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Original Research

How does Environmental Regulation Promote Technological Innovation and Green Development? New Evidence from China

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Abstract

Based on 35 industries during 2005-2015, this paper first uses a slack-based measure data envelopment analysis (SBM-DEA) model and the Luenberger index to measure green total factor productivity (GTFP) for each industry. Then we used a panel threshold model to study the impact mechanisms of environmental regulation on technological innovation and GTFP. Considering industry heterogeneity, the paper further explores whether such mechanisms differ in industries. The main findings are: (1) The impact mechanisms of environmental regulation on technological innovation and GTFP are different. For technological innovation, the effect depends on whether environmental regulation brings enough innovation pressure to firms by the rising cost of compliance. However, in terms of GTFP, the effect depends on the net effect between positive effects and negative effects of environmental regulation. (2) Apart from innovation offset, we also found that environmental regulation can promote GTFP through increasing market concentration and building green market entry barriers in high-pollution emission industries. (3) Such a competitive advantage is only effective in the short term, while technological innovation shows a positive offset effect in the long run.

Keywords: environmental regulation, technological innovation, green total factor productivity, industrial heterogeneity

Introduction

Over the years, the extensive pattern of economic growth has caused devastating environmental pollution in China, which seriously threatens the health of residents and the sustainable development of the economy. Taking 2015 as an example, the cost of pollution and ecological damage caused by environmental problems is as high as 411.61 billion USD, accounting for 3.82% of GDP in that year [1]. In order to protect the environment and improve the efficiency of energy use, China has issued a series of environmental protection policies. Besides, as a regular institutional arrangement to strengthen the construction of ecological civilization, China has sent several teams to carry out environmental protection inspections throughout the country since 2016, and the results of

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the inspection will serve as an important basis for the appointment and removal of local officials. Before that, GDP is the only criterion for officials' performance appraisal. After years of environmental protection efforts, environmental quality has seen positive achievements. For example, after the implementation of the Air Pollution Control Law in 2012, the average density of PM10 in 338 cities at prefecture level and above in 2017 decreased by 22.7 percent compared to 2013 levels, while the average density of PM2.5 in major areas including the Beijing-Tianjin-Hebei region, the Yangtze River Delta and the Pearl River Delta, fell 39.6 percent, 34.3 percent and 27.7 percent respectively [2]. With the implementation of the new environmental protection law and the establishment of the Ministry of ecology and environment in 2018, environmental protection in China has entered a new era.

However, does the improvement of environmental quality mean the sacrifice of production efficiency? In addition to protecting the environment, can environmental regulation simultaneously improve technological innovation and productivity? The debate on these issues has been one of the hotspots in the field of environmental economics and management nowadays.

Before the 1990s, environmental regulation was generally considered to have a significant and negative effect on technological innovation and productivity. This point of view holds that environmental pollution, as an item with negative externality properties, does not need to be treated by its producer before the implication of environmental regulation. However, in the context of environmental regulation, some input of labor and capital factors originally used for technological innovation and product process are now forced into pollution abatement [3]. The reduction of R&D investment and production factor input will inevitably weaken the technological innovation and productivity [4]. Jorgenson and Wilcoxen [5] find that environmental regulation can significantly reduce environmental pollution, but it will also slow down economic development due to higher pollution abatement cost.

However, Porter and Van de Linde [6] argue that this static analysis framework does not include the role of innovation. In the long run, the technology used in the production process is not static. Therefore, environmental regulation can force firms to increase the efficiency of resources as well as reduce pollution through technological innovation. At the same time, the "innovation offset" effect will partially or entirely make up for the compliance cost of environmental regulation, which will in turn promote productivity. This hypothesis is called the "Porter Hypothesis". To explore the impact of environmental regulation on technological innovation and productivity more specifically, Jaffe and Palmer [7] further divide the "Porter Hypothesis" into three sub-hypotheses, namely "weak Porter Hypothesis", "strong Porter Hypothesis" and "narrow Porter Hypothesis". Since then, scholars have mainly conducted empirical studies around the three sub-hypotheses.

In the "weak Porter Hypothesis", scholars mainly focus on whether environmental regulation has significantly promoted technological innovation. Jaffe and Palmer [7], Guo et al. [8], and Li et al. [9] verify the existence of the "weak Porter Hypothesis" by evidence from industrial, regional and firm levels. Guo et al. [8] use 30 provincial panel data in China and a SEM model to explore the relationship between environmental regulation and technological innovation, and find that environmental regulation significantly promotes technological innovation. However, some scholars find the opposite evidence. Taking fossil fuels as an example, Gans [10] finds that strict environmental regulations may reduce the demand of fossil fuels, which will in turn reduce the incentive for firms to increase fuel efficiency.

In the "Strong Porter Hypothesis", scholars are more concerned with the effect of environmental regulation on productivity. Yuan and Zhang [11] and Van Leeuwen and Mohnen [12] find that environmental regulation plays a significant role in promoting productivity. Shi et al. [13] used a DID method to explore the relationship between environmental regulation and urban economic growth. They find that the effect of environmental regulation on economic growth is "marginally increasing". However, Rexhäuser and Rammer [14] and Rubashkina et al. [15] find that although environmental regulation has positively promoted technological innovation, it has no significant effect on the promotion of productivity. Yuan and Xie [16] explore the relationship between environmental regulation and green total factor productivity. They find that the effect of the environment on GTFP is nonlinear, while environmental investment has a linear and negative effect on GTFP.

In the "narrow Porter Hypothesis", Xie et al. [17] explore the effects of different types of environmental regulations on China's green total factor productivity, and find that market-based tools outperform the command-and-control tools. Ren et al. [18] further find that the impacts of different types of environmental regulation on green total factor productivity differ significantly across regions. However, Desrochers and Haight [19] find that the innovation pressure generated by environmental regulation is only one of the factors that promotes technological innovation. And its positive effect on innovation is not more superior than property rights protection.

Above all, most of the current literature use the linear models to study the effects of environmental regulation on technological innovation and productivity, but do not reach a consensus conclusion. For example, Jaffe and Palmer [7] use a linear dynamic panel model and find that environmental regulation has significantly improved technological innovation. However, Yuan and Xiang [20] also use three linear dynamic panel models, but find that environmental regulation has inhibited both technological innovation and green total factor productivity. In recent years, many studies have found that the impacts of environmental regulation on technological innovation and productivity are not immutable linear relationship, but have a nonlinear characteristic [21]. However, scholars have not reached an agreement on the shape of such a nonlinear relationship. For example, "U" type [16], inverted "U" type [22], and inverted "N" [23] are the common shapes found in current literature. In the details of empirical methodology, most of current studies capture the nonlinear characters by adding square terms of explanatory variables in the empirical models. However, this method has two shortcomings: on the one hand, it requires that distributions are symmetrical on both sides of the turning point. On the other hand, it cannot identify the nonlinear effect appearing in the same direction [24].

Besides, most of the literature contains only pollutant emissions as undesired outputs in green total factor productivity, such as waste water, waste gas and solid waste. However, in the context of climate change, the absence of carbon dioxide is not appropriate [25, 26]. Therefore, this paper adds carbon dioxide as an undesired output in the construction of green total factor productivity.

Finally, most of the existing literature takes the industrial sample as a whole to study the effect of environmental regulation on technological innovation and productivity. However, due to the factor input, structure and resource endowment are different among industries, and the effect of environmental regulation may also differ in industries [22]. Therefore, in addition to the analysis of the sample as a whole, we also explore whether the industry heterogeneity exists through two subsamples.

Based on the panel data of 35 industrials during 2005-2015, this paper uses the SBM-DEA model and panel threshold models to investigate the effects of environmental regulation on technological innovation and economic growth, respectively. Besides, with the consideration of industry heterogeneity, this paper further divides the whole sample into two sub-samples according to emission intensity of pollution and explores whether and how the impact mechanisms of environmental regulation differ in industries. The remainder of this paper is organized as follows. Section 2 describes the data source, variables and the econometric model used in this paper. Section 3 presents and discusses the empirical results. Section 4 concludes the paper.

Material and Methods

Data Source and Processing

The data used in this paper comes from China Statistical Yearbook, China Industry Statistical Yearbook, China Environment Statistic Yearbook, China Energy Statistical Yearbook and China Technology Yearbook. During the sample period, some industry names and categories have changed. To maintain the consistence of data, we processed the original data as follows:

(1) We combined the manufacture of rubber and manufacture of plastics into manufacture of rubber and plastics.

(2) We then combined manufacture of automobiles and manufacture of railway, ship, aerospace and other transport equipment into manufacture of transport equipment.

(3) Due to the serious lack of data, we then got rid of mining of other ores, utilization of waste resources, and production and supply of water from our sample.

In the end we obtained a strong balanced sample of 385 observations from 35 industries in 11 years.

Variable Measurement

Green Total Factor Productivity (GTFP)

Compared with the productivity using a single indicator, GTFP combines many important input and output factors into a unified analysis framework. GTFP is closer to the real production process than a single indicator, and can reflect the alternative relationship among different factors. Most of the existing literature uses data envelopment analysis (DEA) to estimate green total factor. DEA is a nonparametric estimation method that does not need to know the exact productivity model in advance and can assign weights to input and output factors depending on the data automatically [17]. However, in most existing studies, GTFP considers only pollutant emissions as undesired output, such as waste water, waste gas and solid waste. Actually, as one of the important factors of climate change, carbon dioxide should be considered in the construction of GTFP. Therefore, we use a non-oriented SBM-DEA model with undesirable outputs and a Luenberger index to calculate GTFP of 35 industries from 2005-2015.

In this paper, 35 industries are used as 35 decision making units (DMUs). Each DMU has 3 inputs (labor, capital and energy), 1 desirable output (total industrial output value) and 3 undesirable outputs (carbon emission, waste water emission and waste gas emission). The production possibility set are as follows:

$$P = \left\{ (x, y, b) \middle| x \geq \sum_{k=1}^{35} \lambda_k x_k, y \geq \sum_{k=1}^{35} \lambda_k y_k, b \geq \sum_{k=1}^{35} \lambda_k b_k, \lambda_k \geq 0 \right\}$$

…where P is the production possibility set, x represents the input ($x = x_1, x_2, x_3$), y represents the desirable output, b represents the undesirable outputs ($b = b_1, b_2, b_3$), and λ represents the intensity variable.

Following Choi et al. [27], the non-oriented SBM-DEA model with undesirable outputs is shown as follows:

$$\rho_k^* = \min \frac{1-\frac{1}{3}\sum_{i=1}^{3}\frac{s_i^x}{x_{i,k}}}{1+\frac{1}{4}\left(\frac{s^y}{y_k}+\sum_{j=1}^{3}\frac{s_j^b}{b_{j,k}}\right)}$$
$$s.t.$$
$$x_{i,k}=\sum_{k=1}^{35}\lambda_k x_{i,k}+s_i^x, i=1,2,3;$$
$$y_k=\sum_{k=1}^{35}\lambda_k y_k - s^y$$
$$b_{j,k}=\sum_{k=1}^{35}\lambda_k b_{j,k}+s_j^b, j=1,2,3$$
$$\lambda_k \geq 0, s_i^x \geq 0, s^y \geq 0, s_j^b \geq 0$$

…where ρ* is the efficiency score, and k, i and j represent the kth DMU ($k = 1, 2,…,35$), the ith input ($i = 1, 2, 3$), and jth undesirable output ($j = 1, 2, 3$), respectively. s_i^x, s^y and s_j^b are slack variables of inputs, desirable output and undesirable outputs, respectively. Equation 2 is the basic model for measuring GTFP. We then linearize equation 2 and obtain a directional distance function. Take the kth industry, for example, and the directional distance function can be expressed as follows:

$$D_C\left(x^{k'},y^{k'},b^{k'},g^x,g^y,g^b\right)=\max_{s^x,s^y,s^b}\left(\frac{1}{3}\sum_{i=1}^{3}\frac{s_i^x}{g_i^x}+\frac{1}{4}\left(\frac{s^y}{g^y}+\sum_{j=1}^{3}\frac{s_j^b}{g_j^b}\right)\right)\Bigg/2$$
$$s.t.$$
$$x_{i,k}=\sum_{k=1}^{35}\lambda_k x_{i,k}+s_i^x, i=1,2,3;$$
$$y_k=\sum_{k=1}^{35}\lambda_k y_k - s^y$$
$$b_{j,k}=\sum_{k=1}^{35}\lambda_k b_{j,k}+s_j^b, j=1,2,3$$
$$\lambda_k \geq 0, s_i^x \geq 0, s^y \geq 0, s_j^b \geq 0 \tag{3}$$

…where D_C is the directional function, and ($x^{k'}, y^{k'}, b^{k'}$), (g^x, g^y, g^b) and (s^x, s^y, s^b) are the input and output vectors, direction vectors and slack vectors of kth industry. Based on directional functions, we calculate the Luenberger index to measure GTFP. For the kth industry in year t, the $GTFP_t$ can be expressed as follows:

$$GTFP_t=\frac{1}{2}\left\{\begin{matrix}\left[D_C^{t-1}\left(x^{t-1},y^{t-1},b^{t-1},g^x,g^y,g^b\right)-D_C^{t-1}\left(x^t,y^t,b^t,g^x,g^y,g^b\right)\right]\\+\left[D_C^{t}\left(x^{t-1},y^{t-1},b^{t-1},g^x,g^y,g^b\right)-D_C^{t}\left(x^t,y^t,b^t,g^x,g^y,g^b\right)\right]\end{matrix}\right\}$$

All the inputs and the outputs are shown in Table 1, and all the price data are deflated to constant price in 2004 by "price indices of industrial producer by sector" provided in the China urban life and price yearbook.

Technological Innovation (TI)

Technological innovation is usually measured in two ways: innovation input and innovation output. In terms of innovation input, the indicators include R&D expenditure (capital investment) [28], R&D personnel (labor input) [29] and R&D institutions (material input) [30]. In terms of innovation output, the indicators include the number of patent applications [31-33] and sales revenue of new products [34, 35]. In this paper, our main purpose is to explore the impact of environmental regulation on the incentives for technological innovation, such as the effect of environmental regulation on the distortion of resources allocated to technological innovation. Therefore, we use the proportion of the internal expenditures of science and technology activities to the total industrial output value to measure technological innovation.

Environmental Regulation (ER)

How to measure the intensity of environmental regulation properly is one of the key points to study the impact of environmental regulation on technological innovation and productivity. However, no measurement has been unanimously recognized by scholars. Different measurements may lead to conclusions. In current literature, six indicators are commonly used to measure environmental regulation. Specifically, (1) the number of regulation policies and the number of inspections by environmental protection agencies [36]; (2) the operating fee of pollution abatement facilities [37]; (3) residents' awareness of environmental protection, such as per capita GDP and per capita years of education [38, 39]; (4) discharge density of different pollutants [40]; (5) environmental information disclosure of listed company [41]; and (6) the proportion of pollution abatement cost to the total cost or output value [42, 43]. Considering the

Table 1. Input and output used for GTFP.

Input/output	Variables	Definition	Source
Input	Labor	The average number of employees	China Industry Statistical Yearbook
	Capital	Annual average balance of net fixed assets	China Industry Statistical Yearbook
	Energy	Consumption of total energy	China Energy Statistical Yearbook
Expected output	Total industrial output value	Total industrial output value	China Industry Statistical Yearbook
Unexpected output	Carbon emission	Calculated according to the method provided by IPCC	China Energy Statistical Yearbook
	Pollutant emissions	Total volume of industrial wastewater discharge and industrial waste gas emissions	China Environmental Statistical Yearbook

availability of data, we use the proportion of pollution abatement cost to total industrial output value to measure environmental regulations.

Control Variables

(1) Industrial size (SCALE):

For industries with different sizes, the proportion of pollution abatement costs on total cost may differ. In general, large-scale industries have capital and human resources advantages, and can promote GTFP through economies of scale [44]. In this paper, we use the net investment in fixed assets to measure industrial size.

(2) Ownership (OWN)

Industries under different ownership structures may have different requirements for environmental protection, technological innovation and improvement of GTFP. Chen and Golley find that the shares of state-owned firms have a significant and negative effect on industrial GTFP growth [45]. In this paper we use the share of state-owned and state-controlled firms in the industry's total industrial output value to measure the ownership structure.

(3) Foreign direct investment (FDI)

The effects of foreign direct investment on technological innovation and green total factor productivity are complicated and uncertain. Liu and Liu [46] find that foreign direct investment can improve technological efficiency and promote productivity through technological spillover. However, the pollution heaven hypothesis argues that FDI will deteriorate the environment of the host country [17]. In this paper, we use the proportion of foreign capital and capital from Hong Kong, Macao, and Taiwan to total capital to measure foreign direct investment.

Econometric Regression Models

In this paper, the panel threshold model is used in our empirical analysis, which aims to solve the nonlinear effect caused by variable jump or structural breakpoint in panel regression analysis. Compared with adding square terms in empirical model, the panel threshold regression model does not require symmetrical distribution on both sides of the inflection point, and can also effectively identify the nonlinear effect of the same direction. Therefore, we construct the empirical models as follows:

$$GTFP=\alpha_0+\alpha_1 ER\times I(\varphi\le\varphi_1)+\alpha_2 ER\times I(\varphi_1<\varphi\le\varphi_2)+\ldots+\alpha_{n+1}ER\times I(\varphi>\varphi_n) +\beta_1 SCALE+\beta_2 OWN+\beta_3 FDI+\mu+\omega+\varepsilon \tag{5}$$

$$TI=\delta_0+\delta_1 ER\times I(\phi\le\phi_1)+\delta_2 ER\times I(\phi_1<\phi\le\phi_2)+\ldots+\delta_{n+1}ER\times I(\phi>\phi_n) +\gamma_1 SCALE+\gamma_2 OWN+\gamma_3 FDI+\mu+\omega+\varepsilon \tag{6}$$

…where I is the dummy variable; φ and ϕ are the threshold variables in each model; α_0 and δ_0 denote the constant terms in each model; and μ, ω and ε are industry fixed effect term, time fixed effect term and residual term, respectively.

Results and Discussion

Industry Classification Based on the Emission Intensity of Pollution

Due to the differences in resource endowment and input structure of production factors, the effects of environmental regulation may vary from one industry to another. In this paper, we divide the whole sample (ALL) into two subsamples: low pollution emission industry (LPE) and high pollution emission industry (HPE), and explore whether and how industry heterogeneity influences the effect of environmental regulation. As the basis for dividing the sample, pollution emission intensity needs to be measured accurately. In current studies, two methods are commonly used to measure it: (1) using pollution control cost and (2) using a weighted sum of several pollutant emissions. Considering the non-additivity of various pollutants, the pollution emission intensity is measured by the sum of several pollutant standardized emissions per unit of output. The specific procedure is as follows:

(1) Calculate pollution emissions per unit of output:

Table 2. Descriptive statistics of variables.

Variables	Observations	Mean	Std. dev.	max	min
GTFP	385	0.92	0.24	1.95	0.45
TI	385	0.71%	0.54%	2.46%	0.01%
ER	385	0.19%	0.25%	1.79%	0.01%
SCALE	385	2548.70	3674.37	29054.05	142.60
OWN	385	16.12%	16.07%	85.66%	0.16%
FDI	385	25.67%	17.48%	76.38%	0.00%

$$UE_{i,j} = \frac{E_{i,j}}{Y_i} \tag{7}$$

…where $E_{i,j}$ is the pollution emissions per unit of output of industry i and pollutant j, $UE_{i,j}$ is the pollution emissions per unit of output of industry i and pollutant j, Y_i is the total industrial output value of industry i.

(2) Standardize the pollution emissions per unit of output among industries:

$$UE'_{i,j} = \frac{UE_{i,j} - \min\left(UE_j\right)}{\max\left(UE_j\right) - \min\left(UE_j\right)} \tag{8}$$

…where max (UE_j) and min (UE_j) are the maximum and minimum values of pollutant i in all industries, and $UE'_{i,j}$ denotes the standardized pollution emission of industry i and pollutant j.

(3) Sum all the $UE'_{i,j}$ of industry i:

$$AE_i = \sum\nolimits_j UE'_{i,j} \tag{9}$$

…where AE_i denotes the pollution emission intensity of industry i.

According to the pollution emission intensity, we divide the 35 industries into 17 low pollution emission (LPE) industries and 18 high pollution emission (HPE) industries based on the median of pollution emission intensity in all industries. The industries included in each subsample are shown as Table 3.

Green Total Factor Productivity

Based on the data of 35 industries during 2005-2015, we use the SBM-DEA model and Luenberger index to measure the green total factor productivity. The results are shown in Table 4. During the sample period, both the value of GTFP in each industry and the average value of GTFP in all industries are greater than 1, which indicates that green total factor productivity has improved. Specifically, *S*melting and Pressing of Ferrous Metals, Production and Supply of Gas, and Production and Supply of Electric Power and Heat Power are the top 3 industries with the highest

Table 3. Industry divided.

Low pollution emission industries	Pollution emission intensity	High pollution emission industries	Pollution emission intensity
Manufacture of Articles for Culture, Education and Sport Activity	0.15%	Manufacture of Leather, Fur, Feather and Related Products and Footwear	5.07%
Printing, Reproduction of Recording Media	0.17%	Manufacture of Metal Products	5.64%
Manufacture of Furniture	0.18%	Manufacture of Computers, Communication, and Other Electronic Equipment	7.29%
Manufacture of Tobacco	0.35%	Manufacture of Chemical Fibers	7.48%
Manufacture of Measuring Instrument	0.78%	Manufacture of Medicines	8.60%
Crafts and Other Manufactures	0.79%	Manufacture of Foods	9.22%
Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products	1.29%	Mining and Processing of Non-ferrous Metal Ores	9.25%
Mining and Processing of Non-metal Ores	1.42%	Manufacture of Wine, Drinks and Refined Tea	12.20%
Manufacture of Special Purpose Machinery	1.56%	Smelting and Pressing of Non-ferrous Metals	14.20%
Manufacture of Electrical Machinery and Equipment	1.71%	Processing of Petroleum, Coking, Processing of Nuclear Fuel	15.13%
Manufacture of General Purpose Machinery	1.82%	Mining and Washing of Coal	19.34%
Manufacture of Rubber and Plastic	1.88%	Processing of Food from Agricultural Products	25.44%
Manufacture of Textile Wearing and Apparel	2.04%	Manufacture of Textile	38.72%
Extraction of Petroleum and Natural Gas	2.41%	Manufacture of Raw Chemical Materials and Chemical Products	49.00%
Production and Supply of Gas	3.98%	Manufacture of Non-metallic Mineral Products	50.88%
Mining and Processing of Ferrous Metal Ores	4.45%	Smelting and Pressing of Ferrous Metals	64.33%
Manufacture of Transport Equipment	4.76%	Manufacture of Paper and Paper Products	69.29%
		Production and Supply of Electric Power and Heat Power	91.03%

Table 4. Green total factor productivity.

Low pollution emission industries	GTFP	High pollution emission industries	GTFP
Manufacture of Articles for Culture, Education and Sport Activity	1.0004	Manufacture of Leather, Fur, Feather and Related Products and Footwear	1.1575
Printing, Reproduction of Recording Media	1.4945	Manufacture of Metal Products	1.1433
Manufacture of Furniture	1.1960	Manufacture of Computers, Communication, and Other Electronic Equipment	1.0214
Manufacture of Tobacco	1.0860	Manufacture of Chemical Fibers	1.1673
Manufacture of Measuring Instrument	1.1550	Manufacture of Medicines	1.2143
Crafts and Other Manufactures	1.2163	Manufacture of Foods	1.2159
Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products	1.3805	Mining and Processing of Non-ferrous Metal Ores	1.2996
Mining and Processing of Non-metal Ores	1.4534	Manufacture of Wine, Drinks and Refined Tea	1.2303
Manufacture of Special Purpose Machinery	1.3097	Smelting and Pressing of Non-ferrous Metals	1.5760
Manufacture of Electrical Machinery and Equipment	1.0438	Processing of Petroleum, Coking, Processing of Nuclear Fuel	1.2586
Manufacture of General Purpose Machinery	1.2077	Mining and Washing of Coal	1.2594
Manufacture of Rubber and Plastic	1.1924	Processing of Food from Agricultural Products	1.5127
Manufacture of Textile Wearing and Apparel	1.4893	Manufacture of Textile	1.1350
Extraction of Petroleum and Natural Gas	1.0821	Manufacture of Raw Chemical Materials and Chemical Products	1.6770
Production and Supply of Gas	2.1741	Manufacture of Non-metallic Mineral Products	1.2483
Mining and Processing of Ferrous Metal Ores	1.4361	Smelting and Pressing of Ferrous Metals	2.4689
Manufacture of Transport Equipment	1.2564	Manufacture of Paper and Paper Products	1.1975
		Production and Supply of Electric Power and Heat Power	2.1019

GTFP, while the lowest 3 industries are Manufacture of Articles for Culture, Education and Sport, Manufacture of Computers, Communication, and Other Electronic Equipment, and Manufacture of Electrical Machinery and Equipment.

Fig. 1 depicts the growth trend of GTFP. From Fig. 1 we can find that the increase of green total factor productivity in high pollution emission industry is significantly greater than that in low pollution emission industry during the sample period. This is consistent

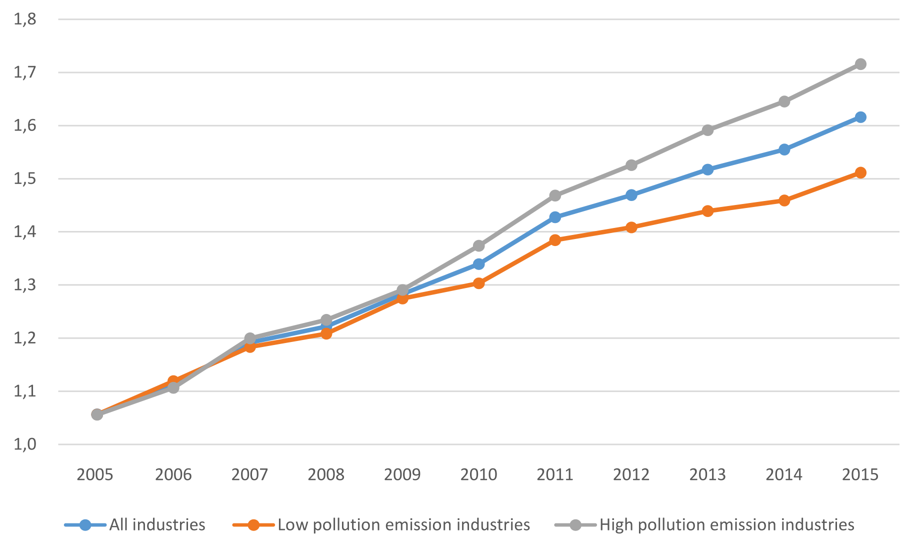

Fig. 1. Average GTFP for all industries, low pollution emission industries and high pollution emission industries.

with Li et al. [47], who argue that the pollution abatement costs account for a higher proportion of their total production cost in high pollution emission industries. Compared with the costly "end-of-pipe" method, firms are more inclined to meet the requirements of environmental regulation through technological innovation and product upgrading, which will in turn improve their green total factor productivity. However, for low pollution emission industries, the pollution abatement costs account for a lower proportion of their total production cost, and firms can easily meet the requirements of environmental regulation through the "end-of-pipe" method. As a result, the low pollution emission industries lack enough incentives to promote their technological innovation and green total factor productivity.

Table 5. Threshold significance test for GTFP.

GTFP	No. of thresholds	Thresholds	F-value	10%	5%	1%	95% confidence interval
ALL	1**	0.04%	0.34%	0.24%	0.27%	0.40%	(0.04%, 0.04%)
	2	0.01% 0.04%	0.16%	0.25%	0.28%	0.37%	(0.01%, 0.01%) (0.04%, 0.04%)
	3	0.01% 0.04% 0.06%	0.07%	0.29%	0.35%	0.41%	(0.01%, 0.01%) (0.04%, 0.04%) (0.06%, 0.06%)
LPE	1*	0.18%	0.23%	0.20%	0.23%	0.31%	(0.15%, 0.18%)
	2	0.12% 0.18%	0.10%	0.17%	0.21%	0.26%	(0.11%, 0.12%) (0.17%, 0.18%)
	3	0.09% 0.12% 0.18%	0.08%	0.20%	0.23%	0.40%	(0.07%, 0.10%) (0.11%, 0.12%) (0.17%, 0.18%)
HPE	1	0.23%	0.11%	0.24%	0.30%	0.42%	(0.23%, 0.24%)
	2	0.03% 0.23%	0.13%	0.19%	0.24%	0.34%	(0.03%, 0.04%) (0.23%, 0.24%)
	3	0.03% 0.23% 0.23%	0.07%	0.24%	0.29%	0.48%	(0.03%, 0.04%) (0.23%, 0.23%) (0.23%, 0.24%)

Note: ***, **, * indicate significance at p<0.01, p<0.05 and p<0.10, respectively.

Table 6. Threshold significance test for technological innovation.

TI	No. of thresholds	Thresholds	F-value	10%	5%	1%	95% confidence interval
ALL	1*	0.12%	0.15%	0.13%	0.17%	0.20%	(0.11%, 0.12%)
	2	0.03% 0.12%	0.08%	0.13%	0.15%	0.19%	(0.03%, 0.03%) (0.11%, 0.12%)
	3	0.03% 0.12% 0.18%	0.08%	0.19%	0.22%	0.26%	(0.03%, 0.03%) (0.11%, 0.12%) (0.16%, 0.18%)
LPE	1	0.11%	0.06%	0.10%	0.12%	0.16%	(0.11%, 0.12%)
	2	0.03% 0.11%	0.06%	0.11%	0.16%	0.21%	(0.03%, 0.03%) (0.10%, 0.12%)
	3	0.03% 0.08% 0.11%	0.05%	0.21%	0.25%	0.40%	(0.03%, 0.03%) (0.08%, 0.09%) (0.10%, 0.12%)
HPE	1*	0.19%	0.14%	0.14%	0.17%	0.24%	(0.17%, 0.19%)
	2	0.19% 0.20%	-0.02%	0.16%	0.19%	0.25%	(0.16%, 0.19%) (0.19%, 0.20%)
	3	0.12% 0.19% 0.20%	0.06%	0.16%	0.19%	0.23%	(0.11%, 0.12%) (0.16%, 0.19%) (0.19%, 0.20%)

Note: ***, **, * indicate significance at p < 0.01, p<0.05 and p<0.10, respectively.

Threshold Significance Test

In this paper, environmental regulation is taken as the threshold variable. Before the panel threshold model regression, we need to determine how many thresholds are needed for the model. Therefore, we conduct a significance test of the single threshold, double thresholds and three thresholds in each model. The results are shown in Tables 5 and 6.

Table 5 shows the threshold significance test results of equation (5), which shows that the whole sample and the subsample of LPE have a significant threshold, respectively, while the subsample of HPE has no significant threshold. Table 6 shows the threshold significance test results of equation (6), which shows that the whole sample and the subsample of HPE have a significant threshold respectively, while the subsample of LPE has no significant threshold. In this paper, we apply panel threshold regression for samples with significant threshold effect. According to the results of Hausman test [22], we choose the panel fixed effect regression for the other samples.

Empirical Results

All Industries

The effect of environmental regulation on technological innovation and GTFP are shown in Table 7 (columns 1 and 4, respectively). In general, although both models have significant threshold effects, the impacts of environmental regulation between technological innovation and GTFP are opposite. The effect on technological innovation has been promoted from significant negative effect (-1.3342) to positive but no significant effect (0.1060), while the significant positive effect on GTFP has been reduced to not significant. Specifically, combined with the thresholds (ER = 0.12%) in model (1) and the thresholds (ER = 0.04%) in model (2), we divide the sample period into three stages.

Stage 1 (ER≤0.04%). In this stage, environmental regulation has a negative effect on technological innovation, but has a positive effect on GTFP. It is an interesting finding that is different from previous studies. This is because most existing studies show that environmental regulation either weakens both technological innovation and GTFP [5], or promotes GTFP by innovation offset [6]. Why does this happen? We think it can be explained by two main reasons. On one hand, due to the high uncertainty of technological innovation, firms usually choose "end-of-pipe" treatment or secondary treatment solutions rather than innovation. At the same time, to offset the rising cost of compliance, firms will seek more output by transferring some existing R&D investment into the production process and pollution abatement [3]. On the other hand, for some firms with high energy consumption and high

Table 7. Empirical results.

Variables	TI			GTFP		
	(1)	(2)	(3)	(4)	(5)	(6)
	ALL	LPE	HPE	ALL	LPE	HPE
ER≤TH1	-1.3342***		-0.7813***	329.8740***	-108.28***	
	(0.4982)		(0.3342)	(73.6575)	(25.3157)	
ER>TH1	0.1060		0.2032**	0.0348	-31.8634***	
	(0.0860)		(0.0875)	(4.4102)	(10.4921)	
ER		-0.0796				8.8316*
		(0.1793)				(5.1258)
SCALE	-0.0000***	-0.0000***	-0.0000***	0.0001***	0.0001***	0.0001***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
OWN	0.0120***	0.0076***	0.0243***	-0.4203***	-0.3007**	-0.5015**
	(0.0020)	(0.0023)	(0.0033)	(0.1024)	(0.1181)	(0.2296)
FDI	-0.0014**	-0.0021***	-0.0010	-0.0091	-0.0051	0.0302
	(0.0007)	(0.0007)	(0.0009)	(0.0336)	(0.0434)	(0.0528)
Cont.	0.0070***	0.0080***	0.0046***	0.7191***	0.8933***	0.6304***
	(0.0005)	(0.0006)	(0.0008)	(0.0245)	(0.0287)	(0.0572)
Obs.	385	187	198	385	187	198

Note: Standard errors in parenthesis; ***, **, * indicate significance at $p < 0.01$, $p<0.05$ and $p<0.10$, respectively.

pollution emission, environmental regulation can lead them to quit the market either for the unbearable cost of pollution abatement or for mandating shutdown by the government. Benefitting from the increase of market concentration and the green entry barrier, environmental regulation promotes GTFP without innovation offset.

Stage 2 (0.04%<ER≤0.12%). In this stage, environmental regulation still plays an inhibitory role on technological innovation. However, the promotion effect of environmental regulation on GTFP is no longer significant. This is because the pressure from environmental regulation is still not enough to stimulate technological innovation, which results in environmental regulation continuing to squeeze out R&D investment and GTFP still cannot be improved through innovation offset. Unfortunately, with the elimination of backward production capacity being almost completed, the benefits from market concentration and the green entry barrier are gradually vanished, which make the competition among incumbent firms fierce again. Under the combined effect of these factors, the significant positive impact of environmental regulation becomes insignificant at this stage. Altogether, this phenomenon shows that the way to improve GTFP through changes in external market conditions is not sustainable.

Stage 3 (ER>0.12%). The effects of environmental regulation on technological innovation and GTFP are both positive but not significant. On one hand, the way through transfer R&D investment to offset the rapid rising cost of compliance is unsustainable in the long term, and the environmental regulation has begun to make firms aware of the importance of technological innovation. At this point, firms will gradually reduce the squeeze on R&D investment until they start to increase. As for GTFP, the reasons are the same as in Stage 2.

Overall, during the sample period, environmental regulation has not yet entered the stage of significantly promoting R&D innovation and GTFP. This is the case in the whole sample. How about the cases in two subsamples? It is interesting to study whether the cases are the same as in the whole sample or have industry heterogeneity in the two subsamples.

Low Pollution Emission Industries

The effect of environmental regulation on technological innovation and GTFP are shown in Table 7 (columns 2 and 5, respectively). The effects of environmental regulation on technological innovation have no significant effect during the whole sample period. The effects on GTFP are significant and negative, but the negative effect diminished after crossing the threshold. Compared with the high pollution emission industries, the same environmental regulation is relatively lax in the low-pollution emission industries. In addition, environmental technological innovation will not bring direct economic benefit to firms. Therefore, the relatively low cost of compliance makes "end-of-pipe" treatment or secondary treatment feasible without technological innovation. Actually, China has failed to break through the "source reduction" and "end-of-pipe" treatment since the 1990s [48].

However, the relatively low cost of compliance also makes them hardly obtain GTFP promotion through increasing market concentration and building green entry barrier. If things continue this way, the increasing cost of marginal pollution abatement will inevitably weaken GTFP. Similarly, Yuan and Xiang [20] find that environmental regulation has inhibited technological innovation and impaired GTFP. However, it is worth noting that the negative effect on GTFP is significantly alleviated when environmental regulation exceeds the threshold (ER = 0.18%). This might be because the innovation offset from existing R&D innovation has played a positive role in alleviating the negative impact on GTFP. Xie [49] found that the direct impact of environmental regulation on GTFP is negative in the short term. However, it has the possibility to promote GTFP in the long run.

High Pollution Emission Industries

The effects of environmental regulation on technological innovation and GTFP are shown in Table 7 (columns 3 and 6, respectively). The effect of environmental regulation on Technological innovation has been changed from significant negative effect (-0.7813) to significant positive effect (0.2032) during the sample period, which suggests that the impact on technological innovation is similar to the "U"-type curve. When environmental regulation is on the left side of the turning point (ER = 0.19%), the pollution abatement cost is a relatively small part of the total cost. In this stage, environmental regulation has not only been unable to provide enough incentives to technological innovation, but also transferred some existing R&D investment into pollution abatement and production process. When environmental regulation entered the right side of the turning point, the pollution abatement cost rose to an unbearable place of the total cost. The still increasing marginal pollution cost will force firms to take green innovation for conserving energy and reducing emissions. This is consistent with Liu et al. [50].

In terms of the effect on GTFP, environmental regulation plays a positive role during this period. This can be explained as follows. On one hand, strict environmental regulation requires firms to bear the cost of pollution abatement, which causes a decline in profits. As the cost of pollution abatement continues to increase, some high pollution emission industries choose to withdraw from the market because they cannot afford the high cost [51]. To some extent, this has increased market concentration and built green entry barriers for incumbent firms, which will further promote GTFP. On the other hand, technological innovation complies with environmental regulation, often improving GTFP

Table 8. Robust test results.

Variables	TI			GTFP		
	(1)	(2)	(3)	(4)	(5)	(6)
	ALL	LPE	HPE	ALL	LPE	HPE
ER≤TH1	-3.3E+07***	-3.4E+07***	-1.1E+04***		-6.2090***	-2.1645***
	(6.0E+06)	(7.0E+06)	(2.6E+03)		(1.3503)	(0.6372)
ER>TH1	-1.8E+04	-1.7E+04	-28.6118		-1.4582**	0.0638
	(1.2E+04)	(1.8E+04)	(140.9775)		(0.5731)	(0.3857)
ER				-0.5265		
				(0.4093)		
SCALE	10.0406***	8.6495***	0.0579***	0.0012***	0.0013***	0.0006***
	(1.3990)	(2.0752)	(0.0166)	(0.0001)	(0.0001)	(0.0000)
OWN	3.6E+04	2.4E+04	-9.2E+02***	0.9827	2.9996	-0.7256
	(3.2E+04)	(6.5E+04)	(277.5610)	(1.1871)	(2.0650)	(0.7503)
FDI	-4.6E+04***	-4.2E+04***	-1.7E+02	-0.2077	0.2859	-0.9138**
	(1.1E+04)	(1.5E+04)	(129.3346)	(0.3579)	(0.4652)	(0.3537)
Cont.	6.1E+04***	7.2E+04***	1.1E+03***	-1.1562***	-2.2147***	0.5068***
	(6.9E+03)	(1.2E+04)	(71.6918)	(0.3117)	(0.3687)	(0.1918)
Obs.	385	187	198	385	187	198

Note: Standard errors in parenthesis; ***, **, * indicate significance at $p < 0.01$, $p<0.05$ and $p<0.10$, respectively.

through innovation offset [6]. In summary, GTFP has been promoted through an advantage obtained from external market conditions and internal innovation offsets.

Robust Test

In order to test whether the empirical test is robust, we have done the same empirical analysis by replacing key variables. (1) Referring to the existing studies, we re-estimate a new GTFP excluding energy consumption and carbon emissions by SBM-DEA model. (2) Choose the number of people engaged in scientific and technological activities instead of R&D investment. (3) Using emission intensity of pollutants represents environmental regulation. The estimated results are shown in Table 8 (which are basically the same as in Table 7).

Conclusions

Based on a panel data of 35 industries from 2005 to 2015, this paper uses a panel threshold model to investigate the effect and the mechanism of environmental regulation on technological innovation and GTFP. Considering the existence of industrial heterogeneity, this paper further divides the whole sample into two subsamples according to the intensity of pollution emission, and then explores the different effects of environmental regulation between the two subsamples. The findings in this paper are shown as follows:

(1) The impact mechanisms of environmental regulation on technological innovation and GTFP are different. For technological innovation, the effect depends on whether environmental regulation brings enough innovation pressure to firms by the rising cost of compliance. However, in terms of GTFP, the effect depends on the net effect between positive effects and negative effects of environmental regulation. The positive effects include competitive advantage form external market conditions and innovation offset from internal technological innovation. The negative effects are mainly the distortion effect of resource allocation by squeezing technological innovation and production input to pollution abatement. During the sample period, environmental regulation plays a positive role in technological innovation and GTFP only in the high pollution emission industry. However, for the whole sample and the low pollution emission industries, the effects of environmental regulation are either negative or insignificant.

(2) Apart from innovation offset, we also find that environmental regulation can promote GTFP by increasing market concentration and building green market entry barriers. This competitive advantage is mainly generated in two ways. Firstly, the government

forces some backward firms to shut down and strictly controls the incremental scale of high pollution emission industries by administrative order. Secondly, the government raises the cost of compliance through tax, trade and loan, and thus compels some unprofitable firms to withdraw from the market. Compared with the first one, the second can also exert innovation pressure on incumbent firms.

(3) We find that not all industries can obtain a competitive advantage by increasing market concentration and green market entry barriers. For example, the low pollution emission industries can easily meet the standard of current environmental regulation for their cleaner production process. And both administrative order and market-based tools are rarely involved in the low pollution emission industry. Therefore, the low pollution emission industries can hardly promote GTFP through such competitive advantage. In addition, even for an industry with this competitive advantage, their incumbent firms can only get GTFP improved in the short term. In the long term, the continuous improvement of GTFP depends on innovation offset. This is mainly reflected in the difference between the latter two stages of the whole sample and the second stage of the high pollution emission industries. Because of the disappearance of competitive advantage and the lack of technological innovation, the promoting effect is not significant in the latter two stages of the whole industry. However, the positive effect of environmental regulation on technological innovation has further promoted GTFP in the second stage of the high pollution emission industries.

The policy implications of this paper are that: (1) The environmental policy should take full account of the existence of industrial heterogeneity to make environmental regulation play a promoting role in both technological innovation and GTFP. Although low pollution emission industries are characteristic and are characterized by low resource consumption and low environment pollution, they may still pose a potential threat to environment protection. The long-term neglect of the policy makers made the intensity of environment regulation on these industries at a low level, which failed to generate enough incentives for promoting technological innovation and green total factor productivity. Therefore, it is necessary to appropriately improve the intensity of environmental regulation in low pollution emission industries. However, for high pollution emission industries, it is necessary to consider the industry's tolerance to environmental regulations. If the environmental regulations exceed the tolerance of the industry, such industry may turn to rent-seeking behavior rather than increase investment in green technological innovation. (2) The policy makers should focus on the dynamic adjustment of the intensity of environmental regulation rather than a certain level. Because of the influence of information asymmetry, policy makers often overestimate or underestimate the actual pollution abatement, which will not provide enough incentives to promote technological innovation and green total factor productivity. Therefore, policy makers need to make timely adjustments to the intensity of environmental regulation to a reasonable level in order to maintain continuous incentives for industries.

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Conflict of Interest

The authors declare no conflict of interest.

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