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On Modeling Environmental Production Characteristics: A Slacks-Based Measure for China's Poyang Lake Ecological Economics Zone

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Abstract Environmental issues are currently of great concern, especially in the area of sustainable development. Thus, data envelopment analysis (DEA) has enjoyed much popularity, given its ability to measure environmental efficiency and shadow prices at the macro-economic level. In this study, we use the duality theory of slacks-based measure in DEA to develop a general procedure for modeling environmental production characteristics. By using the proposed methodology, we can measure environmental technical efficiency, the shadow prices of emissions, and inter-factor substitution possibilities. Further, we use the proposed methodology to carry out an empirical study of the Poyang Lake Ecological Economics Zone in China. Finally, we suggest some policy implications based on the study's empirical results.

Keywords SBM–DEA · Shadow prices of externalities · Substitution possibilities · Poyang Lake Ecological Economics Zone

1 Introduction

Environmental deterioration is a prevalent side effect of economic growth. To address this issue, the World Commission on Environment and Development introduced the concept of sustainable development in 1987, when it defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Our common future). Since then, there has been increasing interest in environmental production modeling, as environmental efficiency and productivity are both key factors in sustainable development.

Among the various environmental production modeling techniques available, the distance function approach has drawn much attention, possibly because it can simul-

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taneously model joint-production technology with good and bad outputs (i.e., pollutants). In addition, unlike the cost function, the distance function does not require large amounts of price-specific data that can be relatively difficult to obtain. Given only the quantity data of inputs and outputs, one can model various critical environmental production characteristics, such as environmental technical efficiency and productivity growth, the shadow prices of pollutants, and inter-factor substitution possibilities.

One can specify the distance function in at least two different ways: the parametric approach, which is based on a specific functional form, and the non-parametric approach, which is also called data envelopment analysis (DEA). The parametric approach requires the adoption of a functional form (usually the translog or quadratic function) for the distance function. It has the advantage of providing an estimated parametric representation of the production technology, which is everywhere differentiable and easy to manipulate algebraically. Therefore, the parametric method can be used to easily estimate the shadow prices of emissions (Färe et al. 1993) and the curvature or substitutability along the frontier (Lee and Zhang 2012). For more on the parametric approach used to model environmental production characteristics, one can refer to Färe et al. (2005). On the other hand, the non-parametric DEA estimation is based on the construction of a piecewise linear combination of all observed outputs and inputs, and it relies on mathematical programming. A major advantage of the DEA approach is that it does not require the imposition of a functional form on the underlying environmental technology. Therefore, DEA provides an easier and more flexible means of estimation.

Färe et al. (2005) first proposed a methodology based on the parametric distance function approach for modeling environmental production characteristics, including environmental adjusted technical efficiency, shadow pricing, and the elasticity of substitution. However, the use of the non-parametric distance function approach to model environmental production characteristics has not been formally proposed. Some empirical studies—such as those of Choi et al. (2012) and Wei et al. (2012) use the non-parametric slacks-based measure (SBM) to analyze carbon emission efficiency and abatement costs; however, only carbon emissions have been empirically studied, and a general procedure for using this methodology to model environmental technology has not yet been proposed.

This study contributes to the current body of relevant literature by using the SBM in DEA to develop a general procedure for modeling environmental production characteristics. Among the non-parametric approaches, the slacks-based measure (SBM) directly accounts for input and output slacks in efficiency measurements, with the advantage of capturing the whole aspect of inefficiency. Thus, via the SBM, the specific-factor efficiency can be calculated. Furthermore, without incorporating the slack, the basic DEA approach may overestimate the efficiency value; on the other hand, the SBM can incorporate the slacks of all inputs and outputs that can reflect the real efficiency.[1] This property is particularly suitable for the reduction of undesirable outputs and energy consumption.

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[1] However, recently, SBM is critical because it adjusts the inefficient observations to the frontier by going the maximum distance which is not consist with basic economic assumption. Alternative Minimum distance-SBM is proposed in Tone (2010) to overcome this problem.

Based on the original SBM, environmental technical efficiency can be calculated. By using the duality theory of SBM, both the shadow prices of emissions and the inter-factor Morishima elasticity of substitution can be derived. It should be noted that, as per Färe et al. (2005), one can estimate the Morishima elasticity of substitution only between outputs, given the use of the output-oriented distance function. Unlike Färe et al. (2005), we employ a free-oriented distance function based on SBM that could calculate substitutability, not only among outputs but also among inputs. Calculations of energy substitution possibilities could give rise to some important suggestions for sustainability. For the Chinese economy subject to environmental regulations, the high substitutability of capital for fossil energy can help achieve the goal of "sustainable development." Based on the proposed methodology, we conduct an empirical analysis of the Poyang Lake Ecological Economic Zone (PLEEZ) in Jiangxi Province. PLEEZ were approved by State Council and upgraded in 2009 to become part of China's national strategy. A number of studies have focused on the environmental and energy efficiency for China at the provincial level (Guo et al. 2011; Wang et al. 2013; Wu et al. 2012); however, no studies have been done for the Poyang Lake Ecological Economic Zone (PLEEZ) at prefecture-level.

The remainder of this paper proceeds as follows. Section 2 describes the methodology of the non-parametric SBM approach, while touching upon environmental adjusted technical efficiency, the shadow prices of emissions, and the Morishima elasticity of substitution among the factors therein. Section 3 presents the contextual setting including the Introduction of PLEEZ and data. In Sect. 4, we employ the methodology to conduct an empirical study of the PLEEZ, using prefecture-level data. Section 6 concludes and offers some policy recommendations.

2 Methodology

In this section, we present the SBM–DEA model, which contains two models used in environmental technology modeling. The first of these is the envelope model, which can evaluate technical efficiency while incorporating undesirable outputs. The second is the dual model, which can estimate the shadow prices of undesirable outputs. Additionally, based on shadow price ratios, we can also derive Morishima elasticities of substitution for various factors.

2.1 Environmental Adjusted Technical Efficiency

Unlike traditional basic efficiency measures—many of which are based on the proportional reduction (enlargement) of input (output)—SBM–DEA, originally developed by Tone (2001), deals directly with the input excess and the output shortfall of the observation, which are called slack variables. The SBM can assist in projecting observations to the furthest point on the efficiency frontier, in the sense that the objective function is to be minimized by finding the maximum amount of slack. Suppose that there are n regions and that each has three factors—namely, inputs, good outputs, and bad outputs—that are denoted by the vectors $x \in R^m$, $y^g \in R^{s1}$, and $y^b \in R^{s2}$, respectively. We define the matrices Y^g, Y^b, and X as $Y^g =$

$[y^g_{r_1 j}] = [y^g_{11}, \ldots, y^g_{s_1 n}] \in R^{s1\times n}$, $Y^b = [y^b_{r_2 j}] = [y^b_{11}, \ldots, y^b_{s_2 n}] \in R^{s2\times n}$, and $X = [x^]_{ij} = [x_{11}, ..., x_{mn}] \in R^{m\times n}$, respectively. The production technology is defined as follows:

$$P(x) = \left\{ (y^g, y^b) | x \text{ produce } (y^g, y^b), x \geq X\lambda, y^g \leq Y^g\lambda, y^b \geq Y^b\lambda, \lambda \geq 0 \right\} \tag{1}$$

Here, λ is a non-negative multiplier vector, indicating that the above definition expresses a constant returns to scale situation. By imposing $\lambda = 1$, $P(x)$ is put in a variant returns to scale situation. By imposing $\lambda \geq 1$, $P(x)$ is put in a non-decreasing returns to scale situation. By imposing $0 \leq \lambda \leq 1$, $P(x)$ is put in a non-increasing returns to scale situation.

Tone's (2001) study does not incorporate undesirable outputs; Zhou et al. (2006) employ the weak disposability to incorporate the undesirable outputs in SBM. Because the weak disposability is critical recently, following Zhang and Choi (2013) and Song et al. (2013), we add the slack for undesirable outputs to the objective function by modifying the constraint for undesirable outputs.

$$\begin{aligned}
&\phi^* = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} \frac{s_{i0}^-}{x_{i0}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r_1=1}^{s_1} \frac{s^g_{r_1 0}}{y^g_{r_2 0}} + \sum_{r_2=1}^{s_2} \frac{s^b_{r_2 0}}{y^b_{r_2 0}}\right)} \\
&S.T. \\
&x_0 = X\lambda + s_0^- \\
&y_0^g = Y^g\lambda - s_0^g \\
&y_0^b = Y^b\lambda + s_0^b \\
&s_0^- \geq 0, s_0^g \geq 0, s_0^b \geq 0, \lambda \geq 0
\end{aligned} \tag{2}$$

$i = 1, 2\ldots, m$	Index of inputs;
m	Number of inputs;
$\mathrm{r}_1 = 1, 2\ldots, S_1$	Index of good (desirable) outputs;
$\mathrm{r}_2 = 1, 2\ldots, S_2$	Index of bad (undesirable) outputs;
S_1	Number of good (desirable) outputs;
S_2	Number of bad (undesirable) outputs;
s_0^-	Slack variables (potential reduction) of inputs;
s_0^g	Slack variables (potential enhancement) of good outputs;
s_0^b	Slack variables (potential enhancement) of good outputs;
Subscript "$_0$"	The DMU whose efficiency is being estimated in the model now (potential enhancement) of good outputs;
λ	A non-negative multiplier vector for linear programming

The observation is efficient in the presence of undesirable outputs if $\phi^* = 1$, indicating that all of the slack variables equal 0 ($s_0^- = 0, s_0^g = 0, s_0^b = 0$), but that the object model (2) is not a linear function. Using the transformation suggested by Tone (2001), we can establish equivalent linear programming for t, φ, S^{-*}, S^b, and S^g, as follows:

$$
\begin{aligned}
&r^* = \min t - \frac{1}{m}\sum_{i=1}^{m}\frac{S_{i0}^-}{x_{i0}}\\
&1 = t + 1 + \frac{1}{s_1+s_2}\left(\sum_{r_1=1}^{s_1}\frac{S_{r_10}^g}{y_{r_10}^g} + \sum_{r_2=1}^{s_2}\frac{S_{r_10}^b}{y_{r_20}^b}\right)\\
&S.T\\
&x_0 t = X\varphi + S_0^-\\
&y_0^g t = Y^g\varphi - S_0^g\\
&y_0^b t = Y^b\varphi + S_0^b\\
&S_0^- \geq 0,\, S_0^g \geq 0,\, S_0^b \geq 0, \varphi \geq 0, t > 0.
\end{aligned}
\tag{3}
$$

With the linear optimal solution of model (3) of (t^*, φ^*, S^{-*}, S^{g*}, S^{b*}), we can solve the linear programming. The efficiency measure ϕ^* includes both economic factors and the environmental factor; therefore, we could define it as the environmental adjusted technical efficiency.

2.2 Shadow Prices of Undesirable Outputs

In this subsection, we discuss the dual SBM model used to estimate the shadow prices of environmental pollutants; this constitutes the dual form of the original SBM model. Our shadow cost function is explained below.

The dual form of model (2) that includes pollutants is shown below, as suggested by Choi et al. (2012):

$$
\begin{aligned}
&\theta^* = max\theta\\
&S.T.\\
&\theta + \nu x_0 - \mu^g y_0^g + \mu^b y_0^b = 1\\
&\mu^g y_0^g - \nu x_0 - \mu^b y^b \leq 0\\
&\nu \geq \frac{1}{m}[1/x_0]\\
&\mu^g \geq \frac{\theta}{s_1+s_2}[1/y_0^g]\\
&\mu^b \geq \frac{\theta}{s_1+s_2}[1/y_0^b]
\end{aligned}
\tag{4}
$$

In model (4), $\nu \in R^m$, $\mu^g \in R^{s1}$, and $\mu^b \in R^{s2}$ are the dual-variable vectors of the inputs ($x \in R^m$), good outputs ($y^g \in R^{s1}$), and bad outputs ($y^b \in R^{s2}$), respectively. The notation $[1/x_0]$ represents the row vector $(1/x_0 \ldots 1/x_{m0})$. The dual variables of the inputs, good outputs, and bad outputs can be estimated via the following linear programming, based on the elimination of the θ variable in model (4):

$$
\begin{aligned}
& Max\ p \\
& p = \mu^g y_0^g - \nu x_0 - \mu^b y_0^b \\
& S.T. \\
& p \leq 0 \\
& \nu \geq \frac{1}{m}[1/x_0] \\
& \mu^g \geq \frac{1+p}{s_1+s_2}[1/y_0^g], \\
& \mu^b \geq \frac{1+p}{s_1+s_2}[1/y_0^b]
\end{aligned} \tag{5}
$$

Model (5) aims to maximize the virtual profit, $\mu^g y_0^g - \nu x_0 - \mu^b y_0^b$, for the regions concerned. Apparently, the dual SBM model is a type of profit maximization model in which the virtual profit is at best zero (non-positive) when $\theta^* = 1$ for the SBM-efficient DMU.

The dual variables ν and μ^b can be interpreted as the shadow prices of the inputs and undesirable outputs, respectively; μ^g denotes the marginal virtual income of the desirable outputs. Assuming that the absolute shadow price of the undesirable outputs is equal to its market price, the relative shadow price of the undesirable outputs with regard to the good outputs can be measured by:

$$\mu^b = \mu^g * \frac{p^b}{p^g}. \tag{6}$$

In other words, the shadow prices of the undesirable outputs can be interpreted as marginal abatement costs that represent the marginal rate of transformation between the undesirable and desirable outputs. Firms are not able to abate pollutants freely: they incur an opportunity cost associated with reducing a desirable output—namely, the output that stems from the diversion of good outputs in emission abatement efforts.

2.3 Morishima Elasticity of Substitution

The curvature of the isoquant reflects the degree of substitutability of the input factors. Following Lee and Zhang (2012), we can calculate the elasticities of substitution between inputs x_i and x_j by employing the idea of indirect Morishima elasticity of substitution, as shown in (7) The Morishima elasticity is defined as the shadow price ratio between the two factors elucidated in the study of Lee and Jin (2012). The Morishima elasticity for inputs captures the degree to which the relative shadow prices of inputs should be altered so as to allow substitutability among inputs. A high-value Morishima elasticity indicates low-level substitutability. It should be noted that $M_{ij} \neq M_{ji}$, because the ratios related to the two input shadow prices differ from each other, depending on which input is used as the basis. Usually, the degree of substitution of x_j for x_i does not coincide with the substitution of x_i for x_j. Since the SBM used here takes a free-oriented form, we can also compute the elasticities of substitution between the undesirable outputs y_r^b and y_s^b, as shown in (8).

$$M_{ij} = \frac{v_i}{v_j} \tag{7}$$

$$M_{rs} = \frac{\mu_r}{\mu_s} \tag{8}$$

3 Contextual Setting

In this section, we describe the basic information of PLEEZ and the process by which we collected data for the inputs and outputs of the SBM–DEA framework.

3.1 Poyang Lake Ecological Economic Zone

Located in the northern part of Jiangxi Province, Poyang Lake is China's largest freshwater lake; it is also an important wetland area globally. In December 2009, the State Council of China officially approved Poyang Lake Ecological Economic Zone Planning, which is the first state-level strategic regional development planning within Jiangxi Province. The PLEEZ contains three cities (Nanchang, Jingdezhen, and Yingtan), and some counties (prefectures): Jiujiang, Xinyu, Fuzhou, Yichun, Shangrao, and Jian (Fig. 1). The area comprises $51,200\,\text{km}^2$ of land. With a land area that encom-

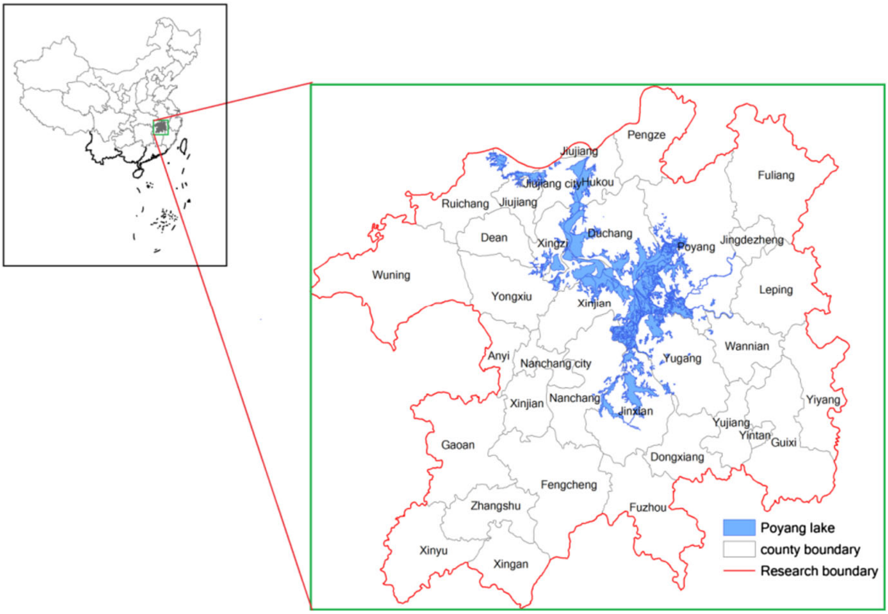

Fig. 1 The location of Poyang Lake Ecological Economic Zone

passes nearly 30 % of Jiangxi Province, the PLEEZ accounts for nearly 50 % of the province's population; it also contributes more than 60 % of its gross domestic product (GDP). In 2010, the PLEEZ accounted for about 65 % of the province's industrial energy consumption, amounting to 27 million tons in terms of standard coal.

The development goal for this area is to explore new modes of coordinated development in terms of both economy and ecology, while making the PLEEZ viable; the goal also is to set a precedent for the comprehensive development of China's other lake areas and large rivers.

The development of the PLEEZ has been planned to occur in two phases. First, during the 2009–2015 period, the primary task is to create a new system and mechanism and enhance the development bases, so as to enhance ecological and economic strengths and form a new developmental mode that coordinates them. Second, during the 2016–2020 period, the main task will be to build a powerful and effective ecological security system, and form an advanced and efficient eco-industrial cluster.

The development of the PLEEZ, if it goes to plan, will make it the leading cluster in Jiangxi Province. The government is planning overall ecological protection initiatives and to construct both upper and lower reaches; development plans also extend to the tributaries of Poyang Lake. The Jiangxi government aims to develop low-carbon, green industry, and simultaneously bring about sound industrial ecology and ecological economic industrialization.

3.2 Data Collection

The models described in Sect. 2 were applied in 2010 to study the environmental production characteristics of the 37 PLEEZ prefectures. We first collected data pertaining to the inputs and outputs described in our framework.

For the output variables, Choi et al. (2010) suggests three indicators to represent economic performance in a systematic evaluation environment: GDP, industrial value-added, and the employment rate. Considering that the current study focuses on regional ecological economies, regional GDP is selected to represent the sole desirable output; this has also been the case in many previous studies (e.g., Hu and Wang 2006; Bian and Yang 2010; Wu 2010). Based on the principles of microeconomics, labor and capital are the two basic inputs of the production process. Employed labor force numbers are used as labor data, and because capital stock data are not available, we use investment in fixed assets as a proxy[2] (Shi et al. 2010). Recently, resources such as fossil energy have also been selected as input variables (Hu and Wang 2006; Shi et al. 2010; Zhang and Choi 2013); therefore, total fossil energy consumption is selected as the energy input, including all types of energy (e.g., coal, oil, and gas). All types are converted into tons of standard coal equivalent. SO_2 emissions, wastewater, and soot emissions are selected as three undesirable environmental outputs. We then collect the input and output data of 37 prefectures for use within our framework. All the data used are listed in the *Jiangxi Statistical Year Book, 2011* and the *Statistics of Poyang Lake Ecological*

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[2] It should be noted that using the investment in fixed asset cannot represent the real capital stock, it is a limitation of this study due to the data unavailability.

Table 1 Descriptive statistics of inputs and outputs, 2010

Variable	N	Unit	Mean	SD	Min	Max
GDP	37	10^9 Y	135	110	26	530
Waster water	37	10^4 Ton	2,457	2,356	394	11,649
SO_2	37	Ton	8,889	12,952	352	58,524
Soot	37	Ton	1,751	1,572	58	6,437
Capital	37	10^9 Y	99	74	12.6	322
Labor	37	10^4	27	19	3.9	85
Energy	37	10^4 Ton	72.	122	0.4	611

Table 2 Correlation matrix of inputs and outputs, 2010

	GDP	Waste	SO_2	Soot	Capital	Labor
Waste	0.817*					
SO_2	0.549*	0.384*				
Soot	0.214*	0.136	0.715*			
Capital	0.710*	0.804*	0.295*	0.166*		
Labor	0.278*	0.072	0.337*	0.333*	0.203*	
Energy	0.682*	0.547*	0.837*	0.582*	0.404*	0.349*

* Represents significance at the 5 % level

Economic Zone, 2011. Table 1 presents the descriptive statistics of these data; as shown in this table, the variations in the variables from Max to Min vary substantially, and thus indicate substantial development differences within this area.

Table 2 is a correlation matrix of the outputs and inputs. This table clearly shows that the correlation coefficients between the outputs and inputs are almost significantly positive; hence, when the inputs are increased, the output values will also increase. Thus, efficiency analysis in this case is quite feasible.

4 Empirical Results

In this section, by using prefecture-level data for the PLEEZ, we illustrate how our model can be used to evaluate the environmental adjusted technical efficiency, the shadow prices of pollutants, and the substitutability of factors.

4.1 Environmental Technical Efficiency

With regard to the average overall environmental technical efficiency of PLEEZ, the results (Table 3) demonstrate that many PLEEZ regions are not performing technically efficiently, given the constraint of environmental factors. The environmental technical efficiency scores of those regions varied from 0.113 to 1, with an average value of 0.553; this indicates that the PLEEZ, on average, could accomplish approximately

Table 3 Environmental technical efficiency of 37 PLEEZ regions, 2010

Regions	ETE	S.ww (10^4 t)	S.so$_2$(t)	S.soot (t)
Anyi Prefecture	0.256	88.271	1,616.923	569.401
Changjiang District	0.480	0.000	2,299.485	513.371
Dean Prefecture	0.314	0.000	722.599	3268.108
Donghu District	1.000	0.000	0.000	0.000
Dongxiang Prefecture	0.131	201.235	4,776.585	3,354.523
Duchang Prefecture	0.234	0.000	366.084	708.162
Fengcheng City	0.295	0.000	22,820.414	2072.573
Fuliang Prefecture	1.000	0.000	0.000	0.000
Gaoan City	0.283	0.000	5,533.954	1,539.886
Guixi City	0.176	1,334.726	29,085.037	2127.915
Hukou Prefecture	0.119	1,678.493	16,117.744	5,529.996
Jinxian Prefecture	1.000	0.000	0.000	0.000
Jiujiang Prefecture	1.000	0.000	0.000	0.000
Leping City	0.113	632.992	12,004.633	3,958.148
Linchuan District	0.163	0.000	5,221.003	2,600.032
Lushan District	0.215	132.688	1,918.951	1,446.440
Nanchang Prefecture	1.000	0.000	0.000	0.000
Pengze Prefecture	0.232	0.000	393.110	1,556.330
Poyang Prefecture	1.000	0.000	0.000	0.000
Qingshanhu District	0.203	6,620.189	17,855.846	1,939.557
Qingyunpu District	0.360	1,415.951	1,333.225	130.908
Ruichang City	0.113	905.637	2,070.414	2,352.148
Wanli District	1.000	0.000	0.000	0.000
Wannian Prefecture	0.397	0.000	1380.750	0.000
Wuning Prefecture	1.000	0.000	0.000	0.000
Xihu District	1.000	0.000	0.000	0.000
Xingan Prefecture	0.406	0.000	947.044	1,311.329
Xinjian Prefecture	0.166	387.651	9,390.148	1,472.225
Xingzi Prefecture	0.302	218.018	49.577	387.112
Xunyang District	1.000	0.000	0.000	0.000
Yongxiu Prefecture	0.138	190.946	1,921.941	1,174.936
Yushui District	1.000	0.000	0.000	0.000
Yugan Prefecture	1.000	0.000	0.000	0.000
Yujiang Prefecture	1.000	0.000	0.000	0.000
Yuehu District	0.354	0.000	4,064.749	106.218
Zhangshu City	1.000	0.000	0.000	0.000
Zhushan District	1.000	0.000	0.000	0.000
Mean	0.553	373.157	3,834.871	1,030.252
StDev	0.383	1,140.171	6,983.431	1,366.336

ETE: Environmental technical efficiency; S.ww: Slack of waster water; S.so$_2$: Slack of SO$_2$; S.soot: Slack of soot a 44.7 % efficiency improvement, if all the regions therein were to operate on the frontier of environmental production technology. Thus, many regions appear to have the potential to reduce their amounts of energy used and emissions. Table 3 presents the slack value of each emission calculated from (2)—a value that indicates the potential emissions reductions. The average potential reduction for wastewater, SO_2, and soot are found to be 1,909,460 tons, 1,921,940 tons, and 1,174,940 tons, respectively.

From the viewpoint of individual region, 15 regions within the PLEEZ have the highest possible environmental technical efficiency score (i.e., 1.000). Table 3 shows that those regions exhibit no emissions potential reduction, thus indicating that these regions already exhibit optimal environmental technical efficiency values. Leping and Ruichang City, on the other hand, have the worst environmental technical efficiency scores. Qingshanhu District shows the largest potential reduction for wastewater (662,020 tons); Guixi City, for SO_2 (29,085.037 tons); and Hukou Prefecture, for soot reduction (5,529.996 tons).

5 Shadow Prices

As reported in Table 4, the estimated shadow prices for the three aforementioned emissions, calculated via (6), can be interpreted as measures of the opportunity cost of emissions abatement; this cost is assessed in terms of GDP lost per unit of emission abatement. Therefore, the shadow prices measure the marginal abatement cost of emissions to the regional PLEEZ economy in general. For instance, from Table 4, we see that the PLEEZ in 2010 could pay, on average, CNY0.419 to abate 1 ton of SO_2 emissions, CNY0.580 to abate 1 ton of wastewater, and CNY0.667 to abate 1 ton of soot emissions. The low shadow prices indicate that these emissions are not strictly regulated. It is therefore suggested that current environmental regulations are not effective in the PLEEZ.

With regard to specific regions, Yugan Prefecture's marginal wastewater abatement cost is CNY1.248/ton—the highest among the PLEEZ regions. Donghu District shows both the highest marginal abatement cost for both SO_2 (CNY2.93/ton) and soot emissions (CNY9.229/ton).

5.1 Elasticities of Substitution

Table 5 presents the indirect Morishima-type elasticities of substitution between individual inputs calculated from (7), which are evaluated based on the shadow price ratio. A high M_{kl} value relative to M_{lk} indicates that capital is relatively more easily substituted for labor. This result reflects the capital-intensive nature of industries in the PLEEZ.

Regarding the degree of substitution of capital for energy, it is found that M_{ek} is greater than M_{ke}; this indicates that the substitutability of capital for energy may be lower than that of energy for capital. Both M_{ek} and M_{ke} are relatively higher than M_{lk} and M_{kl}, indicating that capital and energy are not substitutes but complementary in the PLEEZ in general.

Table 4 Shadow prices of emissions for 37 regions in PLEEZ, 2010

Regions	Waste water	SO^2	Soot
Anyi Prefecture	0.183	0.337	0.221
Changjiang District	1.035	0.053	0.054
Dean Prefecture	1.032	0.092	0.006
Donghu District	0.247	2.930	9.229
Dongxiang Prefecture	0.162	0.165	0.051
Duchang Prefecture	0.645	0.308	0.063
Fengcheng City	0.583	0.033	0.060
Fuliang Prefecture	1.071	0.022	0.002
Gaoan City	0.937	0.062	0.037
Guixi City	0.118	0.073	0.196
Hukou Prefecture	0.094	0.059	0.034
Jinxian Prefecture	0.128	0.721	0.126
Jiujiang Prefecture	1.003	0.285	0.311
Leping City	0.132	0.122	0.077
Linchuan District	0.639	0.136	0.064
Lushan District	0.166	0.609	0.226
Nanchang Prefecture	1.036	0.283	0.176
Pengze Prefecture	1.124	0.128	0.013
Poyang Prefecture	0.941	0.370	0.084
Qingshanhu District	0.085	0.187	0.349
Qingyunpu District	0.157	1.075	2.277
Ruichang City	0.110	0.316	0.067
Wanli District	0.355	1.764	2.123
Wannian Prefecture	0.906	0.065	0.198
Wuning Prefecture	1.013	0.275	0.096
Xihu District	0.171	2.187	6.462
Xingan Prefecture	1.017	0.071	0.030
Xinjian Prefecture	0.145	0.183	0.243
Xingzi Prefecture	0.266	1.836	0.354
Xunyang District	0.959	0.013	0.021
Yongxiu Prefecture	0.178	0.358	0.140
Yushui District	0.626	0.003	0.358
Yugan Prefecture	1.248	0.132	0.009
Yujiang Prefecture	0.956	0.064	0.308
Yuehu District	0.990	0.031	0.168
Zhangshu City	0.988	0.137	0.108
Zhushan District	0.013	0.008	0.326
Mean	0.580	0.419	0.667
StDev	0.417	0.676	1.835

Unit: Y/T

Table 5 Morishima elasticity of substitution for inputs

	M_{kl}	M_{lk}	M_{ek}	M_{ke}	M_{el}	M_{le}
Anyi Prefecture	1.36	0.73	2.92	0.34	3.97	0.25
Changjiang District	0.15	6.52	3.32	0.30	0.51	1.96
Dean Prefecture	0.65	1.55	2.07	0.48	1.34	0.75
Donghu District	0.28	3.62	251.71	0.00	69.62	0.01
Dongxiang Prefecture	1.20	0.83	2.69	0.37	3.24	0.31
Duchang Prefecture	4.27	0.23	4.46	0.22	19.04	0.05
Fengcheng City	1.52	0.66	0.31	3.18	0.48	2.09
Fuliang Prefecture	0.02	42.86	66.21	0.02	1.54	0.65
Gaoan City	1.98	0.51	0.45	2.20	0.90	1.11
Guixi City	0.85	1.18	0.76	1.32	0.64	1.56
Hukou Prefecture	0.53	1.88	0.49	2.03	0.26	3.82
Jinxian Prefecture	13.47	0.07	0.59	1.70	7.94	0.13
Jiujiang Prefecture	6.83	0.15	0.32	3.13	2.18	0.46
Leping City	1.14	0.88	1.77	0.57	2.02	0.50
Linchuan District	1.61	0.62	5.45	0.18	8.75	0.11
Lushan District	0.58	1.72	3.19	0.31	1.85	0.54
Nanchang Prefecture	0.53	1.88	11.86	0.08	6.32	0.16
Pengze Prefecture	1.19	0.84	2.12	0.47	2.51	0.40
Poyang Prefecture	5.78	0.17	47.60	0.02	275.04	0.00
Qingshanhu District	0.17	5.75	0.88	1.14	0.15	6.57
Qingyunpu District	0.15	6.56	8.09	0.12	1.23	0.81
Ruichang City	1.10	0.91	0.98	1.02	1.08	0.92
Wanli District	1.11	0.90	18.15	0.06	20.06	0.05
Wannian Prefecture	2.12	0.47	0.64	1.56	1.35	0.74
Wuning Prefecture	1.23	0.82	10.54	0.09	12.92	0.08
Xihu District	0.07	13.60	78.75	0.01	5.79	0.17
Xingan Prefecture	0.89	1.12	3.46	0.29	3.09	0.32
Xinjian Prefecture	0.84	1.19	0.93	1.07	0.78	1.28
Xingzi Prefecture	0.91	1.10	30.35	0.03	27.47	0.04
Xunyang District	0.75	1.34	1.63	0.61	1.22	0.82
Yongxiu Prefecture	0.75	1.34	1.71	0.59	1.27	0.79
Yushui District	7.85	0.13	0.00	338.73	0.02	43.14
Yugan Prefecture	68.69	0.01	0.02	49.18	1.40	0.72
Yujiang Prefecture	2.49	0.40	8.14	0.12	20.25	0.05
Yuehu District	0.84	1.19	10.05	0.10	8.47	0.12
Zhangshu City	0.78	1.28	1.56	0.64	1.22	0.82
Zhushan District	13.31	0.08	0.02	54.65	0.24	4.11
Mean	4.00	2.84	15.79	12.62	13.95	2.07
StDev	11.403	7.238	43.701	56.345	45.870	7.067

A higher M_{el} value relative to M_{le} indicates that energy is relatively more easily substituted for labor. This result reflects the energy-intensive nature of industry in the PLEEZ.

In investigating individual regions within the PLEEZ, we find that M_{ek} is relatively low in certain regions (e.g., Yushui, Yugan, and Zhushan). This finding indicates the high substitutability of capital for energy in those regions. If industries there succeed in investing in energy-efficient capital, those regions are likely to easily achieve the goal of "sustainable development." Additionally, through the appropriate use of funds gathered through energy-related taxes, those regions, with the government's assistance, could invest in energy-efficient capital.

Table 6 shows the Morishima elasticities of substitution between individual pollutants, as calculated in (8). A higher M_{12} value relative to M_{21} indicates that wastewater is relatively more easily substituted for SO_2. The same phenomenon can be found in comparing M_{13} and M_{31}. This result may stem from the fact that the PLEEZ is rich in water resources: it is quite easy for factories there to discharge their wastewater into the lake. It is suggested that the local government strengthen the intensity of environmental regulation with regard to the discharge of wastewater, to protect the water quality of Poyang Lake.

6 Conclusion

This study uses the duality theory of SBM in DEA to develop a general methodology for modeling environmental production characteristics, based on a non-parametric approach. Using the proposed methodology, we measure total-factor environmental technical efficiency, the shadow prices of emissions, and inter-factor substitution possibilities. An empirical study of the PLEEZ in China is carried out by using the proposed methodology.

We find that many regions in the PLEEZ are not performing technically efficiently, in line with the constraint of environmental factors. The PLEEZ could accomplish an approximate 44.7 % efficiency improvement, if all the regions therein were to operate on the frontier of environmental production technology. We also find emissions to have low shadow prices, and this indicates that the main types of emission are not being strictly regulated in the PLEEZ. The Morishima elasticities of substitution show that capital and energy are not substitutes in the PLEEZ; rather, they are complementary.

Some policy implications are also proposed: First, because there exists regional difference in environmental efficiency, the equitable policy paradigm of environmental performance should be promoted only with great caution in order to avoid the dichotomy associated with eco-friendly economic development. Second, as Jiangxi is currently in the initial stage of emission abatement, a lower market pricing system can be proposed. The result of shadow prices contains some important implications, encouraging policy-makers in PLEEZ to dispense with some of the many complicated regulations inherent to the current emission system.

Third, it is suggested that the regions with high substitutability for energy invest in energy-efficient capital, in order to achieve sustainable development. Finally, we also suggest that the government allow those regions to use funds gathered through

Table 6 Morishima elasticity of substitution for pollutants

Regions	M_{12}	M_{21}	M_{13}	M_{31}	M_{23}	M_{32}
Anyi Prefecture	0.54	1.84	0.83	1.20	1.53	0.65
Changjiang District	19.46	0.05	19.09	0.05	0.98	1.02
Dean Prefecture	11.17	0.09	167.76	0.01	15.02	0.07
Donghu District	0.08	11.84	0.03	37.31	0.32	3.15
Dongxiang Prefecture	0.98	1.02	3.18	0.31	3.25	0.31
Duchang Prefecture	2.10	0.48	10.21	0.10	4.87	0.21
Fengcheng City	17.49	0.06	9.76	0.10	0.56	1.79
Fuliang Prefecture	48.52	0.02	671.21	0.00	13.83	0.07
Gaoan City	15.02	0.07	25.39	0.04	1.69	0.59
Guixi City	1.62	0.62	0.60	1.67	0.37	2.69
Hukou Prefecture	1.60	0.62	2.73	0.37	1.70	0.59
Jinxian Prefecture	0.18	5.64	1.01	0.99	5.71	0.18
Jiujiang Prefecture	3.51	0.28	3.22	0.31	0.92	1.09
Leping City	1.08	0.93	1.71	0.58	1.58	0.63
Linchuan District	4.70	0.21	9.96	0.10	2.12	0.47
Lushan District	0.27	3.66	0.74	1.36	2.69	0.37
Nanchang Prefecture	3.66	0.27	5.88	0.17	1.61	0.62
Pengze Prefecture	8.78	0.11	88.89	0.01	10.13	0.10
Poyang Prefecture	2.54	0.39	11.21	0.09	4.41	0.23
Qingshanhu District	0.46	2.19	0.25	4.08	0.54	1.87
Qingyunpu District	0.15	6.85	0.07	14.51	0.47	2.12
Ruichang City	0.35	2.88	1.63	0.61	4.71	0.21
Wanli District	0.20	4.96	0.17	5.97	0.83	1.20
Wannian Prefecture	13.88	0.07	4.57	0.22	0.33	3.04
Wuning Prefecture	3.68	0.27	10.51	0.10	2.85	0.35
Xihu District	0.08	12.81	0.03	37.86	0.34	2.96
Xingan Prefecture	14.28	0.07	34.21	0.03	2.40	0.42
Xinjian Prefecture	0.79	1.26	0.60	1.68	0.75	1.33
Xingzi Prefecture	0.14	6.91	0.75	1.33	5.18	0.19
Xunyang District	75.17	0.01	46.66	0.02	0.62	1.61
Yongxiu Prefecture	0.50	2.01	1.27	0.79	2.56	0.39
Yushui District	239.27	0.00	1.75	0.57	0.01	136.74
Yugan Prefecture	9.45	0.11	142.61	0.01	15.10	0.07
Yujiang Prefecture	14.83	0.07	3.11	0.32	0.21	4.77
Yuehu District	31.65	0.03	5.89	0.17	0.19	5.37
Zhangshu City	7.20	0.14	9.17	0.11	1.27	0.79
Zhushan District	1.61	0.62	0.04	24.27	0.03	39.13
Average	15.05	1.88	35.05	3.71	3.02	5.87

1 = waster water; 2 = SO_2; 3 = soot

energy-related taxes to invest in energy-efficient capital, and strengthen the intensity of environmental regulations vis-à-vis the discharge of wastewater.

Future study could consider compare the results between non-parametric distance function and parametric distance function. By the comparison, we can investigate the difference in the empirical results conducted by the two approaches, and discuss the possible reasons for the differences.

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