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A dynamic panel threshold model analysis on heterogeneous environmental regulation, R&D investment, and enterprise green total factor productivity

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Environmental regulations are important means to influence manufacturing enterprise green development. However, there are two completely different conclusions both in theoretical and in empirical research, namely the “Follow Cost” theory and the “Porter Hypothesis”. The nonlinear mechanism needs to be considered. Therefore, this study aims to explain the threshold impact of heterogeneous environmental regulations on enterprise green total factor productivity. Environmental regulations are divided into different sub-categories, then based on the panel data of 1220 Chinese manufacturing listed companies from 2011 to 2020, this paper uses threshold regression model to examine the impact of heterogeneous environmental regulations on Chinese manufacturing enterprise Green Total Factor Productivity. The empirical results show that: (1) Command-controlled, market-incentive and voluntary-agreement environmental regulation all have a significant nonlinear impact on enterprise Green Total Factor Productivity. (2) Enterprise R&D investment plays a threshold role in the impact. (3) There are industry and equity type differences in the impact process. This study focuses on the micro level of enterprises and tests the threshold mechanism, which make some theoretical complement to previous researches. The research results are not only beneficial for the government to propose appropriate environmental regulatory policies, but also for enterprises to achieve green growth through heterogeneous R&D investment.

Keywords Environmental regulation, Enterprise green total factor productivity, R&D investment, Digital level, Panel threshold model

Since the implementation of the reform and opening-up policy in 1978, China’s economy has developed rapidly. However, the development of Chinese economy has occurred at the expense of the environment^{1,2}. That is, the traditional extensive economic development mode characterized by “high growth and high energy consumption” has increased the burden on China’s ecological environment, further led to increasingly prominent environmental problems, and become an obstacle to the economy’s sustainable development³. According to the BP World Energy Statistical Yearbook (2022), in 2021, CO₂ emissions generated by energy in China are 10.523 billion tons, accounts for 31.06% of the whole world, far more than other regions. At the same time, the global economy has shown the trend of low-carbon emission and green sustainable development. The implementation of the Paris Agreement has further established a clear agenda for global carbon reduction. Therefore, carbon emissions reduction is an important and arduous task both for environmental remediation in China and for promoting green development throughout the world⁴. GTFP, as a combination strategy under the dual goals of economic development and environmental protection, helps to promote economy’s sustainable development.

Manufacturing enterprises are both micro entities and carbon emitting entities of the national economy. According to the Carbon Emission Ranking of Chinese Listed Companies, the total carbon emissions of the 100 listed companies in 2022 were 5.046 billion tons, accounting for approximately 45.87% of China’s total carbon

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emissions. Obviously, manufacturing enterprises play an important role in achieving green and sustainable development. Green total factor productivity (GTFP) takes into account energy loss and pollution emissions in the production process, and is a comprehensive indicator for measuring economic performance and ecological environment performance. GTFP of manufacturing enterprises is the core and starting point for achieving broader economic and environmental goals. Therefore, it is of great significance to enhance GTFP of Chinese manufacturing enterprises⁵.

Enterprises are profit oriented economic organizations, the market economy, as a powerful engine of human development, has important imperfections⁶, thus relying solely on the invisible hand of the market is difficult to promote its spontaneous green production. Government policies play an important role in promoting sustainable technological progress and environmental sustainability^{7,8}. Environmental regulations have important impacts on manufacturing enterprises GTFP^{9–11}. Thus, the Chinese government has utilized heterogeneous environmental regulations to promote enterprises green development. On one hand, a series of command-controlled environmental regulations have been made, including the Environmental Protection Law of China, the Cleaner Production Promotion Law in China, Atmospheric Pollution Prevention and Treatment Law in China etc. On the other hand, some market-incentive environmental regulations such as carbon emission quotas are used to encourage manufacturing enterprises green development.

Governments around the world actively formulate environmental regulations, hoping to promote green development. And related researches on the impact of environmental regulations on GTFP has attracted great attention. However, there are two completely different views both in theoretical and empirical, “the driving role of environmental regulations” and “the hindering role of environmental regulations”^{12–14}. According to the “Follow Cost” theory, the stricter environmental regulations are, the higher cost of enterprises pollution controls are, which will furthermore restrain the production efficiency and profitability of enterprises, and hinder the improvement of enterprises GTFP¹⁵. However, according to the theory of “Porter Hypothesis”, moderate environmental regulations can encourage enterprises to engage in more innovative activities, which will increase their productivity, offset the investment cost caused by environmental regulations and enhance their profitability in the market^{16,17}.

Empirical research also has completely different conclusions. Some empirical results have found that environmental regulations can improve both industry production efficiency and environmental performance by influencing technological progress, thereby achieving green growth¹⁸. Some other empirical results have showed that environmental regulations have caused cost increases, and their contribution to technological innovation is relatively small or even inhibitory, which is not conducive to the improvement of production efficiency and environmental performance, and thus hinders green growth¹⁹. There are also some empirical researches have confirmed that there is a non-linear relationship or even no correlation between environmental regulations and green development¹⁶.

Theoretical and empirical research have not yet reached a consensus, and there are two possible reasons. Firstly, the existing researches on the impact of environmental regulations on green growth mainly focus at the regional or industry level, related researches at the level of enterprise is insufficient¹⁵. In fact, both the “Following Cost” theory and the “Porter Hypothesis” have their rationality, and the reason of contradiction lies in the coexistence of cost increase and innovation compensation caused by environmental regulations, but there is insufficient discussion on the boundary conditions. As heterogeneous individuals, enterprises may have quite different reactions to the same environmental regulatory policies. And only the exploration that focuses on the micro level of enterprises may open this “black box”. Secondly, environmental regulations are a comprehensive concept that can be further divided into different subcategories, which may lead to inconsistent research conclusions if confusing them together. Therefore, it is necessary to explore the mechanism of environmental regulations affecting GTFP of heterogeneous enterprises at micro level. Thirdly, both theoretical and empirical researches have shown that the impact of environmental regulations on green development may be non-linear. Environmental regulations only generate external conditions that can affect enterprises’ behavior. Whether and to what extent an enterprise innovates is determined by enterprise heterogeneity factors, and R&D investment is an important determining factor. Therefore, this article uses enterprise R&D investment as a threshold variable to explore the threshold impact of heterogeneous environmental regulations on enterprise GTFP.

The contribution of this paper mainly lies in the following: (1) Focusing on the micro level of enterprises, this paper divides environmental regulations into three heterogeneous subcategories including command-controlled type, market-incentive type and voluntary-agreement type, and furthermore clarify the mechanism of heterogeneous environmental regulations affecting enterprise GTFP; (2) Focusing on the micro level of enterprises, enterprise R&D investment is introduced as the threshold variable to clarify the panel threshold mechanism and determine the threshold values; (3) Heterogeneity analysis is conducted based on enterprise industry type and enterprise equity type. The research conclusions can provide theoretical reference and decision-making reference both for enterprises from micro level and for policy makers from macro level. The research framework of this paper is illustrated in Fig. 1.

Literature review and hypothesis

Heterogeneity environmental regulations and enterprise GTFP

The research on the impact of environmental regulations on GTFP has become a fore issue, and different impact direction of the empirical results have also spawned further thinking of scholars. Firstly, researchers propose that environmental regulations should be divided into different subcategories, and the impact of heterogeneous environmental regulations on GTFP are different^{20,21}. Researchers conducted deeper discussions on heterogeneous environmental regulations, and most agree that environmental regulation can be divided into three subtypes, which are command-controlled environmental regulation (CER), market-incentive environmental regulation

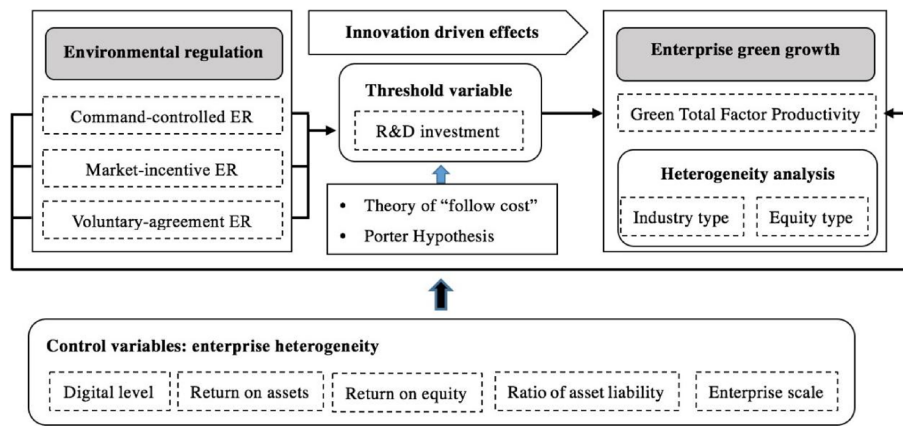


Figure 1. Analytical framework of this study.

(MER) and public-participation environmental regulation (VER)²². Secondly, the existing researches mainly focus on the regional and industry levels, and there is still insufficient research on the enterprise level¹⁵. Thirdly, limited researches on enterprise green growth mainly focus on enterprise green patents. On the one hand, this calculation doesn't consider input–output ratio can easily lead to biased research conclusions. On the other hand, it cannot verify the impact mechanism on many enterprises without green patents. The traditional methods used to measure productivity growth ignore the pollutants that are produced by the production process, while GTFP takes into account pollutant emissions during the production process, and measures enterprise green growth from the perspective of input–output⁷. Thus, GTFP can not only include all enterprises but also better reflect enterprise green growth efficiency.

Undoubtedly, environmental regulation is one of the most important forces in achieving green growth²³. Command-controlled environmental regulation (CER) refers to the government guiding and standardizing the production process of enterprises through a series of administrative means, such as environmental regulations, rules, policies, emission standards and so on. On the one hand, the strict CER given by the government will inevitably increase enterprise environmental governance costs and then lead to excessive environmental governance expenditures in the short term, which is unfavorable for enterprise green growth²⁴. The research utilizing a comprehensive CS-ARDL model and using data of OECD countries from 1990 to 2020 found that environmental policies are effective in reducing carbon dioxide emissions²⁵. The empirical study based on the panel data of China's 31 energy-mineral cities in 2007–2018 showed that CER has an inhibitory impact on energy eco-efficiency, and the inhibitory effect is more obvious in central and northeastern regions²⁶. Research adopted the Spatial Durbin Model found that CER will hinder regional green technology innovation²⁷. On the other hand, CER will significantly increase enterprise environmental legal costs of production and operation process, thereby playing a deterrent role and help to promote enterprise technological innovation, and achieving green growth¹⁵. Based on panel data from 30 provinces in China from 2003 to 2017, the results of Systematic Generalized Method of Moments indicated that CER has a significant promoting effect on green innovation²⁸. The empirical study on the data of Chinese A-share companies listed from 2010 to 2019 found that CER can stimulate enterprise green technology innovation²⁹. Besides, CER may have a nonlinear impact on green development. Some research suggested that CER has a significant threshold impact on green technological innovation³⁰, and when its intensity exceeds a certain threshold, green technological innovation is improved. Similar researches found that with the improvement of economic level, environmental regulation shows a “U” relationship of first restraining and then promoting technological innovation³¹.

From the above analysis, it can be seen that both theoretical and empirical studies have not reached a consensus on CER's impact on GTFP, and threshold effect may exist. Thus, Hypothesis 1 is proposed.

Hypothesis 1 CER has a threshold effect on enterprise GTFP.

Market-incentive environmental regulation (MER) mainly refers to market-oriented institutional regulatory measures especially economic means such as pollution control investment, environmental protection fund investment and other tax standards, aim to guide enterprises achieving green production³².

Theoretical research has not reached a consensus on MER's impact on GTFP. On the one hand, there is a divergence between the “Follow Cost” theory and the “Porter Hypothesis”. On the other hand, even the “Porter Hypothesis” suggested that only those carefully designed environmental regulations can promote green development by enhancing innovation. That is, the mechanism between carefully designed regulation and its potential innovation offsetting effects is not yet clear³³.

The empirical research results are also quite different. Gray and Shadbegian found that higher pollution abatement costs significantly decrease the productivity³⁴. According to the panel data of A-share new energy companies listed in Shanghai and Shenzhen from 2012 to 2020, the research drew the conclusion that MER could promote the green innovation of new energy firms³⁵. Based on the data of 30 provinces in China during

the period of 2000 to 2012, the empirical results showed that environmental expenditure as one type of MER has a U-shaped impact on green productivity growth of China's industry¹⁵. Some scholars pointed that when the intensity of MER is not high, the environmental cost of enterprises is relatively low, so enterprises lack the power of technological innovation and thus prevent the improvement of GTFP, when the intensity of MER is high enough, enterprises have a strong driving force for technological innovation, and then promote the improvement of GTFP^{36,37}. Based on the above analysis, the impact of MER on GTFP is relatively complex and threshold effect may exist. Thus, Hypothesis 2 is proposed.

Hypothesis 2 MER has a threshold effect on enterprise GTFP.

Voluntary-agreement environmental regulation (VER) also known as public-participation based environmental regulation, refers to the regulation of corporate behavior through external supervision by individuals or non-governmental organizations, such as the number of environmental petitions, batches of environmental petitions, and the number of environmental petitions. The public could actively perform duties of environmental protection through environmental letters or visits and media supervision, reflect enterprise environmental pollution problems to the government, so as to supervise enterprise pollution behaviors³⁸. Therefore, it conveys an implicit message to the outside world, that is, the enterprise has social responsibility and pays attention to environmental protection^{33,39}. A good corporate image in turn helps enterprise attract more external investment and provides support for its green technological innovation. According to the research of Jia⁴⁰, the greater VER is, the more enterprises will be encouraged to take more measures to pursue environmental performance, and therefore has a positive impact on GTFP. Taking A-shared listed enterprises in China from 2010 to 2019 as samples, the empirical results showed that VER inhibited enterprise green technological innovation²⁹. Based on panel data of 86 Chinese steel enterprises from 2005 to 2014, the paper analyzed that VER has a direct and positive effects on the enterprise technological innovation⁴¹.

Based on the above analysis, the impact of VER on GTFP may exist a threshold effect. Thus, Hypothesis 3 is proposed.

Hypothesis 3 VER has a threshold effect on enterprise GTFP.

R&D investment and enterprise GTFP

The important mechanism by which environmental regulations affect enterprise GTFP is to promote the internalization of enterprise environmental governance costs, so as to stimulate enterprise innovation activities, and then affect enterprise GTFP⁶. However, it is still unclear for the mechanism between the cost increase caused by environmental regulations and possible innovation compensation³³. The heterogeneity of enterprise, especially enterprises differentiated innovation level became an important determining factor that affects the driving effect. R&D investment is an important indicator to measure the level of innovation⁶. The environmental regulations' driving effect is mainly achieved by influencing enterprise R&D investment. Therefore, it is necessary to further clarify the impact of enterprise R&D investment on GTFP from the enterprise level.

According to the Theory of Endogenous Growth, innovation can form a new production function, and technological progress driven by knowledge spillovers and knowledge transfer is the decisive factor for sustainable growth⁶. R&D investment is the source of enterprise innovation and economic growth. R&D investment is conducive to optimizing production factors and reducing information asymmetry, this not only expand the source of explicit knowledge, but also increase organization flexibility, which can further promote the spillover and absorption of tacit knowledge, and then improve enterprise performance. R&D promotes environmental protection by reducing CO₂ emissions²⁵. Based on the panel data of high-tech enterprises in China from 2012 to 2017, the research proposed that innovation investment plays a mediating role in the impact of heterogeneous environmental regulations on enterprise innovation⁴².

The "Follow Cost" theory suggests that environmental regulations will lead to an increase in enterprises pollution control costs. Especially in the short term, constraints by capital amounts, enterprises have to increase the pollution discharge investment which will inevitably lead to a decrease in R&D investment and resulting "R&D Crowding Out Effect"⁴³. However, the "Porter Hypothesis" suggests that in the long term, reasonable and strict environmental regulations can promote technological practices. The costs of environmental regulations may be partially or entirely offset by the compensating effects of innovation activities, and thus environmental regulations can promote GTFP through the "Innovation Compensation Effect"⁴⁴.

The magnitude of the "R&D Crowding Out Effect" and "Innovation Compensation Effect" affects the performance of environmental regulatory policy. Enterprise R&D investment is an important factor affecting R&D costs and long-term technological innovation capabilities, and may have a significant impact on heterogeneous environmental regulations affecting enterprise green development²⁹.

The continuous developing of relevant research has laid the foundation and provided a new perspective for further exploring the impact of heterogeneous environmental regulations' innovation driving effect. Therefore, this paper introduces enterprises R&D investment in the analysis, and believes that enterprises R&D investment plays an important role in the impact of heterogeneous environmental regulations on enterprises GTFP^{45,46}.

Based on the above analysis, Hypothesis 4, Hypothesis 5 and Hypothesis 6 are proposed.

Hypothesis 4 Enterprise R&D investment plays a threshold role in the impact of CER on enterprises GTFP.

Hypothesis 5 Enterprise R&D investment plays a threshold role in the impact of MER on enterprises GTFP.

Hypothesis 6 Enterprise R&D investment plays a threshold role in the impact of VER on enterprises GTFP.

Research methodology

Sample selection

The samples of this paper are panel data of 1220 A-share manufacturing listed companies in China. The relevant data is obtained from the China Stock Market and Accounting Research Database (CSMAR). Firstly, according to the industry classification codes in the Guidelines for Industry Classification of Listed Companies (2012 Revision) issued by the China Securities Regulatory Commission, 31 categories of A-share manufacturing listed companies are selected. Secondly, excluded enterprises that have not been listed or have been delisted during the study period, excluded enterprises that have been ST、*ST or samples with lots of missing data. Finally, 12,200 pieces of panel data of the sample enterprises from 2011 to 2020 are obtained.

Variables measurement and data sources

Dependent variables

The dependent variable of this paper is sample enterprises GTFP. Scholars have used several methods to measure green productivity issues, such as descriptive analysis, non-parametric analysis including data envelope analysis, input–output analysis, dynamic computable general equilibrium, parametric analysis based on a combined method of parametric analysis⁷. This article constructs the optimal frontier of enterprises green growth based on the Super-SBM Model includes undesirable outputs, and calculates enterprises GTFP according to the Super-SBM Mode^{47–49}. Specifically, the measurement of GTFP involves input factors, desirable output, and undesirable output.

Firstly, referring to related methods for measuring GTFP, this paper selects input indicators includes capital input, labor input, intermediate input, and energy input^{4,50}. Referring to the general method, enterprise capital input is calculated by “the perpetual inventory method” based on the “net value of enterprise fixed assets”, enterprise labor input is calculated by “the cash paid by the enterprise to employees”, enterprise intermediate investment is calculated by “the sum of operational expense, sales expenses, financial expenses, and management expenses minus the cash paid to and for employees, and minus depreciation and amortization”, enterprise energy investment is calculated by “the proportion of enterprise gross output value to the gross industry output value, and multiply the energy consumption of the industry that enterprise belongs to”. Secondly, enterprise desirable output is calculated by “enterprise main business income”. Thirdly, enterprise undesirable output is calculated by “three kinds of enterprise’s industrial waste”, including the industrial wastewater, SO₂, and industrial smoke emissions of enterprise. The relevant data comes from CSMAR, China Statistical Yearbook, China Environmental Statistical Yearbook, and China Urban Statistical Yearbook.

Independent variable

The independent variable of this article are heterogeneous environmental regulations, which includes three subcategories: CER, MER and VER. Referring to current calculation method, CER is calculated by “the number of environmental case proposals submitted by provincial and municipal people’s congresses”²⁶. Investment of environmental pollution control as one of the MER method, can demonstrate the incentive costs invested by regional governments and continuous data can be obtained. Therefore, MER in this article is calculated by “the ratio of the completed investment in industrial pollution control in each region to the regional GDP”^{50–53}. Considering previous research and data availability, VER is calculated by “the number of environmental petitions in each province and city”²⁹. Relevant data are collected from China Environmental Statistical Yearbook.

Threshold variables

The threshold variable of this article is enterprise R&D investment (RD). Firstly, there is a close correlation among environmental regulations, R&D investment and GTFP. According to Porter Hypothesis, environmental regulations have innovation driven effects. In fact, environmental regulations only generate external conditions that can affect enterprises’ behavior. Whether and to what extent an enterprise innovates is determined by enterprise heterogeneity factors, and R&D investment is an important determining factor. Secondly, enterprise R&D investment can be clearly measured. Thirdly, data of R&D investment is reliable. R&D investment can be found in the annual reports of listed companies. The disclosure of this indicator is very comprehensive, with few missing items, and the data is available and reliable. Therefore, enterprise R&D is used this article investment as a threshold variable to explore the threshold impact of heterogeneous environmental regulations on enterprise GTFP. Enterprise R&D investment is measured by the proportion of enterprise R&D amount in sales revenue³⁵. Relevant data is from CSMAR.

Control variables

Referring to relevant literatures on environmental regulations and enterprise green growth, the following indicators are selected as control variables^{54–56}: enterprise digital level (DL), return on assets (ROA), return on equity (ROE), ratio of asset liability (ROL), and enterprise scale (Scale). Enterprise digital level is measured by “the number of digitization-related-words frequencies in enterprise annual reports” based on Python word frequency statistical analysis methods. Enterprise return on assets is measured by “the proportion of enterprise’s net profit in the total assets”. Enterprise return on equity is measured by “the proportion of enterprise’s net profit to net assets”. Enterprise ratio of asset liability is measured by “the proportion of its total liabilities to total assets”. Enterprise scale is measured by “enterprise total assets”.

Grouping variables

In order to test whether there is heterogeneity in the threshold regression results, referring to classic theories and considering enterprise most important heterogeneity, enterprise industry (Indus) and enterprise equity (Equ) type are selected as two grouping variables. Enterprise industry can be divided into three categories based on their pollution emission levels which are high pollution industry, medium pollution industry and low pollution industry. Enterprise equity can be divided into two categories based on the equity status which are state-owned and non-state-owned.

All the variables except for grouping and ratio variables are logarithmically processed after adding one. And the summary of variables is shown in Table 1.

Model construction

Firstly, according to literature review, it was found that environmental regulations have both promoting and inhibiting effects on green development. The current research debate focuses on the conditions for a reasonable explanation of these two effects. Secondly, threshold regression models are non-linear models that are suitable for explaining the non-linear relationships between variables, especially the threshold effect that both positive and negative effects exist simultaneously. Thirdly, this article attempts to explore the threshold impact of heterogeneous environmental regulations on enterprise GTFP. The threshold regression model is very suitable to explain the mechanism that this article proposed.

Based on all the above theoretical analysis, in order to test the research hypotheses H1-H6 and find the optimal range of R&D investment that can maximize enterprise GTFP, the panel threshold model based on Hansen model⁵⁷ is shown as Eq. (1). In the equation, $GTFP_{i,t}$ represents enterprises green total factor productivity, $I(*)$ is the indicator function, enterprise R&D investment is taken as the threshold variable and γ_1 , γ_2 is the threshold of threshold of the effect. α_0 is constant terms, α_1 , α_2 , α_3 , ρ_i are the regression parameters, θ_i is the unobservable individual effect, $\varepsilon_{i,t}$ is the random error term. Other variables are the same as the above.

$$GTFP_{i,t} = \alpha_0 + \alpha_1 ER_{i,t}I(RD_{i,t} \leq \gamma_1) + \alpha_2 x_{i,t}I(\gamma_1 < RD_{i,t} \leq \gamma_2) + \alpha_3 x_{i,t}I(RD_{i,t} > \gamma_2) + \rho_i Control_{i,t} + \theta_i + \varepsilon_{i,t} \quad (1)$$

Results and analysis

Description and correlation analysis

The descriptive statistics of variables and the correlation analysis results are shown in Table 2. It can be seen from the table that the average values of GTFP is 0.698, reacting that many sample enterprises GTFP is not very high, the standard deviation of GTFP is 0.184, indicating that small differences in GTFP among sample enterprises. Among the three subcategory tools for environmental regulations, the standard deviation of MER is the minimum and the standard deviation of VER is maximum. In addition, the variance of most variables is less than the mean value, indicating that the dispersion coefficient is relatively small and the stability of the sample is good. The Pearson correlation analysis results are also shown in Table 2. It can be seen that there is interdependence between variables, but it cannot distinguish the causal relationship of variables. Therefore, it is both possible and necessary to further establish quantitative relationships between variables through regression analysis.

Threshold effect test

Firstly, examine whether the threshold effect exists and determine the number of thresholds. The results are shown in Table 3. According to the results, enterprise R&D investment is the threshold variable, CER, MER and

Variable	Abbreviation	Description
Dependent variables	GTFP	Input factors, desirable output, undesirable output; Super-SBM Model
Independent variables	CER	The number of environmental case proposals submitted by provincial and municipal people's congresses
	MER	The ratio of the completed investment in industrial pollution control in each region to the regional GDP
	VER	Number of environmental petitions in each province and city
Threshold variables	RD	The proportion of enterprise R&D amount in sales revenue
Control variables	DL	The number of digitization-related-words frequencies in enterprise annual reports
	ROA	The proportion of enterprise's net profit in the total assets
	ROE	The proportion of enterprise's net profit to net assets
	ROL	The proportion of its total liabilities to total assets
	Scale	Enterprise total assets
Grouping variables	Indus	Industry pollution level
	Equ	Enterprise equity type

Table 1. The summary of variables.

Variables	1	2	3	4	5	6	7	8	9	10
GTFP	1.000									
CER	-0.005	1.000								
MER	-0.006	-0.242***	1.000							
VER	-0.033***	0.577***	-0.356***	1.000						
RD	0.028***	0.024***	-0.083***	0.075***	1.000					
DL	-0.032***	0.065***	-0.167***	0.161***	0.265***	1.000				
ROA	-0.002	0.001	-0.007	0.005	-0.017*	-0.003	1.000			
ROE	-0.007	-0.018*	0.003	-0.006	-0.002	-0.013	0.827***	1.000		
ROL	-0.020**	-0.023**	-0.040***	-0.021**	-0.155***	-0.040***	-0.056***	0.019**	1.000	
Scale	-0.092***	-0.044***	0.030***	-0.013	-0.110***	0.187***	-0.022**	-0.033***	0.238***	1.000
Mean	0.698	6.491	0.733	8.511	4.010	1.608	3.683	13.784	42.364	22.193
Std	0.184	0.787	0.273	1.112	3.993	1.064	24.739	729.767	31.097	1.230

Table 2. The descriptive statistics and correlation coefficients of variables. ***, ** and * indicate the statistical significance of 1%, 5% and 10% respectively.

ER type	Threshold type	Threshold	95% Conf. Interval	F	p
CER	Single	3.7900***	[3.635, 3.800]	37.03	0.0000
	Double	9.2100***	[8.290, 9.420]	24.76	0.0000
	Triple	-	-	9.96	0.5133
MER	Single	8.1400***	[7.750, 8.290]	32.60	0.0000
	Double	3.3000***	[3.250, 3.320]	25.12	0.0000
	Triple	-	-	9.23	0.7033
VER	Single	3.7900***	[3.635, 3.800]	41.67	0.0000
	Double	8.1400***	[7.775, 8.290]	26.89	0.0000
	Triple	-	-	9.68	0.7600

Table 3. Threshold Test Effect Results. ***, ** and * indicate the statistical significance of 1%, 5% and 10% respectively.

VER all have significant dual threshold effects on enterprise GTFP. Double threshold effect diagram is shown in Fig. 2.

Further threshold regression analysis was conducted on three types of heterogeneous environmental regulations, and the overall results are shown in Tables 4, 5, and 6.

Table 3 and the first column in Table 4 all show that CER has a significant dual threshold impact on enterprise GTFP. If $RD < 3.79$, CER has no significant impact on enterprise GTFP. If $3.79 \leq RD < 9.21$, CER has a significant positive impact on enterprise GTFP. If $RD \geq 9.21$, CER also has a significant positive impact on enterprise GTFP, and the impact degree are enhanced. With the increase of enterprise R&D investment, the positive impact of CER on GTFP increases. The possible reason is that higher levels of R&D investment often incentive enterprise technological innovation, which is more suitable for strict CER. That is, with the increase of enterprise R&D investment, the stricter CER, the more conducive it is to guiding and promoting enterprises to carry out green production.

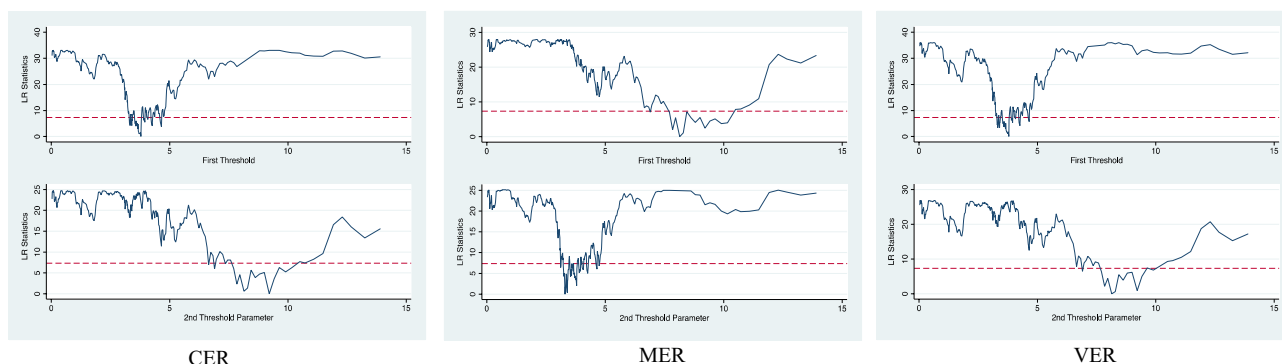


Figure 2. Double threshold effect diagram of the impact of heterogeneous environmental regulations on GTFP.

	Overall GTFP	Industry 1 GTFP	Industry 2 GTFP	Industry 3 GTFP	State GTFP	Non-state GTFP
$RD < r_1$	0.0072 (1.31)	0.0237** (2.04)	-0.0069 (-0.77)	0.0040 (0.51)	0.0071 (0.77)	-0.0074 (1.05)
$r_1 \leq RD < r_2$	0.0119** (2.18)	-	-	0.0089 (1.16)	-	0.0122* (1.73)
$RD \geq r_2$	0.0203*** (3.63)	0.0302** (2.55)	-0.0010 (-0.11)	0.0226*** (2.64)	0.0145 (1.59)	0.0243*** (3.18)
DL	0.0121*** (4.57)	0.0209*** (3.75)	0.0078 (1.52)	0.0107*** (3.02)	0.0145*** (3.03)	0.0116*** (3.67)
ROA	-0.0000 (-0.03)	0.0007 (1.36)	-0.0003 (-0.69)	-0.0024*** (-2.87)	0.0005 (1.30)	-0.0013* (-1.63)
ROE	-0.0000 (-0.17)	-0.0000 (-0.29)	0.0000 (0.63)	-0.0000*** (-4.76)	-0.0000* (-1.72)	0.0000* (1.67)
ROL	-0.0001 (-0.63)	0.0005 (1.09)	0.0000 (0.50)	-0.0004*** (-3.77)	0.0009** (2.17)	-0.0002 (-1.39)
Scale	-0.0629*** (-11.66)	-0.0620*** (-5.30)	-0.0648*** (-6.53)	-0.0604*** (-8.65)	-0.0687*** (-6.36)	-0.0594*** (-9.98)
cons	2.0173*** (17.78)	1.8725*** (7.39)	2.1571*** (10.37)	1.9889*** (13.81)	2.1240*** (9.50)	1.9340*** (15.12)
R ²	0.0292	0.0317	0.0339	0.0447	0.0353	0.0326
F	28.63***	6.98***	10.95***	28.80***	13.41***	21.78***

Table 4. Threshold regression results of CER on enterprise GTFP. ***, ** and * indicate the statistical significance of 1%, 5% and 10% respectively.

	Overall GTFP	Industry 1 GTFP	Industry 2 GTFP	Industry 3 GTFP	State GTFP	Non-state GTFP
$RD < r_1$	-0.0460*** (-3.98)	-0.3511* (-1.60)	0.0076 (0.40)	-0.0879*** (-4.48)	-0.0434** (-2.31)	-0.0451*** (-3.14)
$r_1 \leq RD < r_2$	-0.0113 (-0.98)	-	-	-0.0479*** (-2.82)	-	-0.0137 (-0.93)
$RD \geq r_2$	0.0561*** (3.16)	0.0170 (0.69)	0.0806*** (2.84)	0.0223 (0.92)	0.0069 (0.34)	0.0557*** (2.77)
DL	0.0113*** (4.10)	0.0191*** (3.34)	0.0101* (1.95)	0.0075** (2.07)	0.0131*** (2.77)	0.0104*** (3.23)
ROA	-0.0000 (-0.01)	0.0007 (1.34)	-0.0003 (-0.64)	-0.0025*** (-2.95)	0.0005 (1.27)	-0.0013* (-1.69)
ROE	-0.0000 (-0.19)	-0.0000 (-0.22)	0.0000 (0.58)	-0.0000*** (-4.93)	-0.0000* (-1.68)	0.0000* (1.75)
ROL	-0.0001 (-0.58)	0.0006 (1.16)	0.0000 (0.54)	-0.0004*** (-3.47)	0.0009** (2.20)	-0.0002 (-1.36)
Scale	-0.0617*** (-11.63)	-0.0609*** (-5.16)	-0.0653*** (-6.81)	-0.0592*** (-8.63)	-0.0681*** (-6.39)	-0.0587*** (-9.88)
cons	2.0703*** (18.26)	2.0292*** (8.04)	2.1222*** (10.12)	2.0457*** (13.95)	2.1930*** (9.37)	1.9990*** (15.92)
R ²	0.0291	0.0296	0.0336	0.0475	0.0342	0.0321
F	31.96***	6.95***	9.64***	32.02***	12.88***	20.91***

Table 5. Threshold regression results of MER on enterprise GTFP. ***, ** and * indicate the statistical significance of 1%, 5% and 10% respectively.

Table 3 and the first column in Table 5 all show that MER has a significant dual threshold impact on enterprise GTFP. If $RD < 3.30$, MER has a significant negative impact on enterprise GTFP. If $3.30 \leq RD < 8.14$, MER has no significant impact on enterprise GTFP. If $RD \geq 8.14$, MER has a significant positive impact on enterprise GTFP. The results indicate that the impact of MER on enterprise GTFP presents a “U-shaped” pattern. Only when enterprise R&D investment exceeds the threshold value can MER be conducive to enterprise GTFP. Therefore, when enterprises face an increasing fierce of MER, they should try to increase R&D investment, which can help enterprises cross the threshold of negative impact, and stimulate MER’s promoting effect on GTFP.

Table 3 and the first column in Table 6 all show that VER has a significant dual threshold impact on enterprise GTFP. If $RD < 3.79$, VER has a significant negative impact on enterprise GTFP. If $3.79 \leq RD < 8.14$, VER has a significant negative impact on enterprise GTFP but the negative effect was reduced obviously. If $RD \geq 8.14$, VER has no significant impact on enterprise GTFP. This result shows that the external environmental supervision mechanism increases enterprise environmental governance cost, which has a negative impact on enterprise GTFP in the short term, but this negative impact gradually weakens and tends to be positive with the increase of

	Overall GTFP	Industry 1 GTFP	Industry 2 GTFP	Industry 3 GTFP	State GTFP	Non-state GTFP
$RD < r_1$	-0.0090*** (-3.27)	-0.0258*** (-4.43)	0.0035 (0.79)	-0.0081* (-1.94)	-0.0094** (-2.02)	-0.0872** (-2.53)
$r_1 \leq RD < r_2$	-0.0052** (-1.88)	-	-	-0.0042 (-0.97)	-	-0.0049 (-1.39)
$RD \geq r_2$	0.0006 (0.20)	-0.0211*** (-3.66)	0.0081* (1.78)	0.0019 (0.42)	-0.0035 (-0.78)	0.0045 (1.09)
DL	0.0127*** (4.77)	0.0235*** (4.24)	0.0072 (1.41)	0.0093*** (2.57)	0.0152*** (3.17)	0.0123*** (3.91)
ROA	0.0000 (0.01)	0.0007 (1.41)	-0.0030 (-0.65)	-0.0025*** (-2.94)	0.0005 (1.31)	-0.0013* (-1.62)
ROE	-0.0000 (-0.22)	-0.0000 (-0.40)	0.0000 (0.59)	-0.0000*** (-5.08)	-0.0000* (-1.73)	0.0000* (1.66)
ROL	-0.0001 (-0.63)	0.0005 (1.03)	0.0000 (0.54)	-0.0004*** (-3.49)	0.0008** (2.13)	-0.0002 (-1.38)
Scale	-0.0619*** (-11.56)	-0.0596*** (-5.13)	-0.0660*** (-6.68)	-0.0582*** (-8.45)	-0.0674*** (-6.38)	-0.0584*** (-9.74)
cons	2.1151*** (18.64)	2.1875*** (8.64)	2.1102*** (10.14)	2.0246*** (14.08)	2.2161*** (9.54)	2.0343*** (16.46)
R ²	0.0300	0.0359	0.0345	0.0457	0.0358	0.0333
F	31.02***	8.50***	10.54***	33.88***	13.47***	24.47***

Table 6. Threshold regression results of VER on enterprise GTFP. ***, ** and * indicate the statistical significance of 1%, 5% and 10% respectively.

enterprise R&D investment. Thus, if companies want to avoid the negative impact of VER on GTFP, they should try to increase R&D investment as much as possible and cross the threshold of negative impact.

Heterogeneity analysis

Heterogeneity of industries

The sample enterprises are subdivided into high pollution industries, medium pollution industries and low pollution industries to further discuss the threshold mechanism of heterogeneous environmental regulations affecting enterprise GTFP. The results are shown in Tables 4, 5, and 6. Among them, Industry 1 represents high pollution industries, Industry 2 represents medium pollution industries, Industry 3 represents low pollution industries.

The regression results indicate that CER, MER, and VER all have threshold effects on enterprise GTFP, and the degree of impact varies across industries. Among them, CER has a more significant environmental driving effect on enterprises in highly polluting industries, which is conducive to promoting these enterprises to increase their GTFP. This also reflects that China's current CER is moderately and effective. Overall, they have not increased the environmental governance burden on manufacturing enterprises in medium and low pollution industries, and are also effective regulations for excessive pollution of manufacturing enterprises in high pollution industries. MER increases the internal cost of enterprise pollution governance, so it has a negative impact on enterprise GTFP as a whole. VER has a stronger regulatory effect on high pollution enterprises.

Heterogeneity of ownership

The sample enterprises are further subdivided into state-owned and non-state-owned enterprises to discuss the heterogeneous threshold effect. The results are shown in Tables 4, 5, and 6. Among them, State represents state-owned enterprises, Non-state represents non-state-owned enterprises.

The regression results indicate that CER, MER, and VER all have threshold effects on enterprise GTFP, and the degree of impact varies across equity structure. The impact on non-state-owned manufacturing enterprises is more significant.

Robustness tests

Robustness test is performed by two approaches. On the one hand, the Winsorizing method was made on every variable to test the robustness of research conclusions. Specifically, all continuous variables were Winsorized at the 1% and 99% levels to mitigate the potential impact of outliers on empirical results. On the other hand, threshold regression tests were re-conducted based on the dependent variable set one-period lag. The robustness test results are shown in Table 7. The results show that all variables basically maintain the same impact direction and impact trend, and pass the significance test. The research conclusions are reliable and robust.

Conclusions and limitations

Conclusions and policy implications

Based on the panel data of 1220 Chinese manufacturing listed companies from 2011 to 2020, this paper uses threshold regression model to examine the impact of heterogeneous environmental regulations on enterprise GTFP. Three main conclusions are drawn. (1) Heterogeneous environmental regulation has a double threshold impact on enterprise GTFP. Specifically, CER has a significant positive impact on enterprise GTFP, but the degree

	Sample reduction			GTFP One-period Lagging		
	GTFP (CER)	GTFP (MER)	GTFP (VER)	GTFP (CER)	GTFP (MER)	GTFP (VER)
$RD < r_1$	0.0052 (0.98)	-0.0436*** (-4.40)	-0.0095*** (-3.72)	0.0076 (1.46)	0.0167 (1.50)	0.0064 (2.20)
$r_1 \leq RD < r_2$	0.0089* (0.98)	-0.0131 (-1.34)	-0.0064** (-2.51)	0.0016 (0.31)	-	0.0035 (1.19)
$RD \geq r_2$	0.0153*** (2.92)	0.0394*** (2.47)	-0.0020 (-0.73)	-0.0048 (-0.88)	-0.0324*** (-2.85)	0.0000 (0.00)
DL	0.0112*** (4.72)	0.0101*** (4.21)	0.0119*** (5.02)	0.0061* (1.88)	0.0055* (1.71)	0.0059* (1.85)
ROA	-0.0045*** (-4.80)	-0.0045*** (-4.79)	-0.0045** (-4.81)	0.0008* (1.81)	0.0008* (1.85)	0.0008* (1.86)
ROE	0.0006 (1.44)	0.0005 (1.38)	0.0006 (1.46)	-0.0000 (-0.80)	-0.0000 (-0.90)	-0.0000 (-0.88)
ROL	-0.0003 (-1.49)	-0.0003 (-1.28)	-0.0003 (-1.47)	0.0000 (0.51)	-0.0000** (-2.38)	0.0000 (0.53)
Scale	-0.0597*** (-12.79)	-0.0597*** (-12.95)	-0.0586*** (-12.59)	-0.0149** (-2.18)	-0.0163** (-2.38)	-0.0161** (-2.34)
cons	1.9806*** (20.09)	2.0466*** (20.90)	2.0671*** (21.43)	0.9827*** (6.44)	1.0461*** (6.98)	1.0124*** (6.87)
R ²	0.0428	0.0435	0.0439	0.0098	0.0081	0.0094
F	42.16***	44.19***	45.48***	9.80***	8.16***	8.68***

Table 7. Robustness tests results. ***, ** and * indicate the statistical significance of 1%, 5% and 10% respectively.

of impact decreases. MER has a significant “U-shaped” impact on enterprise GTFP. VER has a significant negative decreasing influence on enterprise GTFP. (2) Enterprise R&D investment plays a threshold role in the impact of heterogeneous environmental regulations on enterprise GTFP. The “Follow Cost” and “Porter Hypothesis” effects act at different stages. And these findings remain valid after a series of robustness tests. (3) There are industry and ownership differences in the impact of heterogeneous environmental regulations on GTFP. In general, environmental regulations have a more significant impact on enterprises in highly polluting industries and non-state-owned enterprises.

These conclusions have valuable policy implications for formulating flexible environmental regulations and promoting Chinese enterprises low-carbon development. Firstly, the empirical results show that environmental regulations are not the stricter the better. On the one hand, the environmental effects motivated by environmental regulations show significant dual threshold effect, and the trend of MER is most obviously. On the other hand, the environmental effects motivated by environmental regulations show industry and ownership differences. Thus, the government should develop a flexible environmental regulation system and prioritize the use of market-incentive environmental regulation measures. Secondly, the empirical results show that enterprises R&D investment determine the influence direction and degree. Therefore, manufacturing enterprises should rely on more R&D investment to decrease the “obstructive effects of environmental regulations”, and achieve green, low-carbon, and sustainable development while improving enterprise productivity simultaneously.

Limitations and future research

This paper still has some limitations which may also be directions for future research. Firstly, in view of limited data, “enterprises industrial wastes data” used in this study is to quantify the industrial wastewater, SO₂ and industrial smoke emissions at the city level to the enterprise level on a year-on-year basis through the “proportion of total output value of enterprises”. In future studies, data algorithms can be further improved to evaluate the effectiveness of heterogeneous environmental regulations on enterprises green growth. Secondly, this article mainly explores the threshold effect of heterogeneous environmental regulations on enterprise GTFP. Nowadays, some studies have pointed out that there is a two-way dynamic relationship between heterogeneous environmental regulations and green development⁵³, and the environmental effects motivated by environmental regulations have spillover effects⁷. Therefore, further research can explore these aspects in depth. Thirdly, digitalization is booming worldwide attention, which has brought both opportunities and challenges to enterprises green development. Although enterprise digital level has been considered as a controllable variable in this article, we didn't mainly discuss its effects. In the future, researches could conduct in-depth researches on the impact of enterprise digital level as a core variable on enterprise GTFP.

Data availability

Data will be made available on request.

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Competing interests

The authors declare no competing interests.

Additional information

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