amount of environmental enforcement fines at the provincial level in the province where the prefecture-level city is located to measure the strength of environmental enforcement proxy municipal environmental enforcement, this paper uses the number of formal administrative penalty decisions of municipal and county-level EPBs, which can better reflect the enforcement strength of grassroots EPBs strength.

Control variables

The level of economic development (Grossman and Krueger 1995), industrial structure, population density (Borck and Schrauth 2021; Chen et al. 2020), fiscal pressure, and foreign investment may affect regional pollutant emissions and environmental enforcement (Brynard 2009; Chen and Zhao 2019; Li and Ramanathan 2020). In this paper, we control for regional GDP (gdp), the square term of GDP (gdp^2), industrial structure (ind), population density (dens), fiscal pressure (fisc), and foreign real investment (fdi). Meanwhile, considering the possible lagged effects of social factors such as sudden environmental pollution accidents and public environmental demands on regional environmental enforcement and pollutant emissions (Li et al. 2021), this paper adds the number of sudden environmental incidents in the previous year (acc) as a control variable. Due to the lack of data on environmental emergencies at the prefecture-level city level, this paper draws on existing literature (Han et al. 2021; Han and Tian 2022) using provincial data from the province where the prefecture-level city is located for matching.

Data sources and descriptive statistics

The data on SO_2 , effluents and fumes are from the "Statistical Yearbook of China's City." Data on provincial environmental monitoring and enforcement, and environmental emergencies is obtained from the "China Environmental Yearbook" in previous years. Data on the regional economy, population, finance, etc., are from the China Stock Market and Accounting Research Database (CSMAR). Missing data on economy, population, and environment of some cities are obtained by collecting the local government's statistical yearbooks of each city to make up for them. Missing data on provincial environmental emergencies are obtained by searching the provincial EPBs. The data on administrative environmental penalty decisions of prefecture-level cities were obtained by searching the PKULAW database for prefecture-level and county-level administrative environmental penalty documents. After excluding sub-province-level cities, ethnic autonomous cities, leagues, cities without districts and counties, and samples with missing data, the unbalanced panel data of 263 prefecture-level cities from 2013 to 2020 were obtained as the samples for this paper. The reasons for using 2013 as the starting year and 2020 as the end year of the sample are as follows: (1) the DID method requires retaining the sample for a period before the implementation of the policy for differential estimation with the period after the implementation of the policy, which should ensure that the explanatory variables are not affected by other policies. Since the Chinese government and society have paid significantly more attention to environmental issues since

Table 1 Descriptive statistics of main variables in a sample of 1749

	Definition	Mean	S.D	Min	Max
SO ₂	Regional industrial SO ₂ emissions (million tons)	2.804	3.188	0.027	15.840
Effluents	Regional industrial wastewater emissions (10 million tons)	4.651	4.798	0.053	26.360
Fumes	Regional industrial smoke emissions (10 million tons)	2.179	2.730	0.031	15.400
Enforcement	Number of environmental administrative penalty decisions (hundred)	1.201	5.381	0.000	2.591
VER	Vertical environment reform, = 1 if a province has been implemented, = 0 otherwise	0.286	0.452	0.000	1.000
gdp	Regional GDP (hundred billion yuan)	2.036	1.846	0.231	10.210
gdp2	Squared items of regional GDP	7.553	16.090	0.054	104.200
dens	Density, = population/area (10,000 people/km ²)	0.041	0.026	0.001	0.185
ind	Industry structure, = GDP of secondary industry/total GDP	0.452	0.098	0.186	0.697
fisc	Fiscal pressure, = fiscal expenditure/fiscal revenue	3.241	1.963	0.876	11.800
fdi	Foreign investment (USD billion)	5.438	8.886	0.000	50.400
acc	Number of environmental emergencies in the previous year	22.900	36.942	0.000	125.000

the 18th CPC Congress in 2012, this paper uses 2013 as the starting year of the sample to avoid the influence of the above factors on the estimation results to a certain extent; (2) since the regional pollutant emission data in this paper are obtained from the China Urban Statistical Yearbook, the latest data currently counted are for the year 2020. Restricted by data acquisition, the year 2020 is the latest point of time when relevant data can be obtained. The sample of 263 prefecture-level cities in this paper covers 27 provinces, which can better represent the overall situation of the country. In order to avoid the influence of extreme values, all continuous variables are conventionally winsorized at 1% and 99%. The descriptive statistics of the main variables in this paper are shown in Table 1.

Empirical analysis

Pollutant reduction effect

In the regression of Eq. (1), columns (1), (2), and (3) of Table 2 report the effects of the vertical environment reform on the regional industrial emissions of SO₂, effluents, and fumes, respectively. The coefficients of the VER in columns (1) and (3) are all negative at the 1% significance level, while the coefficients of the VER in column (2) are negative at the 5% significance level, indicating that the implementation of vertical environment reform has significantly reduced the emissions of SO₂, effluents, and fumes in the region. The hypothesis 1 of this paper is verified.

Mechanism analysis

Column (1) of Table 3 reports the regression results for Eq. (2), omitting the control variables and the constant term.

Table 2 The impact of VER on regional pollutant emissions

	(1) SO ₂	(2) Effluents	(3) Fumes
VER	−0.519*** (−2.992)	−0.543** (−2.318)	−1.303*** (−6.161)
gdp	0.446 (0.960)	−0.559 (−1.299)	0.906*** (2.739)
gdp2	−0.057* (−1.833)	0.019 (0.570)	−0.088*** (−4.082)
dens	25.251*** (3.343)	23.940** (2.440)	12.410** (2.348)
ind	7.296*** (3.764)	5.062*** (3.078)	1.813 (1.405)
fisc	0.119 (0.977)	−0.028 (−0.413)	0.078 (1.023)
fdi	−0.009 (−0.809)	−0.016 (−1.033)	−0.001 (−0.057)
acc	−0.149*** (−4.361)	−0.023 (−0.828)	−0.055*** (−2.840)
Constant	0.902 (0.721)	3.852*** (3.214)	0.759 (1.034)
Year fixed effects	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes
Observations	1749	1749	1749
R-squared	0.579	0.378	0.452

T-values in parentheses; ***, **, and * represent *p* less than 0.01, 0.05, and 0.1, respectively

The coefficient of VER is positive at the 1% level of significance, indicating that VER has significantly improved environmental enforcement at the grassroots level. Columns (2), (3), and (4) of Table 3 report the regressions using Eq. (3) on regional industrial SO₂ emissions, industrial smoke

Table 3 Mechanism analysis

	(1)	(2)	(3)	(4)
	Enforcement	SO ₂	Effluents	Fumes
VER	0.219*** (5.289)	-0.382** (-2.123)	-0.431** (-1.992)	-1.151** (-2.340)
Enforcement		-0.626*** (-3.304)	-0.511*** (-3.598)	-0.693*** (3.482)
Control variables	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes
Observations	1749	1749	1749	1749
R-squared	0.231	0.581	0.387	0.463

*** and ** represent *p* less than 0.01 and 0.05 respectively

emissions, and industrial wastewater emissions, respectively, and the results show that the coefficients of the grassroots enforcement efforts φ are all less than 0 at the 1% significance level, indicating the existence of a mediating effect. The results show that the coefficients of grassroots enforcement are less than 0 at the 1% significance level, indicating that there is a mediating effect. This further verifies hypothesis 2 of this paper: the VER reduces regional pollutant emissions by improving environmental enforcement at the municipal level and below.

Parallel trend test and dynamic effect analysis

The parallel trend assumption of the DID method requires that the treatment group and the control group have the same trend before the policy occurs. In this paper, the difference in pollutant emissions between the treatment and control groups before and after the implementation of the VER was calculated to test the parallel trends and analyze the dynamic effects of the VER. Two dummy variables, $before_{ij}$ and $after_{ik}$, are set. When the observation time of the sample is the year j before the implementation of the VER in city i , the dummy variable $before_{ij}$ is 1; otherwise, it is 0. When the sample is observed in the year k after the implementation of the VER in city i , the dummy variable $after_{ik}$ is 1; otherwise, it is 0. The test model is designed as follows:

$$pollution_{it} = \alpha + \sum_{j=1}^6 \beta_j VER_{it} \times before_{ij} + \sum_{k=1}^4 \beta_k VER_{it} \times after_{ik} + \delta control_{it} + \mu_i + \gamma_t + \epsilon_{it} \tag{4}$$

Equation (4) is the regression equation for the parallel trend test and dynamic effects analysis of pollutant emissions. The equation does not include the VER dummy variable for the year of implementation of the VER to avoid

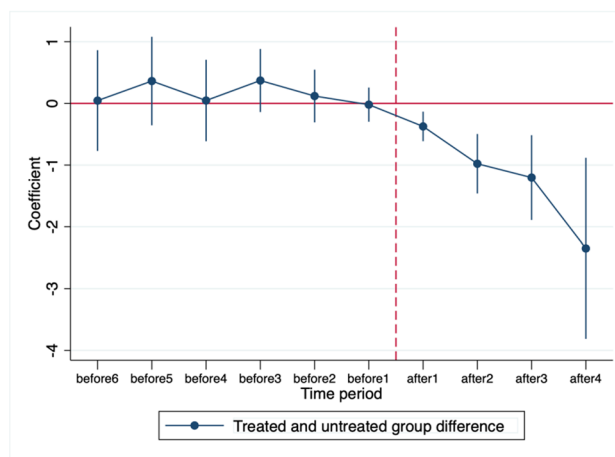


Fig. 3 Parallel trend test and dynamic effect analysis of industrial SO₂ emissions. The horizontal axis of the graph represents the time axis of the 6 years before and 4 years after the implementation of the VER in prefecture-level cities. The vertical axis is the coefficient of VER. The vertical dotted line is the time when the event occurred. The dots represent the estimated values after adding the relevant control variables and controlling for city-fixed effects and year-fixed effects. The vertical solid line shows the upper and lower 95% confidence intervals, and the standard errors are clustered at the city level. The vertical line represents the implementation time of the VER. Same as Figs. 4 and 5

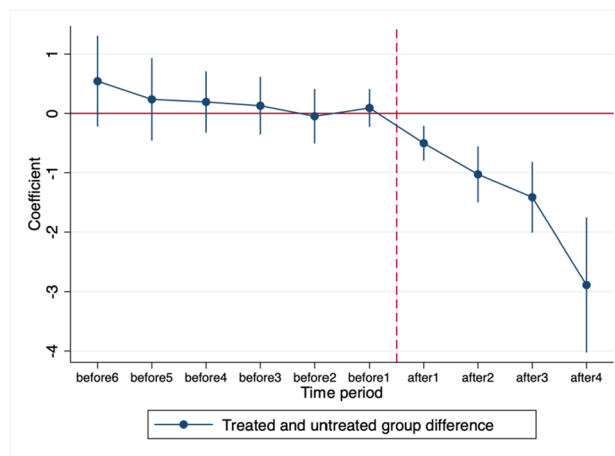


Fig. 4 Parallel trend test and dynamic effect analysis of effluents. This figure shows the difference in effluent emissions between the treated group and untreated groups for the years between 2013 and 2020. The vertical dotted line is the time when the event occurred, and the vertical solid line represents 95% confidence interval of estimation coefficient

full multicollinearity. Other variables and model settings are the same as those in (1). All coefficients of the regression results are plotted as dynamic effects. Figures 3, 4, and 5 show the results of parallel trend tests and dynamic effects analysis for industrial sulfur dioxide emissions, industrial

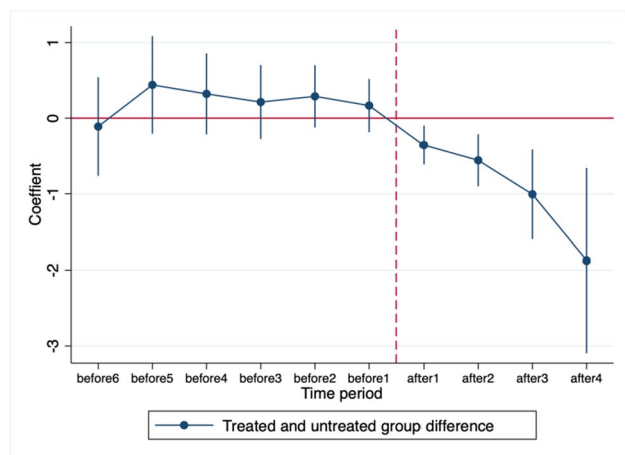


Fig. 5 Parallel trend test and dynamic effect analysis of fumes. This figure shows the difference in fumes emissions between the treated group and untreated groups for the years between 2013 and 2020. The vertical dotted line is the time when the event occurred, and the vertical solid line represents 95% confidence interval of estimation coefficient

wastewater emissions, and fumes, respectively. The results show that estimated values and 95% confidence intervals of the coefficients before the VER were around 0, indicating that the hypothesis of parallel trend is satisfied before the implementation of the VER in each region. The coefficients and 95% confidence intervals of the coefficients in the years after the VER are around 0. The estimated values and 95% confidence intervals of the coefficients are below the 0-axis, indicating that the implementation of the VER has a negative impact on SO₂, effluents, and fumes. The coefficients and 95% confidence intervals of the coefficients are below the 0 axis. The estimated values and 95% confidence intervals of the coefficients have been shifted downward, indicating that the emission reduction effect of the VER has been gradually enhanced over time, and the governance effect of the VER has good sustainability.

Robustness

Sample selectivity bias mitigation (PSM-DID)

If the actual implementation time of VER in each province is related to each province's own characteristics, it will lead to systematic differences between the treatment and control groups at different time points before the occurrence of policy shocks, thus generating sample selection bias (SSB). This paper employs propensity score matching (PSM) to select the samples of the two groups in order to mitigate any potential sample selection bias, and then bases its usage of the DID method on this. Specifically, we use the provincial GDP, the quadratic term of provincial GDP, population

Table 4 PSM-DID estimation results

	(1) SO ₂	(2) Effluents	(3) Fumes
VER	−0.673*** (−4.398)	−0.503*** (−3.372)	−1.607*** (−5.359)
Year fixed effects	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes
Observations	1002	1002	1002
R-squared	0.591	0.393	0.480

*** represents p less than 0.01

density, industrial share, fiscal pressure, actual foreign capital utilization, and the number of environmental emergencies in the previous year as covariates to calculate the propensity score matching for each province for each year of VER using the logit model, and then use the nearest neighbor matching method to find the matching score for the experimental group. The results are presented in Table 4, and the results of the control variables are omitted. The results show that the estimated coefficients β of the matched VER implementation variables on regional industrial sulfur dioxide emissions, industrial wastewater emissions, and industrial smoke emissions are greater than 0 at the 1% significance level, indicating that the VER still has a significant effect on emission reduction after mitigating the selective bias of the sample, which also proves that the estimation results of the baseline regression are robust.

Placebo test

In order to test the effect of VER without randomness, a placebo test was conducted by randomly selecting the implementation point of VER in each prefecture-level city. For each prefecture-level city, the implementation time of the VER was randomly selected between 2013 and 2020, and then, the pollutant emissions were regressed using the model in (1). The above process was randomly simulated 1000 times. The coefficients' T -values from the regression results of 1000 random simulations were generated as kernel density plots, as shown in Figs. 6, 7, and 8, representing the placebo test results for SO₂, effluents, and fumes, respectively. The vertical solid lines in the plots represent the mean T -values of β for 1000 random simulations, and the three vertical dashed lines from left to right in Fig. 6 represent the T -value levels of 1.64, 1.96, and 2.68, respectively. The three vertical dashed lines from right to left in Figs. 7 and 8 represent the T -value levels of −1.64, −1.96, and −2.68, respectively. The results show that the T -values in Figs. 6, 7, and 8 are roughly normally distributed, and the mean T -values are all very close to 0. The absolute values of most of the T -values are less than 1.64, indicating that most of the

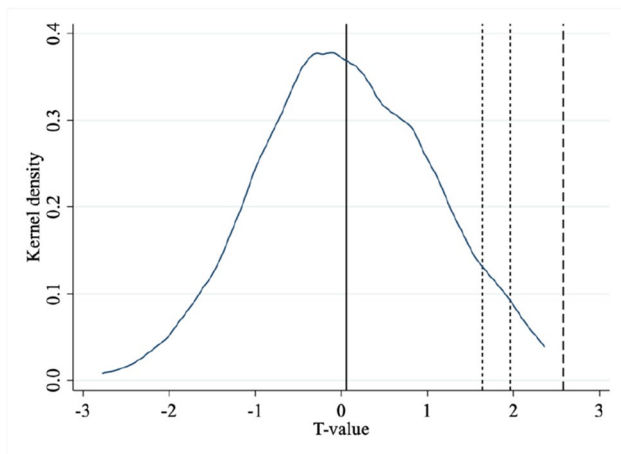


Fig. 6 Placebo test for industrial SO₂ emissions

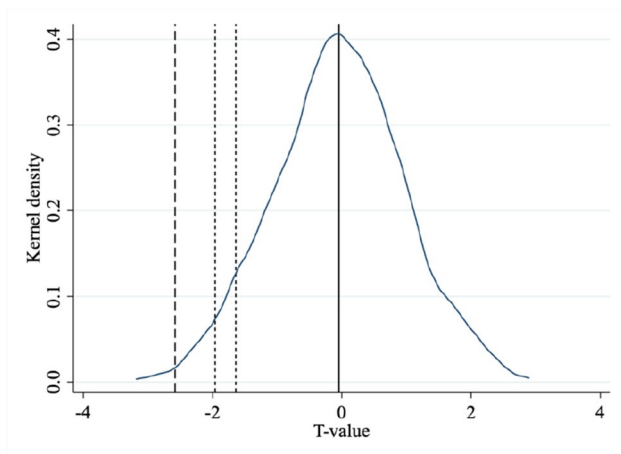


Fig. 7 Placebo test for industrial effluent emissions

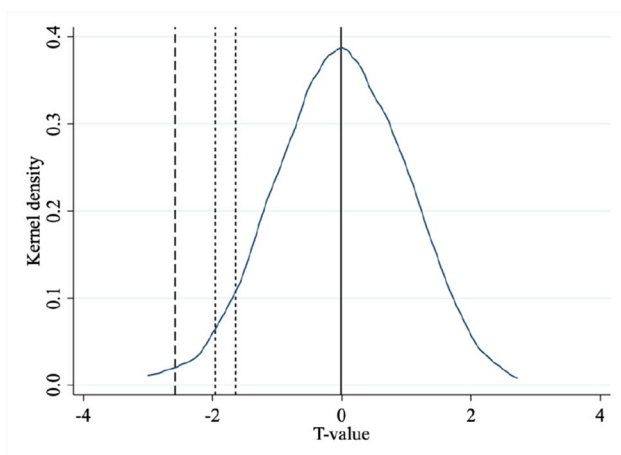


Fig. 8 Placebo test for industrial fumes emissions

random simulation results cannot pass the 10% significance test. Therefore, the random selection of the implementation point of VER has no significant effect on industrial sulfur dioxide emissions, industrial wastewater emissions, and industrial smoke emissions; the placebo is ineffective. This proves that the estimation results of the baseline regression in this paper are robust.

Replacement of the explanatory variable measure

The absolute indicators of the three types of pollutant emissions are used as the explanatory variables in the baseline regression, and two relative indicators of regional per capita pollutant emissions and pollutant emissions per unit of GDP are used here as the explanatory variables for robustness testing. The absolute indicators in the control variables are also converted into relative indicators per capita or relative indicators per unit of GDP. When using pollutant emissions per unit of GDP, *gdp* and *gdp2* are excluded from the control variables. The specific model design is as follows:

$$\begin{aligned} \text{perpullution}_{it} = & \alpha + \beta \text{VER}_{it} + \delta_1 \text{pergdp}_{it} \\ & + \delta_2 \text{pergdp}_{it}^2 + \delta_3 \text{dens}_{it} + \delta_5 \text{ind}_{it} + \delta_6 \text{fisc}_{it} \\ & + \delta_7 \text{perfdi}_{it} + \delta_8 \text{peracc}_{it} + \mu_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{5}$$

$$\begin{aligned} \frac{\text{pullution}_{it}}{\text{gdp}_{it}} = & \alpha + \beta \text{VER}_{it} + \delta_3 \text{dens}_{it} + \delta_5 \text{ind}_{it} \\ & + \delta_6 \text{fisc}_{it} + \delta_7 \frac{\text{fdi}_{it}}{\text{gdp}_{it}} + \delta_8 \frac{\text{acc}_{it}}{\text{gdp}_{it}} + \mu_i + \gamma_t + \varepsilon_{it} \end{aligned} \tag{6}$$

Columns (1), (2), and (3) of Table 5 report the regression results on industrial sulfur dioxide emissions per capita (*perSO₂*), industrial wastewater emissions per capita (*per-effluents*), and industrial smoke emissions per capita (*per-fumes*), respectively. Columns (4)(5)(6) report the regression results on industrial sulfur dioxide emissions per unit GDP (*SO₂/gdp*), industrial wastewater emissions per unit GDP (*effluents/gdp*), and industrial smoke emissions per unit GDP (*fumes/gdp*), respectively. The results show that the coefficients β of the core explanatory variables in columns (1)–(6) are all negative at the 1% or 5% significance level, indicating that the implementation of the VER also has a more significant effect on the reduction of industrial sulfur dioxide, industrial smoke, industrial wastewater emissions per capita, and emissions per unit of GDP. Therefore, the conclusions of this paper are still robust after changing the variable measures.

Heterogeneous treatment effects

DID method requires that the treatment effect is homogeneous in the time dimension; that is, for all individuals who

Table 5 Estimated results of pollutant emissions per capita and per unit of GDP

	(1) PerSO ₂	(2) Pereffluents	(3) Perfumes	(4) SO ₂ /gdp	(5) Effluents/gdp	(6) Fumes/gdp
VER	−0.002*** (−2.859)	−0.002** (−2.103)	−0.004*** (−4.461)	−0.208** (−2.573)	−0.239** (−2.385)	−0.594*** (−3.172)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1749	1749	1749	1749	1749	1749
R-squared	0.397	0.588	0.353	0.372	0.358	0.350

*** and ** represent p less than 0.01 and 0.05, respectively

are treated by policies at the same time, the size of the treatment effect will remain unchanged with the passage of time. However, this important implicit assumption is often ignored when using two-way fixed effect estimator (TWFE) to estimate staggered DID (Chaisemartin and D’Haultfœuille 2020). Goodman-Bacon (2021) pointed out that when the treatment effect is heterogeneous, the same treatment has different effects on different individuals, which will lead to potential estimation bias of TWFE. The paper used the estimator proposed by Callaway and Sant’Anna (2021) to estimate the robustness of this conclusion.³ The results of Callaway and Sant’Anna’s estimator are shown in Table 6. Compared with the standard time-varying DID estimates (Table 2), although the absolute value of the coefficient of VER in Table 6 is smaller, it is still significant at the significance level of 5%. This shows that the TWFE model overestimates the treatment effect of VER, but the robust estimator still shows that VER significantly reduces pollutant emissions.

Heterogeneity analysis

Financial pressure

It has been shown that the higher the financial pressure, the lower the environmental governance efficiency of local governments, and the higher the pollutant emissions (Zhang et al. 2018). The VER blocks the control of local governments over grassroots environmental protection departments through the redistribution of personnel and financial power, which theoretically prevents local governments from relaxing environmental protection supervision and enforcement due to financial pressure. Accordingly, the following model is designed to estimate

Table 6 Estimated results using all not-yet-treated cohorts as controls

	(1) SO ₂	(2) Effluents	(3) Fumes
VER	−0.428** (−2.230)	−0.397** (−2.105)	−1.061*** (−2.674)
Control variables	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes
Observations	1749	1749	1749
R-squared	0.557	0.316	0.374

*** and ** represent p less than 0.01 and 0.05, respectively

the moderating effect of vertical environmental reform on pollutant emissions in areas affected by financial pressure.

$$\text{pollution}_{it} = \alpha + \beta \text{VER}_{it} + \theta \text{VER}_{it} \times \text{fisc}_{it} + \rho \text{fisc}_{it} + \delta \text{control}_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (7)$$

Since fiscal pressure (fisc) has been included in the control variables, Eq. (7) only adds the interaction term of fisc and VER on the basis of Eq. (1), the coefficient θ represents the regulating effect of VER on pollutant emissions in areas affected by fiscal pressure, and the regression results are shown in Table 7. The coefficients of the interaction terms in columns (1), (2), and (3) are all significantly negative at the 1% level, indicating that VER has a significant negative moderating effect on pollutant emissions in areas affected by financial pressure. The transfer of personnel financial power from the local government on the “block” to the environmental protection department within the “article” can avoid the relaxation of environmental protection supervision and enforcement by the local government due to financial pressure.

Government official affiliation

The network of relationships among government officials may influence local environmental protection enforcement as well as local firms’ emissions. In this paper, we determine

³ The approach of Callaway and Sant’Anna (2021) is very similar to Sun and Abraham (2021), while Sun and Abraham (2021) use the last treated cohorts as controls (effectively treating these cohorts as never-treated) and Callaway and Sant’Anna (2021) use all not-yet-treated cohorts as controls. Because all provinces finally implemented VER, this paper uses the method of Callaway and Sant’Anna (2021).

Table 7 Impact of VER to crack financial pressure on regional pollutant emissions

	(1) SO ₂	(2) Effluents	(3) Fumes
VER	-0.248** (-2.294)	-0.179** (-2.318)	-0.938*** (-3.259)
fisc	0.246 (1.293)	0.102** (2.083)	0.195* (1.733)
VER × fisc	-1.320*** (-3.028)	-1.196*** (-2.632)	-1.605*** (-2.953)
Control variable	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes
Observations	1749	1749	1749
R-squared	0.581	0.391	0.456

***, **, and * represent *p* less than 0.01, 0.05, and 0.1, respectively

whether there is an official connection between the local party governments and the EPBs by whether the director of the EPBs of prefecture-level cities had working experiences in the party government of that prefecture-level city. The official association variable connection is designed to take the value of 1 if there is an association; otherwise, it is 0. The specific model is as follows:

$$\begin{aligned}
 \text{pullution}_{it} = & \alpha + \tau \text{VER}_{it} \times \text{connection}_{it} \\
 & + \beta \text{VER}_{it} + \rho \text{connection}_{it} + \delta \text{control}_{it} + \mu_i + \gamma_t + \varepsilon_{it}
 \end{aligned} \tag{8}$$

In Eq. (8), the coefficient τ represents the moderating effect of VER on pollutant emissions in the area affected by officials' connection, and adds officials' connection variables in the control variables, and other settings are the same as in Eq. (1). The regression results are shown in Table 8, and the coefficients of the interaction terms VER in columns (1), (2), and (3) are all at the 1% level. The coefficients of the VER × connection in columns (1), (2), and (3) are all significantly negative at the 1% level, indicating that the “environmental protection reform” has a significant negative moderating effect on the pollutant emissions in the areas affected by officials' connection.

Border contamination

Due to the negative externalities of environmental pollution, under the territorial management system, local governments are prone to opportunistic behavior by placing polluting enterprises at the borders of their administrative jurisdictions, enjoying all the economic benefits brought by the polluting enterprises, but only bearing part of the negative effects of environmental pollution (Agarwal et al. 2020; Silva and Zhu 2009; Hua et al. 2023). By enhancing

Table 8 Impact of VER to break the association of officials on regional pollutant emissions

	(1) SO ₂	(2) Effluents	(3) Fumes
VER × connection	-0.429*** (-3.021)	-0.691*** (-2.975)	-0.583*** (-2.628)
VER	-0.023 (-1.528)	-0.007 (-0.621)	-0.019 (-0.952)
Connection	0.126** (2.031)	0.113** (2.128)	0.202** (2.421)
Control variable	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes
Observations	1749	1749	1749
R-squared	0.579	0.379	0.452

*** and ** represent *p* less than 0.01 and 0.05, respectively

the independence of environmental monitoring and enforcement at the grassroots level, the “environmental protection reform” can avoid the intervention of “local protectionism,” and theoretically, it also has a governance effect on border pollution. The following econometric model is designed:

$$\begin{aligned}
 \text{pullution}_{it} = & \alpha + \eta \text{VER}_{it} \times \text{border}_i \\
 & + \lambda \text{VER}_{it} \times (1 - \text{border}_i) \\
 & + \delta \text{control}_{it} + \mu_i + \gamma_t + \varepsilon_{it}
 \end{aligned} \tag{9}$$

In Eq. (9), the border_i represents whether the prefecture-level city is on the border of a province. If the prefecture-level city borders another province, the coefficient of border_i is zero. η represents the impact of VER on pollutant emissions in the border cities, and the coefficient λ represents the impact of VER on pollutant emissions in non-border cities, and the coefficient of VER on pollutant emissions in non-border cities is added in the control variables. The other settings are the same as Eq. (1). The regression results are shown in Table 9, the coefficients of the interaction term VER × border and the interaction term VER × (1 - border) in columns (1), (2), and (3) are less than 0 at different levels of significance, indicating that the VER has a certain inhibitory effect on pollutant emissions in border cities and non-border cities. The coefficients of the non-border cities are smaller and less significant, indicating that the VER has a more significant effect on pollutant emissions in the border cities and has a more significant governance effect.

Spatial spillover effects

Since VER has improved the environmental enforcement in provincial border cities, Firms have a greater incentive to move polluting industries from areas with strong

Table 9 Effect of the VER on the border pollution

	(1) SO ₂	(2) Effluents	(3) Fumes
VER × border	− 0.724*** (− 5.294)	− 0.802*** (− 6.531)	− 1.384*** (− 6.384)
VER × (1 − border)	− 0.238** (2.053)	− 0.149* (1.702)	− 0.195** (1.998)
Control variable	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes
Observations	1749	1749	1749
R-squared	0.579	0.379	0.452

***, **, and * represent *p* less than 0.01, 0.05, and 0.1, respectively

government intervention to areas with weak government intervention (Wu et al. 2021; Yu et al. 2023). This paper examined whether the implementation of VER will lead to an increase in pollutant emissions in cities in other provinces bordering the province. Spatial interaction terms are embedded in the model to construct SDID model, so as to effectively control the spatial spillover effect. Considering that the spatial Dobbin model (SDM) is usually more general, this paper adopted the following multi-period continuous SDID model based on SDM as the regression model.

$$\begin{aligned}
 \text{pullution}_{it} = & \alpha + \rho \sum_j w_{ij} \text{pullution}_{it} + \beta \text{VER}_{it} \\
 & + \theta \sum_j w_{ij} \text{VER}_{it} + \delta \text{control}_{it} + \psi \sum_j w_{ij} \text{control}_{it} + \mu_i + \gamma_t + \varepsilon_{it}
 \end{aligned}
 \tag{10}$$

w_{ij} is the geographic distance weight matrix. It is defined as:

$$w_{ij} = \begin{cases} \frac{1}{d_{ij}}, & i \neq j \\ 0, & i = j \end{cases}
 \tag{11}$$

d_{ij} is the geographical distance between cities *i* and *j* calculated by latitude and longitude. Other settings of Eq. (10) are the same as those of benchmark regression. $\sum_j w_{ij} \text{pullution}_{it}$ is the spatial lag term of the explained variable. $\sum_j w_{ij} \text{VER}_{it}$ is the spatial lag term of DID variable. Because Eq. (10) introduces the spatial lag term of the explained variable, at this time, the least square method (OLS) and the maximum likelihood method (MLE) may be inconsistent, and the bias correction quasi-maximum likelihood method (BC-QMLE) proposed by Lee and Yu (2010) can effectively solve the above problems, so this paper will use BC-QMLE to estimate Eq. (10).

The results (Table 10) show that the VER is significantly positive at the level of 1% or 5%, but the spatial lag coefficient of VER failed to pass the significance level of 10%. This shows that the implementation of VER in a certain city will not lead to the increase of pollutant emissions in its surrounding cities. I think VER may not have caused

Table 10 Spatial spillover effects of the VER

	(1) SO ₂	(2) Effluents	(3) Fumes
VER	− 0.482*** (− 2.901)	− 0.521** (− 2.212)	− 1.023*** (− 5.320)
W × VER	0.013 (1.192)	0.005 (0.986)	0.032 (0.847)
Control variable	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
City fixed effect	Yes	Yes	Yes
Observations	1749	1749	1749
R-squared	0.582	0.379	0.501

*** and ** represent *p* less than 0.01 and 0.05, respectively

the transfer of polluting industrial enterprises. Because the transfer of polluting industrial enterprises has a fixed cost, and VER is a national policy, which will be implemented in all provinces within five years, so there is no spatial spillover effect.

Results and discussion

The paper used time-varying DID model to examine the pollutant reduction effects of China’s VER policy and comes to the following results: the VER considerably lowers emissions of industrial smoke (dust), industrial wastewater, and sulfur dioxide in the region. From the 11th Five-Year Plan to the 14th Five-Year Plan, these three pollutants were the main focus of the central government’s efforts to reduce emissions. The local environmental protection departments’ ability to carry out the central government’s attempts to reduce pollution has been greatly enhanced by the implementation of VER. The provincial VER of environmental protection departments has decreased regional pollution emissions by enhancing environmental enforcement at the municipal level and lower.

Although a few studies (Han et al. 2021; Han and Tian 2022) have paid attention to the governance effect of VER, this paper provides the latest and most complete evidence for the actual effect of this policy based on the empirical analysis of data from 263 prefecture-level cities across the country. Moreover, this paper not only tests the control effect of VER on air pollutants which are highly concerned in the literature but also tests the governance effect on wastewater pollution, which is a comprehensive evaluation of the effect of VER policy. In addition, compared with related literature, this paper makes a more perfect robust estimation of the regression results of time-varying DID model, including using PSM-DID to alleviate selective bias, using placebo test to ensure the uniqueness of policy effects, and using Callaway and Sant’Anna (2021) robust estimation to deal

with the heterogeneous treatment effects commonly faced by time-varying DID. Although the treatment effect of VER is reduced after the elimination of heterogeneous treatment effects, it is still significant at the level of 5%, which shows that the implementation of VER is indeed helpful in reducing regional pollutants. The estimation results of this paper also respond to a long-standing debate in the field of environmental management, which is the dispute between territorial management and vertical management (Tiebout 1956; Besley and Coate 2003; Millimet 2003; Lipscomb and Mobarak 2017). This paper supports that the governance effect of the environmental vertical management mode will be better than that of the environmental territorial management mode under certain circumstances, such as when local interests are highly dependent on economic growth and local fiscal revenue. At the theoretical level, this paper provides a new theoretical perspective on the debate between the advantages and disadvantages of local and vertical management by analyzing the organizational logic of the shift from the territorial management model to the vertical management model in the field of environmental management in China. In addition, this paper introduces a marginal expansion of the theory of residual control at the municipal and county levels based on the theoretical framework of residual rights of control, which is a further development of the residual control theory in the field of government governance.

Conclusions and policy implications

This paper examined the governance effects of the vertical environmental reform of the sub-provincial environmental protection sector using data from 263 prefectures from 2013 to 2020, and found the reform had reduced regional emissions of pollutants. This paper provides causal evidence that vertical management reform can reduce the damage of local interests to public goods such as the environment in developing countries.

The policy implications are that vertical environmental management can help a country's central government directly control environmental pollution, and it has a significant and lasting effect of reducing pollution. At present, many developing countries' governments have implemented the territorial management system, and environmental protection is often ignored by local governments because it harms short-term economic growth. Starting vertical environmental management in time for these countries can gain better environmental performance than the reform under the territorial management system. Different management systems produce different governance effects. For a country as vast and populous as China, how to adopt an effective management system and achieve effective governance of grassroots affairs is a real challenge for the Chinese government. The debate between the advantages and disadvantages

of territorial and vertical management is both a theoretical focus in academia and a practical dilemma in the real world. Given that developing countries' local government interventions characterized by "local protectionism" have been widely and long-standing in other areas of government governance, the experience of breaking local protectionism found in this paper in the environmental governance area can also be used as a reference for reforming the organizational structure of government in other areas.

Author contribution QC: conceptualization, methodology, investigation, data curation, software, visualization, writing, reviewing, and editing.

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Data availability Some or all data, models, or codes generated or used during the study are available from the corresponding author upon request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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