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Efficiency and reduction cost of carbon emissions in China: a non-radial directional distance function method

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ABSTRACT

The assessment of carbon emission performance is crucial to formulate environmental policies. Few studies have systematically examined environmental efficiency from the perspective of regional temporal–spatial differences and evolution laws. In this paper, we evaluate the carbon emission efficiency and reduction cost in 30 provinces of mainland China from 1996 to 2012 using the non-radial directional distance function method. Three primary carbon emission zones, i.e., the steep-slope zone, flat zone, and plateau zone are classified and compared comprehensively in terms of emission performance (measured by Malmquist index), abatement cost (measured by shadow price), and potential emissions (measured by the growth rates of emissions and economic outputs). Results show that, carbon emission efficiency varies greatly among zones and is closely related to regional economic development. The shadow price for each zone and the whole country between 1996 and 2012 presents a remarkable regularity that it kept increasing at first and decreased afterwards, reaching the maximum value at the year 2000. Furthermore, the carbon emissions in three zones exhibit significant differences. Meanwhile, similarities exist within each zone, indicating that environmental policies designed for different zones and emissions trading across zones are rather necessary and feasible. The empirical estimations from this study provide an analytical basis for the implementation of carbon emission regulations and would facilitate a balanced and sustainable development of China's environment and economy.

1. Introduction

The warming global climate and frequent disastrous weather have made greenhouse gas abatement more complex and difficult since the end of the last century. As the largest carbon dioxide emitter in the world, China is facing extreme pressure from international climate mitigation bodies and domestic emissions reduction targets. In 2009, the government announced a target of cutting the country's carbon emission intensity by 40–45%, based on a projected trajectory of emission intensity levels from 2005 to 2020, in order to demonstrate its commitment to environmental protection. In recent years, the environmental quality in some eastern areas of China (such as Beijing) has improved, while in other areas (such as Shanxi), it has deteriorated. This means that adopting the same emission reduction model in different areas of China may be inappropriate. Therefore, it is urgent to explore the development trends and evolving regularities of carbon emissions, through the evaluation of regional carbon emission efficiency and reduction cost, and the establishment of different reduction policies for local areas (Wu et al., 2012).

Carbon emission efficiency can reflect the level of economic growth promoted by per unit emission in assessed areas. Literature relevant to this topic has expanded widely. A number of evaluation indices have been employed in related studies, including carbon emission intensity (carbon emission per unit of gross domestic production) (Davidsdottir and Fisher, 2011), and carbon productivity (the amount of economic output per unit of carbon emission) (Budzianowski, 2012), etc. These methods are usually considered as partial-factor emission efficiency analyses because they can reflect only some aspects of emission performance. Contrarily, based on the directional distance function (DDF) (Boyd et al., 1996; Lee et al., 2002), the environmental performance index within a total-factor efficiency framework (Zhou et al., 2010) may be more comprehensive. This is the first focus of this article.

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Besides emission efficiency, the cost of carbon reduction (mainly represented by shadow price) is another important factor in emission policy making, which refers to the negative impacts of carbon abatement on the economy. Moreover, the DDF method is typically adopted to estimate the shadow price as it has neither strict data requirements nor strong assumptions relating to parameter estimations of regressive models. Studies adopted this method include the assessment of marginal carbon abatement cost based on the MARKAL-MACRO model by Gao et al. (2004), which is close to the cost estimation of 38 two-digit industries in China from 1980 to 2008 by Chen (2011), but slightly higher than the measurement of the average shadow price of 30 provinces by Liu et al. (2011). This is the second focus of this paper, which provides vital information on the appropriate time and potentials of emissions mitigation.

Further, studies based on DDF method can be classified into two categories: the parametric method (Chung, 1996), and the nonparametric method based on Data Envelopment Analysis (DEA) (Chambers et al., 1996; Zhao et al., 2006; Kaneko et al., 2010). The former developed early can easily calculate the shadow price, but has to compute the distance function coefficients. The latter used widely does not need to preset function forms, and can analyze the shadow price of pollutants in the changes in all directions and that of individual pollution emissions (Zhang and Choi, 2014). Moreover, the traditional radial DEA models tend to overestimate the efficiency of the decision making units (DMU) assessed when there exists non-zero slacks, while the non-radial DEA approach can overcome this problem and be more attractive (Zhou et al., 2012). This constitutes the methodological basis of our study.

In addition, many studies dealing with emission performance provide significant implications for policy formulation, most of which focus on methodology improvement (Zhang et al., 2013; Feiz et al., 2014, etc.), the factors influencing carbon emissions (Zhou et al., 2014; Wu et al., 2014), or the potentials of emission reduction (Moya and Pardo, 2013; Morrow et al., 2014). Few studies have explored the development of laws or key features of carbon emission efficiency on both national and regional levels. Furthermore, the researches on emission reduction cost measured by shadow price have not presented consistent results (Choi et al., 2012). The main reason for this is that these research elements including studying subjects, methods, and spans of literature vary greatly (Chen et al., 2013; Roach, 2013). In particular, these studies are disseminated mainly at national level (Chen, 2005; Song et al., 2013), provincial level (Wei et al., 2013), industrial level (Branco et al., 2011; Lee and Zhang, 2012; Chang et al., 2013; Zhang et al., 2014; Zhang and Xie, 2015) or plant level (Mekaroonreung and Johnson, 2012; Barros et al., 2013; Zhang and Choi, 2013), while rarely focus on this issue at both national and regional levels in the same research. Hence, it can be argued that, the evaluations on emission performance from national and local dimensions considering regional temporal–spatial differences would be crucial for governments to issue the proper carbon emission regulations. This provides sufficient research space for this paper.

The main goal of this paper is to measure the carbon emission efficiency and reduction cost of China during 1996–2012 under a theoretical framework of non-radial DDF, and to divide the whole country into different emission zones using by the clustering method, and then to provide environmental regulation suggestions based on the features of each zone. To our best knowledge, few articles have attached enough importance to this field. This study gives a comprehensive perspective to the policy makers on carbon emission efficiency potentials and reduction cost at national and provincial levels.

The rest of this article is organized as follows. Section 2 presents materials and methodology framework of the nonparametric DEA models. Section 3 empirically studies China's carbon emission efficiency and reduction cost and proposes the idea of three-zone division. Section 4 concludes.

2. Materials and methods

2.1. Study framework

In this study, the assessment of emission efficiency and reduction cost are conducted within the methodological framework of nonparametric DEA analysis. In detail, the non-radial DDF method has an advantage over traditional methods such as radial DDF in that it can measure technical efficiency flexibly considering changes in inputs and outputs at the same time. Based on this methodology, the Malmquist index and shadow price are calculated to evaluate the emission performance and reduction cost of DMUs, respectively. We also estimate the average growth rates of carbon emissions and the economic outputs to reflect the future demands for each DMU's emission growth. Choosing these four variables as clustering indices, we perform a K-means clustering analysis. The number of clusters is specified as three, which is in line with the traditional division of three districts of China based on geographical position (i.e., eastern China, central China and western China) and the consequential regional policies. Coincidentally, these three districts basically correspond to developed, developing, and underdeveloped areas respectively, owing to their different policy orientations over the past few decades. In this sense, these three geographical districts are also referred to as separate economic districts. The appropriate clustering results are obtained by SPSS software, and can be used as important points for emissions policy making.

2.2. Methodology

2.2.1. Environmental production technology

Considering a production process that uses Energy (E), Labor (L), and capital (K) as inputs to generate desirable output (Y) and undesirable output (C), we can then describe the production technology as follows:

$$T = \{(E, L, K, Y, C) : (E, L, K) \mathit{can\ produce} (Y, C)\} \tag{1}$$

where T is often assumed to satisfy the standard axioms as Färe and Grosskopf (2005) suggested, because inactivity is possible and finite amounts of inputs can produce only finite amounts of outputs. Moreover, inputs (E, L, K) and desirable output (Y) are usually supposed to be strongly or freely disposable, indicating that if $(E, L, K, Y, C) \in T$ and $(E', L', K') \geq (E, L, K)$ (or $Y' \leq Y$) then $(E', L', K', Y, C) \in T$ (or $(E, L, K, Y', C) \in T$).

In order to reasonably model the joint-production process, as Färe et al. (1989) described, the following two assumptions are imposed:

(i) Weak disposability of outputs: If $(E, L, K, Y, C) \in T$ and $0 \leq \theta \leq 1$, then $(E, L, K, \theta Y, \theta C) \in T$. This assumption means that the output is not freely disposable (Pittman, 1983). In other words, the reduction in the undesirable output would incur a proportional reduction in the desirable output, which is especially true considering the current level of production technology and potential reduction costs of China (Wu et al., 2012).

(ii) Null-jointness: If $(E, L, K, Y, C) \in T$ and $C = 0$, then $Y = 0$. This assumption indicates that the production of the desirable output must be accompanied by an undesirable output, and