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Estimating Regional Shadow Prices of CO_2 in China: A Directional Environmental Production Frontier Approach

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Abstract: Shadow price of carbon dioxide (CO_2) plays a fundamental role in evaluating CO_2 abatement cost and formulating regional environmental policies. In this study, CO_2 shadow prices are estimated in 29 provinces of China from 2006 to 2015. Directional Environmental Production Frontier Function (DEPFF) measures the distance between actual production points and the effective production frontier surface, which yields the shadow prices of CO_2 emission. With the relationship between CO_2 emission and Gross Domestic Product (GDP) growth which is encapsulated in the shadow price, the provinces are classified into three groups: acceleration zone, buffer zone, and deceleration zone. The acceleration zone is characterized by a smaller emission growth driving a greater economic growth, and the provincial average price of CO_2 is 184.16 US$/ton. In the buffer zone, a significant emission increase brings about less economic growth with the average shadow price at 86.57 US$/ton. In the deceleration zone, a high growth rate of CO_2 emissions is accompanied with an economic output decrease, which implies that the shadow price of CO_2 should be negative, and the mean value is −200.7 US$/ton. As the CO_2 abatement potential differs significantly across provinces, the environmental policy and CO_2 reduction targets should be region-specific.

Keywords: CO_2 shadow price; Directional Environmental Production Frontier Function; region-specific policies

1. Introduction

Global warming is a severe problem confronted by the international community. Kyoto Protocol is an intergovernmental commitment signed to protect the world from climate hazards. Developed countries have promised to reduce their carbon dioxide (CO_2) emissions since 2005, and they have committed to reduce their emissions since 2012 [1]. In 2006, China accounted for 28% of global CO_2 emissions, overtaking the United States to be the world's largest CO_2 emitter, while the United States and Europe accounted for only 14% and 10%, respectively [2]. As a responsive country, China is actively working to reduce its CO_2 emissions. In calculating the consumption of eight kinds of fossil energy, Figure 1 shows CO_2 emissions and the corresponding Gross Domestic Product (GDP) in China during 2006–2015. In 2006–2011, CO_2 emissions grew at a relative high speed of 7.3% annually, and the speed declined to 0.66% during 2012–2015. From 2005 to 2017, China reduced CO_2 emission per unit of GDP by 45% and this remarkable progress is credited to hard work and effective measurements. In the Paris Climate Agreement, China pledges that by 2030, their carbon intensity will be further reduced to 60–65% of the previous level in 2005, and then the emission will reach its peak [3]. Undoubtedly, this future task is difficult. In 2013, the National Development and Reform Commission of China committed to establishing the Emission Trading Scheme (ETS) and launched pilots in the seven districts of Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, and Shenzhen. At the end of 2017, based on the pilot's experiences, China further established a nationwide carbon ETS. While for complexity of the market construction and its far-reaching impact on the entire economy, all of the details are still uncertain now. In theory, CO_2 shadow prices of the market participants determine the equilibrium volume, price, and the participants' benefits or loss. So further exploring CO_2 shadow prices of the nation is urgent and necessary.

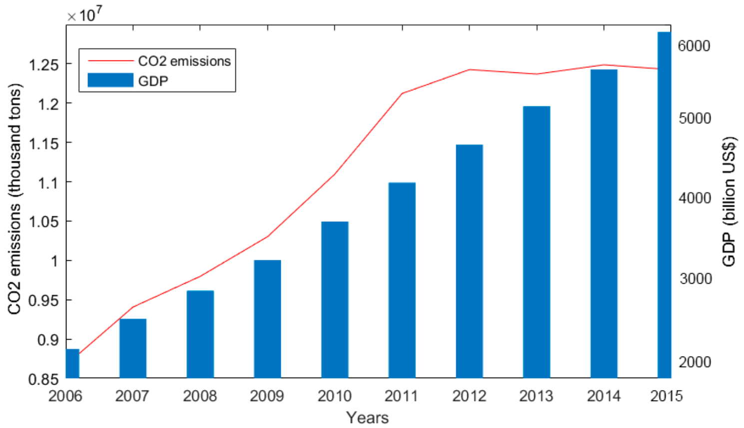

Figure 1. China's overall CO_2 emissions and Gross Domestic Product (GDP) from 2006 to 2015.

This study aims to solve two problems. First, estimate CO_2 shadow prices of 29 provinces in China from 2006 to 2015 with a Directional Environmental Production Frontier Function (DEPFF) approach. Second, analyze provincial differences in relations of CO_2 emission and GDP growth, and then put forward region-specific environmental policies.

Section 2 contains a literature review, while Section 3 outlines the model that is employed to estimate CO_2 shadow prices—the (DEPFF). Section 4 presents the empirical results and discussion of typical cases of CO_2 shadow prices in China's provinces. Section 5 concludes the study and provides some policy implications.

2. Literature Review

CO_2 shadow price can be defined as the opportunity cost of output loss when an additional unit of CO_2 is reduced under a certain technology [4], as estimated with the micro production efficiency model. Given the detailed technology and economic constraints, this type of model defines a set of production possibilities, then reduces CO_2 emissions and captures the opportunity costs. In recent years, the directional distance function (DDF) has been widely used for its not needing the generally unavailable data of input and output prices [5]. The distance function was first proposed by Shephard [6] and later extended by Chung [7] and Färe [8]. Environmental production technology is constructed with the production efficiency model and multiple inputs and outputs. The shadow price of undesirable output is estimated with the output marginal conversion rate which is derived from the dual relationship of distance function (DF) and revenue function. These models can be further divided into parametric and non-parametric kinds. Badau [9] established a parametric environmental production function with the pollutant as undesirable output, then measured the marginal effect of pollution with its partial derivative. Park and Lim [10] applied a distance function based on transcendental logarithm to estimate the CO_2 shadow price for thermal power plants in Korea. Wei [11] derived the shadow price of pollutants in 104 prefecture-level cities with a parameterized quadratic method based on the dual relationship of income function and directional distance function. Chen et al. [12] used the quadratic directional distance function to study the temporal and spatial evolution characteristics of CO_2 shadow prices and their differences in 30 provinces of China from 2000 to

2012. Many other studies [13–19] also did similar work with a parametric approach. In general, the advantage of this kind of method is the production function being differentiable everywhere and easily manipulated algebraically. But its shortcomings are also apparent. First, the estimated parameters and results may be misleading if the function and data are not correctly matched. Second, the parametric model confines the shadow price as an average result and the effect of economic individuals can't be obtained [20].

The other kind is the non-parametric model. Shadow price is derived by constructing a production frontier with a mathematical programming technique and input-output combinations. Chen et al. [21] used the extremely efficient slacks-based measure (SBM) model to calculate the CO_2 shadow prices for 30 provinces in China. Lee et al. [22] used the non-parametric directional distance function to evaluate the shadow price and environmental efficiency of pollutants in the Korean thermal power generation industry. Choi et al. [23] applied a non-radial regression-based data envelopment analysis (DEA) model to estimate the shadow price of CO_2 emissions. Chen [24] employed both the parametric and non-parametric methods to estimate the directional environmental output distance function and measured the CO_2 shadow price for the industrial sub-sectors. Liu et al. [25] estimated the shadow price of China's provincial CO_2 emissions based on the non-parametric distance function method and evaluated the performance. Wang et al. [26] also applied non-parametric methods to estimating CO_2 shadow prices. The non-parametric method has many advantages. First, it avoids the possible mistakes of falsely assuming the function form, and then becomes more flexible to application. Second, it is insensitive to the unit of measure and need not transform the data into dimensionless form. Finally, the weights of inputs and outputs are decided through optimization solution, which improves the objectivity standard of the estimation. Although the non-parametric method ignores the impact of random shocks on the frontier output and its results can't be statistically tested, the random impact is averaged and greatly weakened when the samples are most abundant, and it has less effect on the overall characteristics of the examined region. Therefore, the non-parametric method is more practical for calculating the CO_2 shadow price and is used in this study.

Table 1 shows some studies on the CO_2 shadow price estimation of China. They are different in the choices of samples, period, and method, so the results are greatly divergent. What's more, few articles were concerned with the regional shadow prices in perspective of the relations between CO_2 emissions and GDP growth. Illustrated analysis in typical regions is even more scarce.

Table 1. Summary of reference on estimating CO_2 shadow prices in China's provinces.

Reference	Sample	Period	Model	Method	Average Shadow Price (US$/ton)
Wang et al. [26]	28 provinces	2007	DDF	Non-parametric	57.37
Liu et al. [25]	30 provinces	2005–2007	DDF	Non-parametric	206.44
Wei et al. [27]	29 provinces	1995–2007	DEA	SBM	13.77
Choi et al. [23]	30 provinces	2001–2010	DEA	SBM	5.55
Zhang et al. [15]	29 provinces	2006–2010	DDF	parametric	9.68
Du et al. [16]	30 provinces	2001–2010	DDF	parametric	157.03
He [28]	29 provinces	2000–2009	DF	parametric	12.56
Ma and Hailu [29]	30 provinces	2001–2010	DDF	parametric	271.91
Song et al. [30]	29 provinces	2005–2014	DEA	SBM	132.87

Notes: DDF, DEA, SBM and DF denote directional distance function, data envelopment analysis, slacks-based measure and distance function, respectively.

This study employs the DEPFF to simulate marginal effects of the CO_2 emissions and CO_2 shadow price. Using a positive or negative sign of shadow price, the output changing with CO_2 abatement is available, which strengthens the interpretation of the results and enriches policy implications. Furthermore, three groups are identified for examining the trends of CO_2 shadow price in different regions of China, and corresponding environmental policies are proposed.

3. Materials and Methods

In this section, the concept of directional distance function was first introduced, then the DEPFF model was constructed to estimate shadow prices of CO_2.

3.1. Directional Distance Function

The directional distance function is a general form of the Shephard yield distance function and a generalized representation of the radial data envelopment analysis model. In recent years, it has been widely used in measuring the shadow price of undesirable output. DDF allows for simultaneous observation of the direction of change in desirable output and undesirable output. The decision-making unit (DMU) is only at the forefront of efficiency when the desirable output reaches the maximum and the undesirable output is the minimum. Referring to the definition by Fare [31], assuming input is $x \in R_+^N$, desirable output is $y \in R_+^U$, and undesirable output is $b \in R_+^V$, the production technology set $P(x)$ can be defined as follows:

$$P(x) = \{(y, b) : x \; can \; produce \; (y, b)\} \tag{1}$$

$P(x)$ represents the set of possibilities for production. It gives the set of maximum output y and minimum undesirable output b by given conditions and the possible frontier boundary of environmental output. $P(x)$ also satisfies the following properties:

(1) Desirable outputs and undesirable outputs have joint productivity. If $(y, b) \in P$ and $y = 0$, it is implied that $b = 0$.
(2) Desirable outputs and undesirable outputs have joint weak disposability. If $(y, b) \in P, 0 \leq \theta \leq 1$, it is implied that $(\theta y, \theta b) \in P$.
(3) Desirable outputs are freely disposable. If $(y, b) \in P$ and $y' \leq y$, it is implied that $(y', b) \in P(y, b)$.

Chen and Delmas [32] recommended that undesirable outputs should be defined as strong disposability, on the grounds that some of the areas of production set that are lost due to weak disposition constraints of undesirable outputs should belong to a production set. However, if it is defined as strong disposability, its production set might be illogical. In actual production, the number of undesirable outputs cannot be increased indefinitely, and it should not exceed the maximum amount that can be produced in the production process. In terms of the possible set of production and production front, it is reasonable to define undesirable output as weak disposability.

After considering the above (1)–(3) properties, to constrain the direction of desirable and undesirable outputs, $g = \left(g_y, -g_b\right)$ and $g \neq 0$ are used as the directional vector of the directional distance function, which implies expansion of the desirable outputs and the reduction of the undesirable outputs under production technology $P(x)$, The directional environmental distance function is constructed as follows:

$$D\left(x_i^t, y_i^t, b_i^t; gy_i^t - gb_i^t\right) = \max_{\varepsilon, z}\left\{\varepsilon : \left(y + \varepsilon gy_i^t, b - \varepsilon gb_i^t\right) \in P\left(x_i^t\right)\right\} \tag{2}$$

$$s.t. P^T(X^T) = \left\{ \begin{array}{l} \sum\limits_{i=1}^{I} z_i^t y_{i,u}^t \geq y_{i,u}^t, u = 1, \ldots, U; \\ \sum\limits_{i=1}^{I} z_i^t x_{i,n}^t \leq x_{i,n}^t, n = 1, \ldots, N; \quad z_i^t \geq 0, \sum\limits_{i=1}^{I} z_i^t = 1, i = 1, \ldots, I. \\ \sum\limits_{i=1}^{I} z_i^t B_{i,V}^t = b_{i,v}^t, v = 1, \ldots, V; \end{array} \right. \tag{3}$$

ε represents the degree of efficiency that a given DMU can achieve compared to the most effective DMU on the production frontier surface. $\varepsilon = 0$ indicates that DMU is efficient and located on the production frontier. A higher ε indicates that the technical efficiency of the DMU is lower and located away from the frontier, which indicates that the DMU has a greater potential to reduce the undesirable output while increasing the desirable output. $\left(gy_i^t - gb_i^t\right)$ is the direction vector of the function, εgy_i^t and εgb_i^t

respectively represent the expansion ratios of the desirable output y and the undesirable output b from the production frontier, z_i represents the non-negative weights whose sum is 1, which illustrates that the production technology is variable returns to scale.

3.2. Directional Environmental Production Frontier Function

The DDF model gives the degree of efficiency that can be achieved between DMU i and the most effective DMUs on the production frontier. Therefore, based on the DDF model, the frontier output level of DMU i can be calculated by adding up all outputs to construct the directional environmental production frontier function. Defined by the reference production technology $P^T\left(X^T\right)$, the DEPFF of the DMU $i\left(x_i^t, y_i^t, b_i^t\right)$ at year t is:

$$F^t\left(x_i^t, y_i^t, b_i^t; gy_i^t - gb_i^t\right) = \max_{\varepsilon,z}\left(y_i^t + \varepsilon y_i^t\right) \tag{4}$$

$$\begin{cases} \sum\limits_{i=1}^{I} z_i^t y_{i,u}^t \geq (1+\varepsilon) y_{i,u}^t, u = 1,\ldots,U; \sum\limits_{i=1}^{I} z_i^t x_{i,n}^t \leq x_{i,n}^t, n = 1,\ldots,N; \\ \sum\limits_{i=1}^{I} z_i^t b_{i,v}^t = (1-\varepsilon) b_{i,v}^t, v = 1,\ldots,V; \ z_i^t \geq 0, \sum\limits_{i=1}^{I} z_i^t = 1, i = 1,\ldots,I. \end{cases} \tag{5}$$

DEPFF presents the corresponding frontier output under the conditions of input x, production technology $P(x)$, actual expected output y, undesirable output b, and direction vector g. $F^{t+1}\left(x_i^{t+1} y_i^{t+1}, b_i^{t+1}\right)$ of the DMU $i\left(x_i^{t+1}, y_i^{t+1}, b_i^{t+1}\right)$ at year $t+1$ under the reference production technology $P^{t+1}\left(X^{t+1}\right)$ can be obtained by changing the time to $t+1$ in the algorithm of year t.

3.3. Intertemporal Directional Environmental Production Frontier Function

Before deriving the shadow price, it is necessary to observe the influence of a single change of undesirable output b on the production frontier surface while keeping input x, desirable output y, and directional vector g *constant*, thereby constructing the intertemporal DEPFF of period t and $t+1$. The meaning of the intertemporal DEPFF is the effect of a single change in undesirable output b on frontier output while keeping some factors constant. The intertemporal DEPFF is defined as follows:

Defined by the reference production technology $P^T\left(X^T\right)$, the intertemporal DEPFF of the decision-making unit i in year t which uses intertemporal input-output level $\left(x^t, y^t, b^{t+1}\right)$ is:

$$F^t\left(x_i^t, y_i^t, b_i^{t+1}; gy_i^t - gb_i^t\right) = \max_{\varepsilon,z}\left(y_i^t + \varepsilon y_i^t\right) \tag{6}$$

$$\begin{cases} \sum\limits_{i=1}^{I} z_i^t y_{i,u}^t \geq (1+\varepsilon) y_{i,u}^t, u = 1,\ldots,U; \sum\limits_{i=1}^{I} z_i^t x_{i,n}^t \leq x_{i,n}^t, n = 1,\ldots,N; \\ \sum\limits_{i=1}^{I} z_i^t b_{i,v}^t = b_{i,v}^{t+1} - \varepsilon b_{i,v}^t, v = 1,\ldots,V; \ z_i^t \geq 0, \sum\limits_{i=1}^{I} z_i^t = 1, i = 1,\ldots,I. \end{cases} \tag{7}$$

By the same method, defined by the reference production technology $P^{t+1}\left(X^{t+1}\right)$, the intertemporal DEPFF of DMU i in year $t+1$ with input-output level of $\left(x^{t+1}, y^{t+1}, b^t\right)$ is:

$$F^{t+1}\left(x_i^{t+1}, y_i^{t+1}, b_i^t; gy_i^{t+1} - gb_i^{t+1}\right) = \max_{\varepsilon,z}\left(y_i^{t+1} + \varepsilon y_i^{t+1}\right) \tag{8}$$

$$\begin{cases} \sum\limits_{i=1}^{I} z_i^{t+1} y_{i,u}^{t+1} \geq (1+\varepsilon) y_{i,u}^{t+1}, u = 1,\ldots,U; \sum\limits_{i=1}^{I} z_i^{t+1} x_{i,n}^{t+1} \leq x_{i,n}^{t+1}, n = 1,\ldots,N; \\ \sum\limits_{i=1}^{I} z_i^{t+1} b_{i,v}^t = b_{i,v}^t - \varepsilon b_{i,v}^{t+1}, v = 1,\ldots,V; \ z_i^{t+1} \geq 0, \sum\limits_{i=1}^{I} z_i^{t+1} = 1, i = 1,\ldots,I. \end{cases} \tag{9}$$

3.4. Marginal Effect of Undesirable Output and Shadow Price of CO_2

According to the definition and nature of the production technology, as shown in Figure 2, the relationship between the DEPFF and the undesirable output variable b is given as: under the production technology $P^T\left(X^T\right)$ and the direction vector $g = \left(y^t, b^t\right)$, if $b^t \le b^{t+1}$, it is implied that $F^t\left(y^t, x^t, b^t; y^t, -b^t\right) \le F^t\left(y^t, x^t, b^{t+1}; y^t, -b^t\right)$. Similarly, if production technology is $P^{t+1}\left(X^{t+1}\right)$ and the direction vector is $g = \left(y^{t+1}, b^{t+1}\right)$, if $b^t \le b^{t+1}$, it is implied that $F^{t+1}\left(y^{t+1}, x^{t+1}, b^t; y^{t+1}, -b^{t+1}\right) \le F^{t+1}\left(y^{t+1}, x^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1}\right)$. The difference between the decision unit $A\left(y^{t+1}, b^{t+1}\right)$ and $B\left(y^{t+1}, b^t\right)$, that is, the difference between producer's frontier output $F^{t+1}\left(y^{t+1}, x^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1}\right)$ and $F^{t+1}\left(y^{t+1}, x^{t+1}, b^t; y^{t+1}, -b^{t+1}\right)$, lies in the corresponding. The undesirable output b is different, which means that the frontier output will increase with an increase in b. Moreover, the change in b in different periods leads to different growth rates for frontier output. At this point, as b increases constantly, the production frontier surface will turn sharply to the lower right. The economic implication is that the increase in undesirable output b will contribute to a rapid increase in frontier output for a certain period. However, if the growth of undesirable output b can grow indulgently, it will not promote economic growth, but will lead to negative growth in frontier output.

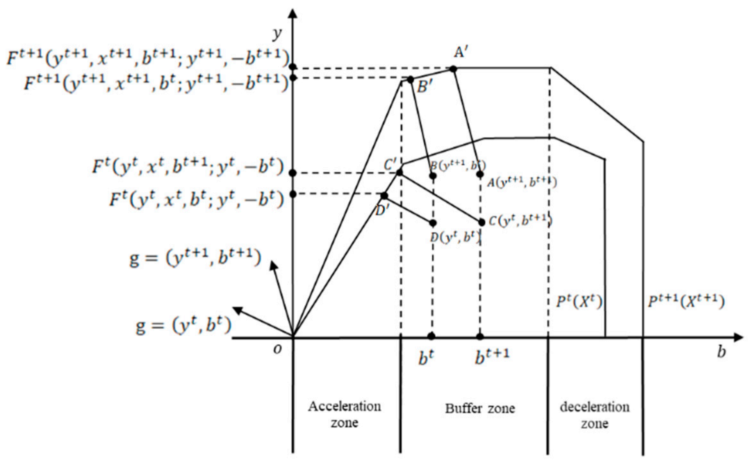

Figure 2. Changes in undesirable output b cause three variation trends in frontier output F of directional environmental production frontier function.

Chung [7] applied a directional distance function containing undesirable outputs to the Malmquist model. The geometric mean of the Malmquist-Luenberger (ML) indices of the two periods using adjacent cross reference is used as the ML index of the evaluated decision unit. The ML can be decomposed into efficiency change EC and technology change TC. According to the idea of the ML index decomposition method and the relationship between the undesirable output b and the DEPFF, it is also possible to use adjacent cross referencing while retaining the condition of reference technology and the input and expected output levels in the two periods. The geometric average of the change in the frontier output F caused by the change in the undesirable output b is used as the marginal effect of undesirable output change on frontier output:

$$MEC = \left[\frac{F^t\left(y^t, x^t, b^{t+1}, y^t, -b^t\right)}{F^t\left(y^t, x^t, b^t, y^t, -b^t\right)} \times \frac{F^{t+1}\left(y^{t+1}, x^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1}\right)}{F^{t+1}\left(y^{t+1}, x^{t+1}, b^t; y^{t+1}, -b^{t+1}\right)}\right]^{1/2} \tag{10}$$

MEC denotes the marginal effects of the CO_2 emissions change on the frontier's desirable output level, which means that undesirable output from b^t to b^{t+1} leads to changes in the frontier output from $F\left(y, x, b^t; y, -b\right)$ to $F\left(y, x, b^{t+1}; y, -b\right)$ while keeping the technical structure P, input level x, and the direction vector g constant. If MEC is equal to 1.15, namely the marginal net effect is 15%, and indicates that the marginal contribution of CO_2 emissions leads to an increase in frontier output by 15% over the previous year. *MEC* is equal to 0.85 and the marginal net effect is −15%, which denotes the frontier output reduced by 15% due to the change in CO_2 emissions. The shadow price of CO_2 is the change amount of frontier output caused by the change of CO_2 emission per unit. Under different reference technologies and input-output levels, CO_2 emissions have different shadow prices, which can measure the impact of emissions reduction on output. *MEC* is the ratio of the change in the undesirable output b^t to b^{t+1} to the frontier output. Linking the absolute effect of marginal output with the amount of CO_2 emission change can derive the CO_2 shadow price formula:

$$SP_{CO_2} = \frac{y_{i,t-1} \times (MEC_{i,t} - 1)}{CO_{2\ i,t} - CO_{2\ i,t-1}} \tag{11}$$

The shadow price of CO_2 is related to the size of the economy and the level of emissions. From the perspective of emissions reduction, a decrease in output caused by the reduction in CO_2 emissions should be as low as possible. At this time, a lower shadow price indicates that emissions reduction has had a lower impact on economic output. Conversely, the increase in output has caused an increase in CO_2 emissions as much as possible. A higher shadow price indicates that the benefits of increased CO_2 emissions are significant. This shows that the shadow price of CO_2 depends on the marginal contribution of output and the scale of CO_2 emissions. Compared with the traditional GDP per unit of CO_2 emission evaluation method, the shadow price of CO_2 strips away many factors that affect output, and it is more practical to link the changes in CO_2 emissions to the changes in frontier output. The relationship between actual CO_2 emissions and output varies regularly. Figure 2 shows that the change of undesirable output causes three variation trends in frontier output of DEPFF. Thus, it can be concluded that the provinces can be classified into three groups, based on the characteristics of CO_2 shadow price changes:

(1) Acceleration zone—its typical feature is that even a small growth in emissions at low emission levels can contribute to greater economic growth, while shadow prices are higher. This means that reducing emissions will lead to a sharp reduction in the economy. Since the cost of cutting emissions is relatively high, CO_2 emission control should be suspended to encourage economic development.
(2) Buffer zone—a significant emission increase brings about less economic growth, and the CO_2 shadow price is relatively low. Therefore, these regions can significantly reduce CO_2 emissions at the expense of smaller economic output. At this point, if producers still pursue economic growth through substantial increases in CO_2 emissions, the environmental cost is huge.
(3) Deceleration zone—it is characterized by a high growth rate of CO_2 emissions accompanied with economic output decreasing, which implies that the shadow price should be negative. That means producers cannot promote economic growth by expanding CO_2 emissions. In this case, environmental regulations should be strengthened by shutting down the enterprises with high energy consumption and low efficiency. besides, the industrial structure and energy consumption structure should be optimized to promote effective emissions reduction.

3.5. Data and Variables

There are 34 provincial administrative regions in China. Hong Kong, Macau, Taiwan, Tibet, and Chongqing were excluded due to a lack of relevant data. The remaining 29 provincial regions were analyzed from 2005 to 2015. This study uses “two inputs and two outputs” as the research sample. The “two inputs” are capital stock and labor, and the “two outputs” are GDP and CO_2 emissions, of which CO_2 emissions are undesirable output. A statistical description of the input-output data is presented in Table 2, and a detailed description of each variable is provided below.

Capital stock—estimated using the perpetual inventory method. We used the approach proposed by Shan [33] to calculate the capital (constant 2000 US$). The formula is $K_t = I_t + (1 - \delta_t)K_{t-1}$, where

K_t is the capital stock in year t, K_{t-1} is the capital stock in year $t-1$, δ is the capital depreciation rate (10.96%), and I_t is the investment in year t. The related data were obtained from China Statistical Yearbook 2016 [34].

Labor—the total number of employees, collected from the China Statistical Yearbook 2016 [34] is used as the input.

GDP—the gross domestic product of each provincial region is chosen as the desirable output based on data at constant prices (constant 2000 US$), obtained from the China Statistical Yearbook 2016 [34].

CO_2 emissions—CO_2 emissions were derived from fossil fuel consumption and its conversion, since there is a lack of official statistical data on CO_2 emissions in China. This study uses the approach introduced in the Intergovernmental Panel on Climate Change (IPCC) to measure the CO_2 emissions of various provinces in China. Therefore, the formula is $b = \sum E_i \times NCV_i \times COF_i \times CEF_i \times 44/12$, where b denotes the types of various sources of energy consumption i, including raw coal, coke, crude oil, gasoline, diesel oil, kerosene, natural gas, and fuel oil, respectively. NCV_i denotes the net caloric value, COF_i denotes CO_2 oxidation factor, CEF_i denotes CO_2 emission factor, 44/12 is the ratio of the molecular weight of CO_2 (44) to the atomic weight of C (12) (named the CO_2 gasification coefficient). Various sources of energy consumption i and NCV_i used in the calculations were obtained from the China Energy Statistical Yearbook 2016 [35]. CEF_i and COF_i were derived from Tables 1–3 and Tables 1–3 and Table 4 of the Energy Volume II of the national greenhouse gas inventory guide published by the IPCC [36].

Table 2. Descriptive statistics of input-output data.

Category	Variable	Samples	Mean	Max	Min	Standard Deviation
Desirable output	GDP (billion US$)	319	133.22	648.49	5.62	116.34
Undesirable output	CO_2 emissions (thousand tons)	319	373,214	1,377,266	16,396	258,755
Input	Capital stock (billion US$)	319	322.62	1451.77	17.687	267.53
	Labor force (thousand persons)	319	26,077.5	66,366	2910.4	17,337.7

Table 3. Division of stages of CO_2 shadow prices in various provinces of China.

Zone	Provinces	Net Effect of Marginal Output of CO_2 Emissions [a] (%)	Absolute Effect of Marginal Output of CO_2 Emissions [b] (Billion US$)	Change in CO_2 Emissions (Thousand Tons)	Shadow Price of CO_2 (US$/ton)
Acceleration zone	Fujian	2.95	4.388	14,473.7	303.19
	Guangxi	2.24	1.854	11,852.1	156.44
	Qinghai	4.06	0.439	3267.9	134.51
	Hainan	5.06	0.984	5960.8	165.11
	Zhejiang	1.55	3.730	14,941.3	249.65
	Sichuan	2.23	3.569	14,923.8	239.19
	Ningxia	5.14	0.578	14,110.5	40.98
Buffer zone	Beijing	0.04	0.043	165.6	265.47
	Shanxi	1.20	0.866	25,036.5	34.59
	Jilin	0.21	0.169	7096.9	23.85
	Inner Mongolia	1.82	1.684	49,069.1	34.32
	Jiangxi	1.66	1.335	10,486.3	127.36
	Jiangsu	−1.01	−3.690	−37,350.2	98.80
	Henan	0.23	0.449	20,842.9	21.54

Table 3. *Cont.*

Zone	Provinces	Net Effect of Marginal Output of CO_2 Emissions [a] (%)	Absolute Effect of Marginal Output of CO_2 Emissions [b] (Billion US$)	Change in CO_2 Emissions (Thousand Tons)	Shadow Price of CO_2 (US$/ton)
Deceleration zone	Tianjin	−0.62	−0.546	7601.7	−71.87
	Shanxi	−0.29	−0.223	31,749	−7.03
	Hebei	−2.01	−3.697	31,618	−116.96
	Liaoning	−1.66	−3.049	20,383.7	−149.62
	Shanghai	−2.57	−4.395	3805.4	−1154.99
	Shandong	−1.66	−5.833	65,073.6	−89.64
	Heilongjiang	−1.36	−1.529	11,707.3	−130.67
	Anhui	−1.72	−1.950	20,365.5	−95.76
	Guizhou	−4.34	−1.702	10,092.2	−168.72
	Gansu	−3.27	−1.245	8040.5	−154.89
	Guangdong	−0.55	−2.377	23,668.6	−100.44
	Hunan	−0.48	−0.658	9453	−69.69
	Hubei	−0.87	−1.190	11,962.8	−99.52
	Yunnan	−1.84	−1.278	2698.5	−473.67
	Xinjiang	−9.34	−4.378	34,496.4	−126.93

Notes: a = marginal effects of the CO_2 emissions (MEC)-1; b = gross domestic product (GDP)×(MEC-1).

Table 4. Two-factor analysis of variance for significant test.

Source	Sum of Squares	Degree of Freedom	Mean Squares	F	*p*-Value	F-Crit
Columns	362,735.8	2	181,367.9	6.1	0.0052	3.245
Rows	587	1	587	0.02	0.889	4.091
Interaction	378,747.1	2	174,373.5	5.86	0.0062	3.245
Error	1,070,398.4	36	29,733.3			
Total	1,782,468.3	41				

4. Results and Discussion

In this section, regional classification of three groups based on shadow prices and time series analysis are presented. The three groups are divided with the net effect of marginal output when the CO_2 emissions changing in provinces of China from 2006 to 2015.

4.1. Regional Classification of Three Groups Based on Shadow Prices

CO_2 shadow price change can be divided into three groups—acceleration zone, buffer zone, and deceleration zone. Figure 3 presents the provincial data of population, per capita GDP, and the share of industry in GDP, which was obtained from the China Statistical Yearbook [34]. Figure 4 shows the provincial data of CO_2 emissions and GDP. Table 3 presents the classification of zone and the detailed values of marginal effect, change of CO_2 emissions, and shadow price. In order to ensure the significance of classification, two-factor analysis of variance was used for statistical verification. Table 4 shows the results of the analysis of variance, "Columns" refers to the acceleration zone, buffer zone and deceleration zone. "Rows" refers to the net effect of marginal output of CO_2 emissions and Shadow price of CO_2. Due to $F_C = 6.1 > F - crit = 3.245, P - value = 0.0052 < \alpha = 0.05$, it is implied that the classification of the three zones passed the significance test. This study calculates the average shadow price of CO_2 in China to be 157.14 US$/ton. Compared with the average shadow price measured in the other studies of Table 1, due to different methods and examining periods, the result of this study is larger than [15,23,26–28,30], but smaller than [25,29].

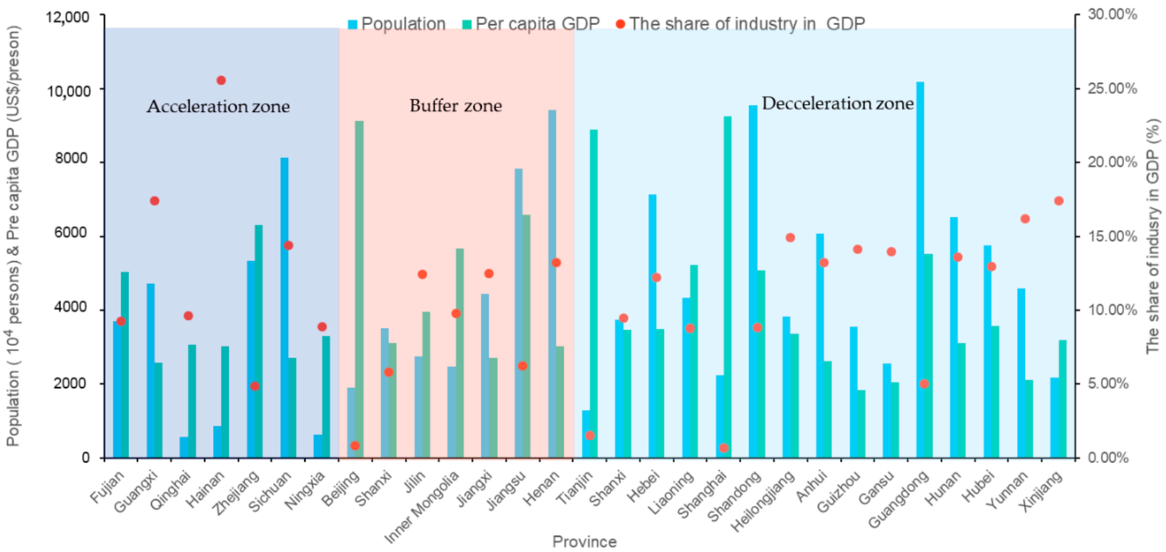

Figure 3. Provincial data of population, per capita GDP and the share of industry in GDP.

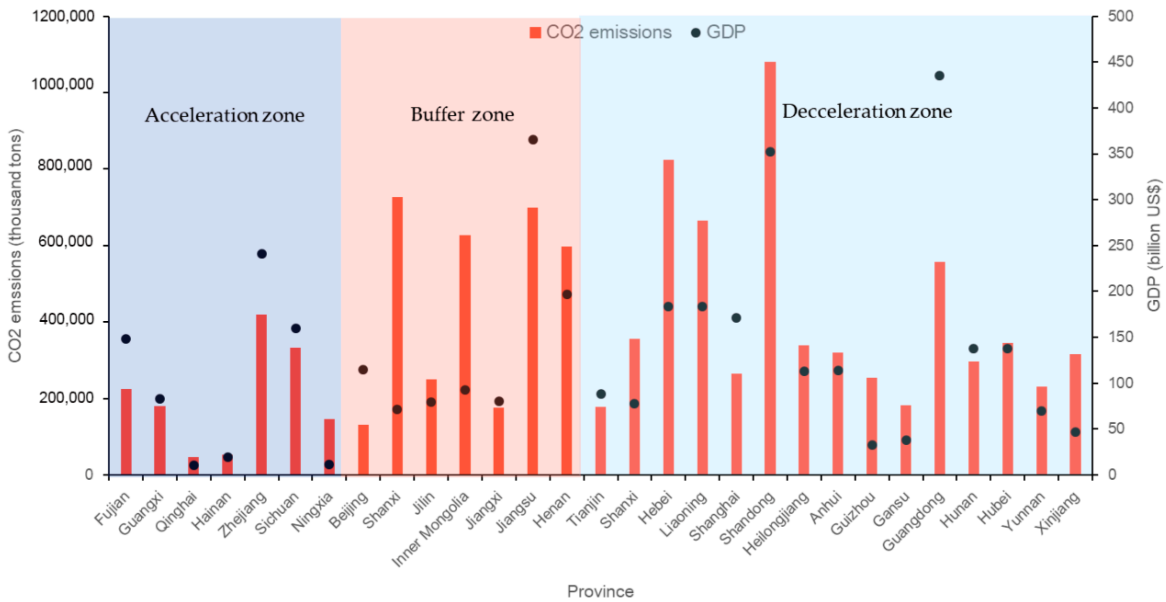

Figure 4. Provincial data of CO_2 emission and GDP.

4.1.1. Analysis of the Characteristics of Shadow Prices in the "Acceleration Zone"

A typical feature of the acceleration zone is that a smaller emission increase at a low emission level can promote greater economic output growth, while the shadow price is higher. A common characteristic of Fujian, Guangxi, Qinghai, Ningxia, Zhejiang, Hainan, and Sichuan provinces are that with a substantial increase in CO_2 emissions, the net effect of its marginal output increased rapidly by more than 2%. Among these provinces, Fujian's annual CO_2 emission growth rate of 7.64% led to an increase of 2.95% in economic output, and the absolute effect of marginal output reached an annual average of 4.388 billion US$. Ningxia has an average annual economic output value of 0.5 billion US$. Figure 5 presents the box plot distribution of the annual shadow price of the provinces in the acceleration zone from 2006 to 2015, and indicates that shadow prices are relatively high each year. To better visualize the interannual variability of provincial shadow prices, Table 5 displays the empirical data of Ningxia province to demonstrate the relationship between CO_2 emissions, economic growth, and shadow prices.

Table 5. Shadow price analysis of Ningxia Province from 2006 to 2015.

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Per capita GDP (US$/person)	1236.8	1423.46	1829.097	2368.694	2630.580	3244.588	3991.471	4396.260	4785.103	5053.391
Share of industry in GDP (%)	8.17	7.88	8.18	8.52	8.76	9.43	9.40	9.88	10.65	10.96
CO_2 emissions (thousand tons)	83,155	94,039.4	104,010.7	114,407.9	135,352.3	180,396.6	193,570.9	205,776.5	209,644.6	216,982.6
Growth rate of CO_2 emissions (%)	9.59	13.09	10.60	10.00	18.31	33.28	7.30	6.31	1.88	3.50
GDP (billion US$)	6.760	7.619	8.579	9.600	10.896	12.217	13.619	14.954	16.150	17.442
Net effect of marginal output of CO_2 emissions [a] (%)	4.56	6.14	5.03	4.74	8.24	13.80	3.34	2.88	0.91	1.72
Absolute effect of marginal output of CO_2 emissions [b] (billion US$)	0.274	0.415	0.384	0.407	0.791	1.503	0.408	0.392	0.136	0.278
Change in CO_2 emissions (thousand tons)	7277.8	10,884.3	9971.3	10,397.2	20,944.5	45,044.3	13,174.3	12,205.7	3868.1	7337.9
Shadow price of CO_2 (US$/ton)	37.66	38.16	38.48	39.12	37.76	33.89	30.95	32.18	35.23	37.86

Notes: [a] = MEC-1; [b] = GDP×(MEC-1).

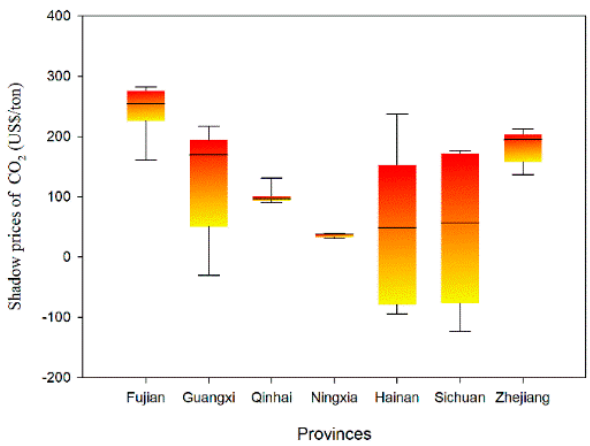

Figure 5. Estimates of shadow prices of CO_2 in the Acceleration zone from 2006 to 2015.

In 2006, Ningxia's CO_2 emissions of 83,155 thousand tons led to a 4.56% increase in the net effect of marginal output, while the absolute effect of marginal output reached 0.274 billion US$. From 2007 to 2010, CO_2 emissions increased by 13.09, 10.60, 10.00, and 18.31%, respectively. The annual cumulative absolute effect of marginal output reached 1.2 billion US$. In 2011, the CO_2 emissions increased 33.28% compared to the previous year. At the same time, the net effect of marginal output reached a maximum of 13.5%, and its contribution value was 1.5 billion US$. From 2012 to 2015, the growth rate of CO_2 emissions has slowed but is increasing at a positive rate. The net effect of marginal output for 2012–2015 remained at a high level of 3.34, 2.88, 0.91, and 1.72%, respectively. The absolute effect of annual cumulative marginal contribution in the four years is 1.21 billion US$. Besides, the share of industry in GDP has increased year by year. These data demonstrate that Ningxia has established many energy-consuming enterprises with large CO_2 emissions through investment promotion and industrial transfer. Therefore, the increase in CO_2 emissions has also driven the province's rapid economic development.

This signifies that provinces in the "acceleration zone" have greater room for economic growth and CO_2 emissions growth due to their lack of development or relatively abundant environmental resources. These provinces focus on driving economic growth by increasing CO_2 emissions. Increasing people's income is the main content of development. With the construction of many infrastructures, CO_2 emissions will increase as the economy grows. Hence, emissions reduction policies can be relaxed to allow moderate growth in CO_2 emissions in these provinces to promote economic development. It is of course necessary to vigorously develop the resource-conserving and environment-friendly industries to enhance the sustainability of economic growth.

4.1.2. Analysis of the Characteristics of Shadow Prices in the "Buffer Zone"

A typical characteristic of the buffer zone is that if a substantial increase in emissions brings about less economic growth, it is implied that the economic costs of reduction emissions are falling. Beijing, Shanxi, Jilin, Inner Mongolia, Jiangsu, Jiangxi, and Henan are characterized by a continuous increase (or decrease) in CO_2 emissions, but the net effect of marginal output is not significant. The annual CO_2 emissions increased by 20,840 thousand tons in Henan province, and the net annual average marginal output was only 0.23%, while the shadow price was relatively low. In Henan Province, a substantial increase in CO_2 emissions cannot lead to rapid economic development. Jiangsu province is a major CO_2 emissions province in China. From 2006 to 2015, the annual average emissions reduction was 37,305 thousand tons. The impact on the economic marginal output fell only by 1.01% with the annual average shadow price being 817.96 US$/ton. This shows that Jiangsu province is carrying out CO_2 emission control at a small economic cost while obtaining a significant reduction in CO_2 emissions. Figure 6 shows the box plot distribution of inter-annual shadow prices from 2006 to 2015 in the buffer zone provinces. Shadow prices of provinces are lower in each successive year. To better visualize the interannual variability of provincial shadow prices, the case of Jiangsu demonstrates the relationship between CO_2 emissions, economic growth, and shadow prices. Table 6 lists the empirical data of Jiangsu province.

As a major economic province in China, Jiangsu Province is also a large CO_2 emissions province. Its economic and technical development are relatively high, and its ability to reduce emissions and allocate resources is strong. In 2006, its emissions reduction was 3.46% compared to the previous year, which caused the net effect of marginal output loss of only 1.03%. From 2008 to 2015, emissions were reduced by 2.22, 2.04, 13.29, 10.44, 4.34, 3.08, 7.21, and 8.66%, respectively, compared to the previous years. Jiangsu's industry accounts for a lower share of GDP. Under the continuous emissions reduction measures, the marginal net effect loss to the economy remained low at −0.93, −0.43, −0.74, −2.16, −3.12, −0.46, −0.49, 0.15, and −0.87%, respectively, which indicated that the industrial structure of Jiangsu province has been adjusted along with the implementation of the emissions reduction, and the contribution of increased CO_2 emissions to economic growth is weakening, meaning that only a small loss of economic output is incurred for the achievement of emissions reduction targets.

In these provinces, the environmental costs of pursuing economic growth are beginning to rise, and the increase in CO_2 emissions does not drive rapid economic growth. CO_2 emissions should be controlled in provinces of this zone—a large reduction in CO_2 emissions will be replaced by a small output loss. Economic growth still must be ensured in the process of governance, and it calls for changes in the developing style by introducing new production technologies, improving energy efficiency and reducing fossil fuel consumption. It is possible to promote the economy and achieve the emission reduction goal by establishing a low carbon industry development model and a low carbon energy structure.

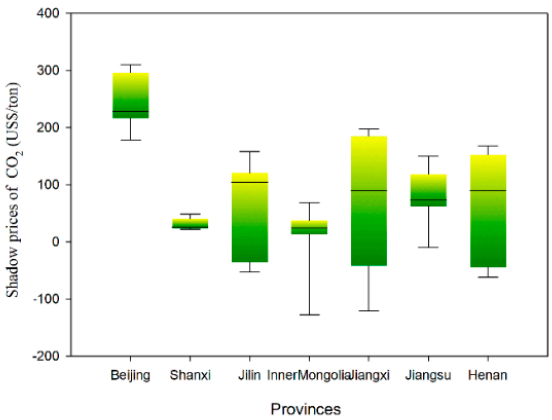

Figure 6. Estimates of shadow prices of CO_2 in the Buffer zone from 2006 to 2015.

Table 6. Shadow price analysis of Jiangsu Province from 2006 to 2015.

	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Per capita GDP (US$/person)	2966.756	3465.041	4087.384	4833.542	5345.598	6382.875	7524.400	8256.063	9102.483	9890.075
Share of industry in GDP (%)	5.68	5.58	5.81	6.32	6.24	6.13	6.56	6.78	6.98	7.11
CO_2 emissions (thousand tons)	834,587.7	840,102.5	821,452.2	804,676.5	697,719.2	624,896.2	597,774.4	579,348.7	537,564.4	491,008.5
Growth rate of CO_2 emissions (%)	−3.46	0.66	−2.22	−2.04	−13.29	−10.44	−4.34	−3.08	−7.21	−8.66
GDP (billion US$)	218.21	250.73	282.57	317.61	357.95	397.32	437.45	479.45	521.16	565.46
Net effect of marginal output of CO_2 emissions [a] (%)	−1.03	−0.93	−0.43	−0.74	−2.16	−3.12	−0.46	−0.49	0.15	−0.87
Absolute effect of marginal output of CO_2 emissions [b] (billion US$)	−1.953	−2.029	−1.078	−2.091	−6.860	−11.168	−1.828	−2.144	0.719	−4.534
Change in CO_2 emissions (thousand tons)	−29,922.9	5514.8	−18,650.3	−16,775.7	−106,957	−72,823	−27,121.8	−18,425.7	−41,784.3	−46,555.9
Shadow price of CO_2 (US$/ton)	65.28	−367.99	57.80	124.64	64.14	153.35	67.38	116.33	−17.21	97.39

Notes: [a] = MEC-1; [b] = GDP×(MEC-1).

4.1.3. Analysis of the Characteristics of Shadow Prices in the "Deceleration Zone "

In the deceleration zone, both the level of economic development and CO_2 emissions are high. A substantial increase in CO_2 emissions does not lead to an increase in the marginal net effect, and the shadow price is negative. Figure 7 shows that the shadow prices in each province are basically negative. This indicates that the environmental and emissions problems in this region are serious. To better visualize the interannual variability of provincial shadow prices, Hebei is a typical case to demonstrate the relationship between CO_2 emissions, economic growth, and shadow prices. Table 7 lists the empirical data of Hebei province.

Hebei is also a large CO_2 emissions province in China. It has maintained a relatively high rate of emissions growth from 2006 to 2011—13.2, 12.8, 10.1, 10, 12.2, and 11.3%, respectively. With such a large scale of emissions, the net effect of marginal output has grown negatively. In 2011, an increase of 11.3% over the previous year's emissions resulted in a marginal output loss of 9.72%, amounting to 17.49 billion US$. The cumulative absolute effect of marginal output decreased by 36.19 billion US$ from 2006 to 2011. In 2012 and 2013, the emissions slowed down sharply. It is worth noting that Hebei province began to reduce emissions by a total of 56,423 thousand tons, and the absolute effect of the cumulative marginal output increased by 9.92 billion US$ from 2014 to 2015. Besides, the proportion of industry in GDP is basically maintained at around 12%. It can be seen from the above that the increase in CO_2 emissions did not contribute to the economy in Hebei province from 2006 to 2013, but rather, it caused environmental damage and affected the increase in output. After 2014, the implementation of the emissions reduction policy resulted in an increase in output.

This suggests that provinces in the "deceleration zone" are already showing signs of weakness in their carbon-driven growth. It is necessary to implement structural reforms on the industrial supply side and promote the optimization and upgrading of industrial structure. In addition, it is necessary to increase industrial restructuring, environmental governance, technological innovation, and increase the share of new/alternative energy consumption. This will ensure that CO_2 emissions will be further reduced while the economy will grow. Besides, new technologies and new management models should be applied for traditional industries. The region must also take the initiative to undertake national emission reduction work.

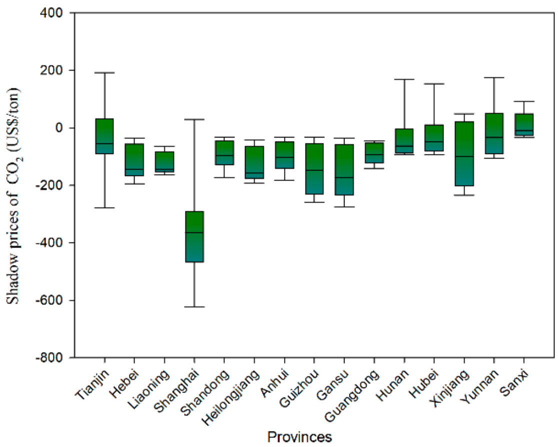

Figure 7. Estimates of shadow prices of CO_2 in the deceleration zone from 2006 to 2015.

Table 7. Shadow price analysis of Hebei Province from 2006 to 2015.

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Per capita GDP (US$/person)	1785.61	2040.73	2375.09	2776.62	2969.29	3462.988	4103.3	4419.21	4700.06	4829.9
Share of industry in GDP (%)	11.54	11.72	11.89	11.99	11.85	12.57	12.81	12.71	13.26	12.75
CO_2 emissions (thousand tons)	646,736	705,324	737,261	786,343	846,392	957,191	970,562	971,621	924,003	91,519
Growth rate of CO_2 emissions (%)	13.20	12.80	10.10	10.00	12.20	11.30	9.60	8.20	6.50	6.80
GDP (billion US$)	117.404	132.431	145.807	160.388	179.955	200.290	219.51	237.518	252.958	270.16
Net effect of marginal output of CO_2 emissions [a] (%)	−1.62	−2.22	−1.45	−3.25	−4.84	−9.72	−1.09	−0.08	3.45	0.68
Absolute effect of marginal output of CO_2 emissions [b] (billion US$)	−1.684	−2.606	−1.920	−4.739	−7.763	−17.492	−2.183	−0.176	8.194	1.720
Change in CO_2 emissions (thousand tons)	47718	58,587	31,937.5	49,081.5	60,048.8	110,799.1	13371	1058.8	−47617	−8805.8
Shadow price of CO_2 (US$/ton)	−35.29	−44.49	−60.136	−96.55	−129.28	−157.87	−163.28	−165.86	−172.09	−195.34

Notes: [a] = MEC-1; [b] = GDP×(MEC-1).

5. Conclusions

The provincial shadow price of CO_2 in China has great differences for the regional gaps in technology and productive efficiency. This study selects 29 provinces of China as examining samples and estimates their CO_2 shadow prices during 2006–2015. The non-parametric directional distance function was applied to construct a DEPFF model, and shadow prices of CO_2 for each province are calculated with the labor and capital stock as inputs, provincial GDP, and CO_2 emissions as desirable and undesirable outputs. Trends of each province from 2006 to 2015 are also identified, and the 29 provinces and regions are finally categorized as acceleration zone, buffer zone, and deceleration zone.

Ningxia and another 6 provinces are in the acceleration zone, where the CO_2 emissions are considerable and their contributions to the economy are also significant. The shadow price of CO_2 is usually high. The average net effect of marginal output of CO_2 emissions in the acceleration zone is 2.95%, and the average shadow price is 184.16 US$/ton. If compulsory emissions reduction measures are mandated, the economy will greatly shrink, which implies a high cost of emissions reduction. Economic growth should be sustained through a lax environmental policy, and meanwhile energy efficiency improvement technologies should be developed to promote economic growth with fewer emissions.

Jiangsu and another 6 provinces are in the buffer zone, which is the transition zone from the acceleration zone. The average net effect of marginal output of CO_2 emissions for the buffer zone is 0.59%, and the average shadow price is 86.57 US$/ton. The sharp increase in CO_2 emissions has gradually diminished the contribution to the economy, and the CO_2 shadow price is relatively low. That means these regions can significantly reduce CO_2 emissions at the expense of smaller economic output. But in the long run, it is necessary to optimize and upgrade the industrial structure and seek new economic points of growth while reducing emissions.

Hebei and another 14 provinces are in the deceleration zone. The average net effect of marginal output of CO_2 emissions for the deceleration zone is −2.172%, and the average shadow price is −200.7 US$/ton. Their CO_2 emissions are considerable and the environmental resource capacity is weakening. The shadow price of CO_2 is negative in these regions, which means that the increase of CO_2 emissions is no longer contributing to economic growth, making emissions reduction urgently required. Stricter emissions control measures are recommended to be imposed in this zone, including shutting down high-energy-consuming industries.

Considering the provincial differences, emission reduction policies and targets should be region-specific in China for optimizing environmental resource allocation. At the same time, all regions must gradually promote the industry and energy consumption structure in order to avoid the excessive economic costs of CO_2 emissions reduction. Provinces and regions may also strengthen cooperation and synergy mechanisms to jointly implement China's CO_2 abatement targets with lower costs.

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