



Effects of different environmental regulations and their heterogeneity on air pollution control in China

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Abstract

This study endeavors to explore the impact of different environmental regulations and their heterogeneity on air pollution control in China. By employing a slacks-based measure of directional distance function model, considering undesirable outputs, the efficiency of air pollution control of China's 30 provinces during 2001–2014 is evaluated. The estimates indicate that the efficiency of air pollution control is fluctuating, and there is obvious regional differences. By using provincial-level panel data and panel threshold models, empirical results show that: (1) There is a nonlinear relationship between environmental regulation and air pollution control efficiency, and it can be positively correlated, but it is constrained by the stringency of regulation: there is a single threshold for formal (command-and-control (CAC) and market-based) regulation, while there is a double threshold for informal regulation. (2) Different environmental regulations have different governance effects. Compared with CAC regulation, market regulation can attract more attention of enterprises. (3) It may be ineffective to expect informal regulation to improve the air pollution control efficiency. Therefore, in order to achieve real sustainable development, the government should set up reasonable regulation stringency and optimize the combination of regulation tools.

Keywords Environmental regulation · Air pollution control · China · Panel threshold model

JEL Classification H23 · O13 · Q53 · Q58

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1 Introduction

According to a study by the World Health Organization, about 7 million people worldwide died of air pollution in 2012. This means that 1 in 8 people in the world died of air pollution that year. Air pollution has become the biggest threat to human health (Bagayev & Lochard, 2017). Since the reform and opening-up, China's economy has achieved remarkable growth in the past three decades, but behind the prosperity, China has also paid a high price. According to the World Development Index 2006 released by the World Bank, China accounts for 13 of the top 20 cities with the most serious air pollution (Huang, 2018). Air pollution has become the fourth leading cause of death for Chinese citizens (Wang et al., 2012). This growth mode that is beneficial to the economy rather than the environment is unsustainable. Therefore, the transition to a low-carbon society and a green economy has become a priority on China's policy agenda for sustainable and high-quality development (Yi & Liu, 2015). In order to cope with serious pollution problems, a series of environmental laws and regulations have been formulated (e.g. Environmental Protection Law, Air Pollution Prevention Law, etc.), and a large amount of money in environmental control has been invested by the Chinese government [e.g. in 2018, the central government has allocated 255.5 billion yuan for pollution control and ecological environment protection (China Eco-environment Bulletin 2018)]. Moreover, with the continuous improvement of public awareness of environmental protection, the number of environmental non-governmental organizations (ENGOs) in China has increased rapidly since the mid-1990s (Li et al., 2018). They address many environmental issues, including water and air pollution, energy conservation, large dams and hydropower projects, biodiversity conservation, and environmental education (Economy, 2014). Although there are so many environmental policy tools used, can these tools improve the efficiency of environmental governance? Which policy tools are more effective? At the same time, considering the reality of great differences in economic and social development levels, under what conditions can these policy tools be more effective in reducing environmental pollution? This series of problems is of great significance for the local government to improve the effectiveness of air pollution control. Therefore, in the context of vigorously improving the government's environmental governance capabilities and the "Pollution Prevention and Control Battle" has entered the critical stage, this paper attempts to answer the above questions and provide a theoretical reference for regulators to optimize environmental policies.

Scholars adopt different methods to analyze the relationship between environmental regulations and pollution reduction, but their results are mixed. Some scholars believe that environmental regulations can promote pollution reduction (Levinson, 2003; Vargas-Vargas et al., 2010; Zhou et al., 2021). For example, Bostan et al. (2016) find that appropriate government environmental spending policies can effectively promote air quality improvement; Basoglu and Uzar (2019) also point that the government's environmental regulation is conducive to the improvement of regional environmental quality. Some scholars provide negative evidence. For instance, Blackman and Kildegaard (2010) investigate inspections conducted by an environmental agency in Mexico and find that clean production technology has nothing to do with pollution reduction. Although there have been many studies in this aspect (Kanada

et al., 2013; Li et al., 2018; Liu & Guo, 2013; Wang & Wheeler, 2005), in the existing literature, most scholars pay attention to the linear relationship between environmental regulation and pollution control, and seldom analyze the non-linear relationship (Li et al., 2019; Xie et al., 2017; Zhou et al., 2019). In addition, most studies only investigate the impact of one kind of environmental regulation instruments on environmental performance but do not distinguish the mechanism of different types of environmental regulations (Chang & Wang, 2010; Cheng et al., 2016; Cole et al., 2005; Deng et al., 2012; Gentzkow & Shapiro, 2010; Lindstad & Eskeland, 2016). Moreover, as for the research of air pollution, few representative indicators are selected from the perspective of pollution control and input–output. Hence, this study attempts to fill these gaps.

The crucial contributions of this paper are as follows: Firstly, unlike the existing literature, we use the slacks-based measure of directional distance function (SBM-DDF) model, considering undesirable outputs to measure the efficiency of air pollution control of China's 30 provinces during 2001–2014. Secondly, in order to take into account the instrument design and stringency of environmental regulation, we divide environmental regulations into three categories: market-based environmental regulations, command-and-control (CAC) environmental regulations and informal environmental regulations, and further investigate whether there is heterogeneity in the impact of different kinds of environmental regulations on air pollution control efficiency. Thirdly, we assume a non-linear relationship between environmental regulations and air pollution control efficiency. Specifically, to objectively study the effect of different kinds of environmental regulations on air pollution control, we first use SBM-DDF to measure the efficiency of air pollution control, and then conduct a threshold effect test to endogenously delimit the threshold according to the characteristics of the data itself, so as to avoid the error of regression results caused by the traditional subjective judgment. Finally, we apply the threshold panel model to detect the non-linear relationship between environmental regulations and air pollution control efficiency, so as to reveal the optimal regulation stringency or interval to improve the efficiency of air pollution control.

The rest of the paper is structured as follows. Section 2 reviews the relative literature. Section 3 describes the regression model. Section 4 defines the variables and explains data collection. Section 5 presents the empirical findings. Section 6 concludes and discusses its policy implications.

2 Literature review

Based on the existing literature and the practice of environmental regulations in the world, the realization of environmental governance is primarily through formal and informal environmental regulations (Li et al., 2018). Among them, formal environmental regulation can be divided into CAC environmental regulations and market-based environmental regulations. The influences of public participation and ENGOs on environmental performance are a voluntary process, so it is classified as informal regulation. This paper reviews the relevant literature from three aspects.

2.1 The effect and mechanism of CAC regulations

CAC regulation is a policy instrument for the government to correct, prevent and control the behaviors of polluting firms, and to force them to comply with and implement environmental standards through environmental laws, regulations and related administrative measures (licensing, prohibition, standard formulation, and implementation) (Holling & Meffe, 1996). Regarding the relationship between CAC regulations and environmental governance, most studies have found that there is a positive relationship between CAC regulations and environmental quality (Becker & Henderson, 2000; Greenstone, 2003; Marconi, 2012). Kanada et al. (2013) conduct an empirical analysis of Japanese air pollution policies from 1960 to 2005 and find that strict air pollution control policies have significantly reduced sulfur dioxide emissions. Tang et al. (2014) point out that reasonable environmental regulation policies can reduce resource consumption and environmental pollution emissions while maintaining the same output. Some studies put forward negative views (Fredriksson & Millimet, 2002; Liu & Guo, 2013; Sinn, 2008). For example, Schlottmann (1976) finds that pollutant emissions are not related to environmental regulations through a survey of SO₂ emissions from the coal industry in the United States. Konisky (2007) finds that local governments imitate each other in implementing environmental regulations, which limits the reduction of pollution and makes “race-to-bottom” possible. Wu et al. (2016) explore the causes of haze pollution in China and find that PM_{2.5} is not significantly correlated to public financial expenditure on environmental protection.

Scholars have explained the reasons why CAC regulations do not work from different perspectives. Blackman and Kildegaard (2010) find that CAC regulations lack real enforcement effectiveness. Further, Arguedas and Rousseau (2015) point out that the interests of local regulators are not entirely in line with those of the central government as local regulators face more realistic problems, such as the economic difficulties of offenders, budget constraints on law enforcement, and the close relationship with regulated entities. Thus, local regulators often evade their enforcement responsibilities by enforcing lax regulations. Konisky and Woods (2012), Deng et al. (2012) and Wu et al. (2019a) argue that increased environmental investment may lead to free-riding due to the interaction of environmental and economic strategies among local governments, which is not conducive to environmental governance.

In China, the most commonly used environmental regulations are CAC regulations. Since China first promulgated the Environmental Protection Law (Trial Implementation) in 1979, many environmental laws and regulations have gradually come into force, and have been revised in later practice. Almost all pollutant emission standards have been established, and factories will be fined or even forced to close if they exceed these standards (Xie et al., 2017). Strict laws, regulations and environmental standards can prevent the occurrence of environmental pollution by directly controlling the behavior of polluters and directly regulating the total amount of pollutants discharged, or limit it to a certain extent. However, the implementation of CAC regulations will also encounter some obstacles. First, once companies meet these standards, there is no further incentive for them to develop clean technologies (Porter & Linde, 1995). Secondly, because of information asymmetry, enterprises often conceal

emission information or even secretly discharge excessive emissions in order to avoid inspection and reduce pollution control costs (Nyborg & Telle, 2006; Zhu & Zhang, 2012). Thirdly, over the past 30 years, the performance appraisal system with GDP as the core and the promotion mechanism of officials have led to serious distortion of local government incentives in China. In order to obtain a political promotion, local government officials may try their best to weaken the stringency of environmental regulation to reduce the compliance costs of enterprises and thus develop the region's economy (Li & Zhou, 2005). Promoting economic growth at the cost of the environment has become the choice of many local governments.

2.2 The effect and mechanism of market-based regulations

Market-based regulation is a policy instrument that takes the market as an intermediary, indirectly influences the economic interests of polluters by means of price, market signals, and other economic variables, and promotes them to change their behavior to reduce or eliminate negative externalities. Scholars have done a great deal of research on the relationship between market-based regulations and environmental governance. Peterson (1977) points out that with the increase of pollutant discharge fee levy standards, enterprises will economically consider reducing pollution emissions. However, Meza (1985) argues that pollutant discharge fees are inefficient in the long run to restrain the enterprise's pollution discharge behavior. In response to the above situation, Paras (1997) elaborates that as the pollutant discharge fee levy standard is often lower than the marginal emission reduction cost, and there are great differences in different regions, the enthusiasm of enterprises in pollution control has declined. To further examine the differences mentioned above, an empirical study on the influence of pollutant discharge fees on sewage discharge from the enterprise level has been made by Dasgupta et al. (2001). Their results show that pollutant discharge fees have a positive effect on the main pollutants of sewage (biological oxygen demand, chemical oxygen demand, and solid suspended matter). Wang and Wheeler (2005) also provide empirical evidence of the positive effects of pollutant discharge fee on pollution reduction. However, Cheng et al. (2016) provide some negative evidence from China, finding that market-based regulations have little impact on pollution emissions. In addition to pollutant discharge fee, some scholars have also studied the relationship between emissions trading and environmental governance (Benkovic & Kruger, 2001; Chang & Wang, 2010; Shin, 2013; Tu & Shen, 2014; Vlachou, 2014; Wu et al., 2019b).

In the 1980s, China's market economic reform provided the institutional basis for market-based regulations. China's market-based regulations are dominated by two major policies: the pollution charge system and emissions trading. According to the "polluter pays" principle, China began to levy a certain proportion of pollution charges on polluters in 1978. In 1979, the promulgation of the Environmental Protection Law (Trial Implementation) marked the beginning of the legalization of the pollution charge system. By the end of 1981, there were 27 pilot provinces in China. In 2003, the Regulations on the Administration of Collection and Use of Pollutant Discharge Fees stipulated in detail the levy objects, charging standards, usage, and management, which is a milestone in the reform of the pollution charge system. Pollution charge is one of

the principal sources of financing for environmental governance, which has achieved rapid development between 1996 and 2012. It wasn't until 2018 that China no longer levied pollution charges, but instead replaced them with environmental taxes. In terms of emissions trading, China's emissions trading began in the late 1980s. In 2001, China launched the "4 + 3 + 1" project. In 2007, China's first emissions trading center was established in Jiaxing, Zhejiang Province. At present, China mainly carries out local pilot projects and has not yet formed a national trading platform.

According to the existing literature and China's reality, the impacts of market-based regulations on environmental governance in China can be achieved mainly through two ways: One is through levying pollutant discharge fees (Chang & Wang, 2010), the other is through emissions trading (Wu et al., 2019b). Concretely, pollutant discharge fee is an economic burden of enterprises. If backward production mode is adopted, the number of pollutant discharge per unit capacity will be very large, and the pollutant discharge fee will also increase, which seriously hinders the development of enterprises. If enterprises want to get out of the predicament, they need to change the backward production mode, improve the utilization efficiency of resources, and urge themselves to control pollution. Besides, in the case of cost differences in pollution source treatment, enterprises with lower treatment costs can sell their remaining emission rights to enterprises with higher pollution control costs. Market transactions make emission rights flow from polluters with low governance costs to polluters with a high governance costs, which may force polluters to reduce governance costs in the pursuit of profitability and seek to reduce pollution.

2.3 The effect and mechanism of informal regulations

Informal regulation refers to the public or ENGOs through voluntary environmental agreements and other non-mandatory measures to urge enterprises or individuals to self-restraint on pollution behavior. Studies have shown that informal regulations have a favorable effect on environment quality (Goldar & Banerjee, 2004; Hårsmann & Qigley, 2010; Li et al., 2018; Pargal & Wheeler, 1996). Tiebout (1956) argues that residents can move out of areas that cannot satisfy their preferences, and move into areas that can satisfy their preferences. By "voting with feet", local governments are under pressure to improve their public services (Zheng et al., 2013). Further, Hirschman (1970) points out that the same effect can be achieved through direct public petitions to managers, appeals or public opinion protests. Moreover, the press can also act as an informal regulator, as the news coverage of pollution may affect local pollution control (Gentzkow & Shapiro, 2010; Kathuria, 2007). However, some scholars are skeptical about the role of informal regulation (Blackman & Kildegaard, 2010; Cole et al., 2005).

In China, with the Environmental Protection Law stipulating the public's obligations and rights in environmental protection, a growing number of people pay attention to environmental protection consciously and express their demands for environmental governance. For example, in 2007, the public boycotted the p-xylene chemical (PX) project planned to be built in Haicang Peninsula in Xiamen City, Fujian Province, for fear that the chemical plant might bring harm to people's health. Finally, the Xiamen

municipal government announced the suspension of the project. During 2006–2010, compared with 980 administrative litigation cases and 30 criminal litigation cases, there were more than 300,000 environmental letters and visits and 2614 administrative reconsideration cases. In 2012, major environmental incidents increased by 120% over the same period last year. China has entered a period of a high incidence of environmental mass incidents (Zheng et al., 2013).

According to the existing literature and the reality of China, the impact of informal regulations on environmental governance can be achieved mainly through three ways: Firstly, the direct interaction between the public and local governments, that is, the public or ENGOs directly reflect their demands for environmental quality improvement to local governments through letters, visits, and reports, then the local governments respond to the public's demands to improve the environment (Betsill et al., 2001; Börzel & Buzogány, 2010; Wang & Connell, 2016); Secondly, the public or ENGOs directly express their dissatisfaction with the local environmental problems and their demands for environmental quality improvement to the superior government through letters and visits, reports and demonstrations (Betsill et al., 2001). The superior government urges the local government to take environmental governance actions; Thirdly, the public or ENGOs lobby the government, enterprises, and people to adopt an environment-friendly way of life and production by possessing professional environmental-related knowledge (Zhan & Tang, 2013).

In summary, although previous studies have provided opportunities to comprehend the relationship between environmental regulations and pollution control, the conclusions drawn by scholars are inconsistent, which may be related to the possible non-linear relationship between the two. However, most previous studies only assumed a linear relationship and ignored the possible non-linear relationship between environmental regulations and pollution control (Hansen, 2011; Li et al., 2019; Wang & Shen, 2016). Porter and Linde (1995) point out that the prerequisite for environmental regulation to play the “innovation compensation effect” is to establish well-designed and stringency appropriate environmental regulation, which implied that the stringency of environmental regulation is not the greater the better, and excessive regulation stringency may inhibit environmental governance (Belenky, 2015). Based on this, the influences of environmental regulations on pollution control may vary with the increase of regulation stringency, that is, there may be a non-linear relationship between environmental regulations and environmental governance. Hence, in order to obtain more objective and reliable conclusions and provide empirical theoretical support for government decision-making, this study uses the panel threshold model developed by Hansen (1999) to analyze the possible non-linear relationship between environmental regulations and air pollution control. In addition, most scholars have not considered the heterogeneous effects of different forms of environmental regulations, nor have they distinguished the potential impact mechanisms among different forms of environmental regulations. Moreover, few scholars consider using undesirable outputs to measure air pollution control efficiency. Therefore, we try to fill these gaps.

3 Empirical model

Referring to the previous literature review (Hansen, 1999), we adopt a threshold effect test to endogenously determine the specific threshold according to the characteristics of the data, and then employ a panel threshold model to explore the possible non-linear relationship between environmental regulations and air pollution control, so as to avoid the estimation errors caused by the subjective setting of environmental regulation intervals.

Assuming that there is a threshold value γ , the relationship between environmental regulations and air pollution control efficiency is significantly different for $er_{it} \leq \gamma$ and $er_{it} > \gamma$. Thus, a single threshold model with regulation stringency as the threshold variable is constructed. The specification of the single threshold model is as follows:

$$eff_{it} = \alpha_0 + a_1 er_{it} * I(M_{it} \leq \gamma) + a_2 er_{it} * I(M_{it} > \gamma) + \beta X_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

where i denotes a province, t is a year. eff is the dependent variable, representing air pollution control efficiency. er is the core independent variable, standing for the stringency of CAC, market-based, and informal regulations. X is control variables, including urbanization level, foreign direct investment and energy consumption intensity. $\alpha_1, \alpha_2, \beta$ are the parameters to be estimated. μ is a regional individual effect and ε is a disturbance term. M_{it} is a threshold variable, γ is a specific threshold value, $I(\cdot)$ is an indicator function, when the corresponding conditions are established, the value is 1, otherwise 0.

The above model assumes that there is only one threshold, but in fact, there may be two or more thresholds. We set the double threshold regression model as follows:

$$eff_{it} = \alpha_0 + a_1 er_{it} * I(M_{it} \leq \gamma_1) + a_2 er_{it} * I(\gamma_1 < M_{it} \leq \gamma_2) + a_3 er_{it} * I(M_{it} > \gamma_2) + \beta X_{it} + \varepsilon_{it} \quad (2)$$

where $\gamma_1 < \gamma_2$. Multiple thresholds can be extended on the basis of single and double thresholds models, which are not discussed here.

4 Variables and data

4.1 Dependent variables

4.1.1 Calculating method of air pollution control efficiency

Traditional data envelopment analysis (DEA) cannot distinguish good outputs and bad outputs. It was not until the directional distance function (DDF) developed by Chambers et al. (1996) that the technical problem of dealing with undesirable outputs was basically solved. However, the disadvantage of DDF is that it does not take into account the slack of input and output variables, which is inconsistent with reality. To solve this problem, Fukuyama and Weber (2009) combine slacks-based measure (SBM) with DDF to form non-oriented and non-radial DDF. Therefore, according

to the research of Färe et al. (2007) and Fukuyama and Weber (2009), we use the SBM-DDF to measure China’s air pollution control efficiency. Assuming that there are k decision-making units (DMUs) at time t and each DMUk ($k = 1, \dots, K$) produces l types of undesirable outputs (‘bads’), $b = (b_1, \dots, b_l) \in R_l^+$ and m types of desirable outputs (‘goods’), $y = (y_1, \dots, y_m) \in R_m^+$, by using n types of inputs, $x = (x_1, \dots, x_n) \in R_n^+$. Further, assume that the set of production possibilities possesses both closed set and convexity, that is, inputs and desirable outputs satisfy strong disposability, whereas undesirable outputs satisfy the hypothesis of weak disposability and null-jointness. The production possibility set is denoted as:

$$p^t(x^t) = \left\{ (y^t, b^t) : \sum_{k=1}^K \lambda_k^t y_{km}^t \geq y_{km}^t, \forall m; \sum_{k=1}^K \lambda_k^t x_{kn}^t \leq x_{kn}^t, \forall n; \sum_{k=1}^K \lambda_k^t b_{kl}^t = b_{kl}^t, \forall l; \sum_{k=1}^K \lambda_k^t = 1, \lambda_k^t \geq 0, \forall k \right\} \tag{3}$$

where λ_k^t is a weight variable, and the constraint assumes variable returns to scale (VRS). If the constraint is deleted, it assumes constant returns to scale.

The SBM under consideration of undesirable outputs is defined as:

$$\begin{aligned} \bar{S}_v^t(x^{t,k}, y^{t,k}, b^{t,k}; g^x, g^y, g^b) &= \frac{1}{3} \max_{s^x, s^y, s^b} \left(\frac{1}{N} \sum_{n=1}^N \frac{s_n^x}{g_n^x} + \frac{1}{M} \sum_{m=1}^M \frac{s_m^y}{g_m^y} + \frac{1}{L} \sum_{l=1}^L \frac{s_l^b}{g_l^b} \right) \\ s.t. \sum_{k=1}^K \lambda_k^t x_{kn}^t + s_n^x &= x_{kn}^t, \forall n; \sum_{k=1}^K \lambda_k^t y_{km}^t - s_m^y = y_{km}^t, \forall m; \sum_{k=1}^K \lambda_k^t b_{kl}^t + s_l^b = b_{kl}^t, \forall l; \\ \sum_{k=1}^K \lambda_k^t &= 1; \lambda_k^t \geq 0, \forall k; s_n^x \geq 0, \forall n; s_m^y \geq 0, \forall m; s_l^b \geq 0, \forall l \end{aligned} \tag{4}$$

where \bar{S}_v^t is the SBM with VRS. $(x^{t,k}, y^{t,k}, b^{t,k})$ denotes the input and output vectors of the provinces at time t ; (g^x, g^y, g^b) is the directional vector that denotes inputs compression, good outputs expansion, and bad outputs compression; (s_n^x, s_m^y, s_l^b) denotes slack variables, representing inputs redundancy, good outputs insufficiency and bad outputs over-scalar vectors of the first DMU. Thus, when (s_n^x, s_m^y, s_l^b) is not completely zero, there is at least one room for improvement in the inputs, desirable and undesirable outputs of air pollution control efficiency. If and only if $s_n^x = s_m^y = s_l^b = 0$, then efficiency value reaches the optimum. The inefficiency value of air pollution control of province i at time t can be obtained by solving the linear programming of formula (4). By referring to Fukuyama and Weber (2009)’s research, we decompose inefficiency into:

The inefficiency of inputs:

$$IE_x = \frac{1}{3N} \sum_{n=1}^N \frac{s_n^x}{g_n^x} \tag{5}$$

The inefficiency of good outputs:

$$IE_y = \frac{1}{3M} \sum_{m=1}^M \frac{s_m^y}{g_m^y} \tag{6}$$

The inefficiency of bad outputs:

$$IE_b = \frac{1}{3L} \sum_{l=1}^L \frac{s_l^b}{g_l^b} \tag{7}$$

The undesirable outputs include industrial smoke and dust, industrial waste gas and sulfur dioxide emissions. Then, the inefficiency of air pollution control can be defined as:

$$IE_b^{APUE} = IE_b^{smoke_dust} + IE_b^{waste_gas} + IE_b^{so_2} \tag{8}$$

According to the theorem of SBM-DDF model, let $g_n^x = x_n^{\max} - x_n^{\min}, \forall n$ and $g_m^y = y_m^{\max} - y_m^{\min}, \forall m$, then $0 \leq \bar{S}_v^t(x^{t,k}, y^{t,k}, b^{t,k}; g^x, g^y, g^b) \leq 1$. The objective can be written as: $0 \leq (IE_x, IE_y, IE_b) \leq 1$. Then the inefficiency value can be converted to the efficiency value, and the evaluation equation of air pollution control efficiency can be established:

$$\begin{aligned} eff &= 1 - IE_b^{APUE} \\ s.t. \quad g_n^x &= x_n^{\max} - x_n^{\min}, \forall n; \\ g_m^y &= y_m^{\max} - y_m^{\min}, \forall m. \end{aligned} \tag{9}$$

4.1.2 Inputs and outputs

The inputs contain labor, energy, and capital. The labor force is measured by total employment. Energy consumption is estimated by primary energy consumption. The capital stock is estimated by the perpetual inventory method. Real gross domestic product (GDP) is chosen as the desired output. Besides, three air pollutant emissions are selected as undesirable outputs, namely, industrial smoke and dust, industrial waste gas and sulfur dioxide emissions. All data can be found in *China Statistical Yearbook (2002–2015)*, *China Labor Statistical Yearbook (2002–2015)*, *China Environmental Yearbook (2002–2015)* and *China Energy Statistical Yearbook (2002–2015)*. All nominal variables are deflated to constant prices in 2001.

4.1.3 Results of air pollution control efficiency

The measurement results of the average air pollution control efficiency in China are represented in Table 1. As shown in Table 1, from 2001 to 2014, the average air pol-

Table 1 Calculation results of air pollution control efficiency

| Provinces | 2001 | 2003 | 2005 | 2007 | 2009 | 2011 | 2013 | Mean |
|-------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| High control efficiency provinces | 0.9707 | 0.9638 | 0.9631 | 0.9647 | 0.9584 | 0.9584 | 0.9568 | 0.9623 |
| Beijing | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| Hainan | 0.9982 | 0.9978 | 0.9970 | 0.9973 | 0.9963 | 0.9967 | 0.9915 | 0.9964 |
| Tianjin | 0.9743 | 0.9651 | 0.9750 | 0.9784 | 0.9761 | 0.9779 | 0.9775 | 0.9749 |
| Qinghai | 0.9873 | 0.9850 | 0.9790 | 0.9770 | 0.9688 | 0.9733 | 0.9682 | 0.9769 |
| Shanghai | 0.9609 | 0.9547 | 0.9597 | 0.9729 | 0.9694 | 0.9756 | 0.9731 | 0.9666 |
| Ningxia | 0.9636 | 0.9515 | 0.9576 | 0.9552 | 0.9541 | 0.9432 | 0.9413 | 0.9524 |
| Fujian | 0.9764 | 0.9614 | 0.9482 | 0.9474 | 0.9354 | 0.9474 | 0.9397 | 0.9508 |
| Jilin | 0.9498 | 0.9506 | 0.9375 | 0.9386 | 0.9237 | 0.9329 | 0.9419 | 0.9393 |
| Gansu | 0.9463 | 0.9306 | 0.9382 | 0.9447 | 0.9340 | 0.9300 | 0.9306 | 0.9363 |
| Yunnan | 0.9500 | 0.9413 | 0.9388 | 0.9356 | 0.9258 | 0.9073 | 0.9045 | 0.9290 |
| Medium control efficiency provinces | 0.9244 | 0.9119 | 0.9120 | 0.9082 | 0.8939 | 0.9129 | 0.9035 | 0.9095 |
| Chongqing | 0.9328 | 0.9288 | 0.9267 | 0.9169 | 0.9023 | 0.9439 | 0.9402 | 0.9274 |
| Heilongjiang | 0.9443 | 0.9345 | 0.9277 | 0.9238 | 0.9060 | 0.9267 | 0.9130 | 0.9251 |
| Jiangxi | 0.9565 | 0.9297 | 0.9192 | 0.9163 | 0.8996 | 0.9173 | 0.9174 | 0.9223 |
| Xinjiang | 0.9638 | 0.9534 | 0.9399 | 0.9257 | 0.8980 | 0.9009 | 0.8585 | 0.9200 |
| Zhejiang | 0.9219 | 0.9005 | 0.9147 | 0.9195 | 0.9020 | 0.9227 | 0.9195 | 0.9144 |
| Hubei | 0.9116 | 0.9074 | 0.9057 | 0.9147 | 0.9032 | 0.9143 | 0.9168 | 0.9105 |
| Anhui | 0.9349 | 0.9080 | 0.9081 | 0.9052 | 0.8798 | 0.9001 | 0.9007 | 0.9053 |
| Guangdong | 0.9153 | 0.8858 | 0.8915 | 0.8968 | 0.8775 | 0.9121 | 0.9084 | 0.8982 |
| Shaanxi | 0.9126 | 0.9012 | 0.8987 | 0.8940 | 0.8927 | 0.8933 | 0.8847 | 0.8968 |
| Guizhou | 0.8506 | 0.8697 | 0.8879 | 0.8688 | 0.8778 | 0.8974 | 0.8762 | 0.8755 |
| Low control efficiency provinces | 0.8269 | 0.8087 | 0.8067 | 0.8191 | 0.8042 | 0.8330 | 0.8333 | 0.8189 |
| Hunan | 0.8701 | 0.8638 | 0.8629 | 0.8592 | 0.8286 | 0.9140 | 0.9131 | 0.8731 |
| Guangxi | 0.8530 | 0.8448 | 0.8461 | 0.8588 | 0.8246 | 0.9079 | 0.9179 | 0.8647 |
| Sichuan | 0.8193 | 0.8258 | 0.8499 | 0.8533 | 0.8736 | 0.8947 | 0.9046 | 0.8602 |
| Jiangsu | 0.8573 | 0.8468 | 0.8492 | 0.8757 | 0.8574 | 0.8589 | 0.8538 | 0.8570 |
| Liaoning | 0.8387 | 0.8397 | 0.8037 | 0.8147 | 0.8084 | 0.8447 | 0.8454 | 0.8279 |
| Inner Mongolia | 0.9008 | 0.8276 | 0.8012 | 0.8147 | 0.7926 | 0.8195 | 0.8007 | 0.8224 |
| Henan | 0.8066 | 0.7903 | 0.7660 | 0.7975 | 0.7810 | 0.8217 | 0.8234 | 0.7980 |
| Shandong | 0.7760 | 0.7606 | 0.7897 | 0.8155 | 0.7941 | 0.7943 | 0.7993 | 0.7899 |
| Shanxi | 0.7687 | 0.7314 | 0.7506 | 0.7626 | 0.7550 | 0.7669 | 0.7748 | 0.7586 |
| Hebei | 0.7783 | 0.7565 | 0.7480 | 0.7395 | 0.7272 | 0.7073 | 0.7004 | 0.7367 |
| Mean | 0.9054 | 0.8926 | 0.8918 | 0.8952 | 0.8832 | 0.8996 | 0.8961 | 0.8948 |

lution control efficiency fluctuates from 0.88 to 0.91, which is close to the production frontier. This indicates that China's air pollution control efficiency maintains at a good level in general. Nevertheless, from a regional perspective, the air pollution control efficiency among regions is quite different. Beijing, Hainan, Tianjin, Qinghai, Shanghai, Ningxia, Fujian, Jilin, Gansu, and Yunnan are the top ten provinces on average in 14 years. We classify them as "high control efficiency provinces". The top three provinces are located in Eastern China. In addition to these ten provinces, the "high control efficiency provinces" also has one province in the Middle of China and four provinces in Western China. Ten provinces in the 11th to 20th ranking are divided into "Medium control efficiency provinces". Among them, there are two provinces in Eastern China: Zhejiang and Guangdong; four provinces in Middle of China: Heilongjiang, Jiangxi, Hubei, and Anhui; and four provinces in Western China: Chongqing, Xinjiang, Shaanxi, and Guizhou. Of all the provinces, Shanxi ranks second to last. Shanxi is a major coal-producing province and a typical representative of extensive economic development model with high energy consumption, high material consumption and high pollution, which seriously affects the improvement of air pollution control efficiency. Hebei ranks the last, which is not only directly related to its extensive mode of production, but also to its special geographical location. Hebei is located between Beijing and Tianjin. Beijing and Tianjin require a higher level of environmental protection and move more traditional manufacturing industries to Hebei Province, such as Shougang Group, which has a certain negative impact on Hebei's air pollution control.

4.2 Independent variables

4.2.1 Core independent variables

Scholars have employed a variety of indicators to represent environmental regulations, such as environmental enforcement (Brunnermeier & Cohen, 2003), the number of laws and policies enacted by the government (Marco & Giménez, 2013), emission standards (Lindstad & Eskeland, 2016), pollutant discharge fees (Levinson, 1996), environmental tax (Paras, 1997), environmental investment (Deng et al., 2012), the proportion of environmental pollution control in production cost or output value, the number of public complaints about pollution events (Levinson & Taylor, 2008), pollution information exposure index (Yao & Liang, 2017), comprehensive index of environmental regulation (Wu et al., 2019a). Accordingly, we set three variables to represent the CAC (*cer*), market-based (*ln pdf*) and informal (*comp*) environmental regulations respectively. Among them, the CAC regulation is represented by the number of environmental laws, standards, and policies. Moreover, the natural logarithm of pollutant discharge fees is selected as a proxy for market-based regulation and the number of public complaints about pollution events is selected as a proxy for informal regulation.

Table 2 Descriptive statistics of variables

| Variable | Obs | Mean | SD | Min | Max |
|--------------|-----|---------|--------|--------|---------|
| <i>eff</i> | 420 | 0.8923 | 0.0702 | 0.7004 | 1.0000 |
| <i>cer</i> | 420 | 3.8643 | 5.0000 | 0.0000 | 35.0000 |
| <i>lnpdf</i> | 420 | 10.3481 | 1.0719 | 6.7637 | 12.5684 |
| <i>comp</i> | 420 | 2.1156 | 1.7358 | 0.0130 | 9.9896 |
| <i>urb</i> | 420 | 0.4835 | 0.1501 | 0.1931 | 0.8960 |
| <i>fdi</i> | 420 | 0.2017 | 0.1734 | 0.0099 | 0.6578 |
| <i>eci</i> | 420 | 1.6212 | 0.8832 | 0.5036 | 4.9826 |

4.2.2 Control independent variables

Referring to relevant literature (Grossman & Krueger, 1991; Lanoie et al., 2008; Liu et al., 2017; York et al., 2003; Zhu et al., 2014), energy consumption intensity (*eci*), urbanization level (*urb*) and foreign direct investment (*fdi*) are taken as control variables. Foreign direct investment, measured by foreign direct investment (FDI), has a complex impact on air pollution control. FDI may not only produce “pollution heaven” effect but bring about environmental clean technology (Bagayev & Lochard, 2017; Zeng & Zhao, 2009). Urbanization is closely related to regional environmental quality (Zheng et al., 2015). The mechanisms of its impacts on environmental quality are complex. On the one hand, the migration of population, the increase of car ownership and the development of industrialization inevitably lead to environmental pollution (Ma et al., 2016). On the other hand, urbanization may bring agglomeration effect, enhance the innovation ability of enterprises and the level of comprehensive utilization of resources, and then promote emission reduction (Deng et al., 2012). The proportion of the urban permanent population to the total permanent population is selected as a proxy for urbanization level. Energy consumption is one of the main causes of air pollution (Deng et al., 2016), so we take the total energy consumption per unit of GDP as its proxy and expect its symbol to be negative.

The variables’ descriptive statistics are shown in Table 2. The provincial-level panel data can be obtained from the 2002–2015 *China Environmental Yearbook*, *China Energy Statistical Yearbook*, and *China Statistical Yearbook*. All monetary variables are converted to real values (in 2001 prices). Moving average method is applied to fill all missing data.

5 Results

5.1 Results of threshold effect tests

Before regression, it is necessary to determine whether there is a non-linear relationship between environmental regulations and air pollution control and the number of

Table 3 Results of threshold effect tests

| Threshold variables | Single (H_0 : no threshold) | | Double (H_0 : at most one threshold) | | Triple (H_0 : at most two threshold) | |
|---------------------|--------------------------------|---------|---|---------|---|---------|
| | F value | P value | F value | P value | F value | P value |
| <i>cer</i> | 3.014* | 0.060 | - 0.942 | 0.420 | 0.797 | 0.367 |
| <i>lnpdf</i> | 12.765** | 0.036 | 5.762 | 0.188 | 4.970 | 0.160 |
| <i>comp</i> | 5.898* | 0.075 | 5.121* | 0.100 | 3.335 | 0.180 |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. F value and P value are obtained from 300 bootstrap replications

thresholds. Then, by using the bootstrap method, the approximate value of F statistics and p value are obtained. The null hypothesis of F statistic is that there is none threshold, one threshold, and two thresholds, respectively. These thresholds are regarded as the “turning point” in the non-linear relationship between environmental regulations and air pollution control. Once one or more valid thresholds are found, the regulation stringency can be divided into different groups and the coefficients of each group can be estimated. In this paper, Stata 14 software is used for 300 bootstrap replications to obtain the approximate value of F statistics and p value. The threshold effect test results are presented in Table 3. From Table 3, we can see that for the CAC regulation (*cer*), a single threshold effect is significant. In terms of the market-based regulation (*lnpdf*), like CAC regulation, only the bootstrap p value for a single threshold is significant at 0.036. As for the informal regulation (*comp*), the bootstrap p value for a single and double threshold is significant, which implies two thresholds.

Table 4 further displays the threshold estimators and 95% confidence intervals. From Table 4, we see that *cer* has only one threshold, so all observations of *cer* are objectively split into two groups: a low *cer* group ($cer \leq 6$) and a high *cer* group ($cer > 6$). The same procedure can be used to split the groups of market-based regulation. All observations of *lnpdf* are objectively split into two groups: a low *lnpdf* group ($lnpdf \leq 10.903$) and a high *lnpdf* group ($lnpdf > 10.903$). Moreover, *comp* has two thresholds, 1.429 and 2.059. Therefore, all observations of *comp* will be divided into three groups: a low *comp* group ($comp \leq 1.425$), a moderate *comp* group ($1.425 < comp \leq 2.059$) and a high *comp* group ($comp > 2.059$).

For more intuitive analysis, Figs. 1, 2, 3 and 4 further show the likelihood ratio

Table 4 Threshold estimators and 95% confidence intervals

| | <i>cer</i> | | <i>lnpdf</i> | | <i>comp</i> | |
|--------|----------------------|--------------------------|----------------------|--------------------------|----------------------|--------------------------|
| | Threshold estimators | 95% Confidence intervals | Threshold estimators | 95% Confidence intervals | Threshold estimators | 95% Confidence intervals |
| Single | 6.000 | [1.000, 8.000] | 10.903 | [9.320, 10.951] | 2.059 | [0.309, 4.052] |
| Double | | | | | 1.425 | [0.309, 4.033] |

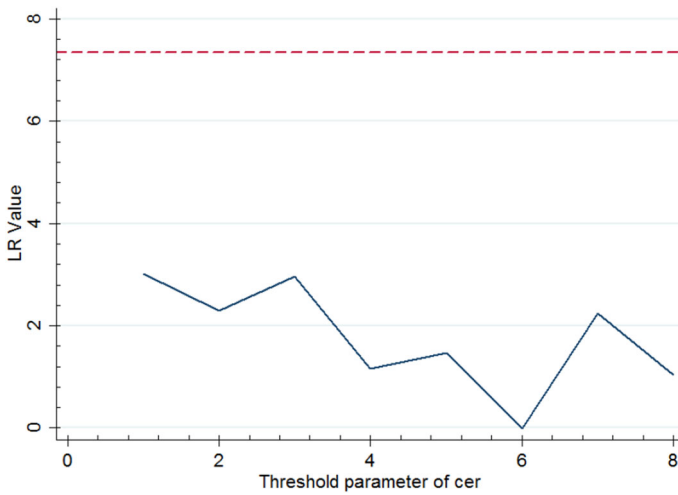


Fig. 1 The threshold estimator and confidence interval of *cer*

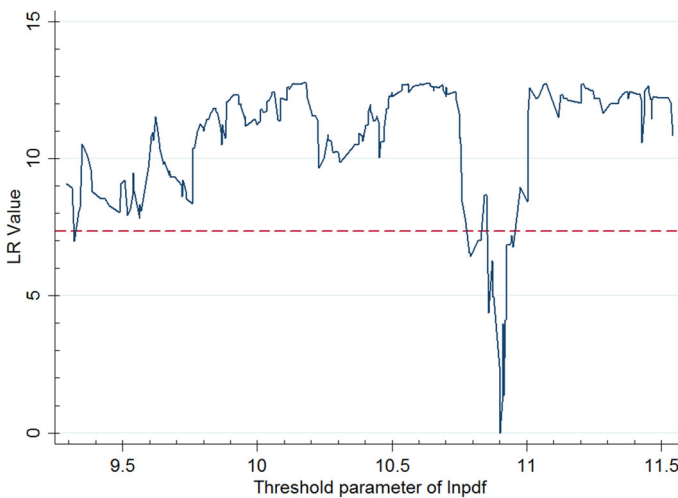


Fig. 2 The threshold estimator and confidence interval of *lnpdf*

(LR) value and threshold parameter diagrams. The threshold estimators are obtained when LR value is zero, and confidence intervals are formed by the critical values of LR value at a significant level of less than 5%. The critical values (dashed line in each figure) refer to the 95% confidence level proposed by Hansen (1999) ($c(a) = 7.35$). For CAC regulation (*cer*), in the single threshold model, the threshold value is 6 (see Fig. 1), the corresponding confidence interval is [1.000, 8.000]; for market-based regulation (*ln pdf*), the threshold value is 10.903 (see Fig. 2) and the corresponding confidence interval is [9.320, 10.951]; for informal regulation (*comp*), the larger

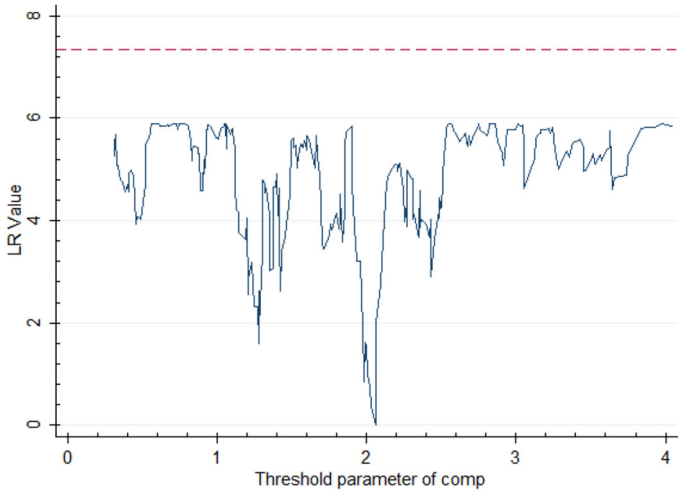


Fig. 3 The first threshold estimator and confidence interval of *comp*

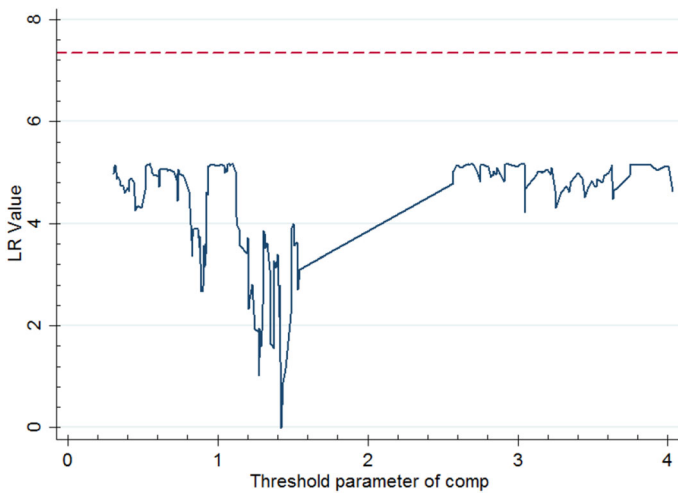


Fig. 4 The second threshold estimator and confidence interval of *comp*

threshold value is 2.059 (see Fig. 3), the smaller threshold value is 1.425 (see Fig. 4), and the corresponding confidence interval is [0.309, 4.052] and [0.309, 4.033].

5.2 Regression results of the threshold model

Based on the results of the threshold effect tests, we further regress the threshold model. For the robustness of the results, we apply two different estimation models:

the fixed-effect (FE) model and the System Generalized Method of Moments (Sys-GMM). The results are shown in Table 5. As we can see from Tables 5, the estimation results of each regulation in different models are very similar, which indicates that these models are robust. In addition, the non-linear relationship between three kinds of environmental regulations and air pollution control has been confirmed. However, given a certain environmental regulation, its impact on air pollution control is fairly different in different regulation stringency groups.

Specifically, for CAC regulation, it can be found from Table 5 that there is an inverted U-shaped relationship between CAC regulation and air pollution control efficiency. Take Model (2) as an example, when $cer \leq 6$, the stringency of CAC regulation is conducive to improving the air pollution control efficiency, which reflects the effect of Porter's hypothesis. The coefficient of cer is 0.0036 and highly significant at 1% level, namely, a one-unit increase in CAC regulation stringency will result in a 0.0036 increase in air pollution control efficiency. However, when $cer > 6$, CAC regulation began to inhibit air pollution control efficiency, thus reflecting the restraint theory of neoclassical environmental regulation. The coefficient of cer is -0.0009 and significant at 1% level, namely, the air pollution control efficiency decreases by 0.0009 units for a one-unit increase of CAC regulation stringency.

The inverted U-shaped relationship between CAC regulation and air pollution control efficiency is mainly due to the following reasons: first, as far as CAC regulation is concerned, although air pollution control efficiency can be improved in the short term, it has not essentially promoted the enthusiasm of pollutant companies for environmental technology innovation. When the government intervenes excessively, the boundary of government power and the boundary of the market are bound to be blurred, and the protection of the environment by CAC regulation will become a dead letter in theory; second, higher CAC regulation stringency will lead to a substantial increase in resource and environmental costs, inevitably eliminating those companies that cannot afford the rising costs (Liu et al., 2021). Within a certain period of time, there is a limit to a region's ability to withstand the impact of the number of enterprises being eliminated. If it exceeds the specific scope, such environmental regulations are not feasible. At the same time, in the context of China, under the GDP-based performance evaluation system, local governments cannot turn a blind eye to the elimination of enterprises. In order to maintain local economic competitiveness and political status, they may be inclined to sacrifice non-economic functional goals (environmental protection) to obtain short-term economic benefits, which will reduce air pollution control efficiency (Li & Zhou, 2005); third, strong regulation also makes companies deceive and conceal real emission information, which will also hinder air pollution control efficiency (Nyborg & Telle, 2006). For these reasons, blindly strengthening the stringency of environmental regulation will dampen the enthusiasm of enterprises for environmental innovation, leading to excessive elimination of a large number of enterprises, especially small and medium-sized enterprises, and causing negative resistance of enterprises, which will damage the improvement of air pollution control efficiency.

In terms of market-based regulation, the estimated results of Model (3) and (4) in Table 5 are similar to those of Model (1) and (2). The results also confirm a non-linear relationship between air pollution control efficiency and the market-based regulation with one turning point. Taking Model (3) as an example, when $\ln pdf \leq 10.903$, its

Table 5 Threshold model regression results

| Model Variables | Single threshold model | | | Double threshold model | | |
|-----------------|-------------------------|-------------------------|--------------------------|-------------------------|-------------------------|-------------------------|
| | (1) FE | (2) Sys-GMM | (3) FE | (4) Sys-GMM | (5) FE | (6) Sys-GMM |
| $cer \leq 6$ | 0.0003** (2.12) | 0.00036*** (4.46) | 0.0013** (2.14) | 0.0010** (2.06) | - 0.0064** (- 2.42) | - 0.0114*** (- 2.65) |
| $cer > 6$ | - 0.0009* (- 1.75) | - 0.0009*** (- 3.56) | - 0.0390*** (- 14.18) | - 0.0109*** (- 4.81) | 0.0039* (1.70) | 0.0082** (2.12) |
| eci | - 0.0855*** (- 8.72) | - 0.0168*** (- 3.73) | - 0.0377*** (- 5.22) | - 0.0144** (- 2.37) | - 0.0319*** (- 3.78) | - 0.0076** (- 2.42) |
| fdi | 0.0137 (0.53) | 0.0555*** (5.05) | 0.0237 (1.32) | 0.0214 (1.36) | 0.0146 (0.70) | 0.0485*** (3.76) |
| urb | 0.0631** (2.32) | 0.0203* (1.83) | 0.1191*** (6.28) | 0.1025*** (8.99) | - 0.0472*** (- 2.93) | 0.0408*** (3.11) |
| L_{eff} | | 0.7481*** (20.15) | | 0.4942*** (12.98) | | 0.7050*** (22.10) |
| Constant | 0.9468*** (58.95) | 0.2115*** (6.79) | 1.2662*** (43.21) | 0.5201*** (27.52) | 0.9459*** (70.50) | 0.2492*** (9.87) |
| N | 420 | 390 | 420 | 390 | 420 | 390 |

Table 5 (continued)

| Single threshold model | | | Single threshold model | | | Double threshold model | | |
|------------------------|--------|----------|------------------------|--------|----------|------------------------|--------|----------|
| Model | (1) | (2) | Model | (3) | (4) | Model | (5) | (6) |
| Variables | FE | Sys-GMM | Variables | FE | Sys-GMM | Variables | FE | Sys-GMM |
| A-B test of AR(1) | / | [0.0009] | A-B test of AR(1) | / | [0.0002] | A-B test of AR(1) | / | [0.0001] |
| A-B test of AR(2) | / | [0.2742] | A-B test of AR(2) | / | [0.1453] | A-B test of AR(2) | / | [0.3615] |
| Sargan | / | [1.0000] | Sargan | / | [1.0000] | Sargan | / | [1.0000] |
| Adj.R ² | 0.2601 | / | Adj.R ² | 0.6423 | / | Adj.R ² | 0.1612 | / |
| F-test | (0.00) | / | F-test | (0.00) | / | F-test | (0.00) | / |

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. t/z -statistics are shown in parentheses. AR (1), AR (2) and sargan test coefficients in [] are P values

coefficient is 0.0013 and significant at 5% level. For every 1% increase of market-based regulation stringency, the air pollution control efficiency will improve by 0.0013%. However, when $\ln pdf > 10.903$, its coefficient is -0.0390 and significant at 1% level. Within this range, market-based regulation stringency hinders the improvement of air pollution control efficiency. This phenomenon may be due to the fact that when the stringency of market-based regulation is moderate, enterprises can be given more incentives to choose more advanced clean technology so that enterprises can achieve maximum pollution control at the minimum cost. However, when the stringency of regulation is too high, the incentive given by market regulation is not enough to encourage enterprises to take the initiative to reduce emissions. Many enterprises would rather pay more pollutant discharge fees than invest in environmental control, thus the air pollution control efficiency will be greatly reduced (Zhang & Wei, 2010). This result once again confirms that environmental regulation is a double-edged sword, only moderate environmental regulation stringency can enhance air pollution control efficiency.

From Model (1) to (4), we can see that compared with the CAC regulation, air pollution control efficiency is more sensitive to the impact of market-based regulation. This may be due to CAC regulation usually requires enterprises to meet certain environmental standards or adopt some clean technology. Under this circumstance, most enterprises tend to choose a one-off investment, for example, by simply purchasing end-pipe facilities rather than investing in expensive research and development. Nevertheless, market-based regulation is the continuous expenditure of regulated enterprises, who may realize that the operating cost burden is heavier. Thus, market-based regulation can better transform the social cost caused by pollution into the private cost of enterprises, which prompts enterprises to seek more fundamental solutions, such as reconfiguring processes and products, optimizing resource allocation, engaging R&D activities (Xie et al., 2017).

As for informal regulation, Model (5) and (6) show that when $comp \leq 1.425$, its coefficient is significantly negative, indicating that when the informal regulation stringency is weak, it can not play the role of pollution control; when $comp 1.425 < comp \leq 2.059$, its coefficient is significantly positive, suggesting that as the informal regulation stringency increases and reaches the appropriate stringency, its role in achieving sustainable development begins to appear; when $comp > 2.059$, its coefficient becomes negative and significant at 5% level, implying that when the stringency of informal regulation continues to strengthen until it crosses the optimal stringency, its role will change from promotion to inhibition. The negative effect of informal regulation on air pollution control efficiency may be due to the blockage of channels and the inadequacy of environmental information disclosure system. If the public can not grasp the real sewage discharge situation of polluting enterprises, the coverage and depth of environmental supervision will be greatly reduced, and the development of informal regulation will be restricted (Yao & Liang, 2017). Moreover, information asymmetry in environmental quality may distort facts and fail to properly urge enterprises to reduce emissions (Zhu & Zhang, 2012).

Regarding control variables, we can see that the coefficients of *urb* are significantly positive in the Model (1), (2), (3), (4) and (6), which indicates that the agglomeration effect of urbanization is greater than the pollution effect. The development of urbanization can effectively improve the comprehensive utilization of resources and

air pollution control efficiency. The coefficients of fdi in all models are positive, although some coefficients are not significant, which indicates that FDI does not produce “pollution heaven” effect. It can introduce advanced clean production technology and sophisticated management methods, which is conducive to improving air pollution control efficiency. The coefficients of eci is significantly negative at 1% level, which is consistent with the conclusions of most literature and in line with our expectations, indicating that energy consumption is a significant cause of air pollution.

5.3 Further discussion

We calculate the number of provinces in different years according to the stringency intervals of environmental regulations (see Table 6). From Table 6, we can see that most provinces' CAC regulation stringency is in the interval of $cer \leq 6$. Based on the previous regression results, within this interval, CAC regulation can improve air pollution control efficiency. In 2014, only Beijing and Qinghai exceeded this level, which implies that most provinces are still in the optimal range, and the current CAC regulation stringency is basically reasonable. For market-based regulation, the number of provinces in the $\ln pdf \leq 10.903$ interval decreases year by year. Based on the minimum $\ln pdf$ threshold (10.903) that market-based regulation can effectively improve air pollution control efficiency in this study, the provinces with $\ln pdf \leq 10.903$ in 2014 include Beijing, Tianjin, Jilin, Heilongjiang, Shanghai, Fujian, Hubei, Guangxi, Hainan, Chongqing, Guizhou, Yunnan, Gansu, Qinghai, Ningxia. This indicates that one-half of the provinces have crossed the optimal range, but still need to avoid the misunderstanding of blindly increasing the market-based regulation stringency. For informal regulation, during the sample period, the regulation stringency of most provinces is either too weak or too high, and only a few provinces are in the optimal range ($1.425 < comp \leq 2.059$). In 2014, only Anhui, Shandong and Guangxi are in the optimal range, while 15 provinces has not yet ushered in an upward period of air pollution control efficiency, and 12 provinces has exceeded the optimal range. This suggests that the role of China's informal regulation has not yet been fully played in improving air pollution control efficiency. This may be because most Chinese citizens still lack environmental awareness and have not expressed their preference for environmental quality through legal channels. Thus, most provinces in China need to increase guidance and assistance to the public and ENGOs.

6 Conclusions and policy implications

Using panel data of China's 30 provinces during 2001–2014, this paper is devoted to examining the possible non-linear relationship between environmental regulations and air pollution control, the heterogeneous effects of different types of environmental regulations on air pollution, and the existence of an optimal regulation stringency interval. Thus, the SBM-DDF model considering undesirable outputs is employed to evaluate the efficiency of air pollution control and the threshold models is used for empirical analysis. Different from previous studies, this paper draws the following

Table 6 The number of provinces in different years

| Threshold and interval | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| $cer \leq 6$ | 23 | 23 | 22 | 21 | 24 | 23 | 25 | 27 | 28 | 25 | 27 | 28 | 25 | 28 |
| $cer > 6$ | 7 | 7 | 8 | 9 | 6 | 7 | 5 | 3 | 2 | 5 | 3 | 2 | 5 | 2 |
| $\ln pdf \leq 10.903$ | 28 | 27 | 26 | 23 | 22 | 22 | 21 | 21 | 21 | 20 | 18 | 16 | 15 | 15 |
| $\ln pdf > 10.903$ | 2 | 3 | 4 | 7 | 8 | 8 | 9 | 9 | 9 | 10 | 12 | 14 | 15 | 15 |
| $comp \leq 1.425$ | 11 | 9 | 6 | 7 | 8 | 10 | 14 | 19 | 19 | 20 | 13 | 12 | 17 | 15 |
| $1.425 \leq comp < 2.059$ | 3 | 4 | 7 | 4 | 4 | 4 | 7 | 1 | 3 | 3 | 6 | 4 | 5 | 3 |
| $comp > 2.059$ | 16 | 17 | 17 | 19 | 18 | 16 | 9 | 10 | 8 | 7 | 11 | 14 | 8 | 12 |

interesting conclusions: (1) The SBM-DDF calculation results show that the overall level of air pollution control efficiency in China is good, but there is significant regional differences. The provinces with low air pollution control efficiency are relatively concentrated in energy rich areas, especially in Shanxi and Hebei. (2) Environmental regulation is a double-edged sword, which has a nonlinear relationship with air pollution control efficiency. Only when the stringency of environmental regulation reaches a certain critical point, can it promote air pollution control efficiency. This finding partly explains the reason why previous research conclusions are inconsistent, and this is what Porter hypothesis emphasizes: Only by designing appropriate regulations can the positive effects of environmental regulations appear. Among them, the formal (CAC and market-based) regulation has a single threshold effect, and its impact on the air pollution control efficiency presents an inverted U-shaped structure, with the critical points of 6 and 10.903 respectively, while informal regulation has double threshold effect, and its impact on air pollution control efficiency is similar to the inverted N-type structure, and the reasonable stringency range is [1.425, 2.059]. (3) Different environmental regulation instruments have different governance effects. Compared with CAC regulation, the influence coefficient of market-based regulation on air pollution control efficiency is larger and more significant, which can attract more attention of enterprises. Thus, policy makers may need to use flexible market means to make enterprises aware of the potential for a win-win situation between environmental protection and economic performance, and help them obtain this benefit. In addition, it may be ineffective to rely on informal regulation to improve the air pollution control efficiency. From the actual situation of China, the informal regulation of most provinces is unreasonable, which has a significant inhibitory effect on air pollution control efficiency.

The above conclusions have important practical significance for the design of environmental regulation by regulators.

First of all, the regional differences in air pollution control efficiency indicate that the Chinese government must make greater efforts to design more prudent and thoughtful policies to avoid the possibility of pollution transfer and catch the tide to move towards sustainable development. Moreover, China should avoid the duplication of the development model of “pollution first, then treatment” in Eastern China in the future.

Second, proper regulation can achieve environmental governance and promote China’s green development. Considering that China is currently in a difficult stage of structural transformation and facing increasingly severe resource and environmental constraints, environmental regulation is still a necessary policy tool. Without the necessary control policies, the economic system will not spontaneously or advance the turning point of the Environmental Kuznets Curve to achieve environmental quality improvement. However, the stringency of regulation designed by the regulators should neither be too strict nor too loose, and must be commensurate with the company’s affordability. In order to better understand the capabilities of enterprises in a timely and better manner, it is necessary for China to conduct comprehensive and timely investigations on the operating conditions and environmental activities of enterprises, and then set reasonable regulation stringency based on the latest investigation results, and dynamically adjust them in the future.

Finally, the choice of environmental regulation forms will have different effects. Recent studies have shown that the key issue of regulation is not “which tool is the best”, but “which combination of tools is the best” (Xie et al., 2017). Therefore, China should optimize its regulation tool portfolio. Regarding the choice of environmental regulation tools, China should strengthen the integration of different types of regulations such as environmental taxes, emissions trading, ecological compensation, environmental information disclosure, and environmental standards, and set the relative weight of each form of regulation based on actual needs and local conditions, so as to better achieve the decision-making goals. In the design of the environmental regulation mechanism, China may need to use more flexible market means to enable enterprises to endogenous emission reduction as a conscious behavior. In addition, China also needs to work hard to stimulate the role of informal regulation, establish and expand environmental information disclosure systems and channels, enable the public to actively participate in the supervision of corporate pollution behavior, and enable companies to consciously abide by environmental policies and regulations.

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