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Determinants of eco-efficiency in the Chinese industrial sector

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Abstract

This study measures productive inefficiency within the context of multi-environmental pollution (eco-efficiency) in the Chinese industrial sector. The weighted Russell directional distance model is applied to measure eco-efficiency using production technology. The objective is to clarify how external factors affect eco-efficiency. The major findings are that both foreign direct investment and investment for pollution abatement improve eco-efficiency as measured by air pollutant substances. A levy system for wastewater discharge improves eco-efficiency as measured by wastewater pollutant substances. However, an air pollutant levy does not significantly affect eco-efficiency as measured by air pollutants.

Key words: eco-efficiency; weighted Russell directional distance model; pollution; China

Introduction

China has achieved rapid economic growth since the 1990s due to industrialisation. In the meantime, environmental problems become more serious year by year with rapid economic growth (Wang and Hao, 2012). Industrial production growth is the key factor of economic growth in developing countries, but it can increase pollutant emissions due to resource consumption. Consequently, there is a conflict between environmental concerns and economic growth. In growth theory, analyses of economic growth and the environment have shown the importance of productive inefficiency improvement and have found that it decreases input demand, leading to lower pollution levels.

To solve environmental pollution problems, the Chinese government has enforced more strict environmental regulations and enacted a levy system to promote wastewater management in Chinese industrial sectors (**Table 1**). According to Shao (2010), the Chinese government has enacted more than 130 policies related to environmental protection since 1979 to curb the deterioration of aquatic environments and to improve surface water quality.

Figure 1 shows the amount of wastewater, waste gas, and solid waste discharges from the Chinese industrial sector from 1992 to 2003. Even though many environmental regulations and policies have been enforced, environmental pollution, especially waste gas and solid waste, has rapidly increased since 2000. This increase was mainly due to the rapidly expanding scale of production in China after its entry to the WTO. Pollution per value added has improved between 1992 and 2003. Wastewater, waste gas, and solid waste emissions per value added decreased nearly 80%, 40%, and 60%, respectively, during this period.

There are several studies on productive inefficiency considering environmental pollution focusing on the Chinese industrial sector using a production function approach. Wang et al. (2008) applied the Malmquist-Luenberger index method to measure the total productivity change, including carbon emissions as undesirable outputs, for 17 Asia-Pacific Economic Cooperation countries and regions for 1980–2004. Hu et al. (2008) use the Malmquist index to rank provincial Total Factor Productivity when incorporating environmental factors for 1999–2005. Cao (2007) uses a time-series input-output table and measures the Green Total Factor Productivity using estimated health damages from undesirable pollution following the Jorgenson Divisia index method. Fujii et al. (2010) apply the directional distance function and Luenberger productivity indicator to estimate productivity change, considering wastewater and CO_2 emissions from iron and steel firms.

Previous studies do not clarify the contribution ratio of productive inefficiency by variables (e.g., input, desirable output, undesirable output). We consider differences in the inefficiency of environmental pollution by type of pollutant, because the main reasons for pollution generation and abatement costs differ. For example, sulphur dioxide (SO_2) and soot emissions are mainly generated by coal combustion, while lead compound and hexavalent chromium (Cr^{6+}) emissions in wastewater are increased by intermediate chemical input use. Therefore, effective

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Table 1 Environmental regulations and projects in China

Year	
1991–1995	Implementation of the law on air pollution prevention and control (1991) The second national conference on the prevention and control of industrial pollution proposed the notion of "Three shifts" (1993) China's Agenda 21 (1994)
1996–2000	Integrated emission standard for air pollutants (1997) Emission standard for air pollutants from industrial kilns and furnaces (1997) Emission standard for air pollutants from coke ovens (1997) Implementation of the law of the People's Republic of China on water pollution prevention and control (2000) The state council approved plotting programs for acid rain control regions and SO_2 control regions (enacted in 1998, implemented in 2002)
2001–2003	Emission standard for air pollutants from coal-burning, oil-burning, and gas-fired boilers (2001) State environmental protection administration (SEPA) issued interim measures on administration for discharge licenses of key water pollutants in the Huai River and Tai lake basins (2001) Technology policies on SO_2 emissions control from coal combustion (2002) Law on the promotion of cleaner production (2003) The state council issued regulations on pollution levies (2003)

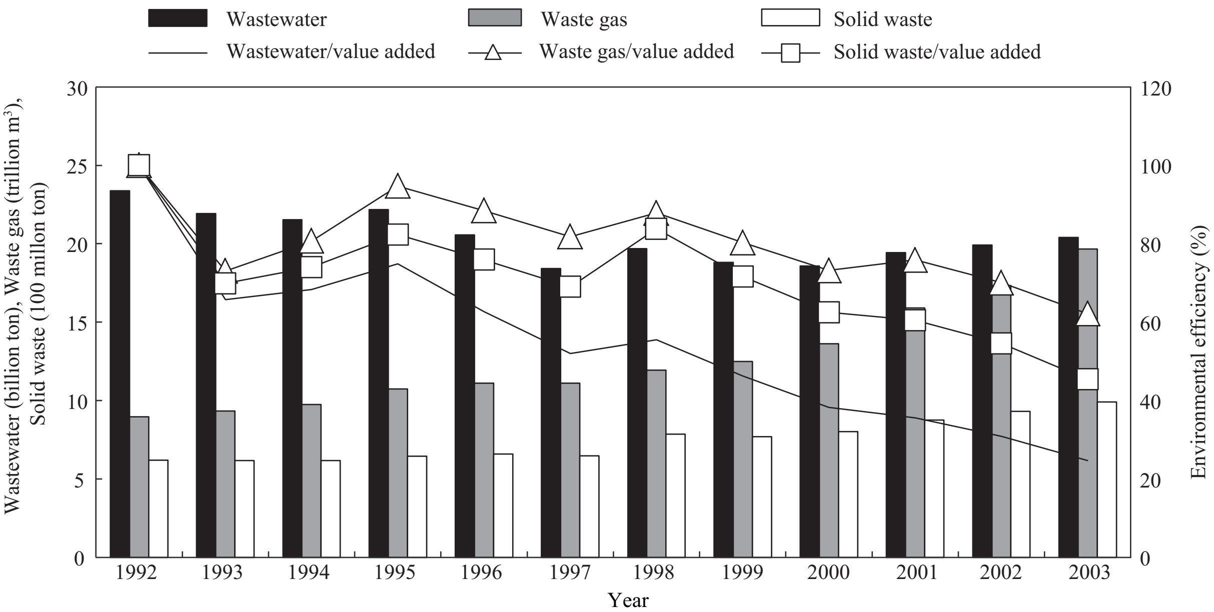

Fig. 1 Environmental pollution emissions and emissions per value added in the Chinese industrial sector. For the change of environmental efficiency (standardised as 1992 = 1). Source: China Statistical Yearbook, China Environmental Yearbook Committee (1993–2004).

environmental policy is different by type of pollutant. Thus, the main objective of this article is to understand how productive inefficiency with respect to environmental pollution (eco-efficiency, referred hereafter to as EE) changes with each input/output, which has not been considered in previous studies. We also try to clarify how external factors affect EE by pollutant type.

1 Methodology and data

1.1 Weighted Russell directional distance model

This study measures EE in the Chinese industrial sector. The weighted Russell directional distance model (WRDDM) was applied to measure EE using production technology following Chen et al. (2011) and Barros et al. (2012), who demonstrated that WRDDM has a strong advantage, in that it decomposes inefficiency scores by each input/output variable.

Suppose there are decision-making units (DMUs) in the dataset. Each DMU uses inputs $x = (x_1, x_2, \ldots, x_n)$ to jointly produce desirable outputs $y = (y_1, y_2, \ldots, y_m)$ and undesirable outputs $b = (b_1, b_2, \ldots, b_l)$. The WRDDM for inefficiency calculation of DMU k can be described as follows:

$$\vec{D}(x_k, y_k, b_k|g) = \text{Maximize}\left(\frac{1}{N}\sum_{n=1}^{N}\beta_n^k+\frac{1}{M}\sum_{m=1}^{M}\beta_m^k+\frac{1}{L}\sum_{l=1}^{L}\beta_l^k\right) \quad (1)$$

subject to

$$\sum_{j=1}^{J} z_j y_{mj} \geq y_{mk} + \beta_m^k g_{ymk} \tag{2}$$

$$\sum_{j=1}^{J} z_j b_{lj} = b_{lk} + \beta_l^k g_{blk} \tag{3}$$

$$\sum_{j=1}^{J} z_j x_{nj} \leq x_{nk} + \beta_n^k g_{xnk} \tag{4}$$

$$z_j \geqslant 0, j = 1, 2, \ldots, k, \ldots, J \tag{5}$$

where, $\beta^k{}_m$, $\beta^k{}_l$, and $\beta^k{}_n$ are the individual inefficiency measures for desirable outputs, undesirable outputs, and inputs, respectively. Z_j is an intensity variable to shrink or expand the individual observed activities of DMU k for the purpose of constructing convex combinations of the observed inputs and outputs. To estimate productive inefficiency, we set directional vector $g = (g_{xnk}, g_{ymk}, g_{blk}) = (-x_{nk}, y_{mk}, -b_{lk})$. The WRDDM with variable returns to scale is shown as follows:

$$\vec{D}(x_k, y_k, b_k|g) = \text{Maximize}\left(\frac{1}{N}\sum_{n=1}^{N}\beta_n^k + \frac{1}{M}\sum_{m=1}^{M}\beta_m^k + \frac{1}{L}\sum_{l=1}^{L}\beta_l^k\right) \tag{6}$$

subject to

$$\sum_{j=1}^{J} z_j y_{mj} \geq y_{mk}(1 + \beta_m^k) \tag{7}$$

$$\sum_{j=1}^{J} z_j b_{lj} = b_{lk}(1 - \beta_l^k) \tag{8}$$

$$\sum_{j=1}^{J} z_j x_{nj} \leq x_{nk}(1 - \beta_n^k) \tag{9}$$

$$z_j \geq 0, \quad j = 1, 2, \ldots, k, \ldots, J \tag{10}$$

This type of directional vector assumes that an inefficient province can decrease productive inefficiency while increasing desirable outputs and decreasing undesirable outputs and/or inputs in proportion to the initial combination of actual inputs and outputs.

One of the strong points of the WRDDM is that it is able to determine the effect of each variable's contribution to inefficiency. This contribution effect cannot be determined in conventional productive inefficiency analysis. The contribution effects enable us to discuss how and why each province successfully decreased its productive inefficiency.

1.2 Panel Tobit analysis

EE scores estimated by WRDDM using pooled data (Pooled WRDDM) will be used as dependent variables in panel Tobit modelling to find factors contributing to EE. Panel Tobit analysis can be used to measure the effects of external factors such as foreign direct investment and levies on pollutants. The principal aim of this analysis is to measure EE and identify the external factors that may be related to performance. The EE scores from Pooled WRDDM are used as dependent variables in the panel Tobit model. Panel Tobit models have an advantage when the dependent variable is censored and limited. This study uses one-year time-lag independent variables for estimation.

$$EE_{it}^* = \beta_0 + \beta X_{it-1} + \eta_i + \mu_t + \varepsilon_{it} \tag{11}$$

$$EE_{it} = EE_{it}^* \quad \text{if } 0 \leqslant EE_{it}^* \leqslant 1 \tag{12}$$

$$EE_{it} = 0 \quad \text{otherwise} \tag{13}$$

1.3 Data

Data for the study were collected from two main sources: the China Environmental Yearbook (CEY) (China Environmental Yearbook Committee, 1993–2004) and the China Statistical Yearbook (CSY) (National Bureau of Statistics of China, 1993–2004). The dataset covers the twelve-year period from 1992 to 2003. To understand the differences of regional characteristics, we group provinces into coastal, central, and western regions. The coastal area includes Beijing, Tianjin, Shandong, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The central area consists of Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan. Finally, Sichuan, Chongqing, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Inner Mongolia, Guangxi, and Xinjiang are located in the western area. Tibet is excluded because some relevant data are not available. Data for Chongqing, which was separated from Sichuan in 1997, is merged with data for Sichuan. Thus, our data sample includes 29 provinces over the 1992 to 2003 time period.

The main variables used in the analysis are value added (CNY) as the desirable output; amount of Labor (number of persons), net value of fixed assets (CNY), and coal consumption (tons) as inputs; and chemical oxygen demand (COD) discharge (tons), lead compound discharge (tons), Cr^{6+} discharge (tons), SO_2 emissions (tons), dust emissions (tons), soot emission (tons), and solid waste discharge (tons) as undesirable outputs. In this case, we can describe WRDDM calculation of DMU k as follows.

$$\overrightarrow{D}(x_k, y_k, b_k|g) = \text{Maximize}\left\{\begin{array}{l} EE^k_{value} + \frac{1}{3}\left(EE^k_{Capital} + EE^k_{Labor} + EE^k_{Coal}\right) \\ + \frac{1}{7}\left(\begin{array}{l} EE^k_{SO_2} + EE^k_{Duts} + EE^k_{Soot} + EE^k_{COD} + \\ EE^k_{Lead} + EE^k_{Chrome} + EE^k_{Solid} \end{array}\right) \end{array}\right\} \quad (14)$$

subject to

$$\sum_{j=1}^{J} z_j \text{value added}_j \geq \text{value added}_k(1 + EE^k_{Value}) \quad (15)$$

$$\sum_{j=1}^{J} z_j SO_{2j} = SO_{2k}(1 - EE^k_{SO_2}) \quad (16)$$

$$\sum_{j=1}^{J} z_j \text{Dust}_j = \text{Dust}_k(1 - EE^k_{Dust}) \quad (17)$$

$$\sum_{j=1}^{J} z_j \text{Soot}_j = \text{Soot}_k(1 - EE^k_{Soot}) \quad (18)$$

$$\sum_{j=1}^{J} z_j \text{COD}_j = \text{COD}_k(1 - EE^k_{COD}) \quad (19)$$

$$\sum_{j=1}^{J} z_j \text{Lead}_j = \text{Lead}_k(1 - EE^k_{Lead}) \quad (20)$$

$$\sum_{j=1}^{J} z_j \text{Cd}^{6+}{}_j = \text{Cd}^{6+}{}_k(1 - EE^k_{Chrome}) \quad (21)$$

$$\sum_{j=1}^{J} z_j \text{Solid waste}_j = \text{Solid waste}_k(1 - EE^k_{Solid}) \quad (22)$$

$$\sum_{j=1}^{J} z_j \text{Capital stock}_j \leqslant \text{Capital stock}_k(1 - EE^k_{Capital}) \quad (23)$$

$$\sum_{j=1}^{J} z_j \text{Employee}_j \leqslant \text{Employee}_k(1 - EE^k_{Labor}) \quad (24)$$

$$\sum_{j=1}^{J} z_j \text{Coal}_j \leqslant \text{Coal}_k(1 - EE^k_{Coal}) \quad (25)$$

$$z_j \geqslant 0, j = 1, 2, \ldots, k, \ldots, J \quad (26)$$

To discuss the EE differences among input and multi outputs, we define the aggregated EE score as follows.

$$EE_{Input} = \frac{1}{3}(EE_{Labor} + EE_{Capital} + EE_{Coal}) \quad (27)$$

$$EE_{Wastewater} = \frac{1}{3}(EE_{COD} + EE_{Lead} + EE_{Chrome}) \quad (28)$$

$$EE_{Waste\ gas} = \frac{1}{3}(EE_{Dust} + EE_{Soot} + EE_{SO2}) \quad (29)$$

$$EE_{Total} = \frac{1}{3}EE_{Value} + \frac{1}{3}EE_{Input} + \frac{1}{3}(\frac{1}{3}EE_{Wastewater} + \frac{1}{3}EE_{Waste\ gas} + \frac{1}{3}EE_{Solid}) \quad (30)$$

For EE calculations, we use a provincial-level panel data set. The data sample size is 348 (29 provinces × 12 years) observations. All financial variables are deflated to year 2000 prices. The CSY includes data for all of China; however, CEY data is estimated by sample survey data. Therefore, productivity estimation using both CSY and CEY data directly is not consistent because of the mismatch of data coverage. To overcome this problem, we adjust the data from CEY so as to be able to compare the data to the CSY. Sales data are included in both the CEY and the CSY. Therefore, we calculate an adjustment coefficient by taking the ratio of sales data in the CEY and that in the CSY. We then multiply the adjustment coefficients to expand the data coverage of CEY, which vary by year and province. This adjustment technique follows procedures by Managi and Kaneko (2009).

As shown in **Table 2**, labor and wastewater pollutant emissions decrease rapidly from 1994 to 2000. In contrast, value added, capital stock, coal use, and SO_2 emissions increase after 1999.

We employ five variables as the independent variables for the panel Tobit analysis. First, we use foreign direct investment (FDI), which affects industrial production technology due to technological transfer (Managi and Kaneko, 2009). The second independent variable is investment in pollution abatement, which contributes to pollution reduction and improves resource use efficiency (Kaneko et al., 2010). The remaining three independent variables are pollution levies for wastewater, air emissions, and solid waste. This is because the pollution levy system gives a strong economic incentive for industrial sectors to reduce pollution emissions (Wang and David, 2005).

2 Results and discussion

Figure 2 represents the average EE scores of 29 provinces from 1992 to 2003, and **Fig. 3** shows average EE_{Total} by region. From **Fig. 2**, EE scores (except EE_{Value}) do not change largely from 1992 to 1997 while EE_{Value} rapidly increased during this period. After 1998, all EE scores decrease, implying that the Chinese industrial sector improved its productive efficiency over all input and output measures.

Figure 3 shows EE_{Total} score by region from 1992 to 2003. There is not a large difference in EE_{Total} among the three regions in 1992. However, after 1998, the coastal region underwent a rapid decrease in EE_{Total}. One explanation for this is that China joined the Association of Southeast Asian Nations in 1996 and the General Agreement on Tariffs and Trade in 2001. These events made it easier for other developed countries to trade with China and provided a strong incentive to invest in

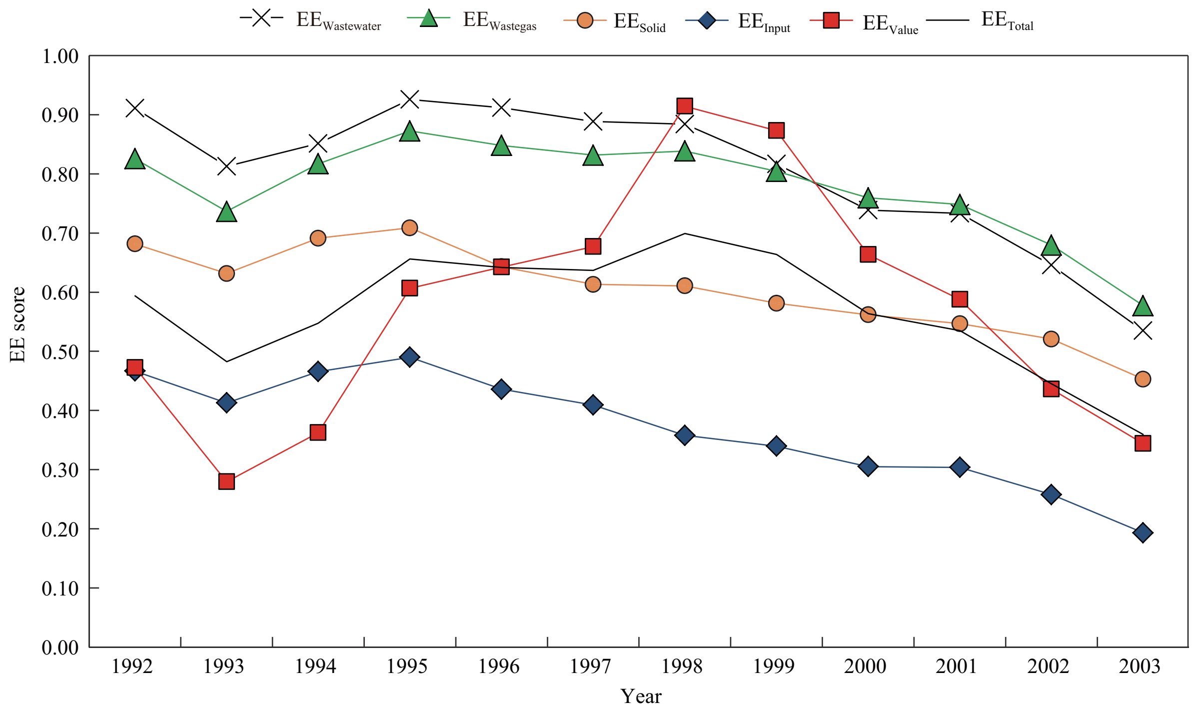

Fig. 2 Eco-efficiency (EE) score by variables from 1992 to 2003.

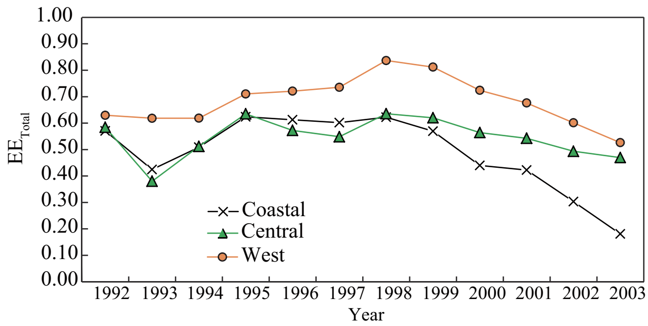

Fig. 3 Average EE_{Total} score from 1992 to 2003.

China, especially in coastal areas, which have a geographic advantage in international trade.

Table 3 presents the average EE score by region and the results of the Kruskal-Wallis test for checking the significance of EE score differences among the three regions. Coastal region have low EE_{Total} score, while provinces in west and central areas have high EE_{Total} scores. These results suggest that the production performance of the manufacturing sector in coastal region is more efficient than that in other regions. One explanation for this result is that coastal provinces receive a lot of FDI in 2003. In addition, the industrial sector represents a large share of gross regional product, and coastal provinces have several special economic zones, which receive tax incentive and subsidy programs for promoting rapid industrialisation.

However, the coastal region has a high $EE_{Capital}$ score because the industrial sector shifted to more capital-intensive production process and away from labor-intensive processes by the modernisation of production equipment. This trend occurred more rapidly in coastal areas due to a high concentration of FDI.

Table 2 Average score of industrial sector in 29 provinces in China

	Value added (10,000 CNY)	Labor number (10,000 person)	Capital stock (10,000 CNY)	Coal use (10,000 ton)	SO_2 emissions (Million ton)	Dust emissions (Million ton)	Soot emissions (Million ton)	COD emissions (10,000 ton)	Lead emissions (ton)	Cr^{6+} emissions (ton)	Solid waste (10,000 ton)
1992	420	273	767	2952	6501	4234	2873	36	45	20	3008
1993	599	286	878	4144	8016	5377	3822	39	66	24	3793
1994	565	293	927	5141	9530	5677	4170	49	83	26	4389
1995	531	292	1035	5158	9563	5606	4375	54	84	23	4373
1996	588	283	1196	3923	8367	4487	3412	44	65	13	3938
1997	636	271	1330	3645	8178	3975	3293	41	66	13	3895
1998	636	214	1456	3580	8625	6167	7,269	44	56	14	4140
1999	728	201	1651	3795	7737	5040	6512	37	46	11	4122
2000	871	192	1802	4007	8455	4961	5286	36	34	7	4228
2001	981	188	1950	4577	8174	4354	4322	31	28	7	4653
2002	1158	191	2123	5114	8731	4310	4213	29	26	7	5067
2003	1480	198	2393	6258	10827	4783	5594	31	31	7	5750

Table 3 Average EE score by region and the results of the Kruskal-Wallis test

	EE_{Value}	EE_{Labor}	$EE_{Capital}$	EE_{Coal}	EE_{SO_2}	EE_{Dust}	EE_{Soot}	EE_{COD}	EE_{Lead}	EE_{Chrome}	EE_{Solid}	EE_{Total}
Coastal region	0.346	0.582	0.055	0.378	0.534	0.757	0.818	0.763	0.844	0.663	0.440	0.458
Central region	0.524	0.667	0.004	0.546	0.604	0.887	0.904	0.863	0.907	0.741	0.711	0.577
West region	0.858	0.590	0.032	0.506	0.698	0.913	0.925	0.805	0.940	0.749	0.698	0.684
Kruskal-Wallis	***	***	***	***	***	***	***	***	***	**	***	***

, * represent 5%, 1% significance, respectively.

Table 4 Determinants of EE

	EE_{Total}	EE_{COD}	EE_{Lead}	EE_{Chrome}	EE_{SO_2}	EE_{Dust}	EE_{Soot}	EE_{Solid}
FDI	0.08	0.03	0.14	–0.02	–0.27**	–0.32**	–0.19**	–0.44***
$Levy_{Water}$	–7.49***	–6.39***	–8.09***	0.67				
$Levy_{Gas}$	8.37*				13.88**	11.91**	10.70*	
$Levy_{Solid}$	–20.79							–17.15
$Invest_{Pollution}$	–0.38**	–0.24	–0.26	–1.05***	–0.32*	–0.41**	–0.36*	–0.25
Log likelihood	107.50	–31.40	–88.99	–146.36	17.36	–0.83	–28.82	39.93

*, **, *** represent 10%, 5%, 1% significance, respectively.

From **Table 3**, EE scores for environmental pollution are significantly lower in coastal areas than others. One explanation for this result is the differences in production technology compared to other areas. Modern production equipment has the potential to save energy and reduce pollution emissions in the industrial sector (Fujii et al., 2010).

Table 4 shows the result of the panel Tobit analysis. Dependent variables are EE measured by each input/output variable. Independent variables are FDI, levy for wastewater discharge ($Levy_{Water}$), levy for air pollution discharge ($Levy_{Gas}$), levy for solid waste discharge ($Levy_{Solid}$), and investment for pollution abatement ($Invest_{Pollution}$).

From **Table 4**, this study clarifies that $Levy_{Water}$ and $Invest_{Pollution}$ contribute to reduced EE. Additionally, the results show both FDI and $Invest_{Pollution}$ decrease EE measured by air pollutants while $Levy_{Gas}$ increases it. These results imply that investment is more effective in managing air pollution than a levy system. One interpretation of that is $Levy_{Gas}$ is much lower than the operating costs of air pollution abatement, especially when the operating cost of the desulphurisation process is high (Kaneko et al., 2010). In this case, producers do not have a strong economic incentive to manage air pollution.

$Levy_{Water}$ improves productive EE measured by wastewater pollutant substances, especially COD and lead compounds. However, the EE score measured by Cr^{6+} is improved by increases in $invest_{Polltion}$ but is not affected significantly by changes in $Levy_{Water}$.

3 Conclusions

This analysis clarifies that key determinants of eco-efficiency are different among types of pollution. The results suggest that the Chinese government can set tax incentives and subsidy programs to increase foreign direct investment and investment in pollution abatement to manage air pollution and solid waste emissions. Additionally, strengthening the levy system for wastewater discharge can be effective in managing chemical oxygen demand and lead compounds in industrial wastewater.

The Chinese government will need to consider differences between the key determinants of eco-efficiency to set effective environmental policies and standards. Additionally, technological transfer is an important factor that can improve eco-efficiency without decreasing economic growth. There is still a large eco-efficiency gap between coastal areas and other regions in China. Thus, we recommend that the Chinese government set new policies to promote foreign direct investment in western and central regions of the country.

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References

Barros C P, Managi S, Matousek R, 2012. The technical efficiency of the Japanese banks: Non-radial directional performance measurement with undesirable output. *Omega–The International Journal of Management Science*, 40(1): 1–8.

Cao J, 2007. Measuring green productivity growth for China's manufacturing sectors: 1991–2000. *Asian Economic Journal*, 21(4): 425–451.

China Environmental Yearbook Committee, 1993–2004. China Environmental Yearbook. China Environmental Yearbook Press, Beijing.

Chen P C, Yu M, Managi S, Chang C, 2011. Non-radial directional performance measurement with undesirable outputs.

Working Paper. Tohoku University.

Fujii H, Kaneko S, Managi S, 2010. Changes in environmentally sensitive productivity and technological modernization in China's iron and steel industry in the 1990s. *Environment and Development Economics*, 15(4): 485–504.

Hu A, Zhen J, Gao Y, Zhang N, Xu H, 2008. Provincial technology efficiency ranking with environment factors (1999–2005). *China Economic Quarterly*, 7(3): 933–960.

Managi S, Kaneko S, 2009. Environmental performance and returns to pollution abatement in China. *Ecological Economics*, 68(6): 1643–1651.

National Bureau of Statistics of China, 1993–2004. China Statistical Yearbook. China Statistical Press, Beijing.

Kaneko S, Fujii H, Sawazu N, Fujikura R, 2010. Financial allocation strategy for the regional pollution abatement cost of reducing sulfur dioxide emissions in the thermal power sector in China. *Energy Policy*, 38(5): 2131–2141.

Shao W, 2010. Effectiveness of water protection policy in China: A case study of Jiaxing. *Science of the Total Environment*, 408: 690–701.

Wang B, Wu Y, Yan P, 2008. Environmental regulation and total factor productivity: An empirical work on APEC countries. *Economic Research Journal*, 5: 19–32.

Wang H, Wheeler D, 2005. Financial incentives and endogenous enforcement in China's pollution levy system. *Journal of Environmental Economics and Management*, 49(1): 174–196.

Wang S, Hao J, 2012. Air quality management in China: Issues, challenges, and options. *Journal of Environmental Sciences*, 24(1): 2–13.

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