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Synergistic Effects of Environmental Regulations on Carbon Productivity Growth in China's Major Industrial Sectors

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Abstract: It is crucial that the implementation of environmental regulations have a positive synergistic effect on carbon productivity growth (i.e., environmentally adjusted productivity growth with the consideration of carbon emissions) for China to realize its sustainable development goals because the country is currently under tripartite pressures of economic growth, carbon emissions control, and environmental pollution reduction. This paper investigates the impact of changes in environmental regulation stringency on industrial-level carbon productivity growth in China. Through utilizing the information entropy method, a new index of environmental regulation stringency is established by taking into account the effects of both pollution reduction consequences and pollution reduction measures. In addition, based on the data envelopment analysis (DEA) method, a Malmquist carbon productivity index is proposed to estimate the industrial carbon productivity growth of 21 major industrial sectors in China’s 30 provinces over 2004-2014. Finally, an econometric regression model is applied to test the synergistic effects of environmental regulations on carbon productivity in China's major industrial sectors. The results show that (i) a stringent environmental regulation is associated with an increase in overall industrial carbon productivity growth in China; (ii) there exist significant pass-through effects in China's major industrial sectors that technology can transmit effectively from leader to follower; (iii) there also exist obvious follow-up effects in China's major industrial sectors, i.e., the industrial sectors that have larger technological gaps with the leaders catch up faster than others; and (iv) the environmental regulations have different

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effects on industrial sectors with different polluting levels, i.e., there is a positive linear relationship between environmental regulation stringency and industrial-level carbon productivity growth in low-polluting industrial sectors, a parabolic nonlinear relationship between them in high-polluting industrial sectors, and an inverted U-shaped relationship between them in moderate-polluting industrial sectors.

Keywords: China's industrial sector; environmental regulation; industrial heterogeneity; pollution intensity; total factor carbon productivity

1 Introduction

With the enhancement of global warming, countries around the world have taken a wide range of actions to avoid dangerous climate change. Improving carbon productivity is an important way to address climate change, since carbon productivity combines economy development and emission reduction. China is currently under the tripartite pressures of economic growth, carbon emissions control, and environmental pollution reduction. It is crucial that the implementation of environmental regulations have a positive synergistic effect on carbon productivity growth (i.e., environmentally adjusted productivity growth with the consideration of carbon emissions) for China to realize its sustainable development goals.

China promulgated the Environmental Protection Law of the PRC (People's Republic of China) in 1979, marking the beginning of the development of environmental protection in China. China is currently achieving several goals related to energy saving and emission reductions. First, China's oil and coal consumption has transformed from a rapidly growing stage to a slow growth stage. Second, coal consumption growth in China has entered a decline channel since the high energy-consuming industries have gradually entered the platform period; moreover, energy supply reform has been conducted in recent years. With the gradual improvement due to the reform, coal consumption has been declining for five years, from 70.2% in 2010 to 62.3% in 2016. In 2014, the national coal output declined by 2.5%, which is the first time that coal production has declined in China, which is considered a landmark result in the adjustment of China’s energy mix. However, according to the 2017 BP (British Petroleum) World Energy Statistics Yearbook (BP, 2017), the ratios of coal consumption in primary energy consumption in the US and Canada are 15.8% and 5.7%. The gap between China and the developed countries remains very large, and China's energy consumption structure needs to be continually adjusted.

China is currently under the tripartite pressures of economic growth, carbon emissions control, and environmental pollution reduction. Reducing carbon emissions means reducing the dependence on energy consumption. Under China’s current economic development mode, the reduction of energy consumption will inevitably impede the growth of the economy. To achieve low-carbon economic transition goals, increasing carbon productivity is the only way to achieve economic growth and control CO_2 emissions (Li et al., 2014). Pan et al. (2010) point out that carbon productivity gives new constraints to social and economic development from the perspective of input factors and becomes a new indicator that can be compared with traditional labor productivity and capital productivity.

The ongoing tightening of environmental regulation may influence industries' incomes and outcomes, thus affecting carbon productivity. Conventional economic wisdom has long suggested that environmental regulation is an additional burden that industries are required to comply with. Industries face added cost (i.e., extra regulatory costs for environmental protection) or must reduce output. These effects reduce profitability. In the 1990s, a revision viewpoint called the Porter Hypothesis (PH) emerged (Porter, 1991; Porter and van der Linde, 1995), which argues that environmental regulation could promote productivity through incentives in innovation, efficiency improvements, and resource reallocation. The PH suggests that environmental regulation may improve productivity and even result in lower costs. Jaffe and Palmer (1997) characterize three variants of the PH: the weak version, the strong version, and the narrow version. The weak PH claims that environmental regulation will stimulate innovation. The strong PH suggests that environmental regulation will drive innovation offsets that exceed the cost of regulatory compliance. Environmental regulation will result in net productivity growth. The narrow PH implies that certain types of environmental regulations (i.e., flexible and market-based instruments), which are well designed, can provide industries more incentives to innovate in productivity. Levinson and Taylor (2008) propose that these types of environmental regulations can affect market access. Polluting firms may exit or enter the market, decrease or increase their outcomes, and further decrease or increase their productivities.

Empirical evidence of the synergistic effect of environmental regulations and productivity is inconclusive. Few researchers have examined the synergistic effects of environmental regulations on carbon productivity growth. This paper aims to explore the synergistic effect of environmental regulation and carbon productivity growth from a meso-level perspective. The data used in this article include input elements (capital, labor, and energy), industrial output, population, GDP per capita, etc. Our research focuses on the following: (i) the status of environmental regulation stringency in China; (ii) the status of carbon productivity in China; (iii) whether the implementation of environmental regulations have positive synergistic effects on carbon productivity growth in China; and (iv) whether there is a heterogeneity of synergistic effects among different industries. The results of the study will help make more targeted policies for different types of industries.

Our results show that stringent environmental regulation is associated with increased industrial carbon productivity growth in China. There exist significant pass-through effects in China's major industrial sectors allowing technology to be transmitted effectively from leader to follower. There also exist obvious follow-up effects in China's major industrial sectors; the industrial sectors that have larger technological gaps with the leaders catch up faster than others. Moreover, environmental regulations have different effects on industrial sectors with different pollution levels. Specifically, there is a positive linear relationship between environmental regulation stringency and industrial-level carbon productivity growth in low-polluting industrial sectors; a parabolic nonlinear relationship between them in high-polluting industrial sectors; and an inverted U-shaped relationship between them in moderate-polluting industrial sectors.

This paper is organized as follows. Section 2 provides an overview of the relevant empirical literature on the effects of environmental regulation stringency on productivity growth. Section 3 proposes the measuring method for environmental regulation stringency and total factor carbon productivity growth. The econometric model for estimating the synergistic effects is also proposed in Section 3. Section 4 provides the data resource and the computing method. Section 5 explains the main results, and Section 6 concludes the paper.

2 Literature review

Early research on the relationship between environmental regulation stringency and productivity provided different conclusions (OECD, 2010). Some studies found that environmental regulation stringency increases the cost of industries. Regulations bring newly imposed constraints on production cost decisions, the enterprise's management decisions, and production output (Palmer and Portney, 1995). The PH indicates that appropriate environmental regulation can make the enterprise conduct more innovation activities, which can offset costs by improving productivity growth, ultimately improving industrial productivity (Porter and van der Linde, 1995). However, some research has opposed the PH, arguing that firms may not conduct innovation activities on their own unless the government pushes them to do so because the regulations conflict with the profit maximization assumption of neoclassical economics. Ambec et al. (2013) support this opinion through reviewing a cross-section of studies and found that more recent studies have tended to find positive synergistic effects of environmental regulation and productivity. Their research also proposed that environmental regulation can push industries with high emissions and low productivity to go out of business or transfer, thus improving industry productivity growth. Moreover, environmental regulation may hinder the entry of an industry and reduces the competition among enterprises in the industry, ultimately reducing industry productivity.

Some scholars in China have also used different methods and samples to study the relationship between productivity growth and environmental regulation. Wang et al. (2015) use a non-radial and non-oriented SBM model to measure China's provincial industrial carbon productivity over the period 2003-2013. They found that the environmental regulation has no influence on China's industrial carbon emissions performance. He (2014) uses data from China's 36 industrial sectors to calculate industrial carbon emissions over the period 2001-2010. The results showed that increased environmental regulation stringency improves the entire industry's carbon emission performance. Ambec et al. (2013) propose that one of the most spectacular outcomes of environmental regulation over the past decades has been the emergence of the environmental goods and the service industry. Li and Lu (2010) examine the effect of environmental regulation and innovation in improving China’s provincial carbon productivity, finding that environmental regulation and innovation both promote China's provincial carbon productivity growth significantly. Wang and Liu (2014) use a sample of China’s industries from 1998 to 2011 and measured the impact of environmental regulation on total factor productivity growth. They found that the relationship between environmental regulation and total factor productivity growth of industries is in conformity with an inverted N-shaped curve.

Only a few studies focus on the impact of environmental regulation stringency on carbon productivity in academic circles. Most of the current studies focus on the relationship between environmental regulation stringency and productivity, and environmental regulation stringency has not been regarded as the core explanatory variable in these studies. It can be seen from the above research that the impact of environmental regulation stringency on carbon productivity requires further attention.

This paper focuses on the effects of environmental regulation stringency (ERS) on the carbon productivity growth index (CPI) by investigating the impact of changes in environmental regulation stringency on industrial-level carbon productivity growth in China. First, we establish a new index of environmental regulation stringency by taking into account the effects of both pollution reduction consequences and pollution reduction measures using the information entropy method. Then, we propose a Malmquist carbon productivity index to measure the industrial carbon productivity growth of 21 major industrial sectors in China’s 30 provinces over the period 2004-2014 based on the data envelopment analysis (DEA) method. Finally, we apply an econometric model to test the synergistic effects of environmental regulations on carbon productivity in China's major industrial sectors.

3 Methodology

3.1 Index for environmental regulation stringency

We establish an index using two dimensions to measure environmental regulation stringency. Previous articles which calculated environmental regulation stringency always measure it from the perspective of pollution reduction consequence. The province which with higher soot removal rate and comprehensive utilization rate has stricter environmental regulation stringency. But pollution reduction consequence is serious affected by provinces’ resource endowment and the positional condition. Thus, in our study, we add pollution reduction measures as a supplement to pollution reduction consequences. Pollution reduction measures presents the strength of environmental regulation in the process of collecting sewage charges. These two mentions together make the Index for environmental regulation stringency more representative. One dimension is pollution reduction consequences (measured by indicators of the comprehensive utilization rate of industrial solid waste, wastewater discharge compliance rate, SO_2 removal rate, and soot removal rate), and the other dimension is pollution reduction measures (evaluated through indicators of environmental protection investment as a share of GDP, wastewater discharge fee collection efforts, and SO_2 discharge fee collection efforts).

The information entropy method is utilized in this paper for calculating the index of environmental regulation stringency. Entropy is a measure of diversity or uniformity in microscopic state of thermodynamics, indicating the degree of disorder of the system. Information entropy method can determine information weights of the uncertainty degree of the information source. Finally, we can get more considerable weight of each index through this method.

First, we set up the original evaluation matrix $X=(x_{jh})$, where x_{jh} is the raw data of the indicator; $j=1,\ldots,J$, represents the Chinese provinces included in our evaluation, while $h=1,\ldots,H$, represents the indicators. In this study, $J=30$ and $H=7$. To avoid the influence of the scale of each indicator, we normalize each indicator k for each province j as follows:

$$y_{jh} = \frac{x_{jh} - \min_j x_{jh}}{\max_j x_{jh} - \min_j x_{jh}} \qquad (1)$$

In Equation (1), y_{jh} represents the normalized data, and the normalized matrix is $Y=(y_{jh})$. Each indicator h has an entropy weight W_h, which can be calculated using the following equations:

$$e_h = -m\sum_{j=1}^{J} p_{jh} \times \ln p_{jh} \qquad (2) \qquad IW_h = \frac{1-e_h}{\sum_{h=1}^{H}(1-e_h)} \qquad (3) \qquad W_h = IW_h \times DW_h \qquad (4)$$

where $m = 1/\ln J$, and $p_{jh} = y_{jh} \Big/ \sum_{j=1}^{J} y_{jh}$. Note that when $p_{jh}=0$, $p_{jh}\times\ln p_{jh}=0$; $0 \le W_h \le 1$, $\sum_{h=1}^{7} W_h = 1$; DW_h is the subjective dimension weight, and we set $DW_h = \frac{1}{2}$ since we consider the two dimensions, i.e., pollution reduction consequences and pollution reduction measures, to have the same importance in the measure of environmental regulation stringency. Finally, we can obtain the index for environmental regulation stringency, ERS_j, for province j by linearly aggregating each indicator as follows:

$$\mathrm{ERS}_j = \sum_{k=1}^{7} W_k \times y_{jk}, \ j=1,\ldots,30 \qquad (5)$$

3.2 Index for total factor carbon productivity growth

We measure the carbon productivity growth, i.e., environmentally adjusted productivity growth with the consideration of carbon emissions, through a Malmquist index for China's 30 provinces from 2004 to 2014, and the DEA method is applied to derive the Malmquist carbon productivity growth index. The efficiency scores in this study are estimated using DEA based Russel measure which is multiplicative by nature, and thus the productivity change should be computed by using the Malmquist productivity index which is multiplicative by nature. Luenberger productivity indicator is an additive measure of productivity change and is appropriate to be combined with the directional Russel measure of efficiency or slacks-based measure of efficiency (Wang and Wei, 2016). Therefore, we chose Malmquist productivity index in this study. The Malmquist index is defined using distance functions that allow one to describe a multi-input and multi-output production technology without specifying a behavioral objective (such as cost minimization or profit maximization). Input distance functions and output distance functions can be defined. An input distance function characterizes the production technology by searching the minimal proportional contraction of the input vector given an output vector; an output distance function considers a maximal proportional expansion of the output vector given an input vector. In this study, we utilize an output distance function.

Each industry sector in each province of China is taken as a decision-making unit (DMU) in this study. Following Färe et al. (1994), we suppose that in each period t=1,...,T, each DMU$_k$, k=1,…,K, uses n=1,...,N inputs x^t_{kn} to produce m=1,...,M outputs y^t_{km}. Each phase of the reference technology under the condition of constant returns to scale (C) and strong disposability (S) of inputs and outputs is defined as follows:

$$L^t(x^t, y^t \mid C, S) = \{y^t \le \lambda^t Y, \lambda^t X \le x^t, \lambda^t \in R_+^K, x^t \in R_+^N, y^t \in R_+^M\} \qquad (6)$$

The non-parametric programming DEA model used to calculate the Farrell technical efficiency of each DMU is as follows:

$$\begin{aligned} & F_k^t(x^t, y^t \mid C, S) = \max_{\theta,\lambda} \theta_k \\ & s.t.\ \theta_k y^t_{k_0 m} \le \sum_{k=1}^{K} \lambda_k^t y^t_{km}, m = 1, ..., M \\ & \quad x^t_{k_0 n} \ge \sum_{k=1}^{K} \lambda_k^t x^t_{kn}, n = 1, ..., N \\ & \quad \lambda_k^t \ge 0, k = 1, ..., K, t = 1, ..., T \end{aligned} \qquad (7)$$

To obtain the Malmquist productivity index, we introduce the distance function. According to Färe et al. (1997), the distance function is the inverse of the Farrell's technical efficiency obtained in Model (7), so the output distance function $D_k^t(x^t, y^t)$ under the reference technology $L^t(x^t, y^t \mid C, S)$ can be defined as follows:

$$D_k^t(x^t, y^t) = 1 / F_k^t(x^t, y^t \mid C, S) \qquad (8)$$

The output distance function is the maximum approximation of a production point (x^t, y^t) to the ideal maximum output point, i.e., the ratio of one output to the largest possible output. Production is technically efficient if $D_0^t(x^t, y^t)=1$, and then (x^t, y^t) is at the production boundary. Production is technically ineffective if $D_0^t(x^t, y^t) > 1$, and (x^t, y^t) is within the production boundary. At time t + 1, we can obtain the distance function $D_0^{t+1}(x^{t+1}, y^{t+1})$ by changing t to t+1.

According to Caves et al. (1982), the Malmquist productivity index can be expressed as follows:

$$M_k^t = D_k^t(x^{t+1}, y^{t+1}) / D_k^t(x^t, y^t) \qquad (9)$$

This index measures the change in total factor productivity growth from period t to t + 1 under the technical condition of period t. Similarly, we can define the Malmquist productivity index from period t to t + 1 under the technical condition of period t + 1 as follows:

$$M_k^{t+1} = D_k^{t+1}(x^{t+1}, y^{t+1}) / D_k^{t+1}(x^t, y^t) \qquad (10)$$

Following Färe et al. (1992), the change in productivity can be calculated using the geometric mean of two Malmquist productivity indices:

$$M_k(x^{t+1}, y^{t+1}, x^t, y^t) = \left[\frac{D_k^t(x^{t+1}, y^{t+1})}{D_k^t(x^t, y^t)} \times \frac{D_k^{t+1}(x^{t+1}, y^{t+1})}{D_k^{t+1}(x^t, y^t)} \right]^{\frac{1}{2}} \qquad (11)$$

The Malmquist productivity index can be decomposed into changes in technical efficiency and technological progress. In this paper, we use only the Malmquist productivity growth index as our explained variable; thus, decomposition to technical efficiency and technological progress is omitted here.

3.3 Econometric model

We apply an econometric model to test the synergistic effects of environmental regulations on carbon productivity in China's major industrial sectors. We augment the regression model of Bourlès et al. (2013) with environmental regulations, allowing the latter to have different effects on the CPI by setting a heterogeneous effect of regulations and the technological gap. The most technologically advanced industry is likely to have more resources to invest into R&D or knowledge-based capital and scale up energy efficiency gains from abatement. They may also be better suited to adapt to new environmental regulations and have the best access to financial markets, hence being better suited to accommodate policy changes. However, less technologically advanced industries may find it difficult to comply with new environmental regulations. The econometric model for testing the synergistic effects of different industry sectors is as follows:

$$cpi_{cit} = \alpha_1 + \alpha_2 ed_{i2004} ers_{ct} + \alpha_3 ed_{i2004} ers_{ct} gap_{cit} + \alpha_4 gap_{cit} + \alpha_5 cpi_i + \gamma \chi_{cit} + \eta_t \qquad (12)$$

In Equation (12), *ers* indicates environmental regulation stringency, *cpi* is the carbon productivity growth index, cpi_{cit} is the carbon productivity growth index for each combination of province *c* and its industry sector *i* at time *t*, and *ed* indicates environmental dependence, which is represented by pollution intensity in this paper. The environmental regulations are likely to affect carbon productivity depending on the sectors' exposure to the regulation. The higher the pollution intensity of the industry, the more sensitive of it to responds to environmental policies, and the higher environmental dependence of it. An industry sector with higher *ed* is more susceptible to environmental regulation stringency. We set a heterogeneous effect of policy and *ed*. The identification strategy is based on the fact that environmental policies are likely to affect industry productivity growth heterogeneously, although this depends on the industry's exposure to the regulation (Rajan and Zingales, 1998). This study's period is 2004 to 2014, so we chose 2004 as the base year to calculate ed. Then we use entropy weight method to generate four indicators including total amount of industrial solid waste emissions, industrial waste water emissions, industrial waste gas emissions and industry smoke dust emissions.

Thus, in the empirical specification, *ers* interacts with the pollution intensity of the industry. See the data section for more details on the environmental dependence variable. Moreover, we set a heterogeneous effect of policy and the technological *gap*, which is defined as the distance to the industry frontier $gap = \ln(cpi_i / cpi_{ci})$. The fourth term in Equation (12) is the distance to the productivity frontier, which allows for measuring technological catch-up effects. The industry frontier cpi_i is defined as the highest *CPI* across provinces by industry.

We use three different scenarios in terms of controls χ_{cit}. Scenario one includes the GDP per capita and FDI/GDP (to control for market openness). In scenario two, an additional dummy variable is included for the financial crisis. In scenario three, we additionally control for the fact that R&D intensive industries are more likely to have higher productivity growth; therefore, R&D/GDP is added as a control variable. Finally, we control for a time trend η_t. In addition, we sort the industrial sectors into three parts based on the highest- to the lowest-polluting intensity, and the specific classification is introduced in Table 1.

Table 1 Classification of industrial sectors regarding their pollution intensity

Classification	Industry
Light polluting industry	Equipment for Special Purposes Textile Manufacture of General Electric Equipment and Machinery Transportation Equipment Telecommunications Equipment
Moderate polluting industry	Instruments, Meters, Cultural and Office Machinery Medical and Pharmaceutical Products Tobacco Processing Printing and Record Medium Reproduction Manufacture of Textile Wearing Food Processing Metal Products
Severe polluting industry	Papermaking and Paper Products Nonmetal Mineral Products Chemical Fiber Beverage Production Smelting and Pressing of Nonferrous Metals Smelting and Pressing of Ferrous Metals Raw Chemical Materials and Chemical Products Petroleum Processing and Coking Food Processing

According to Table 1, the majority of the low-polluting industries are high-tech industries. Moreover, moderate-polluting industries are mainly traditional light industries, and the majority of the high-polluting industries are traditional heavy industries.

4 Data

The data used in this study are obtained from the China City Statistical Yearbook, the China Energy Statistical Yearbook, and the CEAD database. The following are the main features of the data used in this study:

Province coverage: The study includes 30 provinces in China. Taiwan, Hong Kong, Macao and Tibet are not included because due to the lack of data.

Time period: The study period is 2004 to 2014, which covers the 2007-2008 global financial crisis.

Outputs: Studies often use GDP, regional GDP, and industrial value added as good outputs. This study refers to Chen and Li (2006) and applies the gross industrial output value (constant prices based on 2004) as the indicator of good output. There has been no strict definition of the choice of bad output in previous research, and the indicators commonly used for bad outputs are industrial waste (Zhang et al. 2011), SO_2 emissions (Tu, 2008), COD (Wang et al., 2010), and CO_2 emissions (Zhang et al., 2013). Because the carbon productivity growth measured in this paper is actually a total factor carbon productivity growth index that takes CO_2 emissions into account, CO_2 emissions from industry sectors are used as a representation of bad output.

Inputs: This study has three input elements: capital, labor, and energy. According to data availability, we select the net value of fixed assets (constant price in 2004) of each industrial sector as the capital input variable, the average number of all employees in each industrial sector as the labor input variable, the total energy consumption (in terms of standard coal equivalent) in each industrial sector as the energy input variable.

Among the control variables of econometric model, the population comes from "National Bureau of Statistics - annual data of the province - population"; the FDI comes from "National Bureau of Statistics - annual data of the province - foreign direct investment"; the per capita GDP comes from "the National Bureau of Statistics - the annual data of the province - the gross regional product"; and the R&D comes from the "National Bureau of statistics - Annual data of provincial data - R&D". The time trend use "1, 2, …, 11" instead of "2004, 2005, …, 2014".

5 Results

5.1 Environmental regulation stringency

The index of environmental regulation stringency, ERS, of 30 provinces in China from 2004 to 2014 is first calculated using Equations (1) to (5), and the results are shown in Table 2.

Table 2 ERS of 30 provinces from 2004 to 2014

Province	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Beijing	0.74	0.72	0.75	0.66	0.61	0.63	0.60	0.58	0.54	0.54	0.63
Tianjin	0.70	0.75	0.56	0.67	0.64	0.65	0.66	0.65	0.62	0.62	0.59
Hebei	0.67	0.61	0.54	0.53	0.64	0.70	0.68	0.65	0.56	0.56	0.54
Shanxi	0.61	0.48	0.43	0.60	0.71	0.80	0.79	0.79	0.69	0.69	0.37
Inner Mongolian	0.68	0.56	0.60	0.61	0.66	0.68	0.76	0.76	0.71	0.71	0.72
Liaoning	0.75	0.54	0.49	0.46	0.49	0.64	0.53	0.62	0.62	0.62	0.54
Jilin	0.58	0.49	0.38	0.58	0.56	0.57	0.61	0.58	0.55	0.55	0.55
Heilongjiang	0.61	0.38	0.34	0.50	0.45	0.61	0.56	0.56	0.48	0.48	0.55
Shanghai	0.63	0.67	0.62	0.65	0.64	0.63	0.60	0.59	0.55	0.55	0.59
Jiangsu	0.73	0.73	0.63	0.65	0.72	0.72	0.69	0.68	0.64	0.64	0.65
Zhejiang	0.67	0.62	0.53	0.55	0.76	0.63	0.65	0.64	0.61	0.61	0.56

Anhui	0.65	0.51	0.44	0.50	0.66	0.73	0.66	0.68	0.65	0.65	0.65
Fujian	0.61	0.59	0.49	0.50	0.63	0.68	0.61	0.61	0.57	0.57	0.57
Jiangxi	0.61	0.58	0.50	0.54	0.68	0.77	0.76	0.79	0.75	0.75	0.62
Shandong	0.63	0.59	0.56	0.57	0.67	0.72	0.65	0.65	0.63	0.63	0.63
Hebei	0.67	0.61	0.54	0.53	0.64	0.70	0.68	0.65	0.56	0.56	0.54
Hubei	0.60	0.52	0.44	0.42	0.55	0.64	0.57	0.59	0.56	0.56	0.54
Hunan	0.58	0.37	0.28	0.25	0.46	0.58	0.47	0.48	0.44	0.44	0.43
Guangdong	0.59	0.55	0.49	0.54	0.52	0.65	0.59	0.58	0.56	0.56	0.57
Guangxi	0.73	0.39	0.26	0.47	0.55	0.73	0.71	0.67	0.60	0.60	0.57
Hainan	0.17	0.56	0.54	0.58	0.59	0.68	0.66	0.72	0.71	0.71	0.64
Chongqing	0.81	0.60	0.50	0.37	0.57	0.59	0.67	0.68	0.61	0.61	0.57
Sichuan	0.60	0.31	0.34	0.57	0.60	0.66	0.55	0.60	0.61	0.61	0.63
Guizhou	0.60	0.55	0.51	0.57	0.61	0.55	0.48	0.57	0.62	0.62	0.65
Yunnan	0.56	0.51	0.38	0.51	0.56	0.68	0.64	0.63	0.58	0.58	0.63
Gansu	0.63	0.59	0.52	0.50	0.55	0.60	0.60	0.68	0.67	0.67	0.63
Qinghai	0.57	0.39	0.29	0.22	0.42	0.49	0.50	0.47	0.25	0.25	0.40
Ningxia	0.77	0.74	0.52	0.81	0.84	0.85	0.75	0.77	0.77	0.77	0.77
Xinjiang	0.52	0.36	0.09	0.30	0.17	0.31	0.18	0.27	0.31	0.31	0.34

5.2 Total factor carbon productivity growth

The results of the index for total factor carbon productivity growth, CPI, are reported in this section. Because we have 10 years of data for 30 provinces with 21 industry sectors, there are 21×30×10=6,300 CPI observations.

Figures 1 and 2 show the average CPI of each province and the average CPI of China’s eastern, central, and western areas. The eastern area includes the 11 provinces of Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; the central area includes the 8 provinces of Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan; and the western area includes the 11 provinces of Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Ningxia, Qinghai, and Xinjiang. The Efficiency change in time is similar to the findings of Wang et al. (2018b). The CPI in the eastern area is higher than that of the central area; the CPI of the western area is the lowest. During 2008 and 2014, the CPI of the eastern, central, and western areas all showed slow upward trends; the growth rates of the CPI in the central and western areas increased. The CPI gap between the eastern area and the central and western areas began to narrow.

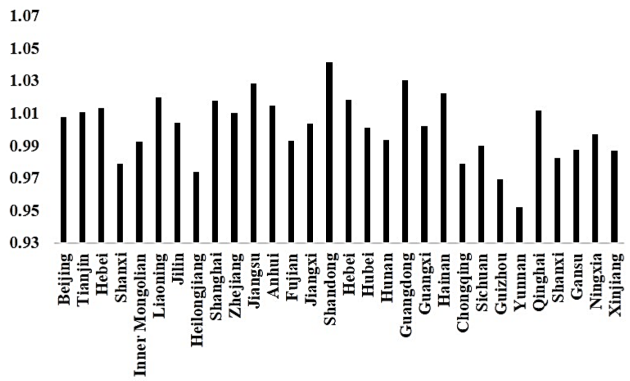

Figure 1 Annual average CPI of China's 30 provinces during the period 2004-2014

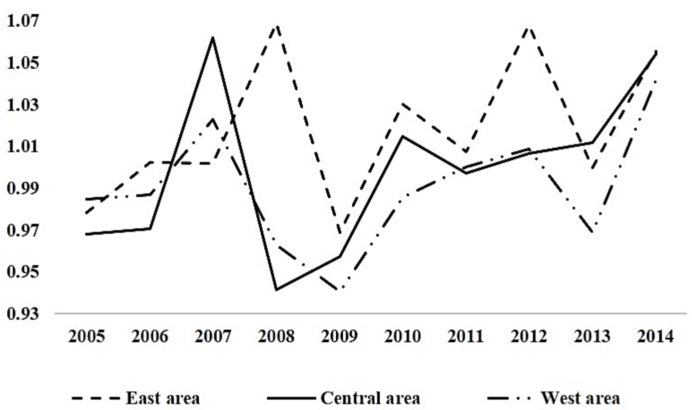

Figure 2 Provincial average CPI in China's eastern, central, and western areas

5.3 Synergistic effects of ERS on CPI: entire industrial sectors

The fixed-effect regression model is applied for estimating the parameters in Model (12), and the results are shown in Table 3.

Table 3 Regression outcome of entire industrial sectors

	Scenario One	Scenario Two	Scenario Three
cpi	0.17***	0.18***	0.18***
	(0.01)	(0.01)	(0.01)
gap	0.13**	0.11**	0.11**
	(0.01)	(0.05)	(0.05)
ed×ers	0.05*	0.05*	0.05*
	(0.03)	(0.03)	(0.03)

$ed \times ers^2$	-0.22***	-0.22***	-0.22***
	(0.03)	(0.03)	(0.03)
$gap \times ed \times ers$	0.18***	0.19***	0.19***
	(0.02)	(0.03)	(0.02)
t	0.00	0.00	0.00
	(0.00)	(0.00)	(0.00)
crisis		-0.02***	-0.029***
		(0.00)	(0.00)
per GDP	0.02***	0.01***	0.01***
	(0.00)	(0.00)	(0.01)
FDI/GDP	0.00	0.00	0.01
	(0.01)	(0.00)	(0.01)
R&D/GDP			0.04
			(1.78)
Constant	3.30	2.81	2.82
	(3.62)	(3.62)	(3.65)

Note: Standard errors are in parentheses; ***, ** and * denote significance at 1%, 5%, and 10% levels, respectively.

Table 3 reports the results of the different scenarios. In line with previous literature, the coefficient on the CPI of the leader is positive, indicating a pass-through effect from the leader industries to the lagging industries. Moreover, there is evidence of catch-up effects (positive and significant coefficient of *gap*), which means industries that are further from the technology frontier tend to grow faster in carbon productivity. The coefficient of cross term $ers \times gap$ is positive and significant, indicating that the implementation of environmental regulation is more effective in improving the carbon productivity of industries with a large technology gap. The time trend captures the slowdown of the CPI, which is similar to the findings of Gordon (2012); the remaining control variables are not significant and are not discussed here.

According to Table 3, all scenarios indicate that environmental regulation stringency can improve the overall industry carbon productivity growth. Thus, stringent environmental regulation is associated with increased industrial carbon productivity growth in China's major industrial sectors. The regression coefficient of the environmental regulation stringency $ed \times ers$ is positive, whereas that of $ed \times ers^2$ is negative (they all pass the significance test), showing that there is an inverted U-shaped relationship between environmental regulation stringency and industrial-level total factor carbon productivity growth. This finding indicates that when environmental regulation is in the initial stage and the stringency is relatively low, the increase of environmental regulation stringency will promote carbon productivity growth. We consider three possible reasons for this effect. (i) Synergy effect - environmental regulations push enterprises to control and reduce the consumption of energy-containing pollutants, such as smoke and dust, directly. The reduction of energy consumption leads to the reduction of carbon emissions and thus leads to the promotion of carbon productivity. (ii) Efficiency effect - environmental regulations push enterprises to promote industrial processes and improve energy quality, ultimately improving energy utilization efficiency. Thus, the carbon emissions per unit of energy consumption are reduced, which further leads to increased carbon productivity. (iii) Scale effect - environmental regulation makes enterprises adjust to the optimal production scale and shift to scale economy. As a result, the reduction rate of pollutants is higher than the decline rate of good output; alternatively, the increase rate of pollutants can be lower than the increase rate of good output, thus promoting the growth of carbon productivity.

Furthermore, the existence of an inverted U-shaped curve indicates that there is an inflection point in carbon productivity growth. On the right side of the inflection point, increased environmental regulation stringency will restrain the growth of carbon productivity, possibly because the environmental regulation itself will increase production costs in an industry. When the environmental regulation strengthens further, (i) enterprises may require additional energy consumption to reduce the emissions of pollutants through increasing the capital investment in end-of-pipe pollution control equipment, which will inevitably lead to additional energy consumption and producing additional carbon emissions, thus restraining the increase in carbon productivity; (ii) enterprises need to increase the investment of additional manpower and capital to reduce emissions, which will result in increased operation costs and management costs of enterprises and eventually slow the increase in carbon productivity; (iii) enterprises will transmit the investment of production to the investment of emission reduction measures to keep the total input cost fixed; these measures will reduce the output of production and restrain the promotion of carbon productivity; and (iv) enterprises will choose to transfer the original resources that are used for technological innovation to pollution control, resulting in an extrusion effect. Markets often fail to give feedback on the value of innovation in the environment; thus, enterprises will think that investment in the environment will not produce synergistic effects with their own technological innovation in product; thus, the innovation in the environment is not likely to be carried out. Ultimately, environmental regulation will have an adverse effect on energy saving and emission reduction and inhibit the improvement of carbon productivity.

5.4 Synergistic effects of ERS on CPI: three industrial sectors with different polluting intensities

Pollution intensities of different industries vary substantially. The sensitivities of industries to environmental regulations are also different. Therefore, we further divide the industrial sectors into three groups according to their environmental dependence index. These three groups are low-polluting industries, moderate-polluting industries, and high-polluting industries. We use the aforementioned scenario three for regression, and the fixed-effect regression model is applied. The results are reported in Table 4.

Table 4 Regression outcome of three industrial sectors with different polluting intensities

	Light polluting industry	Moderate polluting industry	Severe polluting industry
cpi	0.10***	0.20***	0.22***
	(0.02)	(0.01)	(0.01)
gap	-0.35	0.12	0.31***
	(0.25)	(0.09)	(0.06)
ed×*ers*	0.30***	0.10*	-
	(0.11)	(0.05)	
ed×ers^2	-	-0.28***	-0.14***
		(0.05)	(0.02)
gap×*ed*×*ers*	-0.17**	0.20 ***	0.13***
	(0.07)	(0.05)	(0.03)
t	-0.01	-0.00	0.00
	(0.00)	(0.00)	(0.00)
crisis	-0.01	-0.03 ***	-0.01***
	(0.01)	(0.01)	(0.01)
per GDP	0.01	0.01	0.01*
	(0.01)	(0.01)	(0.01)
FDI/*GDP*	0.01	-0.01	-0.01*
	(0.01)	(0.01)	(0.01)
R&D/*GDP*	-4.06	1.51	1.54
	(3.81)	(3.09)	(2.38)
Constant	1.70	7.57	-1.69
	(7.86)	(6.37)	(4.89)

Note: Standard errors are in parentheses; ***, ** and * denote significance at 1%, 5%, and 10% levels, respectively.

In line with the regression results for all industrial sectors, Table 4 shows that the coefficient on the CPI of the leader is positive, indicating a pass-through effect from the leader to the lagging industries. However, the coefficients of high-, moderate-, and low-polluting industries are 0.22, 0.20, and 0.10, respectively, which means that industries with higher emissions show greater pass-through effects, i.e., the advanced one can drive the laggard one to develop more vigorously. Moreover, there is also evidence of catch-up effects (positive and significant coefficient of *gap*) in high-polluting industries. A possible explanation for this finding is that the pressure to reduce emissions in high-polluting industries is higher than the other two industries. The shutdown probability for the laggards in this industry by the government is higher; thus, these industries are more likely to accelerate their carbon productivity growth for fear of closing. The coefficient of the cross term *ers*×*gap* is positive and significant in moderate- and high-polluting industries, indicating that the implementation of environmental regulations is more effective in improving the carbon productivity of these industries. The financial crisis restrained the industrial-level carbon productivity growth in low- and high-polluting industries. A possible reason for this effect is that during 2004 and 2014, the majority of China's export products included textile, clothing, fabrics, products, electronic products, and instruments. The occurrence of the global financial crisis reduced the demand significantly for these products in western countries, which led to large numbers of small- and medium-sized enterprises in these industries to become bankrupted and shut down in China.

A very interesting result derived from Table 4 is that environmental regulations have different effects on industries with different levels of emissions. There is a positive linear relationship between environmental regulation stringency and industrial-level carbon productivity growth in low-polluting industries, a parabolic nonlinear relationship between them in high-polluting industrial sectors, and an inverted U-shaped curve relationship between them in moderate-polluting industrial sectors. Figure 3 illustrates these three types of relationships.

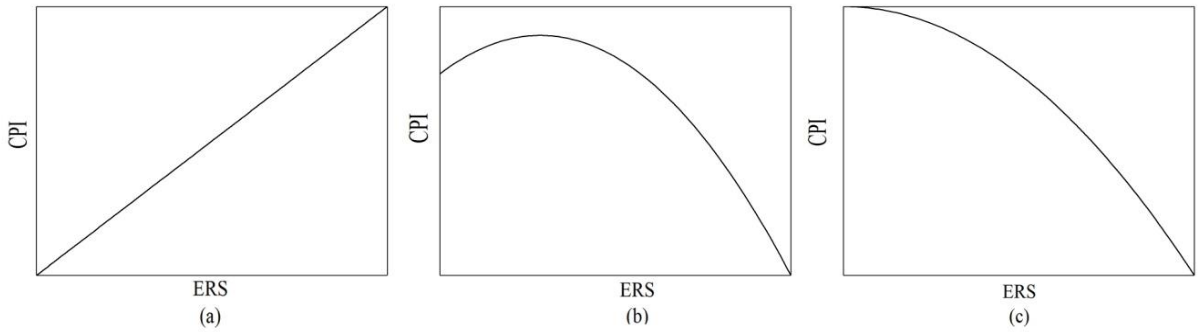

Figure 3 Relationship between ERS and CPI in three industrial sectors with different polluting intensities

Appropriate environmental regulation stringency is one of the prerequisites for the establishment of the Porter Hypothesis. Environmental regulations should be specified to provide sufficient coordinated effects of environmental regulation stringency and carbon productivity. The majority of low-polluting industries, such as the general equipment manufacturing industry and the special equipment manufacturing industry, are high-tech and environmentally friendly industries. When facing the rising production costs caused by environmental regulation stringency, these industries may offset those rising costs through technological innovation more easily, leading to synergy effects, scale effects, and efficiency effects (as explained in Section 5.3). Therefore, the strengthening of environmental regulation stringency in these industries is associated with increased industrial-level carbon productivity growth. Therefore, the government could increase the environmental regulation stringency and guide enterprises to increase low-carbon technological innovation, which may help further accelerate carbon productivity growth in low-polluting industries.

For some of the moderate-polluting industries, such as tobacco manufacturing and pharmaceutical manufacturing, there is an inflection point on the inverted U-shaped relationship of environmental regulation stringency and carbon productivity. On the left side of the inflection point, environmental regulation stringency is associated with increased industrial-level carbon productivity growth; on the right side of the inflection point, increased environmental regulation stringency will prevent the growth of carbon productivity. For the industries that had passed the inflection point, the environmental regulation should not be further strengthened at the current technical conditions. The government should keep the current stringency and avoid further increases in environmental regulations on these industries. Moreover, the government should encourage technological innovation and technology diffusion by providing the technological leaders in each industry with incentives or compensation for additionally improving their carbon productivity.

The high-polluting industries, most of which are capital-intensive industries and heavy industries, are currently facing the supply side of structural reform. They bear the pain of cutting excessive industrial capacity to adjust their supply-side structure. Moreover, when the market cannot give feedback to industry's innovation behaviors in the short term, the industry will not choose to devote itself to innovation and investment in environmental protection. Therefore, the improvement of environmental regulation stringency will have a negative synergetic effect on carbon productivity. For these industries, the government should pay more attention to the diversification of environmental regulations. The introduction of market-based tools, such as an emission trading system and an emission permits system, could force enterprises to choose ways that suit them most to promote carbon productivity when facing environmental regulation policies. Although environmental regulation stringency will have a negative synergetic effect on carbon productivity in the short term for high-polluting industries, in the long term, continuous environmental regulation policy will give the society a green signal. Environmental technology innovation will integrate with product innovation gradually, which will produce a synergistic effect. In addition, enterprises with a longer standing period and larger scale in heavy industry are more capable of accessing advanced production and abatement technologies. They may also have the best access to financial markets and make economies of scale. Thus, it will be easier for them to accommodate to new environmental regulations. Therefore, for the high-polluting industries, the government should continue carrying on structural reform on the supply side and encourage mergers and reorganization of enterprises. Carbon productivity will be promoted when industries adjust their production to optimal scales.

6 Conclusion

We investigate the impact of changes in environmental regulation stringency on industrial-level carbon productivity growth in China. Through utilizing the information entropy method, a new index of environmental regulation stringency is established by taking into account the effects of both pollution reduction consequences and pollution reduction measures. In addition, based on the DEA method, a Malmquist carbon productivity index is proposed to estimate the industrial carbon productivity growth of 21 major industrial sectors in China’s 30 provinces over the period 2004-2014. Lastly, we set up an econometric model to determine whether there are synergistic effects of environmental regulations on carbon productivity in China's major industrial sectors.

The results show that stringent environmental regulation is associated with an increase in overall industrial carbon productivity growth in China. When environmental regulation is in the initial stage and is relatively low, increased environmental regulation stringency will promote carbon productivity growth through synergy effects, efficiency effects, and scale effects. Entire industrial sectors and three industrial sectors with different polluting intensities all have significant follow-up effects, while industrial sectors with higher pollution intensity show greater pass-through effects. However, catch-up effects exist only in high-polluting industrial sectors.

The relationships between carbon productivity growths for three different polluting intensity industrial sectors and environmental regulation stringency are diverse. In low-polluting industries, there is a positive linear relationship between them. In moderate-polluting industries, there is an inverted U-shaped relationship between them. In high-polluting industries, there is a parabolic nonlinear relationship between them. Regulations should be more targeted to industrial sectors with different polluting intensities. For low-polluting industries, the government can enhance the environmental regulation stringency appropriately. Enterprises should be guided to innovate in the low-carbon technological area. For moderate-polluting industries, the government should avoid excessive regulations. Moreover, technological innovation and technology diffusion should be aimed at industry technical leaders and progress makers. For high-polluting industries, the government should pay attention to the diversification of environmental regulations. Structural reform on the supply side is also encouraged to accelerate the process of enterprise merger and reorganization.

Since the implementation of environmental regulation, China has experienced a rapid development stage, but there are still many unsound aspects in the construction of environmental regulation system in China. Environmental policy should considered transform gradually from command-and-control based one to more flexible and market-based one (Wang et al., 2016a; Wang et al., 2016b; Wang et al., 2016c). For example, a unified national carbon market has been established at the end of 2017. A market-oriented regulation is going to be established through the development of emissions trading, discharge and other incentives (Wang et al., 2018a).

The conclusion of this paper also shows that there exist significant pass-through effects in China's major industrial sectors and follow-up effects in China's major industrial sectors. Therefore, in order to improve the positive synergies between environmental regulation and carbon productivity, government is encouraged to support the development of low-carbon technologies and accelerate the diffusion of low-carbon technologies within the industry (Xian et al., 2018).

The result shows that there is a positive linear relationship between environmental regulation stringency and industrial-level carbon productivity growth in low-polluting industrial sectors, a parabolic nonlinear relationship between them in high-polluting industrial sectors, and an inverted U-shaped relationship between them in moderate-polluting industrial sectors. Those indicated that the lower the pollution intensity of the industry, the more significant the positive synergies of environmental regulation on carbon productivity will be. Therefore, an important path to promote the effect of positive synergies is upgrading industrial structure and eliminating the backward production capacity of high-polluting industries. This paper provides empirical evidence for the positive role of environmental regulation to promote the structural reform of the supply side that environmental regulation can promote the withdrawal of low productivity and high pollution enterprises. At the same time, the entrance threshold of the environment is raised, which a batch of clean production enterprises with high carbon productivity will formed.

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References

Ambec S, Cohen M, Elgie S, Lanoie P (2013) The Porter Hypothesis at 20: can environmental regulation enhance innovation and competitiveness? Review of Environmental Economics and Policy 7(1):2–22

Bourlès R, Cette G, Lopez J, Mairesse J, Nicoletti G (2013) Do product market regulations in upstream sectors curb productivity growth? panel data evidence for OECD countries. Review of Economics & Statistics 95(5):1750-1768

BP (2017) Statistical Review of World Energy. http://bp.com/statisticalreview. Accessed 20 December 2017

Caves DW, Christensen LR, Diewert WE (1982) The economic theory of index numbers and the measurement of input, output, and productivity. Econometrica 50(6):1393-1414

Chen Y, Li XP (2006) Construction of panel data of china's industries and evaluation on it's capital deepening: 1985-2003. Journal of Quantitative & Technical Economics 23(10):57-68 [in Chinese]

Färe R, Grosskopf S, Lindgren, B, Roos P (1992) Productivity changes in Swedish pharmacies 1980–1989: a non-parametric Malmquist approach. Journal of Productivity Analysis 3(1-2):85-101

Färe R, Grosskopf S, Lovell CAK (1994) Production Frontiers. Cambridge: Cambridge University Press. 58-72

Färe R, Grosskopf S, Norris M (1997) Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries: Reply. American Economic Review, 87(5):1040-1044

Gordon RJ. (2012) Is U.S. Economic Growth Over? Faltering Innovation Confronts The Six Headwinds. NBER Working Papers, 4

He K (2014). Environmental regulation intensity, industry heterogeneity and china's industrial total factor of carbon emission performance. Forum on Science & Technology China 20(4):62-67 [in Chinese]

Jaffe AB, Palmer K (1997) Environmental regulation and innovation: a panel data study. Review of Economics & Statistics 79 (4):610-619.

Levinson A, Taylor MS (2008) Unmasking the pollution haven effect. International Economic Review. International Economic Review 49 (1): 223-254

Li XP, Lu XX (2010) International trade, pollution industry transfer and CO_2, emissions in Chinese industries. China Economist (3): 89-99 [in Chinese]

Li XP, Wang SB, Zhou JS (2014) Changes of carbon productivity and the evolution of export sophistication:1992-2009. Journal of Quantitative & Technical Economics (9): 22-39 [in Chinese]

OECD (2010) Linkages between Environmental Policy and Competitiveness, OECD Environment Working Paper No.13

Palmer K, Portney P (1995) Tightening environmental standards: the benefit-cost or the no-cost paradigm? Journal of Economic Perspectives 9(4):119-132

Pan JH, Zhuang G, Zheng Y (2010) Clarification of the concept of low-carbon economy and analysis of its core elements. International Economic Review (4): 88-101 [in Chinese]

Porter ME (1991) America's green strategy. Scientific American, 193-246

Porter ME, van der Linde C (1995) Toward a new conception of the environment–competitiveness relationship. Journal of Economic Perspectives 94: 97-118

Rajan RG, Zingales L (1998) Financial dependence and growth. Social Science Electronic Publishing 88(3): 559-586

Tu Z (2008) The Coordination of Industrial Growth with Environment and Resource. Economic Research Journal (2): 93-105 [in Chinese]

Wang B, Wu Y, Yan P (2010) Environmental efficiency and environmental total factor productivity growth in china's regional economies. Economic Research Journal (5): 95-109 [in Chinese]

Wang H, Wang SQ, University H & Office D (2015) A study on dynamic evolution of industrial carbon emissions performance and its factors in china. China Population Resources & Environment 25(9): 29-36 [in Chinese]

Wang J, Liu B (2014) Environmental regulation and enterprises' TFP—an empirical analysis based on china's industrial enterprises data. China Industrial Economics 3: 44-56 [in Chinese]

Wang K, Mi Z, Wei YM (2018a) Will pollution taxes improve joint ecological and economic efficiency of thermal power industry in China? A DEA-based materials balance approach. Journal of Industrial Ecology, doi: 10.1111/jiec.12740.

Wang K, Wei YM (2016) Sources of energy productivity change in China during 1997-2012: A decomposition analysis based on the Luenberger productivity indicator. Energy Economics 54, 50-59

Wang K, Wei YM, Huang Z (2016a) Potential gains from carbon emissions trading in China: A DEA based estimation on abatement cost savings. OMEGA-International Journal of Management Science 63: 48-59.

Wang K, Wei YM, & Huang Z (2018b) Environmental efficiency and abatement efficiency measurements of China's thermal power industry: A data envelopment analysis based materials balance approach. European Journal of Operational Research 269(1): 35-50

Wang K, Xian Y, Zhang J, Li Y, & Che L (2016b) Potential carbon emission abatement cost recovery from carbon emission trading in China: An estimation of industry sector. Journal of Modelling in Management 11(3): 842-854

Wang K, Zhang X, Yu X, Wei YM, Wang B (2016c) Emissions trading and abatement cost savings: An estimation of China's thermal power industry. Renewable and Sustainable Energy Reviews 65: 1005-1017.

Xian Y, Wang K, Shi X, Zhang C, Wei YM, Huang Z (2018) Carbon emissions intensity reduction target for China’s power industry: An efficiency and productivity perspective. Journal of Cleaner Production 197: 1022-1034.

Zhang C, Lu Y, Guo L, et al (2011) The intensity of environmental regulation and technological progress of production. Economic Research Journal 2: 113-124 [in Chinese]

Zhang W, Zhu Q, Li H (2013) Energy use, carbon emission and china's total factor carbon emission reduction efficiency. Economic Research Journal 2013(10): 138-150 [in Chinese]