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RESEARCH ARTICLE

Does information disclosure mitigate air pollution? Evidence from China

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Abstract
From 2013 to 2015, China gradually established nationwide air quality monitoring stations and began to release real-time air pollution information to the public. We exploit step-by-step environmental regulations across cities to identify the effects of information disclosure on air pollution. We find that information disclosure significantly decreases the concentrations of $PM_{2.5}$ and PM_{10}. Through mechanism analysis, we find that information disclosure raises the level of government awareness, increases the amount of investments in air pollution prevention and control, stimulates green innovation, and forces heavily polluting enterprises to shut down. Additionally, we find evidence that the effectiveness of information disclosure varies across cities.

Keywords: air pollution; government awareness; green innovation; information disclosure; investment in air pollution

JEL classification: D80; O38; Q53

1. Introduction

Compared with developed countries, developing countries face more serious air pollution threats. In 2013, the annual concentration of average $PM_{2.5}$ in developing countries was more than five times higher than that in the US (Brauer *et al.*, 2016). Therefore, environmental regulations and environment-related policies have been implemented in developing countries, including China (Viard and Fu, 2015; Fu and Gu, 2017; Hao *et al.*, 2018; Fan *et al.*, 2019). However, whether environmental regulations are effective remains inconclusive.[1] For China, the effectiveness of environmental regulations has long been questioned due to corruption, collusion and rent-seeking behaviors (Zhou

[1]Some studies have proven that environmental regulation is efficient. For example, Fan *et al.* (2019) found that by implementing a stringent 11th Five-Year Plan in China, chemical oxygen demand (COD) emissions decreased at the firm level. He *et al.* (2016) showed that environmental regulation is useful in mitigating pollutant emissions. However, other studies have challenged the efficiency of environmental regulations, especially in developing countries. For example, Hao *et al.* (2018) found that environmental

et al., 2020). Recently, an easily overlooked factor has attracted scholarly attention: the lack of pollution information disclosure is likely to result in the failure of environmental regulations by blocking the supervisory channel of the public and government (Barwick *et al.*, 2019; Greenstone *et al.*, 2022).

To solve the problem of the lack of air pollution disclosure information, the *New Environmental Regulation* (hereafter referred to as the *New Regulation*) was implemented in 2013. The Chinese government has gradually established high-quality air quality information monitoring stations covering the whole country. The *New Regulation* provided a special perspective from which to study the effect of information disclosure on air quality. Three features enable the *New Regulation* to be a proper 'shock' in terms of analyzing our empirical study. First, this regulation provides the most accurate and detailed air quality data in Chinese history. Monitoring stations are capable of collecting and publishing real-time data for each pollutant on an hourly basis. Second, air pollution data are collected and released by third-party organizations, which eliminates the possibility of manipulative behaviors by local governments. Finally, the public has easier access to air quality knowledge. Since the implementation of the *New Regulation*, it has been required that daily air quality information be published through various media outlets.

Using satellite-based data from 2005 to 2019, we exploit exogenous temporal and geographical variations in the enforcement of the *New Regulation* to estimate the causal effect of information disclosure on air pollution. We find that information disclosure decreases $PM_{2.5}$ and PM_{10} by 2.7 and 2.5 per cent, respectively. Additionally, by examining the mechanisms leading to these results, we find evidence of channels affecting the degree of government awareness, amount of investments in preventing and controlling air pollution, number of green innovations and the shut downs of heavily polluting enterprises. Specifically, we find that the air pollution information disclosure system raises the government's level of concern about air pollution, thereby stimulating an increase in the amount of green investments, encouraging green innovation, and forcing heavily polluting enterprises to shut down. These are potential mechanisms through which information disclosure reduces air pollution.

This study contributes to the current literature in the following ways. First, this article enriches the literature on the effects of high-quality information and supervision. In recent years, scholars have found that high-quality information disclosure or supervision can have more significant policy effects than can low-quality information disclosure or supervision (Duflo *et al.*, 2013; Barnwal, 2014; Muralidharan *et al.*, 2016; Barwick *et al.*, 2019). By using a randomized controlled trial of audits, Duflo *et al.* (2013) find that an increase in the quality of audit reports from third-party auditors decreases the amount of pollution emissions. Barnwal (2014) finds that distributing gas subsidies through new technologies reduces the amount of leakage to ghost beneficiaries, a conclusion that

control measures did not achieve the desired goal of reducing pollution in the period 2003–2010. This conclusion is also supported by Barwick *et al.* (2019). Moreover, an abundant number of studies have proven that the usefulness of environment controls varies across regions, industries and enterprise types. Liu *et al.* (2017) found that the total COD discharge of the textile printing and dyeing industry in Lake Tai, China, decreased; the dominant effect was on domestically-owned private enterprises, with little effect on state- and foreign-owned enterprises. Focusing on the stricter regulation of SO_2 emissions, Hering and Poncet (2014) reached a similar conclusion and found that the effect of regulation on higher-polluting industries was larger. Furthermore, Chen *et al.* (2018) found that the level of pollution was reduced more effectively in highly regulated areas, while in regions with less strict regulations, the reduction in the level of pollution was limited.

is strengthened by Muralidharan *et al.* (2016). Moreover, Zou (2021) researches local strategic responses to a cyclical schedule with air quality monitoring once every six days under the Federal Clean Air Act and shows that air pollution rebounds on days without monitoring, which implies that low-frequency supervision has insufficient effects on the degree of pollution control. Our study focuses on a typical form of high-quality supervision, the *New Regulation*, to study its effects on air pollution. Our research shows that high-quality supervision and the *New Regulation* significantly decrease the concentrations of $PM_{2.5}$ and PM_{10} in the long term, strengthening the conclusion that high-quality supervision has better enforcement effects than does low-quality supervision.

Second, our study enriches the literature assessing the effects of environmental information disclosure. Recently, an emerging body of literature has focused on the effects of air pollution information disclosure. For example, some studies exploit a comparable variable, the Chinese Pollution Information Transparency Index (PITI),[2] published in 2008, to study the effects of pollution information disclosure on enterprises' emissions, exports (Xie *et al.*, 2022), environmental performance (Zhang *et al.*, 2022) and air pollution (Tu *et al.*, 2019; Feng *et al.*, 2021). Liu *et al.* (2021) studied the effects of the National Ambient Air Quality Monitoring Network, which was implemented in 1980, on $PM_{2.5}$ emissions. The above literature focuses on air pollution information disclosure policies with low disclosure frequency, insufficient openness, and unreliable data quality (Greenstone *et al.*, 2022). The difference between our study and the above studies lies in the extremely high quality of pollution information disclosure about which we are concerned. The *New Regulation* is the information disclosure policy with the highest quality, widest coverage, and highest frequency and is likely to have different effects than those of other information disclosure policies. Moreover, Greenstone *et al.* (2022) focus on the effect of the *New Regulation* and find that there is an obvious truncation of data before and after its implementation, which shows that the *New Regulation* increases the quality of air pollution information disclosure. However, Greenstone *et al.* (2022) focus mainly on the effects of manipulation behavior on air quality data before such regulation and do not directly measure the effects of the regulation on decreasing the amount of air pollution, which is the main aim of this study. Our study strengthens and measures the effects of information disclosure on the control of air pollution.

From a broader perspective, this paper enriches the literature on environmental regulations. Current studies measure the influence of environmental regulations on air pollution from the perspective of environmental protection regulations, for example, air pollution regulations (Bao *et al.*, 2021; Liu *et al.*, 2021), heating policies (Almond *et al.*, 2009), and low emission zones (Gehrsitz, 2017). However, the current literature is controversial in terms of the effectiveness of environmental regulation (Blackman and Kildegaard, 2010). In this study, we use a less focused type of environmental regulation – pollution information disclosure – to assess the effect of environmental regulation. Our

[2]Compared to the PITI, the *New Regulation* is a proper measure with which to represent air pollution information disclosure and has advantages in terms of policy coverage, data release frequency, social influence and data objectivity. First, the information disclosure in 2013 covered all cities in China. However, the PITI covers only 120 key environmental protection cities in China, the majority of which are large and well-developed cities. Second, since the implementation of the *New Regulation*, air quality information is released on an hourly basis on the official website of each city. Compared with the *New Regulation*, the PITI provides only annual reports. Third, data released by the monitoring stations established after the *New Regulation* became an authoritative and reliable measure of local governments' efforts toward pollution control. However, the PITI is not a measure of government performance.

results show that the implementation of an environmental information disclosure policy significantly decreases the amounts of air pollution in developing countries, which provides valuable experience for less-developed areas to develop and implement similar environmental policies.

The rest of the paper is organized as follows. Section 2 introduces the background. Section 3 introduces the data sources and empirical strategy. Section 4 presents the main results and robustness checks. Section 5 analyzes the mechanisms through which information disclosure operates. Section 6 reports the results of the heterogeneity analysis. Section 7 concludes the paper.

2. Policy background

Although environmental regulations have gradually improved, China has lacked the high-quality public monitoring of air quality data for a long period. At the end of 2011, the US Embassy in Beijing released air quality data based on its own monitoring, and these data were of much higher quality than were those released by the Chinese government. This event aroused a heated social debate, and air pollution control received unprecedented attention throughout China. On February 29, 2012, the Ministry of Environmental Protection and the General Administration of Quality Supervision, Inspection and Quarantine jointly issued the strictest ever standard – the *New Regulation*. Before this regulation was enacted, the dominant pollutants monitored by the Chinese government were total suspended particulate (TSP) from 1998 to 2000, PM_{10} from 2000 to 2007, and nitrogen oxide and SO_2 from 1998 to 2007. A general daily air pollution index was disseminated. However, pollutants such as $PM_{2.5}$, CO and O_3 were not monitored. Starting in 2012, cities across the nation began to install and debug automated monitoring equipment in batches and began to release daily pollution information, as scheduled, beginning in 2013. The air quality index values and concentrations of PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO and O_3 were released.

The *New Regulation* was implemented in three stages.[3] In the first stage, 74 cities, which were required to complete the installation of monitoring stations and begin to release air pollution information on January 1, 2013, were covered. In the second stage, 87 cities were covered; for these cities, the implementation date was January 1, 2014. In the last stage, 177 cities comprising the last batch began to implement the *New Regulation* on January 1, 2015. In each stage, air quality data were released to the public from the beginning of the year after the equipment was installed. Figure 1 shows the implementation steps of the cities in this study.

The air quality data released after the implementation of the *New Regulation* have unprecedented advantages for three reasons. First, the data are the most accurate and detailed in Chinese history. Monitoring stations are capable of collecting and publishing real-time data for each pollutant on an hourly basis. This program covers 1,438 stations around China, with all stations being built according to uniform technology standards and sharing the same criteria for measuring and releasing air quality levels. Such a national pollution monitoring system with wide coverage and accurate data is very rare in developing countries.

Second, air pollution data are collected and released by third-party organizations, which eliminates the possibility of manipulative behaviors by local governments. Since

[3]The source of publication of the *New Regulation* is the website of the Ministry of Ecology and Environment of the People's Republic of China.

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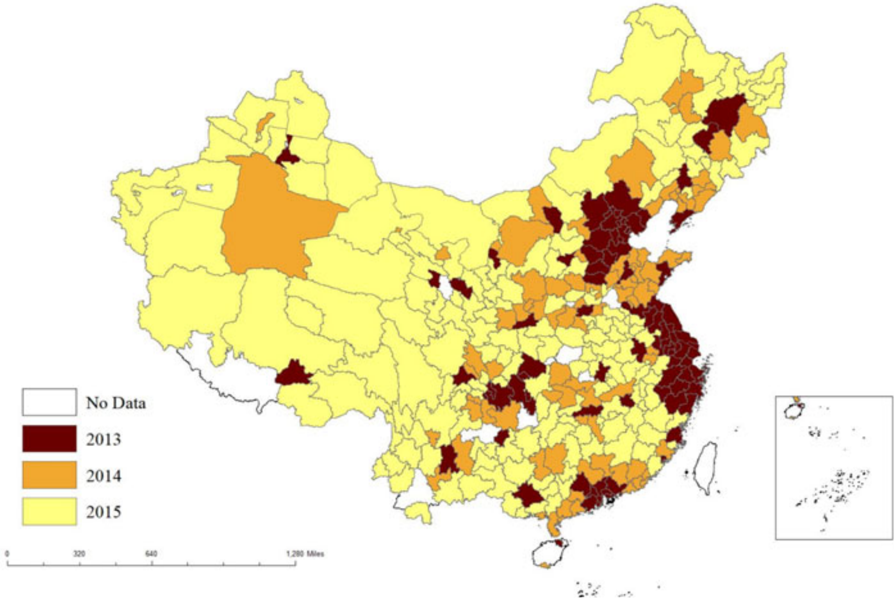

Figure 1. Implementation steps of the New Environmental Regulation.
Notes: The regulation was implemented in three stages from 2013 to 2015. Figure 1 indicates the cities covered in each stage.

local officials who are able to eliminate or prevent air pollution are more likely to receive promotions (Wu and Cao, 2021), they have an incentive to manipulate air quality data. However, after the national air pollution monitoring stations were built, the Chinese Meteorological Bureau, which is an independent institution that is not under the purview of local governments, became responsible for collecting and releasing air pollution information. As a result, it is difficult for local officials to tamper with such pollution data.

Finally, the public has easier access to knowledge about air quality. Since the implementation of the *New Regulation*, daily air quality information has been required to be published through various media outlets, such as newspapers, the websites of local governments and environmental protection departments, and social media, such as Weibo and WeChat. Therefore, residents can obtain air quality information for each prefecture-level city through multiple channels.

3. Data and empirical strategy

3.1 Data

We use multiple sources of data to conduct comprehensive research on the effect of information disclosure on air pollution. The datasets include satellite-based air pollution data, data on meteorological conditions, data on the economic and social characteristics of cities, and data for mechanism analysis. The datasets cover annual city-level information from 2005 to 2019.[4] After dropping the observations with missing air quality data,

[4]We do not use data after 2019 to avoid the potential disturbance of COVID-19.

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city-level economic and social characteristics, and singleton observations, we obtain 3,973 observations.

3.1.1 Air pollution data

The air pollution dataset consists of satellite-based data. Although China began to release air pollution information in 2005, the quality of these data has been in doubt due to the abovementioned manipulation problem (Greenstone *et al.*, 2022).[5] The data on the concentrations of the pollutants come from the MERRA-2 released by the National Aeronautics and Space Administration (NASA) of the US.[6] Following the method of Provençal *et al.* (2017), we estimate the daily concentrations of $PM_{2.5}$ and PM_{10}.[7] By averaging daily information, we finally obtain city-level air pollution information for each pollutant. Since the concentrations of $PM_{2.5}$ and PM_{10} are representative of the level of air quality (see figure A1 in the online appendix)[8], we choose to study them in this work.

3.1.2 Data on meteorological conditions

Current studies have proven the correlation between air pollution and meteorological factors (Feng *et al.*, 2010; Cai *et al.*, 2016). To better identify the potential effects of meteorological conditions, we add the average annual surface temperature, specific humidity, precipitation, and wind speed as weather factors. The weather data source is MERRA-2, as well as another product named M2TMNXAER version 5.12.4. The raw data are also raster data in the form of $0.5° \times 0.625°$ (approximately 50 km × 60 km) grids. We select daily records, aggregate the raw grid data to city-level daily records, and then obtain the individual average annual data.

3.1.3 Data on city-level economic and social characteristics

To better mitigate the effects of potential bias from unobserved city economic and social characteristics, we select the following variables: the average annual per capita gross domestic product (GDP), fiscal expenditure on science, the proportion of industry in GDP, and the fiscal income at the city level. The data come from the China Urban Statistical Yearbook. To prevent possible bias due to the effect of the *New Regulation* on cities' economic and social development, we also use the interactions between year fixed effects and city characteristics in 2012. The summary statistics are presented in table 1.

[5] Greenstone *et al.* (2022) proved that an obvious truncation appeared after the implementation of the *New Regulation*. The satellite-based records are free from the bias caused by discontinuous data.

[6] We use the M2I6NPANA version 5.12.4 product from Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) to obtain original data for the elements that constitute $PM_{2.5}$ and PM_{10}. MERRA-2 provides daily raster data and divides the ground into $0.5° \times 0.625°$ (approximately 50 km × 60 km) grids from 1980 to the present. By averaging the data of all grids in each city, we obtain the daily concentrations of the main constituents of $PM_{10}/PM_{2.5}$ at the city level.

[7] The main constituents of PM_{10} and $PM_{2.5}$ are dust, sea salt, black carbon, organic carbon and sulfate particulates. $PM_{2.5}$ and PM_{10} concentrations can be estimated based on these five elements. For details of the method, refer to Provençal *et al.* (2017).

[8] According to figure A1, we find that for 34.21 per cent of days, the primary pollutant was $PM_{2.5}$, and for 54.11 per cent of days, it was PM_{10}; together, these pollutants accounted for 88.32 per cent of the days from 2013 to 2019.

Table 1. Summary statistics

Variable	Definition and unit	Mean	SD	Observations
Panel A: Interest variables				
POLICY	Dummy variable of whether policy had enacted	0.38	0.49	3973
Panel B: Dependent variables				
$PM_{2.5}$ (log)	Annual average concentration of PM_{10} (ug/m^3)	3.63	0.37	3973
PM_{10} (log)	Annual average concentration of $PM_{2.5}$ (ug/m^3)	4.1	0.47	3973
Panel C: Control variables				
PRE	Annual average of total precipitation (g/m^{2}s)	42.73	24.6	3, 973
TLML	Annual average surface temperature (K)	286.79	5.13	3, 973
QLML	Annual average surface specific humidity (1)	80.95	28.6	3, 973
SPEED	Annual average surface wind speed (m/s)	5.11	0.87	3, 973
GDP	Average per capita GDP (1 million yuan)	0.042	0.106	3, 973
SCI	Fiscal expenditure of science (10 billion yuan)	0.069	0.256	3, 973
IND	Proportion of industry in GDP (1)	0.477	0.11	3, 973
FI	Fiscal income (10 billion RMB yuan)	18.61	36.62	3, 973

Data sources: Chinese City Statistical Yearbook, 2005–2019; MERRA-2 from NASA; Chinese Innovation Research Database (CIRD); China Industrial and Commercial Registration Enterprise Database; Government Work Reports in prefecture-level city, 2005–2019.

3.2 Empirical strategy

In this study, we aim to determine whether information disclosure is effective in improving air quality. From 2013 to 2015, the air quality information disclosure policy was gradually implemented in three steps, which represents a good shock for the purposes of using a difference-in-differences (DID) method. Specifically, as a first difference, the air quality levels of those cities that had implemented the regulation were different from those of cities that had not implemented it. Furthermore, as a second difference, the air quality levels of cities before and after the implementation of the regulation were also different. Specifically, the estimation specification is as follows:

$$P_{ct} = \beta_0 + \beta_1 \text{Policy}_{ct} + \beta_2 X'_{ct} + W'_{ct}\varphi + \sum_k x^k_{c,2012} * \delta_t + \lambda_c + \delta_t + \mu_{ct}, \qquad (1)$$

where P_{ct} represents the logarithm of the average annual level of PM_{10} and $PM_{2.5}$ for city c in year t. Policy_{ct} is a policy dummy variable for information disclosure reform that equals 1 if city c implements the policy in year t and 0 otherwise. The coefficient β_1 represents the effects of information disclosure on air pollution. We assume that β_1 is negative, which means that after the air pollution information is exposed, air pollution concentrations significantly decrease.

X'_{ct} represents a set of city-level economic and social characteristics containing per capita GDP, fiscal expenditure on science, fiscal income, and the proportion of industry in GDP for city c in year t. To isolate the potential influence of weather conditions, we control for meteorological factors W'_{ct}, including wind speed, precipitation, air temperature and humidity. Moreover, city-level fixed effects λ_c control for all time-invariant factors, including geographical environments. Year fixed effects δ_t control for shocks, for

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example, the interference of national regulations or industrial economic development, to all cities in a certain year. Standard errors are clustered at the prefecture city level.

The effectiveness of the identification strategy is based on whether the implementation date of each city is exogenous. That is, if the *New Regulation* had never been implemented, then the cities in the treatment and control groups would exhibit the same air pollution trend. Therefore, the greatest threat to the identification strategy is the implementation date not being random. To solve this problem, we allow the trend to change with city characteristics to control for the different annual trends of air pollution in different cities. Specifically, we add an interaction of city baseline characteristics in 2012 and year fixed effects, $x^k_{c,2012} * \delta_t$.

4. Estimation results

4.1 Baseline results

Table 2 presents the estimation results based on formula (1). Columns (1)–(3) show the results with $PM_{2.5}$ as the dependent variable, and columns (4)–(6) show the results with PM_{10} as the dependent variable. The baseline estimation results are shown in columns (1) and (4) for $PM_{2.5}$ and PM_{10}, respectively. It is shown that air pollution information disclosure systems help mitigate air pollution. City and year fixed effects are controlled in the regression. We further add the interaction of city characteristics in 2012 and year fixed effects.

Other columns report the results that allow the flexible function of city and weather controls. In columns (2) and (5), weather conditions are included. In columns (3) and (6), we further add the city characteristics to the estimation. We obtain consistent results, that is, that there are negative and significant effects of information disclosure on air pollution.

Specifically, the results in columns (3) and (6) show that after the implementation of the *New Regulation*, the annual concentration of $PM_{2.5}$ decreased by 2.7 per cent, and the annual concentration of PM_{10} decreased by 2.5 per cent. This finding indicates the effectiveness of information disclosure in controlling air pollution. Moreover, Zou (2021) studied the effect of an intermittent monitoring system on air pollution. He found that air quality near monitoring stations is significantly worse during days when pollution monitors are scheduled to be off, which shows that information disclosure has effects on air pollution reduction. Our research strengthens the importance of information disclosure in controlling air pollution.

4.2 Robustness checks

4.2.1 Parallel trend test

Formula (1) assumes that there are underlying parallel trends in the dependent variables in both the control and treatment groups. To check this assumption and study the dynamic effects of air pollution information disclosure, we estimate the event study specification based on formula (2) as follows:

$$P_{ct} = \beta_0 + \sum_{k=-5}^{4} \gamma_k \cdot D_{c,\, t_0+k} + \beta_2 X'_{ct} + W'_{ct}\varphi + \sum_k x^k_{c,2012} * \delta_t + \lambda_c + \delta_t + \mu_{ct}, \quad (2)$$

where t_0 represents the year of the implementation of the *New Regulation* for city i. $D_{c,\, t_0+k}$ is a set of dummy variables that represent the city in year k after the

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Table 2. Baseline results

	$PM_{2.5}$			PM_{10}		
Dependent variable	(1)	(2)	(3)	(4)	(5)	(6)
POLICY	−0.018 (0.010)	−0.027 (0.010)	−0.027 (0.010)	−0.018 (0.008)	−0.025 (0.008)	−0.025 (0.008)
PRE		0.001 (0.000)	0.001 (0.000)		0.001 (0.000)	0.001 (0.000)
QLML		−0.012 (0.001)	−0.012 (0.001)		−0.009 (0.001)	−0.009 (0.001)
SPEED		−0.013 (0.024)	−0.013 (0.024)		−0.020 (0.016)	−0.020 (0.016)
TLML		0.088 (0.006)	0.088 (0.006)		0.063 (0.004)	0.063 (0.004)
GDP			0.005 (0.004)			0.003 (0.003)
BI			−0.000 (0.000)			−0.000 (0.000)
SCI			0.034 (0.017)			0.022 (0.013)
IND			−0.089 (0.057)			−0.045 (0.038)
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Control2012 × Year	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,973	3,973	3,973	3,973	3,973	3,973
R^2	0.896	0.924	0.924	0.895	0.923	0.924

Notes: (1) Table 2 presents the baseline results. $PM_{2.5}$ and PM_{10} separately represent the annual concentration of $PM_{2.5}$ and PM_{10} in logarithm, respectively. In columns (1) and (4) we report the results without controlling for both city characteristics and weather heterogeneities. In columns (2) and (5) we report the results controlling for weather heterogeneities. In columns (3) and (6) we report the results controlling for both city characteristics and weather heterogeneities. City characteristics include average per capital GDP, fiscal expenditure of science, proportion of industry in GDP, and fiscal income. The weather controls include annual average precipitation, annual average surface temperature, annual average surface specific humidity, and annual average surface wind speed. The baseline regressions also control city level fixed effects, year fixed effects, and interaction of city control in 2012 and year fixed effects. (2) Robust standard errors in parentheses are clustered at the city level.

implementation of the regulation and the start of information disclosure. The data cover 5 years before and 4 years after the start of information disclosure. We are interested in the coefficient γ_k. The results satisfy the parallel trend assumption if the coefficients are negative and significant when $k \geq 0$ and if the coefficients are nonsignificant when $k < 0$.

The results of the parallel check are shown in figure 2. We find that the coefficients of pollutants $PM_{2.5}$ and PM_{10} suddenly drop to negative but nonsignificant in the year in which the regulation was implemented. In the year following the implementation of the regulation, the coefficients became significant, and the effects lasted for several years. The results of the parallel trend checks are consistent with the baseline results.

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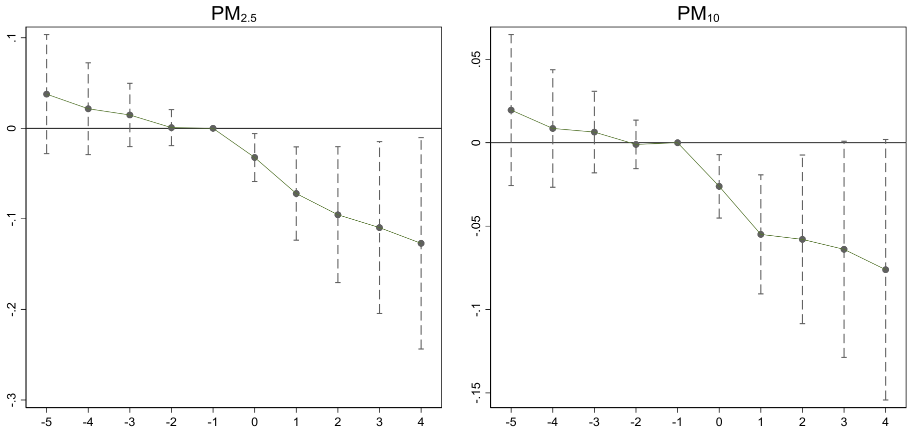

Figure 2. Parallel trend test: event study.
Notes: The panels in the figure plot the coefficients and associated 95% confidence intervals from estimating the leads and lags of information disclosure policy, separately for pollutants $PM_{2.5}$ and PM_{10}. All effects are relative to the one year before the policy went into effect.

4.2.2 Placebo test

Another possible threat to the reliability of the baseline results is time-invariant unobserved characteristics at the city level. Each city has specific characteristics. By controlling for city-level fixed effects in the baseline regression, we try to remove the effect of the time-invariant factors of cities on air pollution, but we are unable to control for changes in these factors over time. Even though we add economic and social characteristics at the city level, it is impossible to include all influential factors. As a result, following Ferrara *et al.* (2012), we use a placebo check to exclude possible bias in the baseline results. From formula (1), we know that $\hat{\alpha}$ can be obtained from formula (3):

$$\hat{\beta} = \beta + \gamma \cdot \frac{\text{cov}(\text{treat}_{ct},\ \varepsilon_{ct}|W)}{\text{var}(\text{treat}_{ct},\ |W)}. \tag{3}$$

In formula (3), we include a set of variables containing all controls and fixed effects, with γ representing the influence of unobserved factors on air pollution. If $\gamma = 0$, then $\hat{\beta}$ is proven to be unbiased. However, $\gamma = 0$ cannot be proven. To check for unbiasedness, we use a placebo check by replacing the variable of interest with an influential and randomly selected 'false' treat_{ct}. $\hat{\beta}$ is assumed to be 0. If $\hat{\beta} \neq 0$, then 'false' treat_{ct} has an effect on air pollution. The baseline regression omits this influential factor; thus, the results are biased. Specifically, we randomly generate a 'false' variable of interest to produce a 'false' estimation, $\hat{\beta}^{\text{random}}$. This process is repeated 1,000 times, producing 1,000 corresponding $\hat{\beta}^{\text{random}}$ estimations. Figure A2 in the online appendix represents the distribution of $\hat{\beta}^{\text{random}}$, from which the coefficients of $\hat{\beta}^{\text{random}}$ for all pollutants are normally distributed. The results are shown in figure A2 and are consistent with the expectation of the placebo check.

4.2.3 Excluding the potential effects of other regulations

Additionally, other environmental regulations were implemented during the period 2005–2019, which may have caused errors in the baseline results. To address this concern, we consider important environmental regulations in this period, namely, low

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Table 3. Mechanisms

	Government awareness	EP Investments		Green innovation		Firm exit
	MPC proposal	IPSM	IEGT	Green patents	Practical green patents	Elimination
Dependent variable	(1)	(3)	(4)	(5)	(6)	(7)
Policy	0.675 (0.314)	0.752 (0.221)	0.499 (0.170)	0.334 (0.052)	0.149 (0.044)	0.082 (0.046)
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
City_2012 × Year_dummy	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,869	3,481	3,750	3,840	3,840	3,973
R^2	0.398	0.776	0.737	0.829	0.879	0.696

Notes: (1) Table 3 presents the results of mechanism checks. Columns (1) and (2) check the effects of information disclosure on government awareness. The dependent variable in column (1) indicates the number of air pollution-related words in each city's government work report. Columns (3) and (4) check the mechanism of increasing environmental protection investments. The dependent variable in column (3) shows the investments in managing industrial pollution source (IPSM). The dependent variable in column (4) shows the investments in exhaust gas treatment (IEGT). Columns (5) and (6) check the mechanism of increasing green innovation. The dependent variable in column (5) represents the number of granted green patents in logarithm. The dependent variable in column (6) represents the number of granted practical green patents in logarithm. Column (7) checks the effect of the information exposure on the closure of heavily polluting enterprises, which is measured by the number of heavily polluting enterprises being shut down in logarithm. (2) Robust standard errors in parentheses are clustered at the city level.

carbon cities from 2010 to 2013 and the PITI. Additionally, by controlling for year fixed effects, we exclude the potential effects of nationwide environmental regulations, such as environmental laws. By adding dummy variables for these policies to the regression, we control for their potential effects. The results are shown in table 3. We find that the coefficient of each pollutant decreases but is still significant and slightly different from that in the baseline results. After excluding the potential effects of other environmental regulations, the results remain robust.

4.2.4 Heterogeneous treatment effects

Some recent studies suggest that the DID estimates with staggered treatment rollouts may be biased by heterogeneous treatment effects because staggered DID models compare units treated later to already treated units, which may lead to negative weighting (Goodman-Bacon, 2021). To address this concern, we apply the estimators developed by Callaway and Sant'Anna (2021) and De Chaisemartin and d'Haultfoeuille (2020). Table 4 presents the results, which are shown to still be valid. Our estimates are robust to heterogeneous treatment effects.

5. Mechanism analysis

5.1 Government awareness

Information disclosure may decrease the amount of air pollution through the channel of increasing the degree of government awareness. An important feature of the Chinese economy is the positive role played by local governments at different levels (Li *et al.*,

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Table 4. Determinants of city specific estimates

	Estimate: $PM_{2.5}$	Estimate: $PM_{2.5}$	Estimate: PM_{10}	Estimate: PM_{10}
Dependent variable	(1)	(2)	(3)	(4)
lnpm25 (lnpm10)	−0.280 (−0.035)	−0.293 (−0.036)	−0.384 (−0.042)	−0.401 (−0.044)
lngdp2012	0.023 (0.007)	0.022 (0.008)	0.019 (0.005)	0.019 (0.005)
Age: secretary		0.001 (0.001)		0.001 (0.001)
Edu: secretary		0.001 (0.002)		0.000 (0.002)
Native: secretary		0.003 (0.025)		0.011 (0.017)
Age: mayor		0.000 (0.001)		−0.000 (0.001)
Edu: mayor		0.004 (0.002)		0.002 (0.002)
Native: mayor		−0.021 (0.031)		−0.007 (0.021)
Observations	271	255	271	255
R^2	0.222	0.236	0.274	0.291

Notes: (1) Table 4 presents the possible influence factors affecting the city specific estimates. Lnpm25 and lnpm10 separately represent the annual concentration of $PM_{2.5}$ and PM_{10} in logarithm. Lngdp2012 represents the GDP in 2012 in logarithm. Other variables separately indicate secretary (mayor)'s age, education level, and whether he/she was local when the *New Regulation* was implemented. (2) Robust standard errors in parentheses are clustered at the city level.

2012). Corporate behavior, especially that of state-owned enterprises, is guided by the local government (Holmstrom, 1999). Against the backdrop of the long-term use of economic growth as the main measure of official promotion (Maskin *et al.*, 2000), China developed its economy at the cost of a clean environment. However, the Implementation of Ambient Air Quality Standards (GB3095-2012), which is essential in the implementation of the *New Regulation*, states that strengthening the regulation on air pollution is 'a necessary requirement to meet public demand and improve the credibility of the government'. Since then, local officials in China have faced unprecedented pressure to reduce air pollution since the effectiveness of pollution control has become an important criterion for their political performance. Therefore, we assume that information disclosure decreases the amount of air pollution by increasing the degree of government awareness. Government work reports are among the most essential official documents for local governments, summarizing their social and economic achievements in the past year and laying out work plans for the coming year. The content of these work reports reflects the work focus of the city government (Chen *et al.*, 2018).

Therefore, we use the number of words related to air pollution in each city's government work report to represent that government's awareness of the need to reduce the amount of ambient pollution. The results are shown in column (1) in table 3. After the implementation of the *New Regulation*, the number of words related to air pollution in the cities' government work reports significantly increased by 0.675, which verifies our assumption that strengthening government awareness of air pollution is a possible channel through which to decrease the amount of air pollution. This result is consistent

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with existing research conclusions: many studies have proven that pollution control is connected to cadre promotion in China (Chen *et al.*, 2016; Wang and Lei, 2020).

5.2 Environmental protection investments

Due to officials' increased attention to pollution caused by information disclosure, the government, society and enterprises are likely to increasingly invest in protecting the environment. We assume this to be the second possible mechanism. The current literature confirms that under stricter environmental regulation, some enterprises directly reduce the amount of pollutants in production, preventing the generation of pollution at the source (Liu *et al.*, 2017). Some enterprises install end-of-pipe pollution treatment equipment to reduce the amount of final emissions (Liu *et al.*, 2017; Liao, 2018; Huang and Lei, 2021).

We check this channel using the variables of investments in controlling pollution both at the source and at the end of the pipe at the city level. We use investments in industrial pollution source management (IPSM) to measure the intensity of pollution prevention. IPSM is not purely government or corporate behavior. The funding sources for IPSM include government budget funds and self-raised funds from enterprises as well as bank loans and foreign investment, indicating that the governance of industrial pollution sources is the responsibility of society as a whole, rather than the obligation of a single entity. Therefore, IPSM can measure the effectiveness of information disclosure in reducing emissions at the source better than can corporate investment in pollution source management. In column (2) in table 3, we present the results of the effect of information disclosure on IPSM, which show that the *New Regulation* increases IPSM by 7,520 yuan. We also use investment in exhaust gas treatment (IEGT) to measure the effect of information disclosure on final emission reduction. The results, shown in column (3) in table 3, indicate that since the implementation of the *New Regulation*, the amount of IEGT has increased by 4,990 yuan. Both of the above results show that information disclosure has a significant positive effect on increasing the amount of environmental protection investments at the city level.

5.3 Green innovation

We also assume green innovation to be a possible mechanism through which information disclosure reduces the amount of air pollution. Abundant literature has proven that stricter environmental regulations encourage enterprises to increase their amount of green investments (Gao and Zheng, 2017; Liao, 2018; Fan *et al.*, 2019). Studies also show that information exposure affects firms' environmental behaviors by increasing the degree of innovation (Liu *et al.*, 2017; Blundell *et al.*, 2020). Most studies utilize green innovation data from listed companies for microscopic research. In this study, we pay more attention to green innovation at the city level.

We use the green innovation level, which is measured by the numbers of granted green patents and granted applied green patents per year in each city. The data come from the Chinese Innovation Research Database. After dropping enterprises in the financial and real estate industries and listed companies that have suffered losses for two consecutive years or whose stocks have been subject to special treatment (ST enterprises), we calculate the numbers of green patents approved and applied green patents approved by each prefecture-level city each year from 2005 to 2019. Columns (5) and (6) in table 3

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present the results. Information disclosure is shown to significantly increase the numbers of green patents and applied green patents by 33.4 per cent and 14.9 per cent, respectively.

5.4 Closure of heavily polluting enterprises

From the above analysis, it can be seen that information disclosure encourages society as a whole to make positive efforts toward reducing the amount of environmental pollution. However, the environmental Kuznets curve shows that developing countries are likely to experience economic challenges due to stricter environmental regulations (Barbier, 1997). With lower emission requirements, some enterprises reduce the amount of pollutants through environmental investments and technological innovation, as demonstrated earlier. Enterprises that are unable to reduce the amount of emissions through proactive means can only reduce their levels of production to meet emission standards, or even shut down (Wang *et al.*, 2018; Petroni *et al.*, 2019; Cui and Moschini, 2020). Therefore, elimination may also be a mechanism through which information disclosure reduces the amount of air pollution.

Moreover, we measure the closure status of heavily polluting enterprises at the city level. We summarize the number of heavily polluting enterprises that were shut down each year in each city from 2005 to 2019. The enterprise shutdown information comes from the China Industrial and Commercial Registration Enterprise database, which contains the registration and cancellation information of all enterprises beginning in 1978 and accurately records the dates of enterprise shutdowns. After choosing companies belonging to the heavily polluting industries defined by the 'Guidelines for Information Disclosure of Listed Companies', we calculate the number of heavily polluting enterprises that are shut down each year in each city. Column (7) in table 3 shows that after the implementation of the *New Regulation*, the number of heavily polluting enterprises that were shut down increased by 8.2 per cent, which verifies elimination as a possible mechanism.

6. Heterogeneity analysis

6.1 City-specific estimates

Following the method of Greenstone *et al.* (2022) and Zou (2021), we make estimations based on equation (1) for each city to capture the specific effect of information disclosure on the amount of air pollution for the 271 cities separately. Their estimates and corresponding 95 per cent confidence intervals are presented in figure 3. It is shown that 78.97 per cent and 76.75 per cent of the coefficients are negative and significant, respectively, at the 95 per cent confidence interval, which means that the *New Regulation* alleviated air pollution in the majority of cities. This finding supports our baseline results that information disclosure helps control air pollution. Specifically, the average coefficients are -0.094 and -0.079 for $PM_{2.5}$ and PM_{10}, respectively.[9]

[9] Additionally, we need to provide an explanation for cities with positive and significant coefficients. We find that they share commonalities in terms of having low pollution levels and low proportions of secondary industry. For both $PM_{2.5}$ and PM_{10}, more than 70 per cent of cities with positive coefficients belong to the 10 per cent with the lowest pollutant value in the full sample. The mean of the secondary industry proportion for these cities is 38.472, which is very low compared to 47.707 per cent for the full sample. Among these cities, a large proportion rely on the agricultural industry. For example, Yichun in Heilongjiang Province is known for forestry being its pillar industry, and Hulunbuir is known for its animal husbandry. For these cities with low levels of air pollution, a positive coefficient is acceptable.

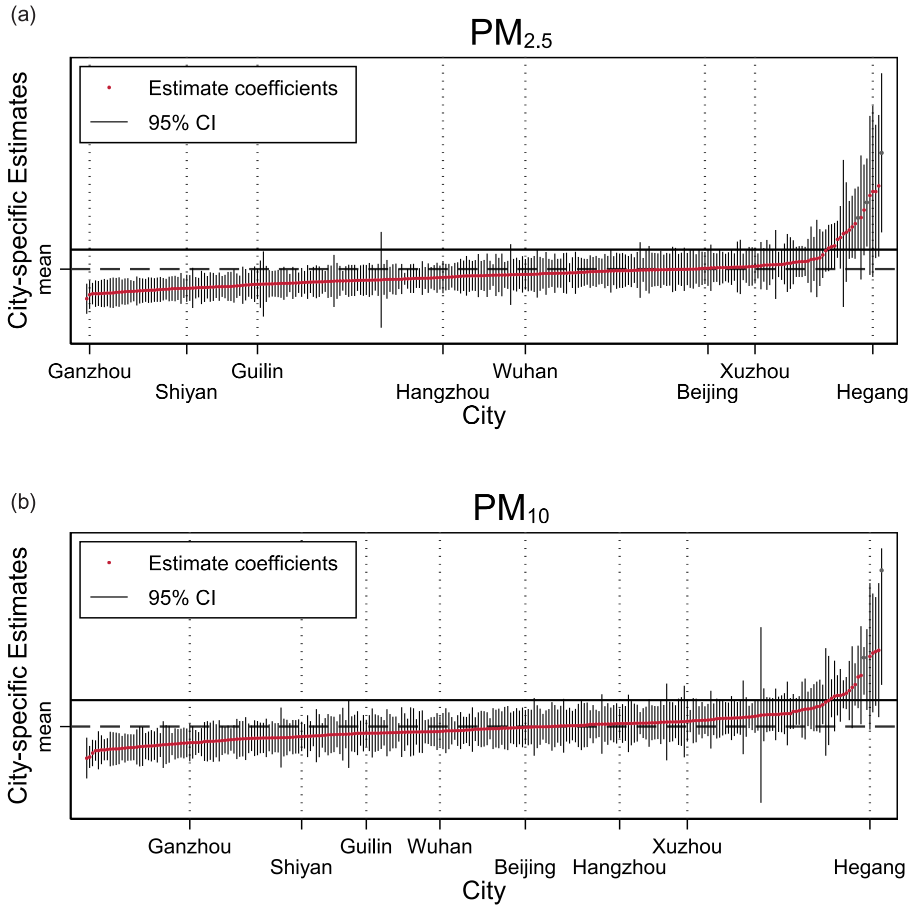

Figure 3. Magnitudes of information disclosure in Chinese cities.
Notes: The panels in the figure plot the city's specific estimates and their 95% confidence intervals for 271 cities separately for pollutants $PM_{2.5}$ and PM_{10}.

We further perform regression to analyze the determinants of the coefficients of city-specific estimates. We regress the coefficients of $PM_{2.5}$ and PM_{10} on the pollution level (separately measured by annual concentrations of $PM_{2.5}$ and PM_{10} in logarithmic form) before the implementation of the *New Regulation*, including the economic levels and characteristics of leaders, which include age, education level, and whether they are local for both the mayor and secretary. The results are shown in table 4. We find that the initial pollution and economic levels are influential in causing heterogeneous effects among cities, while the leader's personal characteristics have no effects, which shows that high-quality information disclosure better controls the principal-agent problem.[10] The above

[10]Existing literature has proven that leaders' personalities affect the levels of local economic and social development, as well as environmental protection (Yao and Zhang, 2015; Chen *et al.*, 2016). However, due to information disclosure, the heterogeneity of local leaders' personal characteristics no longer impacts the

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Table 5. Heterogeneity analysis

	$PM_{2.5}$	$PM_{2.5}$	PM_{10}	PM_{10}
	(1)	(2)	(3)	(4)
Dependent variable	Cities with more monitoring stations		Cities with fewer monitoring stations	
Policy	−0.030 (0.015)	−0.029 (0.013)	−0.027 (0.009)	−0.023 (0.011)
City controls	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Control2012 × Year	Yes	Yes	Yes	Yes
Observations	2,720	1,184	2,720	1,184
R-squared	0.917	0.914	0.919	0.974
P-value	0.000		0.000	

Notes: (1) Table 5 represents the results of heterogeneity checks based on different amounts of monitoring stations. Columns (1) and (2) present the effect of information disclosure on $PM_{2.5}$ and PM_{10} for cities with more monitoring stations. Columns (3) and (4) present the effect of information disclosure on $PM_{2.5}$ and PM_{10} for cities with fewer monitoring stations. (2) Robust standard errors in parentheses are clustered at the city level.

findings strengthen the conclusion that information disclosure decreases the amount of air pollution.

6.2 Cities with different numbers of monitoring stations

We also perform a heterogeneity check based on the number of monitoring stations for different cities. For cities with few air pollution monitoring stations, it may be difficult to accurately monitor air quality in areas far from the monitoring equipment. We divide the sample into two groups using the median number of monitoring stations for heterogeneity analysis. The median number of monitoring stations established at the beginning of the *New Regulation* was four. Moreover, we divide cities into two groups. The group with a higher number of monitoring stations includes cities with at least four monitoring stations; the group with a lower number of monitoring stations includes cities with fewer than four monitoring stations. The results are shown in table 5. Both $PM_{2.5}$ and PM_{10} decrease more in cities with higher numbers of monitoring stations, and the difference is significant (p value = 0.000), compared with cities with lower numbers of monitoring stations. By increasing the amount of investment in monitoring equipment, a city is likely to better control air pollution. Although few studies provide direct evidence of the number of monitoring stations impacting the effectiveness of information disclosure for air pollution, there is some implicative evidence. One possible explanation is that the intensity of supervision influences the effectiveness of pollution control. Chakraborti (2016) shows that plants in communities with lower median ages, higher median incomes and lower percentages of the workforce being employed in manufacturing are more responsive to improving water quality. Such individuals have a deeper understanding of pollution's negative influence and pay more attention to the pollution

effectiveness of air pollution reduction because high-quality information disclosure can partly solve the principal-agent problem.

behavior of nearby enterprises, forming a disguised form of supervision. Monitoring frequency is another dimension in measuring the intensity of supervision. For example, Zou (2021) finds that air quality near monitoring stations is significantly worse during days when pollution monitors are scheduled to be off. These studies indirectly verify our conclusions.

7. Conclusions

In this study, we analyze the effects of information disclosure on mitigating air pollution after the implementation of an environmental regulation. From 2013 to 2015, Chinese cities gradually built air pollution monitoring stations and published daily air quality information. We find that the information disclosure system dramatically reduces the levels of $PM_{2.5}$ and PM_{10}, which are the most dominant and influential pollutants in China. Specifically, after the implementation of the regulation, $PM_{2.5}$ concentrations decreased by 2.7 per cent, and PM_{10} concentrations decreased by 2.5 per cent. A series of checks prove that the baseline results are robust. We also find that information disclosure mitigates air pollution by raising the government's degree of awareness of air pollution, increasing the amount of investments in preventing and controlling air pollution, stimulating green innovation, and forcing heavily polluting enterprises to shut down. Additionally, we study the heterogeneous effects for cities with different characteristics. By analyzing city-specific effects, we find that cities with higher initial pollution levels and lower economic levels before the implementation of the *New Regulation* decreased their air pollution more than did their counterparts after its implementation. We also show that leaders' personalities have no effects on air pollution control. Moreover, information disclosure affects cities with a higher number of monitoring stations more than it does those with a lower number of monitoring stations by decreasing $PM_{2.5}$ and PM_{10} concentrations.

For government agencies in charge of environmental affairs, this article provides some useful implications from three perspectives. First, to the best of our knowledge, only four developing countries in the world have a platform for air pollution information disclosure (Barwick *et al.*, 2019). Therefore, developing countries should establish nationwide air pollution disclosure systems as soon as possible, considering the effectiveness of information disclosure in controlling air pollution. Second, the mechanism checks find that green innovations and investments in air pollution prevention and reduction are important channels through which air pollution can be controlled. Therefore, the government can simultaneously implement information disclosure and emission reduction policies to achieve better results. Finally, the heterogeneity checks prove that local leaders' personalities do not influence the effects of information disclosure on air pollution, which implies that high-quality information disclosure can partly reduce the influence of the principal-agent problem on air pollution.

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Competing interests. The authors declare none.

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