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Collaborative Allocation of Energy Consumption, Air Pollutants and CO₂ Emissions in China

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Abstract: Energy consumption is an important source of the emissions of CO₂ and air pollutants such as SO₂ and NO_x. Reducing energy consumption can realize the simultaneous reduction of air pollutants and CO₂ emissions to a certain extent. This study examines the collaborative allocation of energy consumption and the emissions of SO₂, NO_x and CO₂ in China. In contrast to previous studies, this paper proposes an improved centralized DEA model that takes into account the correlation between energy consumption and air environmental emissions, the economic development demand and the energy resource endowment of different provinces. The initial allocation scheme is obtained based on the principle of equity. Then, the initial allocation results are brought into the improved centralized DEA model to maximize the expected output. The empirical analysis of projected data for 2025 shows that the looser the restrictions of energy consumption, the greater the optimal economic output. When the energy consumption of each province is allowed to fluctuate within the range of 85% to 115% of the initial quota, the total GDP is the largest and 20.62% higher than the initial GDP. The optimal allocation scheme is more equitable than the initial scheme and realizes absolute interpersonal equity and economic equity. Eighteen provinces bear the pressures of energy saving, emission reduction or GDP growth, with average pressure indexes of 11.46%, 16.85% and 40.62%, respectively. The pressures on the major regions involved in the “Belt and Road”, Beijing-Tianjin-Hebei region and Yangtze River Economic Belt national strategies will thus be reduced significantly; the maximum pressures on energy saving, emission reduction and GDP growth are 10.03%, 12.17% and 29.84%, respectively. China can take a series of measures to promote regional coordinated development and improve the realization of optimal allocation schemes, including establishing unified resource asset trading platforms, improving the methods of regional cooperation, building effective transportation and logistics transport networks to weaken the barriers among regions and implementing differentiated regional policies and regional interest coordination mechanisms.

Citation: Song, J.; Chen, R.; Ma, X. Collaborative Allocation of Energy Consumption, Air Pollutants and CO₂ Emissions in China. *Sustainability* **2021**, *13*, 9443. <https://doi.org/10.3390/su13169443>

Academic Editors:
Kittisak Jermisittiparsert,
Thanaporn Sriyakul and
Muhammad Haseeb

Received: 3 July 2021
Accepted: 20 August 2021
Published: 23 August 2021

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Keywords: energy consumption; SO₂ and NO_x emissions; carbon emissions; collaborative allocation; equity and efficiency; centralized DEA model

1. Introduction

Energy consumption drives economic development, but it also causes emissions of CO₂ and air pollutants such as SO₂ and NO_x. Although CO₂ is not considered to be a traditional air pollutant, its emissions also cause environment damage. The Chinese government attaches great importance to the control of energy consumption, air pollutants and carbon emissions and has adopted a series of measures such as total quantity control, provincial quota allocation and emissions trading. Statistics show that China has achieved the 2020 targets for energy saving and emissions reduction set in the 13th Five-Year Plan ahead of schedule. However, China’s energy consumption and atmospheric emissions continue to grow, the gap between energy supply and demand is widening and the quality of urban atmospheric environment is still poor. According to the 14th Five-Year Plan [1], the Chinese government will continue to strengthen its energy saving and emission reduction

to achieve the 2025 targets, i.e., energy consumption per unit of GDP and CO₂ emissions per unit of GDP by 2025 will be reduced by 13.5% and 18%, respectively, compared with 2020, and the total emissions of major pollutants will continue to decrease.

Energy consumption has a definite impact on the environment. Scholars have analyzed that energy consumption is an important factor causing environmental pollution or GHG emissions [2–4], and the synergistic emission reduction of air pollutants and GHG can be promoted by improving energy efficiency or energy structures [5–7]. Thambiran et al. [8] proposed that the direct benefit of reducing energy consumption is a reduction in air pollutants and GHG emissions. There is also a correlation between air pollutants and GHG emissions. Ayres and Walter [9] discussed the costs and benefits of GHG emission reduction and pointed out that the indirect benefits include air pollutant reduction and related health effects. Messner [10] discussed the synergies and policy conflicts of CO₂ and SO₂ emissions reduction. The third assessment report of the IPCC proposed the concept of co-benefits; that is, there is an interactive relationship between air pollutants and GHG [11]. The fourth and fifth Assessment Report of the IPCC [12,13] discussed the collaborative governance policies of GHG and air pollutants in more depth. Liang et al. [14] studied the co-control of CO₂ emissions and pollutants in China from the perspective of adjusting final use behaviors. Song et al. [15] constructed econometric analysis models to verify the synergistic effect between SO₂ and CO₂ emissions reduction in China. Wang et al. [16] summarized the progress of research on the synergetic emission reduction of GHG and air pollutants and proposed that the cooperative governance of GHG and air pollutants is a “win-win” strategy. It can be seen that energy consumption, air pollutant emissions and CO₂ emissions are closely related, and it is feasible and scientific to allocate these three elements collaboratively.

This paper makes contributions in three main areas. Firstly, according to the correlations between SO₂, NO_x and CO₂ emissions and energy consumption, the total control amounts of these factors are determined. Secondly, an improved centralized DEA model is proposed to allocate multiple elements, which not only takes into account the economic development goals of various provinces but also their energy resource endowment. Thirdly, the provincial quotas in 2025 are allocated, and the corresponding suggestions are proposed.

The rest of this paper is organized as follows. Section 2 reviews the literature, analyzes the deficiency of the existing research and determines the position of this paper. Section 3 presents our research methodology, including the allocation methods based on equity and the centralized DEA model based on efficiency. Section 4 presents data sources and forecasts the values of the indicators in 2025. The collaborative allocation results are presented in Section 5. Section 6 discusses the empirical results and proposes the corresponding suggestions, and the paper is concluded in Section 7.

2. Literature Review

China has a vast territory, and different provinces have different levels of economic development, resource endowment and population distribution [17]. Yu et al. [18] proposed that the provincial allocation of Chinese national targets should follow the principle of “common but differentiated responsibilities”. There are mainly two research ideas for the allocation of energy consumption, air pollutants emissions and CO₂ emissions:

(1) Allocation based on single or composite indicators. Moltafet et al. [19] allocated energy consumption according to various fairness indicators such as max-min fairness, proportional fairness and minimum delay potential fairness. Yi et al. [20] established a comprehensive indicator based on per capita GDP, accumulated fossil fuel and energy consumption per unit of industrial added value and allocated carbon emissions intensity. Wu et al. [21] and Dong et al. [22] studied the initial allocation principles of CO₂ emissions including grandfathering, egalitarian and ability to pay principles.

(2) Allocation based on the data envelopment analysis (DEA) model. This method usually optimizes the efficiency of the initial quota given by other allocation methods or

forecasts. The proposed DEA models mainly include three types: (a) the zero-sum-gains data envelopment analysis (ZSG-DEA) model. Sun et al. [23] constructed an environmental ZSG-DEA model to allocate total energy consumption. Xiong et al. [24] constructed a weighted ZSG-DEA model to allocate various levels of energy consumption. Miao et al. [25] constructed environmental ZSG-DEA models to allocate SO₂ and NO_x emissions. Jiang et al. [26] used the ZSG-DEA model to optimize the CO₂ allocation result obtained from the fairness principle. Miao et al. [27] constructed an environmental ZSG-DEA model to allocate provincial CO₂ emissions. Wang et al. [28] constructed a weighted ZSG-DEA model to allocate total energy consumption, CO₂ emissions and non-fossil fuel consumption. (b) The fixed cost allocation model (FCAM). Pan et al. [29] proposed an FCAM for allocating carbon emissions. Dong et al. [30] selected the egalitarian principle of ability to pay as a constraint condition and modified the FCAM to allocate carbon emissions. Song et al. [31] constructed an environmental FCAM with comprehensive fair convergence for allocating carbon emissions. (c) A centralized DEA model. Zhou et al. [32], Sun et al. [33] and Li et al. [34], respectively, proposed centralized DEA models for the spatial, temporal and spatial-temporal allocation of CO₂ emissions.

A literature review shows that the allocation of energy consumption, air pollutant emission or/and CO₂ emission is a current research hotspot, and the allocation principle mostly includes equity and efficiency. However, the existing research has some deficiencies. Firstly, there are only a few studies on the collaborative allocation of these three elements simultaneously. Secondly, the inconsistency of indicators in the indicator-based allocation methods leads to weak interpretability, and the weighting method of indicators is not objective. Thirdly, the ZSG-DEA model and FCAM pursue the optimal relative efficiency of allocation rather than the maximization of national GDP. The centralized DEA model pursues the latter, but its allocation scheme may result in the GDP of some provinces being lower than the planned value, making the scheme not feasible. However, with the implementation of a regional integration strategy, the flow of production elements among provinces is accelerated and the feasibility of a centralized DEA scheme is greatly improved. In order to promote the medium-high economic growth of China and provinces in the “new normal” context, this paper modifies the traditional centralized DEA model and conducts a collaborative allocation of energy consumption, air pollutant emission and CO₂ emission based on the principles of equity and efficiency.

3. Methodology

3.1. Allocation Methods Based on Equity

The equity principles of energy consumption and emission right allocation mainly include grandfathering, egalitarian and ability to pay principles [21,22]. The principle of grandfathering means that the total quota is allocated according to the proportion of the index value of each province to the sum of all provinces in the base period. This principle is conducive to ensuring the continuity of economic production. It can be expressed by Equation (1):

$$R_k = R \times \frac{r_k}{\sum_{k=1}^K r_k} \quad (1)$$

where R_k is the quota obtained by the k th province, R is the total quota that needs to be allocated and r_k is the index value of the k th province in the base period.

The egalitarian principle means that the total quota is allocated according to the proportion of the population of each province in the base period, which reflects the per capita equity. It can be expressed by Equation (2):

$$R_k = R \times \frac{p_k}{\sum_{k=1}^K p_k} \quad (2)$$

where p_k is the population of the k th province in the base period.

The ability to pay principle emphasizes the idea that the emission reduction cost of each province is directly associated with its economic level. A more developed province

should bear more responsibility for emission reduction, reflecting the historical responsibility of development. This can be expressed by Equation (3):

$$R_k = R \times \frac{p_k (g_k / p_k)^{-\alpha}}{\sum_{k=1}^K p_k (g_k / p_k)^{-\alpha}} \quad (3)$$

where g_k is the GDP of the k th province in the base period and α is a correction parameter, $0 < \alpha < 1$. If α is smaller than 1, this indicates that the increasing (or decreasing) amplitude of the quota is smaller than the decreasing (or increasing) amplitude of the per capita GDP. This assumption guarantees that the quota of one province will not be reduced drastically when its per capita GDP increases. In this paper, we set α as 0.7 to emphasize the responsibility for emission reduction in provinces with a higher per capita GDP.

3.2. Efficiency Allocation Approach

DEA is a method for evaluating the relative efficiency of a decision-making unit (DMU) with multiple-inputs and multiple-outputs. Färe et al. [35] proposed the concept of environmental production technology (EPT), in which a weak disposability of undesirable outputs and null-jointness of desirable and undesirable outputs are included. The former indicates that a reduction of undesirable outputs can be attained by the reduction of desirable outputs. The latter means that if the undesirable outputs are not produced, the production of desirable outputs is not feasible. Based on the EPT, Zhou et al. [32] developed a centralized DEA model for allocating some inputs and undesirable outputs. In this paper, we choose population and capital stock as unallocated inputs, energy consumption as the allocated input, GDP as a desirable output and SO_2 , NO_x and CO_2 emissions as undesirable outputs. Due to the lack of data in Tibet, Hong Kong, Macao and Taiwan, we consider the allocation for the other 30 provinces in China. The basic centralized DEA model can be expressed by Equation (4):

$$\begin{aligned} & \max \sum_{k=1}^{30} \hat{G}_k \\ \text{s.t.} \left\{ \begin{array}{l} \sum_{k=1}^{30} \delta_{kl} P_k \leq P_l, l = 1, \dots, 30 \\ \sum_{k=1}^{30} \delta_{kl} I_k \leq I_l, l = 1, \dots, 30 \\ \sum_{k=1}^{30} \delta_{kl} E_k \leq \hat{E}_l, l = 1, \dots, 30 \\ \sum_{k=1}^{30} \delta_{kl} G_k \geq \hat{G}_l, l = 1, \dots, 30 \\ \sum_{k=1}^{30} \delta_{kl} U_{ik} = \hat{U}_{il}, i = 1, 2, 3; l = 1, \dots, 30 \\ \sum_{k=1}^{30} \hat{E}_k = \alpha \sum_{k=1}^{30} E_k \\ \sum_{k=1}^{30} \hat{U}_{ik} = \theta_i \sum_{k=1}^{30} U_{ik}, i = 1, 2, 3 \\ \delta_k \geq 0, \hat{E}_l \geq 0, \hat{G}_l \geq 0, \hat{U}_{il} \geq 0, i = 1, 2, 3; k, l = 1, \dots, 30 \end{array} \right. \end{aligned} \quad (4)$$

In Equation (4), the objective function represents the maximization of the total GDP of 30 provinces; G_k and $\hat{G}_l$ are the planned and optimized GDP, respectively; E_k and $\hat{E}_l$ are the initial and optimized energy consumption quota, respectively; P_k and I_k are the population and capital stock, respectively; U_{ik} and $\hat{U}_{il}$ ($i = 1, 2, 3$) are the initial and optimized quotas of SO_2 , NO_x and CO_2 emissions, respectively; α and θ_i ($i = 1, 2, 3$) are the contraction coefficients of energy consumption and undesirable outputs relative to their planned values, respectively, where $0 < \alpha, \theta_i \leq 1$.

The basic centralized DEA model implies the assumption that the production elements can flow freely among different provinces, and maximizes the national GDP by optimizing the provincial GDP and the elements to be allocated. However, there are three deficiencies. First, limited by the energy resource endowment and transportation, the energy element cannot flow freely between provinces, which means that the optimized energy consumption of each province cannot be greatly reduced or increased on the basis of its initial allocation result. Second, the allocation scheme of centralized DEA may result in the optimized GDP of some provinces being lower than their planned GDP or even regressive from current levels, which does not meet the needs of provincial economic development. Third, the

model cannot reflect the synergies between energy saving and emission reduction. In order to make up for the above deficiencies, we add the following three constraints to improve the centralized DEA model.

$$\begin{aligned}\theta_i &= \theta_i(\alpha), i = 1, 2, 3 \\ \hat{G}_k &\geq G_k, k = 1, 2, \dots, 30 \\ \underline{\mu}E_k &\leq \hat{E}_k \leq \bar{\mu}E_k, k = 1, 2, \dots, 30\end{aligned}$$

The first constraint means that the contraction coefficients of undesirable outputs are related to that of energy consumption, reflecting the synergies between energy saving and emission reduction. The second constraint reflects the economic development need of each province and guarantees that the optimized GDP cannot be lower than the planned level. The third constraint means that optimized energy consumption cannot be reduced or increased substantially, where $\underline{\mu}$ and $\bar{\mu}$ are the lower and upper limit coefficients of energy consumption, respectively.

4. Materials

The methods proposed in Section 3 have been used to study the allocation of the projected energy consumption, SO₂, NO_x and CO₂ emissions in 2025.

(1) The population data of each province in 2011–2019 were taken from the China Statistical Yearbook (2012–2020). Based on the average population growth rate from 2016 to 2019 after the universal two-child policy was implemented in 2016, the population data of each province in 2025 were predicted.

(2) The capital stock data of each province in 2011–2017 were calculated by using the perpetual inventory method [36] and converted into the values under the price level of 2015. The regression of the capital stock data of each province in the past seven years shows a good linear relationship. Taking Shandong province as an example, the regression equation is as follows:

$$y = 16,601.08x + 94,753.84, \quad R^2 = 0.999$$

Its F value is 85,322.77, and the significance is 0.0000, which means the regression effect is significant. Its t-Statistic value for the estimated coefficient of the x variable is 92.37, and the significance is 0.0000. This shows that the annual number has a significant positive impact on the value of capital stock. By inputting the annual number 15, corresponding to 2025, into the above formula, the predicted capital stock value of Shandong province in 2025 is 343,770 billion yuan. Similarly, we calculate the predicted capital stock values of the other 29 provinces in 2025.

(3) The GDP data of each province in 2011–2019 and 2020 were taken from the China Statistical Yearbook (2012–2020) and China's Provincial Statistics Bulletin (2020), respectively. All of the data were converted into the values under the price level of 2015. According to the GDP in 2020 and the economic growth target in the 14th Five-Year plan of each province, we calculated the planned GDP of all the provinces in 2025.

(4) The energy consumption data of each province in 2011–2019 were taken from the *China Energy Statistics Yearbook* (2012–2020). According to the 14th Five-Year Plan announced by the Chinese government, the energy consumption intensity in 2025 will be 13.5% lower than that in 2020. Based on the total planned GDP of 30 provinces of 1,299,898.8 billion yuan in 2025 and the energy consumption intensity of 0.5125 tce per 10,000 yuan in 2020, we found that the limits of energy consumption intensity and total energy consumption in 2025 are 0.4433 tce 10,000 yuan and 57.63 billion tce, respectively.

(5) The data of SO₂ and NO_x emissions of each province in 2011–2017 were taken from the *China Statistical Yearbook* (2012–2018). The CO₂ emission data in 2011–2018 were calculated using the IPCC emission factor method:

$$C_k = \frac{44}{12} \times \sum_{j=1}^J c_j \times d_j \times \beta_j \times E_{kj} \quad (5)$$

where C_k is the CO₂ emission of the k th province; c_j , d_j and β_j are the carbon emission coefficient, carbon oxidation factor and standard coal coefficient of the j th energy source, respectively; and E_{kj} is the j th energy consumption of the k th province. Since it is difficult to determine the emission coefficients of heat and electricity as secondary energy, the relevant energy consumptions used for thermal power generation and heating are included. According to the 14th Five-Year Plan, the CO₂ emission intensity in 2025 will be reduced by 18% compared with 2020. Based on the CO₂ emission intensity of 1.4448 tons per 10,000 yuan in 2020, we can see that the CO₂ emission limit in 2025 should be 154 billion tons.

(6) China's energy consumption and CO₂ emissions are on the rise, while SO₂ and NO_x emissions are on the decline. It is impossible to directly reflect the collaborative effect of energy saving and emission reduction by using their total amounts. Considering that SO₂ emission intensity, NO_x emission intensity, CO₂ emission intensity and energy consumption intensity all show a downward trend, we measure the synergistic effect by using the values of these four intensity indicators. Figure 1 shows their change trends.

Figure 1. Energy consumption intensity, SO₂, NO_x and CO₂ emission intensity in China.

Taking energy consumption intensity (e) as the independent variable and SO₂ emission intensity (s), NO_x emission intensity (n) and CO₂ emission intensity (c) as dependent variables, respectively, the regression functions are as follows:

$$\begin{aligned} s &= 11.568 \times 10^{-3}e - 5.04 \times 10^{-3}, R^2 = 0.8845 \\ n &= 10.334 \times 10^{-3}e - 3.81 \times 10^{-3}, R^2 = 0.9561 \\ c &= 2.64479e + 0.118827, R^2 = 0.9794 \end{aligned}$$

The F values of these three regression equations are 38.286, 108.889 and 285.281, and the significance values are 0.0016, 0.0001 and 0.0000, respectively. Therefore, the regression effects are all significant. The t-Statistic values for the coefficient of energy consumption intensity are 6.188, 10.435 and 16.890. The significance values are 0.0016, 0.0001 and 0.0000, respectively, which means that the energy consumption intensity has significant positive impacts on emissions intensity. Based on the energy consumption intensity and GDP in 2025, the limits of SO₂, NO_x and CO₂ emissions in 2025 will be 1.21 million tons, 9.99 million tons and 167.86 billion tons, respectively. Because the CO₂ emission limit from the national planning policy is less than that from the synergy effect, we set the CO₂ emission limit as 154 billion tons.

(7) Assuming that China's energy saving target is exactly achieved in 2025—that is, the situation below the target is not taken into account—the contraction coefficient of energy

consumption α is 1. Because the constraint values of SO_2 and NO_x emissions are not set in the 14th Five-Year Plan, we assume that their limits are equal to the values considering a synergistic effect, so the contraction coefficients θ_1 and θ_2 are both 1. Since the CO_2 emission limit is equal to the planned value, the contraction coefficient θ_3 is 1.

(8) Considering the energy resource endowment and energy mobility, the fluctuation range of the energy consumption of each province is set as 5–15% based on the initial allocation. With a step size of 5%—i.e., $\underline{\mu} \in \{0.85, 0.9, 0.95\}$ and $\bar{\mu} \in \{1.05, 1.1, 1.15\}$, there are nine $(\underline{\mu}, \bar{\mu})$ combination schemes.

5. Results

5.1. Initial Allocation Result Based on Equity

Since energy consumption is an important physical resource for provincial economic development and its mobility is poor, we initially allocated the energy consumption based on the principle of grandfathering. SO_2 , NO_x and CO_2 emissions have good spatial mobility, and they can be allocated based on the equity principles including grandfathering, egalitarian and ability to pay. In order to determine the weights of these three principles, we invited authoritative experts to distinguish them by the Analytic Hierarchy Process (AHP) method. The pairwise comparison judgment matrix is as follows:

$$\begin{bmatrix} 1 & 3 & 1 \\ 1/3 & 1 & 1/3 \\ 1 & 3 & 1 \end{bmatrix}$$

The consistency ratio of the judgment matrix is 0, which means that the judgment matrix had a satisfactory consistency. The weights of the three equity principles were 3/7, 1/7 and 3/7. We input the relevant data into Formulas (1)–(3) and obtained the allocation result based on the various principles. By weighting the results, we obtained the initial allocation results of the SO_2 , NO_x and CO_2 emissions.

Table 1 shows the initial allocation results of energy consumption and the emissions of SO_2 , NO_x and CO_2 and the planned GDP of each province in 2025.

As can be seen from Table 1, the initial allocation values of each element of various provinces vary greatly. Shandong is the province with the highest allocation of energy consumption, which is close to 5 billion tce, while Hainan province with the least allocation is less than 0.25 billion tce. The three provinces following Shandong are Guangdong, Hebei and Jiangsu, with an allocation of nearly 4 billion tce. The energy consumption obtained by the top four provinces accounts for nearly 30% of the total allocation. The top three provinces in terms of SO_2 , NO_x and CO_2 emissions are Shandong, Henan and Hebei, and their sum of each element accounts for about 20% of the total allocation. The last two provinces of each environmental emission are Hainan and Qinghai, and their sum of each element accounts for only about 1%. The top three provinces in terms of GDP are Guangdong, Jiangsu and Shandong, accounting for 10.05%, 9.56% and 8.51% of the total GDP, respectively, while the last three provinces are Qinghai, Ningxia and Hainan, each accounting for less than 1%.

5.2. Collaborative Allocation Result Based on Efficiency

The initial allocation results were substituted into the improved centralized DEA model, and the model was solved by invoking the Linprog function in the optimization toolbox of MATLAB. The Linprog function can be expressed as $[x, fval] = \text{linprog}(f, A, b, Aeq, Beq, lb, ub)$, where f is the coefficient vector of the objective function; A and Aeq are the coefficient matrixes of inequality constraints and equality constraints, respectively; b and Beq are the constant vectors of inequality constraints and equality constraints, respectively; and lb and ub represent the lower and upper bounds. The outputs from MATLAB include the optimal objective function value $fval$ and the optimal decision variable values including δ_{kl} , $\hat{G}_l$, $\hat{E}_l$ and $\hat{U}_{il}$, $i = 1, 2, 3$; $k, l = 1, 2, \dots, 30$.

The optimized GDP of collaborative allocation under different $(\underline{\mu}, \bar{\mu})$ combination schemes are shown in Table 2.

Table 1. The initial allocation results and the planned GDP of each province in 2025.

Province	Energy Consumption (10 ⁴ tce)	SO ₂ Emissions (10 ⁴ tons)	NO _x Emissions (10 ⁴ tons)	CO ₂ Emissions (10 ⁴ tons)	Planned GDP (10 ⁸ yuan)
Beijing (BJ)	8997.42	0.92	9.12	14,161.36	38,312.33
Tianjin (TJ)	10,295.09	1.02	9.85	18,349.94	27,566.96
Hebei (HeB)	38,890.74	7.34	66.70	122,927.92	53,716.42
Shanxi (SX)	25,236.75	5.37	39.89	58,994.04	21,407.82
Inner Mongolia (IM)	25,814.76	4.39	33.10	49,559.02	28,162.72
Liaoning (LJ)	27,086.55	4.55	34.96	61,366.25	41,702.02
Jilin (JL)	10,066.35	2.31	21.75	30,603.68	23,905.05
Heilongjiang (HLJ)	15,859.24	3.42	32.15	42,435.76	24,522.35
Shanghai (SH)	14,367.48	1.32	13.70	23,943.36	42,108.06
Jiangsu (JS)	38,865.47	5.43	50.99	88,710.90	124,323.69
Zhejiang (ZJ)	25,404.54	3.68	32.38	51,421.99	77,043.20
Anhui (AH)	15,779.88	4.90	46.52	68,936.94	41,895.77
Fujian (GJ)	15,358.75	2.53	21.95	35,854.75	49,856.25
Jiangxi (JX)	10,665.33	4.08	33.07	48,143.55	33,896.85
Shandong (SD)	49,774.07	8.58	68.73	110,719.48	110,659.65
Henan (HeN)	28,957.44	8.25	72.49	100,157.39	67,298.65
Hubei (HuB)	21,188.88	4.37	35.59	59,811.69	60,000.00
Hunan (HuN)	20,548.05	5.23	41.69	65,717.70	54,317.06
Guangdong (GD)	39,432.79	6.55	62.16	91,893.75	130,654.36
Guangxi (GX)	12,652.50	4.03	33.10	51,044.80	31,058.68
Hainan (HaN)	2472.70	0.59	6.06	8636.52	7946.81
Chongqing (CQ)	11,191.96	2.81	19.05	28,218.88	29,794.01
Sichuan (SC)	25,121.03	6.83	51.85	81,972.19	56,479.73
Guizhou (GZ)	12,435.25	4.85	29.15	43,287.10	22,147.64
Yunnan (YN)	13,754.44	4.86	36.28	53,313.32	28,824.89
Shaanxi (S'X)	14,961.78	3.91	29.89	40,036.39	32,881.39
Gansu (GS)	9435.84	3.29	23.84	33,295.58	12,164.20
Qinghai (QH)	5055.44	0.73	5.26	6957.69	4234.14
Ningxia (NX)	7241.43	1.36	10.74	12,676.56	5376.25
Xinjiang (XJ)	19,349.86	3.43	27.13	36,898.81	17,641.82
Total	576,261.81	120.92	999.15	1,540,047.31	1,299,898.78

By comparing Tables 1 and 2, the following conclusions can be made: firstly, the optimized GDPs of the nine groups are all larger than the initial GDP. Group 9 and Group 1 have the largest and smallest GDP, at 20.62% and 19.68% greater than the initial GDP, respectively. This is because the provinces in Group 9 have the loosest constraints on energy consumption, while those in Group 1 have the harshest constraints. Secondly, in all the nine groups, there are 19, 20 or 21 provinces whose optimized GDPs are larger than their planned GDP. Thirdly, the sensitivity of the optimized GDP to $\bar{\mu}$ is higher than that to $\underline{\mu}$. Taking $\underline{\mu} = 0.95$ as an example, when the $\bar{\mu}$ increases from 1.05 to 1.1, the optimized GDP increases by 7475.64 billion yuan; when the $\bar{\mu}$ continues to increase to 1.15, the GDP growth slows down, but still increases by 306 billion yuan. Taking $\bar{\mu} = 1.05$ as another example, when $\underline{\mu}$ decreases from 0.95 to 0.9, the optimized GDP increases by 397.12 billion yuan; when $\underline{\mu}$ continues to decrease to 0.85, GDP only increases by 97.21 billion yuan. The collaborative allocation results of Group 9 are shown in Table 3.

Table 2. The optimized GDP of collaborative allocation under different $(\underline{\mu}, \bar{\mu})$ schemes in 2025.

Province	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
	(0.95, 1.05)	(0.95, 1.10)	(0.95, 1.15)	(0.90, 1.05)	(0.90, 1.10)	(0.90, 1.15)	(0.85, 1.05)	(0.85, 1.10)	(0.85, 1.15)
BJ	38,312.33	38,312.33	38,312.33	38,312.33	38,312.33	38,312.33	38,312.33	38,312.33	38,312.33
TJ	27,566.96	27,566.96	27,566.96	27,566.96	27,566.96	27,566.96	27,566.96	27,566.96	27,566.96
HeB	60,208.05	55,897.74	56,002.58	63,466.93	62,969.64	53,716.42	61,555.80	67,701.57	59,509.93
SX	22,959.01	22,959.01	22,959.01	24,510.21	24,510.21	21,407.82	26,061.40	26,061.40	21,407.82
IM	28,162.72	28,162.72	28,162.72	28,162.72	28,162.72	28,162.72	28,162.72	28,162.72	28,162.72
LJ	55,206.92	55,548.67	55,548.67	50,563.64	57,378.72	57,167.53	49,250.74	59,043.61	57,570.21
JL	44,395.69	46,348.63	46,546.42	44,395.69	46,348.63	45,928.48	44,395.69	46,348.63	45,278.71
HLJ	42,287.16	41,283.77	41,283.77	42,046.54	43,198.06	43,198.06	40,927.55	43,198.06	43,198.06
SH	42,108.06	42,108.06	42,108.06	42,108.06	42,108.06	42,108.06	42,108.06	42,108.06	42,108.06
JS	124,323.69	124,323.69	124,323.69	124,323.69	124,323.69	124,323.69	124,323.69	124,323.69	124,323.69
ZJ	81,392.20	77,747.13	79,406.54	81,392.20	83,756.21	84,570.80	81,392.20	83,756.21	84,570.80
AH	49,061.57	49,061.57	48,922.66	49,061.57	49,061.57	49,061.57	49,061.57	49,061.57	49,061.57
FJ	61,411.18	59,996.39	58,581.60	61,411.18	59,996.39	58,581.60	61,411.18	59,996.39	58,581.60
JX	33,896.85	33,896.85	33,896.85	33,896.85	33,896.85	33,896.85	33,896.85	33,896.85	33,896.85
SD	136,711.33	143,706.23	143,706.23	137,033.77	131,686.68	142,600.92	138,115.87	127,657.76	146,383.64
HeN	115,964.20	121,300.41	118,632.96	115,964.20	121,300.41	118,632.96	115,964.20	121,300.41	118,632.96
HuB	69,197.21	69,471.08	69,471.08	68,391.71	66,070.92	69,471.08	68,391.71	66,070.92	69,471.08
HuN	63,428.40	65,603.28	65,603.28	63,428.40	61,177.80	65,603.28	63,428.40	61,398.67	58,927.20
GD	130,654.36	130,654.36	130,654.36	130,654.36	130,654.36	130,654.36	130,654.36	130,654.36	130,654.36
GX	46,152.63	47,736.08	48,205.34	46,152.63	47,736.08	46,570.58	46,152.63	47,736.08	46,570.58
HaN	9095.79	9767.34	10,438.88	9095.79	9767.34	10,438.88	9095.79	9767.34	10,438.88
CQ	31,849.28	33,863.73	33,863.73	31,849.28	30,010.94	33,783.22	31,849.28	30,918.30	29,794.01
SC	56,479.73	56,479.73	56,479.73	56,479.73	56,479.73	56,568.18	56,479.73	56,479.73	61,331.92
GZ	26,591.92	23,872.52	23,872.52	22,821.68	27,552.56	25,597.40	22,821.68	22,403.58	28,513.19
YN	52,150.25	50,883.24	52,445.97	52,150.25	50,883.24	52,002.84	52,150.25	50,883.24	50,228.44
S'X	49,975.83	50,050.33	50,050.33	49,975.83	50,050.33	52,918.19	49,975.83	48,731.26	50,050.33
GS	12,164.20	12,164.20	12,164.20	12,164.20	12,164.20	12,164.20	12,164.20	12,164.20	12,164.20
QH	8035.51	8118.22	8118.22	8035.51	7925.65	8118.22	8035.51	7925.65	7348.32
NX	6258.00	6300.51	6162.10	7288.80	5376.25	6947.94	8671.03	5820.77	5376.25
XJ	29,685.15	29,977.04	29,977.04	33,378.61	33,408.72	26,623.28	33,803.31	34,855.90	28,503.68
Total	1,555,686.18	1,563,161.82	1,563,467.82	1,556,083.30	1,563,835.24	1,566,698.43	1,556,180.51	1,564,306.23	1,567,938.33

Table 3. The collaborative allocation results of Group 9 in 2025.

Province	Energy Consumption (10 ⁴ tce)	SO ₂ Emissions (10 ⁴ tons)	NO _x Emissions (10 ⁴ tons)	CO ₂ Emissions (10 ⁴ tons)
BJ	8997.42	0.92	9.12	14,161.36
TJ	10,295.09	1.02	9.845	18,349.94
HeB	33,057.13	9.30	63.24	92,205.22
SX	21,451.24	5.17	38.59	53,964.13
IM	25,814.76	4.39	33.10	49,559.02
LJ	23,023.57	3.30	29.16	46,099.68
JL	11,576.31	1.31	12.63	20,248.93
HLJ	14,376.24	2.57	22.95	36,206.23
SH	14,367.48	1.32	13.70	23,943.36
JS	38,865.47	5.43	50.99	88,710.90
ZJ	28,382.68	4.23	39.11	63,262.79
AH	15,516.62	5.64	45.91	67,121.64
FJ	17,662.56	2.79	25.54	42,595.17
JX	10,665.33	4.08	33.07	48,143.55
SD	48,723.99	6.61	62.31	103,291.34
HeN	33,301.05	6.79	59.14	91,380.69
HuB	21,755.59	4.47	39.06	62,785.12
HuN	23,630.26	7.30	50.90	77,723.69
GD	42,391.84	9.69	82.63	128,203.02
GX	14,550.38	4.18	34.90	52,878.39
HaN	2843.61	0.72	6.11	9021.19
CQ	12,669.27	3.35	24.24	37,340.70
SC	21,352.88	7.53	60.43	88,014.26
GZ	10,569.96	3.32	26.67	39,079.50
YN	15,817.60	3.92	33.31	51,637.01
S'X	15,665.09	2.89	25.72	42,202.96
GS	9435.84	3.29	23.84	33,295.58
QH	5813.75	0.98	7.52	11,308.05
NX	7241.43	1.36	10.74	12,676.56
XJ	16,447.38	3.04	24.68	34,637.34
Total	576,261.81	120.92	999.15	1,540,047.31

As can be seen from Table 3, the top three provinces in terms of energy consumption are Shandong, Guangdong and Jiangsu, and their quota ratios are 8.46%, 7.36% and 6.74%, respectively. The last three provinces are Hainan, Qinghai and Ningxia, whose quota ratios are all less than 1.5%. The top three provinces in terms of SO₂ emission are Guangdong, Hebei and Sichuan, and the sum of their quota ratios is 21.93%. The top three provinces in terms of NO_x and CO₂ emissions are Guangdong, Hebei and Shandong, and the sum of each element is about 20%. The last three provinces in terms of SO₂ and NO_x emissions are Hainan, Qinghai and Beijing, whose quota ratios are all less than 1%. The last three provinces in terms of CO₂ emissions are Hainan, Qinghai and Ningxia, each accounting for less than 1%.

6. Discussion and Suggestions

6.1. Discussion

6.1.1. Comparison with Initial Allocation Scheme

In order to verify the equity of the collaborative allocation scheme, we drew the Lorenz curves for the results obtained from the initial allocation scheme and the improved centralized DEA model, as shown in Figure 2.

Figure 2. Cont.

Figure 2. Lorenz curves of collaborative allocation scheme and initial allocation scheme.

The diagonal from the coordinate origin to another vertex of the square is a bisector that represents an absolute equity that generally does not exist. The area between diagonal and Lorenz curve stands for the value of the Gini coefficient [37]. The greater the Gini coefficient, the more inequitable the allocation. It can be seen from Figure 2 that, although all Lorenz curves show similar trends, the collaborative allocation scheme based on the centralized DEA model is more equitable than the initial allocation scheme. By using the trapezoidal area method, we calculate that the Gini coefficients of per capita energy consumption and per capita SO_2 , NO_x and CO_2 emissions are 0.1739, 0.1440, 0.0897 and 0.0679, respectively. They are all less than 0.2, indicating that the allocation achieves absolute interpersonal equity. The Gini coefficients of the intensity of the above four elements are 0.1503, 0.2929, 0.2409 and 0.2084, respectively. Except for the energy consumption allocation, which achieves absolute economic equity, the Gini coefficients of the other three factors are all in the range of 0.2 to 0.3, indicating that the allocation of SO_2 , NO_x and CO_2 emissions achieves economic equity.

6.1.2. Pressures on Energy Saving, Emissions Reduction and GDP Growth

It is assumed that the planned GDP of each province is achievable, and the initial allocation scheme puts equal pressure on all the provinces. In order to measure the pressure

of the collaborative allocation scheme relative to the initial scheme, we define the pressure index as follows:

$$P_{ij} = \frac{(X_{ij}^0 - X_{ij})}{X_{ij}^0} \times 100\% \quad (6)$$

where P_{ij} is the pressure index of the j th allocation element of the i th province, and X_{ij}^0 and X_{ij} are the initial and collaborative allocation values of the j th element of the i th province, respectively. $P_{ij} > 0$ means that the energy saving or emission reduction pressure is increased, and $P_{ij} \leq 0$ means that there is no pressure. It is assumed that SO_2 , NO_x and CO_2 emissions can be reduced by adopting certain technical or management measures for all provinces. The pressure indexes of these three elements are equivalent, and they can be synthesized into an emission reduction pressure index with an equal weight of $1/3$.

Similarly, we also give the GDP growth pressure index function for each province:

$$S_i = \frac{(Y_i - Y_i^0)}{Y_i^0} \times 100\% \quad (7)$$

where S_i is the GDP growth pressure index of the i th province, and Y_i^0 and Y_i are the planned and optimized values of GDP of the i th province. Figures 3 and 4 show the energy saving, emission reduction and economic growth pressure indexes of the collaborative allocation scheme.

Figure 3. The energy saving and emission reduction pressure indexes of the collaborative allocation scheme.

By calculating the average pressure index of the provinces whose pressure index is greater than 0, we obtain the average pressure indexes of energy saving, emissions reduction and GDP growth, which are 11.46%, 16.85% and 40.62%, respectively. Here, we define a pressure index greater than the average as high pressure, an index lower than the average as low pressure, and an index that is less than or equal to zero as no pressure. There are nine provinces with energy saving pressures larger than zero. Hebei, Shanxi, Liaoning, Sichuan, Guangzhou and Xinjiang are in the high-pressure zone, and Heilongjiang, Anhui and Shandong are in the low-pressure zone. In terms of emissions reduction, Liaoning, Jilin and Heilongjiang are in the high-pressure zone, and Hebei, Shanxi, Shandong, Henan, Guangzhou, Yunnan, Shaanxi and Xinjiang are in the low-pressure zone. As regards to the pressure on GDP growth, Jilin, Henan, Heilongjiang, Yunnan, Qinghai, Xinjiang, Shaanxi and Guangxi are in the high-pressure zone, and Hebei, Liaoning, Zhejiang, Anhui, Fujian, Shandong, Hubei, Hunan, Hainan, Guizhou and Sichuan are in the low-pressure zone.

Figure 4. The GDP growth pressure index of the collaborative allocation scheme.

6.2. Implications and Suggestions

According to the pressure zones for energy saving, emission reduction and GDP growth for each province, the 30 provinces can be divided into seven categories, as shown in Table 4.

Table 4. Provincial classification based on energy saving, emission reduction and GDP growth pressure.

Category	Energy Saving	Emission Reduction	GDP Growth	Province
I	No pressure	No pressure	No pressure	BJ, TJ, IM, SH, JS, JX, GD, CQ, GS, NX
II	No pressure No pressure	No pressure No pressure	Low pressure High pressure	ZJ, FJ, HuB, HuN, HaN GX, QH
III	Low pressure No pressure	No pressure Low pressure	Low pressure High pressure	AH, HeN, YN, S'X
IV	No pressure Low pressure	High pressure High pressure	High pressure High pressure	JL HLJ
V	Low pressure	Low pressure	Low pressure	SD
VI	High pressure High pressure High pressure	No pressure Low pressure Low pressure	Low pressure Low pressure High pressure	SC HeB, GZ XJ
VII	High pressure	High pressure	Low pressure	LN

(1) Category I includes ten provinces: Beijing, Tianjin, Inner Mongolia, Shanghai, Jiangsu, Jiangxi, Guangdong, Chongqing, Gansu and Ningxia. These provinces do not have any pressure. The existing policies and measures can be followed to ensure the realization of the original objectives.

(2) Category II includes seven provinces: Zhejiang, Fujian, Hubei, Hunan, Hainan, Guangxi and Qinghai. These provinces have no pressures on energy saving and emission reduction, but they have varying degrees of economic growth pressure. Guangxi and Qinghai have high economic growth pressure, and they can adopt some economic development measures or sell energy consumption and emission quotas to promote economic development. Other provinces have less pressures on economic growth, and they can slightly optimize the existing industries and technologies to achieve their GDP growth goals.

(3) Category III includes four provinces: Anhui, Yunnan, Shaanxi and Henan. These provinces have certain energy saving pressure or emission reduction pressure and have different degrees of economic growth pressure. Anhui has no pressure on emission reduc-

tion but has low energy saving and economic growth pressures. It can adopt energy saving technologies, change its energy and industrial structure and develop the service sector. Yunnan, Shaanxi and Henan have no pressure on energy saving but have low emission reduction pressure and high economic development pressure. These three provinces can reduce their emissions by waste gas treatment and the use of clean energy. Meanwhile, they should accelerate the adjustment of their industrial structure and increase the proportion of the service industry to increase their economic outputs.

(4) Category IV includes Jilin and Heilongjiang. These two provinces have no pressure on energy saving but high pressures on emission reduction and economic growth. They should eliminate backward production capacity, develop low-carbon emission reduction technologies and adjust their industrial structure.

(5) Category V only includes Shandong province. It has some pressure on all three elements and should actively implement the transformation of old and new kinetic energy and introduce and develop highly efficient and new technologies.

(6) Category VI includes four provinces: Sichuan, Guizhou, Hebei and Xinjiang. They have high energy saving pressure, low emission reduction pressure and different degrees of GDP growth pressure. These provinces have rich traditional energy reserves. They should actively improve their existing energy structures, use clean and efficient energy, change their development modes and increase the proportion of tertiary industry.

(7) Category VII only includes Liaoning province. It experiences high pressures on energy saving and emission reduction and low pressure on GDP growth. With the support of the Northeast Revitalization Plan, Liaoning should strengthen its technological innovation, accelerate the completion of industrial transformation and upgrading and improve its energy consumption structure to reduce the energy saving and emission reduction pressures.

According to the provincial pressure index, it is difficult for some provinces to achieve both energy saving and emission reduction goals and their GDP growth goals at the same time. For example, the optimized GDP of Heilongjiang will result in more growth pressure on the basis of the planned GDP, and its energy saving and emission reduction pressures are also relatively high. However, some provinces, such as Beijing, Tianjin and Shanghai, have less pressures on energy saving, emission reduction and economic growth. Therefore, if the regional integration development strategy is adopted and the provinces in the region jointly undertake the overall regional goal, this can be expected to solve the problem of the large gaps in energy saving, emission reduction and economic growth pressures in various provinces.

In the “Outline of the 13th Five-Year Plan for National Economic and Social Development of the People’s Republic of China” [38], China has clearly proposed three major regional development strategies; i.e., “Belt and Road” construction, the coordinated development of the Beijing-Tianjin-Hebei region and the construction of the Yangtze River Economic Belt. At the same time, China has also proposed a detailed “Belt and Road” strategic plan in “Vision and proposed actions outlined on jointly building the Silk Road Economic Belt and 21st-Century Maritime Silk Road” [39]. Table 5 shows the energy saving, emission reduction and GDP growth pressures for the major regions involved in the three national strategies.

Relying on the Yangtze River Golden Waterway, the Yangtze River Economic Belt, which is effectively connected to the eastern, central and western regions of 11 provinces, has a surplus of 2.04% of energy saving pressure space and 5.73% of emission reduction space. The pressure indexes of the Beijing-Tianjin-Hebei region and the 21st Century Maritime Silk Road are relatively small. The maximum pressures of the New Eurasian Continental Bridge Economic Corridor and the China–Mongolian Economic Corridor are around 30%. The three national strategic regions cover almost all provinces, so regional integration can relieve the energy saving and emission reduction pressures in various provinces, promote the coordinated development of provinces and lead to the achievement collaborative allocation scheme.

Table 5. Pressure index of energy saving, emission reduction and GDP growth in regions involved in three national strategies.

National Strategic Region	Energy Saving	Emission Reduction	Economic Growth
Beijing-Tianjin-Hebei (BJ, TJ, HB)	10.03%	0.91%	4.62%
Yangtze River Economic Belt (SH, JS, ZJ, AH, JX, HuB, HuN, CQ, SC, YN, GZ)	−2.04%	−5.73%	10.76%
21st Century Maritime Silk Road (LN, HwB, TJ, SD, SH, JS, ZJ, FJ, GD, GX, HaN)	0.16%	−3.77%	13.16%
New Eurasian Continental Bridge Economic Corridor (JS, AH, HeN, S'X, GS, QH, XJ)	−1.99%	5.03%	29.84%
China–Mongolia–Russia Economic Corridor (BJ, TJ, HeB, IM, LJ, JL, HLJ)	7.20%	12.17%	25.94%

Note: The “Belt and Road” strategy also includes the China–Central Asia–West Asia Economic Corridor, China–Indochina Peninsula Economic Corridor, China–Pakistan Economic Corridor and Bangladesh–China–India–Myanmar Economic Corridor. Because these four economic corridors involve much fewer provinces, they are not considered.

In order to promote regional coordinated development and improve the realization of the optimal allocation scheme, this paper puts forward the following suggestions. First, China should improve the initial distribution and trading system of emission rights, carbon emission rights and energy rights, establish national trading platforms, break regional restrictions and interest barriers and improve the efficiency of resource allocation. Second, China should improve the methods of regional cooperation, including developing regional industry associations, establishing cross regional and cross industry cooperation platforms for technology and talents, exploring the collaborative governance model of urban agglomeration and encouraging the establishment of various forms of urban alliances. Third, China should strengthen the construction of transportation and other infrastructure, build a complete logistics network and promote the flow of production factors. For example, the government can build some detour roads to avoid various traffic bottlenecks in the urban center, which can solve the traffic congestion in the urban area with more smooth and efficient traffic operation management [40]. Fourth, China should consider regional characteristics, give full play to regional comparative advantages and implement differentiated regional policies; at the same time, it should establish a regional interest coordination mechanism of sharing costs and interests to promote long-term and sustainable cooperation within and between regions.

7. Conclusions

In order to realize the equity and efficiency of allocation, this paper constructs an improved DEA model to allocate energy consumption, and SO₂, NO_x and CO₂ emissions. In contrast to the basic centralized DEA model, this model makes three innovations. Firstly, the centralized DEA model considers the regional resource endowment differences, transportation network and other factors, and proposes an assumption that the energy consumption cannot be increased or reduced significantly. Secondly, it considers the collaborative effect on energy saving and emission reduction. On the basis of previous studies, it not only allocates energy consumption and CO₂ emissions but also SO₂ and NO_x emissions. Thirdly, this model considers the economic development need of each province and ensures that the optimized GDP of each province will not be less than the planned level.

By comparing the optimized GDP results of collaborative allocation with the planned GDP, it is found that the GDPs of 19 provinces in the collaborative scheme are improved and the total GDP increases by 20.62%. A comparison of the Lorenz curves of the two schemes shows that the fairness of the collaborative allocation scheme is better than that of

the initial scheme. By calculating the pressure of energy saving, emission reduction and GDP growth of each province, it is found that 10 provinces, including Beijing, Tianjin and Inner Mongolia, are under no pressures in the three aspects, but other provinces such as Jilin, Liaoning and Xinjiang are under pressure in at least one aspect. The 30 provinces can be divided into seven categories and different suggestions are made for each category. After measuring the pressure of national strategic regions, it is proposed that regional integration can relieve this pressure.

There are some defects in this study. Firstly, due to the availability of data, fewer undesirable outputs have been selected. Some other air pollutants such as PM_{2.5} can be included in further research. Secondly, due to the lack of data on SO₂ and NO_x emissions in recent years, the predicted data in this paper may exhibit some deviation from the actual values. More comprehensive and accurate statistical data will help to improve the accuracy of our conclusions.

Author Contributions: Conceptualization, J.S.; methodology, J.S.; writing—original draft preparation, R.C.; writing—review and editing, J.S., X.M. and R.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fundamental Research Funds for the Central Universities, grant number 20CX04003B.

Institutional Review Board Statement: This paper does not contain any studies with human or animal participants performed by the author.

Informed Consent Statement: This paper does not contain any studies with human or animal participants performed by the author.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author upon request.

Acknowledgments: The authors are grateful to anonymous reviewers and editors for their comments and suggestions on this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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