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Research article

A regional cooperative reduction game model for air pollution control in North China

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ABSTRACT

Due to variations in economic scale, economic structure, and technological advancement across different Chinese provinces and cities, the cost of air pollution reduction differs significantly. Therefore, the total reduction cost can be decreased by capitalizing on these regional discrepancies in reduction cost to carry out cooperative emission reduction. In this paper, taking NO_x reduction in North China as an example, a regional cooperative reduction game (CRG) model was constructed to minimize the total cost of emission reduction while achieving future emission reduction targets. The fair allocation of benefits from cooperation plays a crucial role in motivating regions to participate into the cooperation. A comprehensive mechanism of benefits allocation was proposed to achieve fair transferred compensation. The mechanism combines the consumption responsibility principle based on input-output theory and the Shapley value method based on game theory. Compared to the cost before the optimized collaboration, the CRG model will save 20.36% and 13.71% of the total reduction cost in North China, respectively, under the target of 17.68% NO_x reduction by 2025 and 66.44% NO_x reduction by 2035 relative to 2020. This method can be employed in other regions to achieve targets for air pollution reduction at minimum cost, and to motivate inter-regional cooperation with this practical and fair way of transferred compensation.

1. Introduction

The rapid economic growth has raised the demand for energy in China. Despite China's efforts to transition towards a greener energy mix (Chen et al., 2019; Tong et al., 2019), the substantial consumption of fossil energy such as coal continues to exert considerable strain on air quality management. Atmospheric pollution poses a severe threat to public health (Hu et al., 2017; Xue et al., 2022), destroys species diversity (Ahmed Bhuiyan et al., 2018) and causes huge economic losses (Ma et al., 2021). The heavy haze caused by $PM_{2.5}$ in North China is still a prominent atmospheric environmental problem (Fan et al., 2020; Song et al., 2021), and O_3 exceedances in Beijing, Tianjin, Hebei and surrounding areas need to be solved urgently (Gong et al., 2020). According to the National Air Quality Bulletin (MEE, 2022), 8 of the 20 cities with the worst air quality among 168 key cities in China in 2021 are situated in North China.

NO_x is one of the important precursors of $PM_{2.5}$ and O_3, and its pollution control has been gradually paid attention to in recent years. Since 2011, NO_x has been listed as one of the air pollutants that need to be controlled in the China's total pollution control plan. In the current 14th Five-Year Plan (2021–2025) of China, it was clearly stipulated that the national target is to reduce the total NO_x emissions by more than 10% (The Central People's Government of the People's Republic of China, 2021). Local governments in various regions, including North China, have also formulated corresponding emission reduction target plans.

With the accumulation of experience in air pollution control, more and more studies and empirical evidence showed that regional cooperation in air pollution reduction is more cost-effective than independent local emission control (Wang et al., 2019b; Xue et al., 2020; Zhao et al., 2021). The implementation of relevant policies for regional joint prevention and control of air pollution has a positive effect on the reduction of air pollutants and the economic benefits often outweigh the costs of implementation (Liu et al., 2023). The Air Pollution Prevention and Control Action Plan that China has initiated since 2013 has led to a significant reduction in $PM_{2.5}$ and a decrease of 16.8% in $PM_{2.5}$-induced

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mortality from 2013 to 2019 (Lian et al., 2022). The joint prevention and control of atmospheric pollution policy can effectively control border pollution, for example, reducing $PM_{2.5}$ concentrations by 3.5% (Lin et al., 2023). The clean heating policy implemented in "2 + 26" cities of China in 2016 brought about 109.85 billion yuan in health economic benefits, which is a net-positive benefit program with environmental and public health improvements (Feng et al., 2021). These studies proved the necessity and effectiveness of cross-regional control of air pollution. The cooperative reduction model takes into account the mobility of air pollutants and the "public goods" property of ecological environment (Guo and Lu, 2019), which avoids "free-rider behavior" to a certain extent and thus carries out air environment management more effectively. Xue et al. (2015) applied an interprovincial cooperative game model to the case of SO_2 abatement in the Beijing-Tianjin-Hebei region and found that cooperation helped reduce the total regional SO_2 abatement cost by 4.58%–11.29% during the period 2003–2009. In a subsequent study, Xue et al. (2019) achieved a reduction of 9.6% in total SO_2 abatement costs in Beijing-Tianjin-Hebei region in 2015 through a cooperative econometric model. However, more cross-sectoral issues and more complex air pollutants present new challenges to collaborative governance. Central governments need to improve collaborative pollution reduction mechanisms and provide more flexible policy tools to facilitate effective regional collaborative governance (Yang et al., 2021).

In the absence of a reasonable regulatory mechanism, the direct outcome of a simple cost-optimized cooperation model for emission reduction may fail to guarantee that all parties benefit from the cooperation. Whether to gain benefits in cooperation and how to allocate the benefits are crucial issues in a cooperative game. Commonly used methods of benefits allocation include MCRS (Minimum Cost-Residual Savings) (Xue et al., 2019) method, GQP method (Game Quadratic Programming) (Wang et al., 2019a), Shapley value method (Shuai et al., 2019), etc. The MCRS method and the GQP method adhere to similar principles of apportionment, both taking the marginal cost of the alliance as an important basis for cost sharing among local governments. These methods only consider the case where all members participate in cooperation (Liu et al., 2022b), however, realistic conditions may not ensure full cooperation. The Shapley value method integrates the cooperative pollution control alliances involving some and all members in the region, and considers the probability of a particular member participating in the cooperation, i.e., it incorporates the benefits allocation in the case of insufficient cooperation. Meanwhile, this method enables a more even distribution of costs or benefits among the participants, with more moderate results compared to other methods (Liu et al., 2022a). Therefore, the Shapley value method is more widely used in cooperative game issues in the environmental field (Xie et al., 2016; Zhou et al., 2019).

Most existing research on the application of Shapley game theory in the field of atmospheric environment cooperation focused on SO_2 rather than more complex pollutants. However, SO_2 pollution has been largely solved in China so far, while atmospheric problems caused by NO_x and VOCs are getting noticed. Furthermore, most of the existing cooperative game studies were oriented towards air pollution control that had already occurred in the past, focusing on the removal cost of pollutants generated and emitted in a certain year. The single time scale and the cases that have occurred make the existing studies limited in guiding future scenarios.

The core of this study is to minimize the total cost of NO_x emission reduction through CRG model in North China under different future scenarios, which means that the cost optimized by the CRG model is further decreased than the cost under the original model in which each region independently accomplishes its own reduction target. Moreover, we combined the transferred compensation of the consumption responsibility principle containing the emission transfer correlation matrix with the Shapley value method to propose a more feasible benefits allocation mechanism. The consumption responsibility principle based on input-output model is also utilized to calculate the compensation from the place of consumption to the place of production (Zhang et al., 2022). These new attempts can further enrich the research field of regional cooperation in pollutant reduction, establish a compensation mechanism to promote regional cooperation, and achieve the goal of minimizing the total cost of air pollution emission reduction.

2. Methodology

In this work, a CRG model was first constructed to optimize the total cost of NO_x reduction. Secondly, cases under different future scenarios in North China were studied to verify the validity of the CRG model. Finally, a comprehensive compensation mechanism that integrates the consumption responsibility principle and the Shapley value method was proposed to enhance the willingness of each region to cooperate. The framework of cost-minimizing optimization strategy is displayed in Fig. 1.

2.1. The cooperative reduction game (CRG) model

2.1.1. Establishment of the CRG model

The general cooperative game seeks to maximize total benefits or minimize total costs. The cooperative game model mainly contains the objective function, the participants and constraints. In the game process, each participant makes and alters decisions not only based on their own variables, but also based on the decisions of other participants.

The multi-participant cooperative reduction game (CRG) model is expressed as Eqs. (1)–(3). The model outputs the optimal pollutant reduction rate for each participant when the total reduction cost is minimized.

$$MIN\sum_{x_i} RC_i(x_i) \tag{1}$$

$$s.t. \sum_{n}(P_{i2020}\times x_i) \ge \sum_{n} R_{ig} \tag{2}$$

$$\alpha_i \le x_i \le \beta_i \quad i = 1, 2, \ldots, n \tag{3}$$

where, x_i denotes the NO_x reduction rate relative to the base year for region i ($x_i = R_{i0}/R_{i2020}$). $RC_i(x_i)$ represents the total NO_x reduction cost function for region i. P_{i2020} refers to the NO_x emissions of region i in the base year of 2020. R_{ig} denotes the NO_x reduction target for region i set by the government. α_i and β_i signify the lower bound and upper bound of the NO_x reduction rate in region i, respectively. i denotes each region in North China, and $i = 1, 2, 3, 4, 5$ represent Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia, respectively.

Eq. (1) implies the objective function of the model. It indicates that the overall NO_x reduction cost of the whole region is minimized by choosing the optimal reduction rate in each region through the cooperative game.

Eq. (2) describes the constraints for the whole region. It states that the sum of NO_x emission reductions for each region relative to the base year of 2020 should not be less than the sum of the emission reduction targets set by the government for each region.

Eq. (3) indicates the restraints for each region, which means the NO_x reduction rate of each region should be within a reasonable range. The lower bound α_i means the minimum requirement for emission reduction rate. The upper bound β_i means the utmost limit of emission reduction capacity (details in Supplementary Note 1).

2.1.2. Estimation of NO_x reduction cost

The reduction cost (RC_i) was estimated with marginal reduction cost curves. In contrast to obtaining cost curves with cost assessment tools from the perspective of end-of-pipe control technologies and energy mix adjustment (Bielen et al., 2020; Sun et al., 2021; Xing et al., 2019b; Zhang et al., 2019, 2020), cost curves constructed with models such as

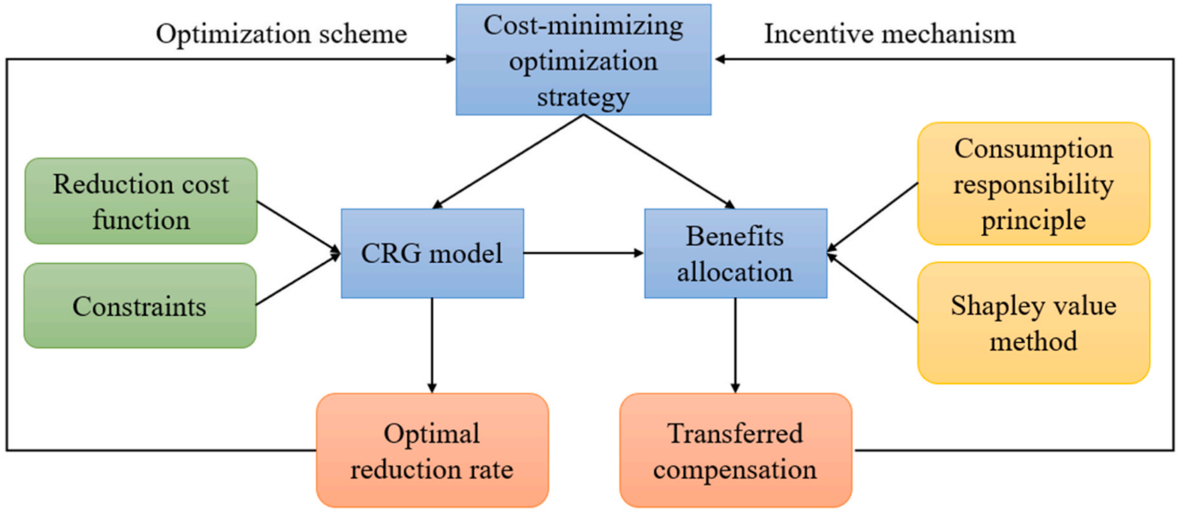

Fig. 1. Framework of cost-minimizing optimization strategy.

CGE from a macroscopic socioeconomic perspective are continuous and smooth. In this way, the cost curves can be expressed as a function, which is easy to input into the CRG model for analysis (Chen and Wang, 2022; Li et al., 2019, 2022).

We fitted the marginal cost functions in the form of the power function (Eq. (4)) according to the marginal cost curves of NO_x emission reduction for Beijing, Tianjin and representative cities in Hebei in 2020, established with CGE model by Li et al. (2022).

$$MRC_i(x_i) = a_i \cdot x^{b_i} \tag{4}$$

where, $MRC_i(x_i)$ represents the marginal NO_x reduction cost function for region i. a_i and b_i are the coefficients of the marginal NO_x reduction cost function.

The study area of this paper is North China, including five administrative regions of Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia. Thus, we extrapolate the marginal reduction cost curves of Shanxi and Inner Mongolia using the taxation levels of each region on this basis. According to environmental tax theory, the taxation of a pollutant characterizes the reduction cost at the macro level. The reduction cost is minimized when the marginal reduction cost is equal to the pollutant tax (Tietenberg and Lewis, 2019). The differences in the cost of air pollutant reduction across regions can be reflected by the different taxation levels applied to different regions. Depending on the NO_x taxation levels in different regions (Table 1), the marginal reduction cost curves of Shanxi and Inner Mongolia can be obtained from that of Beijing based on the environmental tax multiples between Shanxi, Inner Mongolia and Beijing, as shown in Eqs. (5) and (6).

$$RC_4 = (rate_4/rate_1) \cdot RC_1 \tag{5}$$

$$RC_5 = (rate_5/rate_1) \cdot RC_1 \tag{6}$$

Table 1
Environmental tax rates of NO_x across North China (CNY/USD = 0.15).

Region NO.	Region	NO_x tax rate (US$/kg)
1	Beijing	1.77
2	Tianjin	1.47
3	Hebei	First grade: 1.42 (13 counties (cities and districts) adjacent to Beijing) Second grade: 0.88 Third grade: 0.71
4	Shanxi	0.27
5	Inner Mongolia	0.18

where, $rate_1$, $rate_4$ and $rate_5$ denote the NO_x taxation levels in Beijing, Shanxi and Inner Mongolia, respectively.

Eventually, the marginal reduction cost functions of Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia were obtained. According to the derivative relationship between the marginal cost and the total cost, the total cost function in the form of power function (Eq. (7)) for each region is then acquired. Since the mechanism of the reduction cost changes over time is difficult to express in the form of an explicit function, it is assumed that the cost function for each region does not change dramatically over the time scale of our study. In addition, the reduction cost is closely related to pollutant tax rates, i.e., the higher the tax rate, the higher the reduction cost (Liu et al., 2021; Mardones and Mena, 2020). We discussed the impact of different tax rates in the Supplementary Note 6.

$$RC_i(x_i) = \int_0^{x_i} a_i x_i^{b_i} dx = \left[a_i \middle/ (b_i + 1)\right] x_i^{b_i+1} \tag{7}$$

Note: Data was obtained from the Standing Committee of Beijing Municipal People's Congress, the Standing Committee of Tianjin Municipal People's Congress, Hebei Provincial Department of Finance, the Standing Committee of Shanxi Provincial People's Congress and Department of Ecological Environment of Inner Mongolia Autonomous Region.

2.2. Benefits allocation mechanism based on the consumption responsibility principle and the Shapley value method

The CRG model constructed above is capable of minimizing the reduction cost of the region as a whole, which satisfies the principle of collective rationality. In order to make the game not against the principle of individual rationality, a reasonable benefits allocation method is required as the guarantee and incentive mechanism for cooperation.

2.2.1. Benefits allocation mechanism under the consumption responsibility principle

The consumption responsibility principle means that each region needs to bear the cost of pollution reduction caused by its consumption, rather than just that caused by production. Generally, the consumption responsibility principle is regarded as a more fair and reasonable way of bearing the cost than the production responsibility principle. In this principle, the cost of pollution control in a region accounts for not only the reduction cost of local emissions, but also the emission reduction cost in other regions caused by local production and consumption. The difference between the reduction cost under these two principles in a region is considered as the transferred compensation. We assume that producers can achieve this transferred compensation through market tools, such as adding pollution reduction cost to the price of goods or services sold to consumers. Therefore, this transferred compensation realized through market mechanisms can be used to regulate the changes in reduction cost of each region after cooperation.

Based on the environmental extended input-output table (EEIO), the flow of pollutants with economic activities across regions, i.e., the emission transfer correlation matrix, can be obtained. According to the basic equilibrium relationship of the input-output model (Miller and Blair, 2009) (details in Supplementary Note 2), the air pollutant emission in a region can be calculated as

$$E = NBY \tag{8}$$

where, E refers to the local pollutant emissions generated to satisfy the production and consumption of each region. B is the Leontief inverse matrix. N denotes the air pollution emission factor matrix, which is a diagonal matrix, and the diagonal elements are the corresponding pollutant emission factors of each region.

Define $T = (t_{rs})_{n\times n}$ as the emission transfer correlation matrix between places of air pollution emission and places of commodity consumption (details in Supplementary Note 3).

$$T = \begin{bmatrix} t_{11} & t_{12} & \dots & t_{1n} \\ t_{21} & t_{22} & \dots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_{n1} & t_{n2} & \dots & t_{nn} \end{bmatrix} \tag{9}$$

where, t_{rs} reflects the proportion of emissions generated by region r to meet the production and consumption of region s to the total local emissions, and $\sum_s t_{rs} = 1$.

Therefore, under the consumption responsibility principle, region s should bear the same proportion of the cost of air pollution reduction occurring in region r. Then, the reduction cost of region s under the consumption responsibility principle is represented as

$$RC_s^c = \sum_{r=1}^{n} t_{rs} * RC_r^p \tag{10}$$

where, RC^p and RC^c denote the reduction cost under the production responsibility principle and consumption responsibility principle, respectively.

Then, the transferred compensation (TC_i^1) which is the difference between the reduction cost under these two principles in a region is calculated as follows:

$$TC_i^1 = RC_i^{p*} - RC_i^{c*} \tag{11}$$

where, RC_i^{p*} and RC_i^{c*} signify the NO_x reduction cost under the CRG model for region i in terms of the production responsibility principle and the consumption responsibility principle, respectively.

If $TC_i^1 > 0$, it implies that region i should accept compensation from other regions, and if $TC_i^1 < 0$, it means that region i should give the transferred compensation to other regions.

2.2.2. The Shapley value method

In this work, the Shapley value method was adopted to measure the benefits accruing to each participant in the cooperative game, that is, the benefits they contribute in the cooperation. The Shapley value method is the process of allocating the total reduction cost savings to each participant according to their contributions.

Set $N = \{1, 2, \dots, n\}$ represents the collection of the n potential participants in a region. There are five potential participants in the study region, thus $n = 5$. Set $S = \{1, 2, \dots, s\}$ is a subset alliance (i.e., $S \subseteq N$) which contains s actual participants ($s \le n$).

As shown in Eq. (12), $v(S)$ denotes the difference in total NO_x reduction cost before and after optimization by the CRG model, which is the benefits of cooperation. Meanwhile, $v(S)$ should meet the conditions of $v(\Phi) = 0$ and $v(S_i \bigcup S_j) \ge v(S_i + S_j)$, where $v(S_i \bigcap S_j) = \Phi$.

$$v(S) = \sum_{i=1}^{s} RC_{i0} - \sum_{i=1}^{s} RC_i^* \tag{12}$$

where, RC_{i0} represents the NO_x reduction cost before applying the CRG model in region i, and RC_i^* represents the NO_x reduction cost corresponding to the optimal NO_x reduction rate under the CRG model for region i.

According to the Shapley value method, $\varphi_i(v)$, representing the benefits allocated to participant i (i.e., the actual cost savings in region i (CS_i)), can be calculated by Eqs.(13) and (14):

$$W(|S|) = \frac{(|S|-1)!(|N|-|S|)!}{|N|!} \tag{13}$$

$$\varphi_i(v) = \sum_{S\subseteq N} W(|S|)[v(s) - v(s - \{i\})] \tag{14}$$

Here, $|S|$ and $|N|$ refers to the number of participants in alliance S and N, respectively. $W(|S|)$ is a weighting factor, which denotes the probability that participant i get involved in alliance S in random order. $v(s-\{i\})$ is the cooperation benefits when participant i does not get involved in the cooperation. Thus, the change in cooperation benefits due to the absence of participant i can be expressed as $v(s) - v(s - \{i\})$, that is, the contribution of participant i to alliance S.

The total transferred compensation (TC_i) is calculated by Eq. (15):

$$TC_i = CS_i - (RC_{i0} - RC_i^*) \tag{15}$$

where, $(RC_{i0} - RC_i^*)$ indicates the cost savings of NO_x reduction in region i after cooperation, where a positive value denotes a decrease in NO_x reduction cost and a negative value denotes an increase in NO_x reduction cost.

$$TC_i^2 = TC_i - TC_i^1 = CS_i - \left[(RC_{i0} - RC_i^*) + TC_i^1\right] \tag{16}$$

As shown in Eq. (16), TC_i^2 signifies the transferred compensation that is still needed to achieve reduction cost savings in each region after the transferred compensation (TC_i^1) under the consumption responsibility principle. Regions where costs increase receive compensation ($TC_i^2 > 0$) to reach their calculated benefits of cooperation, while regions where the cost savings exceeds their calculated benefits pay compensation ($TC_i^2 < 0$).

2.3. Scenario design

We designed two scenarios, i.e., the 2025 baseline scenario and the 2035 baseline scenario. These two baseline scenarios serve as independent emission reduction pattern for each region before the application of the cooperation model.

The 2025 baseline scenario is derived from the NO_x reduction targets in the 14th Five-Year Plan (2021–2025) of each government in North China. In addition, we used the emission reduction rates during the 13th Five-Year Plan (2016–2020) to determine the range of emission reduction rates for each region.

The 2035 baseline scenario is based on the study by Ding et al. (2022). They introduced a novel integrated assessment system and predicted the essential range of NO_x emission reduction target to meet the National Ambient Air Quality Standard (NAAQS) in the Beijing-Tianjin-Hebei cities and their surrounding regions. We adjusted the NO_x reduction target and the range of reduction rates for 2035 from the original base year of 2017 to a base year of 2020. Therefore, this scenario allows regional air pollutant concentrations to meet the

NAAQS. The details for NO_x reduction targets of these two baseline scenarios, setting of relevant parameters in the CRG model and the specific parameter amendment method are shown in Supplementary Note 1.

Our objective is to further minimize the total NO_x reduction cost for the whole region through the CRG model while meeting the reduction target of each baseline scenario, and to explore how the cost savings can be distributed and compensated among the participants.

2.4. Data sources

The sources of applicable tax amounts for NO_x environmental protection tax across North China were summarized in Table S16. The NO_x emission of each region in North China from 2016 to 2020 was derived from China Statistical Yearbook on Environment (NBS, 2019, 2020, 2021(NBS, 2019); 2020, 2021)). The NO_x emission reduction targets in 2025 were acquired from the "14th Five-Year Plan" for Ecological and Environmental Protection of each region (Beijing Municipal People's Government, 2021; People's Government of Hebei Province, 2022; People's Government of Inner Mongolia Autonomous Region, 2021; Shanxi Provincial Department of Ecological Environment, 2022; Tianjin Municipal People's Government, 2022). The national multi-regional input-output table for 2017 were retrieved from CEADs())CEADs, 2017.

3. Results

3.1. Cost optimization effects under the CRG model

Regional cooperation may significantly lower the total emission reduction cost. As shown in Table 2 and Table 3, the total reduction cost savings for completing the same reduction tasks as their corresponding baseline scenarios in 2025 and 2035 were US\$126.48 $\times$ 10^6 and US \$2158.80 $\times$ 10^6, accounting for 20.36% and 13.71% of the total cost in corresponding baseline scenarios in North China region, respectively.

Actually, the underlying reason for the decline in the total regional reduction cost is that there are differences in reduction cost across regions, and thus there is space for optimization in the redistribution of reduction quantity (R_i). Some studies have shown that the total cost curves for NO_x reduction are overall in the order of Hebei, Shanxi, Beijing and Tianjin from high to low at the same reduction rate (Xing et al., 2019b), with the total cost curve of Shanxi being close to that of Beijing (Xing et al., 2019a). The total cost curves in this study are generally consistent with the results of these studies. The marginal reduction cost of each region is closely related to the current conditions of local economic development, air pollution status and technological update level. The marginal reduction cost in Beijing is much higher than those in other regions (Fig. 2a), mainly due to the predominant share of tertiary industries in Beijing which limits its potential for further technological emission reductions. Consequently, under the CRG model, Beijing's NO_x reduction rate (x_i) was decreased to 2.55% and 48.50% in 2025 scenario and 2035 scenario, respectively (Tables 2 and 3). The marginal reduction cost is relatively close in the four regions except Beijing, but the cost gap gradually expands as the reduction rate rises. Therefore, under the scenario of greater emission reductions in 2035, the emission reduction rates in regions with lower marginal cost will increase, such as to 78.00% and 77.00% in Shanxi and Inner Mongolia, respectively (Table 3). In this way, the total regional reduction cost in North China is decreased by transferring part of the reduction tasks from high marginal cost regions to low marginal cost regions.

As a result of their lower reduction rates, the cooperation resulted in lower reduction cost (RC_i) for Beijing and Hebei in 2025 scenario and Beijing, Tianjin and Hebei in 2035 scenario (Tables 2 and 3). However, the cost of reducing NO_x emissions under the CRG model is higher than the corresponding baseline scenario in some regions with lower marginal reduction cost due to the additional reduction tasks. For instance, the reduction cost of Shanxi will increase by US\$40.99 $\times$ 10^6 after applying the CRG model in 2025 (Table 2). These regions do not enjoy the benefits of the cooperative emission reduction. This will inevitably affect the cooperation. Therefore, it is necessary to reasonably allocate the total regional cost savings (i.e., cooperation benefits) to each participant through an inter-regional cost compensation mechanism to incentivize cooperation in pollution control for the purpose of minimizing the reduction cost.

3.2. Transferred compensation under the consumption responsibility principle

Fig. 3 shows the emission transfer correlation matrix for North China based on the national multi-regional input-output table. The regions on the diagonal generate the largest emissions for their own consumption. Moreover, Shanxi and Inner Mongolia generate relatively large emissions for the consumption in Hebei.

Under the consumption responsibility principle, a transferred compensation mechanism has been established based on the emission reduction cost that each region needs to be borne for its consumption, which means that each region bears corresponding reduction cost for the pollution emissions caused by its consumption in other regions. For instance, the consumption of Beijing caused 89%, 6.5%, 6.0%, 3.9% and 6.9% of pollution emissions in local, Tianjin, Hebei, Shanxi and Inner Mongolia, respectively, so Beijing should shoulder the corresponding proportion of the reduction cost in each region. Thus, the reduction cost savings in Beijing will decline from US\$155.06 $\times$ 10^6 to US\$127.41 $\times$ 10^6 after the this kind of transferred compensation in 2025 (row A and C in Table 4). That is, Beijing should pay the transferred compensation US \$27.65 $\times$ 10^6 to other regions according to Eq. (11) (row B in Table 4). This transferred compensation can be achieved by means of market mechanisms. The production region may add the reduction cost to the price of the product.

Comparing rows C and A in Tables 4 and 5, after the transferred compensation under the consumption responsibility principle, the disparity in cost savings across regions is narrowed, which will facilitate collaboration (also seen in Fig. S3). Nevertheless, the results of the

Table 2
Comparison of NO_x reduction effects under the 2025 baseline scenario and the CRG model.

		Beijing	Tianjin	Hebei	Shanxi	Inner Mongolia	Total
Baseline	x_{i0} (%)	15.93	17.78	18.25	14.22	21.13	–
	R_{i0} (10^4t)	1.38	2.08	14.05	8.01	10.05	35.57
	RC_{i0} ($\times$ 10^6 US\$)	158.28	19.74	209.66	97.96	135.54	621.19
CRG	x_i^* (%)	2.55	19.75	16.77	16.73	22.50	–
	R_i^* (10^4t)	0.22	2.31	12.91	9.43	10.70	35.57
	RC_i^* ($\times$ 10^6 US\$)	3.22	26.34	170.73	138.95	155.46	494.71
Cost savings ($RC_{i0} - RC_i^*$) ($\times$ 10^6 US\$)		155.06	−6.60	38.93	−40.99	−19.92	126.48

Note: x_{i0}, R_{i0} and RC_{i0} denote the NO_x reduction rate, the NO_x reduction quantity and the NO_x reduction cost under baseline scenario in region i, respectively. x_i^*, R_i^* and RC_i^* signify the optimal NO_x reduction rate, the optimal NO_x reduction quantity and the NO_x reduction cost corresponding to the optimal NO_x reduction rate under the CRG model for region i, respectively.

Table 3
Comparison of NO_x reduction effects under the 2035 baseline scenario and the CRG model.

		Beijing	Tianjin	Hebei	Shanxi	Inner Mongolia	Total
Baseline	x_{i0} (%)	64.23	74.26	60.12	71.05	69.70	–
	R_{i0} (10^4t)	5.57	8.69	46.27	40.03	33.15	133.71
	RC_{i0} ($\times$ 10^6 US$)	3602.82	1359.48	5133.77	3616.22	2034.71	15747.01
CRG	x_i^* (%)	48.50	62.90	54.02	78.00	77.00	–
	R_i^* (10^4t)	4.20	7.36	41.58	43.95	36.62	133.71
	RC_i^* ($\times$ 10^6 US$)	1868.30	820.77	3789.59	4525.57	2583.98	13588.22
Cost savings ($RC_{i0} - RC_i^*$) ($\times$ 10^6 US$)		1734.52	538.71	1344.18	−909.35	−549.27	2158.80

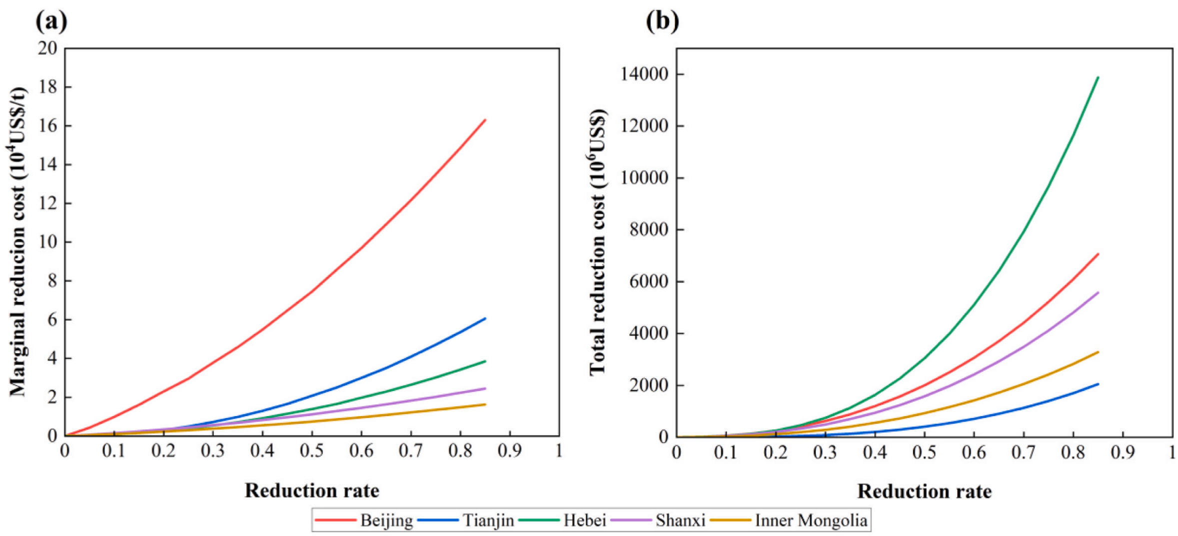

Fig. 2. (a) Marginal NO_x reduction cost curves and (b) total NO_x reduction cost curves for five regions in North China.

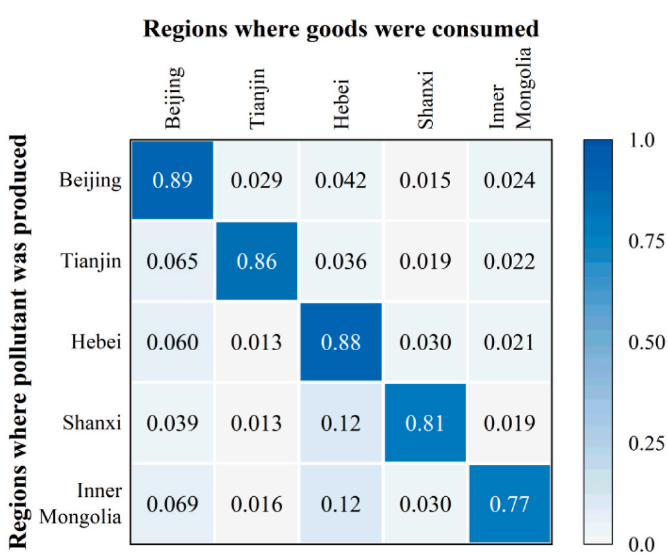

Fig. 3. The NO_x emission transfer correlation matrix between regions of pollutant generation and regions of goods consumption across North China.

compensation still show that the reduction cost declines in some regions and rises in others. For example, the NO_x reduction cost in Tianjin and Shanxi are still US$9.34 $\times$ 10^6 and US$ 25.33 $\times$ 10^6 higher than before the cooperation in 2025 scenario, respectively (row C Table 4). It is not possible to reach the situation that each region benefits from the cooperative game which still hinders the cooperation. Therefore, in the next section, we use the Shapley value method based on game theory to calculate how much each region contributes to the total cost savings, and accordingly suggest transferred compensation to ensure that each region can profit.

3.3. Benefits allocation based on the Shapley value method

The specific calculation process based on Eqs.(12)–(14) is shown in Tables S3–S12 in Supplementary Note 4. Fig. 4 illustrates the benefits of each cooperative alliance. Cooperative alliances involving Beijing usually have higher benefits of cooperation, especially in 2025 scenario, where the benefits of cooperation with Beijing's participation are much higher than those without Beijing's participation. Meanwhile, the more participants in the cooperation, the more significant the benefits of cooperation, especially in 2035 scenario.

Row D in Tables 4 and 5 illustrates the contribution benefits (i.e., actual cost savings) due to each region based on the Shapley value method. At this stage, the cost savings from the optimization of the CRG model were redistributed after adopting the compensation scheme with the consumption responsibility principle. Row E in Tables 4 and 5 shows the transferred compensation through administrative means for each region according to Eq. (16).

Beijing, Hebei and Inner Mongolia in 2025 scenario and Beijing, Tianjin and Hebei in 2035 scenario are required to pay transferred compensation to other regions at this stage. They are the beneficiaries of cost savings from the cooperation, except for Inner Mongolia in 2025 scenario, as they shift part of the NO_x emission reduction burden to other regions in the cooperation. Moreover, after compensation from the consumption responsibility principle, their cost savings still exceed the benefits they deserve. Taking Beijing in 2025 scenario as an example, its contribution to cooperation is measured to be US$94.19 $\times$ 10^6 according to the Shapley value method (row D in Table 4). After the transferred compensation of the consumption responsibility principle, Beijing's cost savings are US$127.41 $\times$ 10^6, which still exceed its contribution to the

Table 4
Cost savings and transferred compensation after the CRG model in 2025 ($\times$ 10^6 US$).

	Beijing	Tianjin	Hebei	Shanxi	Inner Mongolia	Total
A: Cost savings after the CRG model	155.06	−6.60	38.93	−40.99	−19.92	126.48
B: Transferred compensation based on the consumption responsibility principle	−27.65	−2.74	−14.28	15.66	29.02	0
C: Cost savings after transferred compensation $C = A + B$	127.41	−9.34	24.65	−25.33	9.10	126.48
D: Actual cost savings based on Shapley value method	94.19	6.05	8.42	10.22	7.60	126.48
E: Transferred compensation based on Shapley value method	−33.22	15.39	−16.23	35.55	−1.50	0
F: Cost savings after transferred compensation $F = C + E = D$	94.19	6.05	8.42	10.22	7.60	126.48

Table 5
Cost savings and transferred compensation after the CRG model in 2035 ($\times$ 10^6 US$).

	Beijing	Tianjin	Hebei	Shanxi	Inner Mongolia	Total
A: Cost savings after the CRG model	1734.52	538.71	1344.18	−909.35	−549.27	2158.80
B: Transferred compensation based on the consumption responsibility principle	−427.66	−83.98	−468.98	611.15	369.47	0
C: Cost savings after transferred compensation $C = A + B$	1306.86	454.73	875.20	−298.20	−179.80	2158.80
D: Actual cost savings based on Shapley value method	1078.56	187.88	269.76	237.75	384.85	2158.80
E: Transferred compensation based on Shapley value method	−228.30	−266.85	−605.44	535.95	564.65	0
F: Cost savings after transferred compensation $F = C + E = D$	1078.56	187.88	269.76	237.75	384.85	2158.80

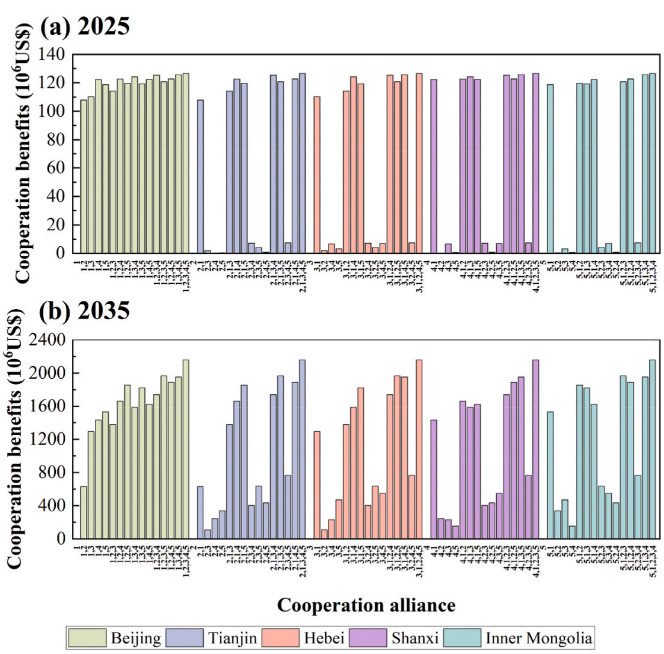

Fig. 4. The cooperation benefits under different cooperation alliances in (a) 2025 scenario and (b) 2035 scenario. The different colors represent the cooperation of all the combinations involved in each region.

cooperation (row C in Table 4). Therefore, Beijing should continue to compensate the other regions with US$33.22 $\times$ 10^6 (row E in Table 4). In this way, even though Beijing is the payer of transferred compensation, it still gets benefits from the cooperation, i.e., saving US$94.19 $\times$ 10^6 in reduction cost (row F in Table 4).

Tianjin and Shanxi in 2025 scenario and Shanxi and Inner Mongolia in 2035 scenario should accept the compensation. These regions take on additional emission reduction tasks from other regions in the cooperation, so the reduction cost rises. Meanwhile, compensation based solely on the consumption responsibility principle cannot cover their losses. To ensure regional cooperation, they need to be appropriately compensated. For instance, Shanxi increases its reduction cost by US$40.99 $\times$ 10^6 due to the cooperation (row A in Table 4), and after accepting the compensation of US$15.66 $\times$ 10^6 through the consumption responsibility principle (row B in Table 4), the increased cost became US $25.33 $\times$ 10^6 (row C in Table 4). The Shapley value method measured that Shanxi's contribution to the cooperation is US$10.22 $\times$ 10^6 (row D in Table 4), hence after compensating Shanxi another US$35.55 $\times$ 10^6 (row E in Table 4), it allowed Shanxi to ultimately benefit from the cooperative game by US$10.22 $\times$ 10^6 (row F in Table 4). In summary, both the regions that pay compensation and the regions that receive compensation are able to get their fair share of benefits from cooperation. Such a cost-benefit analysis of emission reduction can promote regional cooperation to minimize the total cost.

Therefore, we propose to implement the transferred compensation process in two stages (Fig. 5). In the first stage, the cost change in each region after the regional cooperation is compensated once through market mechanisms to moderate the disparity of cost savings among regions, especially to make up for part of the increased cost of cost-rising regions. In the second stage, the remaining unbalanced cost savings in each region should be adjusted through administrative means, so that each region can finally obtain their fair benefits measured by the Shapley value method from the cooperation.

4. Discussions

The biggest uncertainty affecting the results of this study comes from the upper and lower bounds of the NO_x reduction rate (see β_i and α_i in Eq. (3)). Here, we discussed the impact of parameter changes for 2035 scenario, and the relevant content for 2025 scenario is in the Supplementary Note 5.

4.1. Impact of changes in the upper bounds on the outcome of the cooperative game

First of all, we calculated the scope of possible changes in the upper bound (β_i). Here we use δ to represent it. The upper bound of the reduction rate should be greater than the reduction rate target of each region and less than 1. In addition, its value range is required to ensure that the same reduction target can be achieved under both the CRG model and the baseline scenario in 2035. Therefore, the variation $\delta \in [-6.2\%, 19.6\%]$.

During the change of δ from −6.2% to 19.6%, the total cost savings in North China gradually climbed from 9.9% to 15.5% and remained stable due to the expansion of the optimizable space (Fig. 6a). A positive value of transferred compensation for a region indicates that the region receives compensation, and conversely, a negative value indicates that the region pays compensation. In comparison with other regions, Beijing and Tianjin were relatively stable in their transferred compensation as payers (Fig. 6b). Similarly, the change in δ did not change Shanxi and Inner Mongolia as recipients. Only Hebei changed from the recipient to

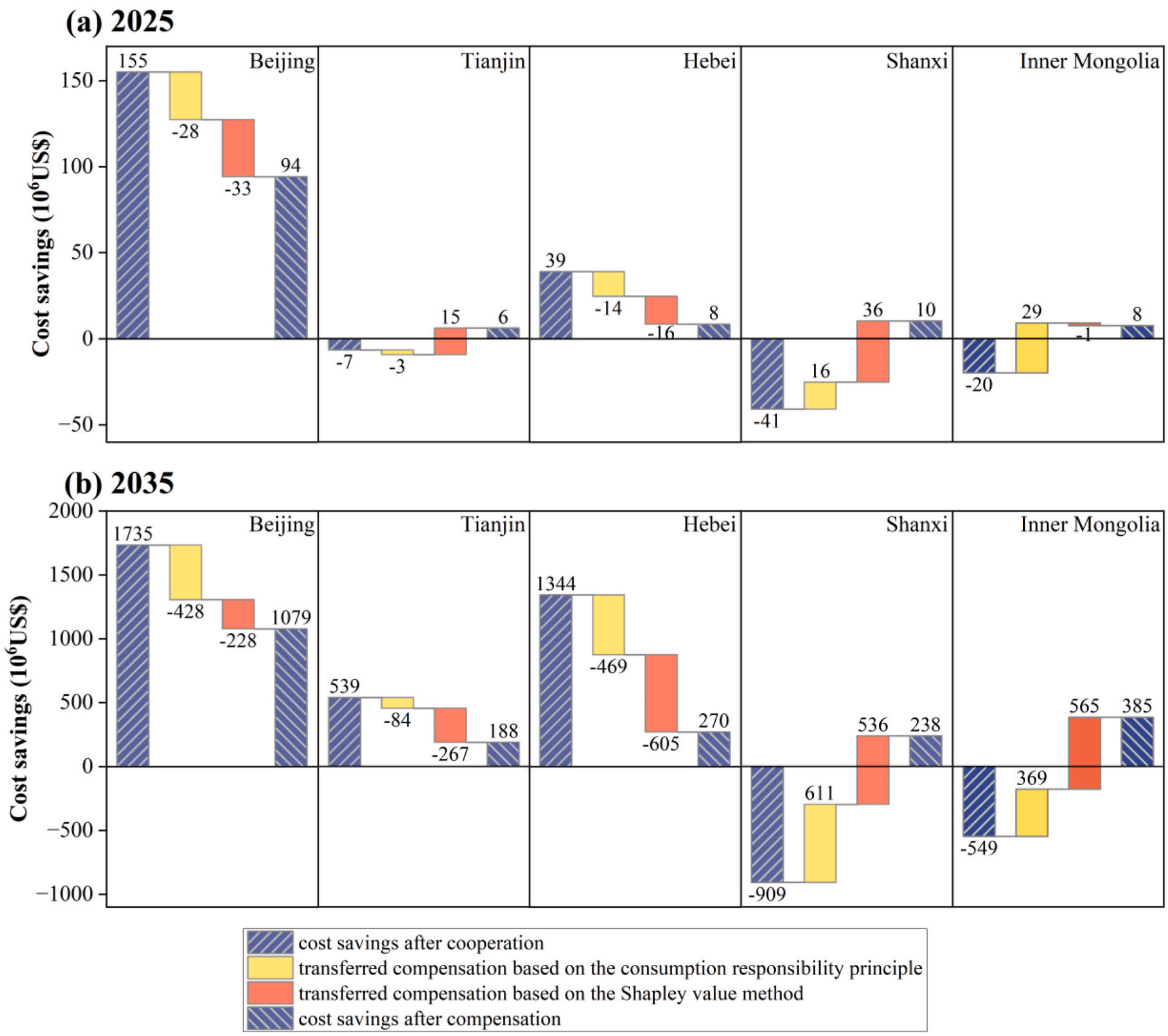

Fig. 5. Variation of cost savings before and after transferred compensation in (a) 2025 scenario and (b) 2035 scenario. A positive cost savings and a negative cost savings indicate a decrease and an increase in reduction cost after cooperation, respectively. A positive transferred compensation suggests that region *i* receives compensation and a negative one suggests that region *i* pays compensation.

the payer at point A, i.e., $\delta = -3.9\%$ (Fig. 6b).

4.2. *Impact of changes in the lower bounds on the outcome of the cooperative game*

Similar to the sensitivity analysis of the upper bound, the lower bound (α_i) of the reduction rate of each region changed δ simultaneously. The lower bound of each region should satisfy that it is smaller than the respective upper bound, enables the targets of the scenarios before and after the cooperation to be reached, and ensures the target emission reductions remain unchanged. As a result, $\delta \in (0, 11.4\%]$.

As seen in Fig. 6c, as the lower bound of emission reduction rate increased continuously in each region, the total cost savings of NO_x cooperative emission reduction in North China decreased constantly from 12.7% to 7.5%. In contrast to the impact of the change in the upper bound on transferred compensation, the impact of the lower bound was more moderate, and the transferred compensation of each region was maintained within a narrow range. Only Tianjin underwent a role change at point B, i.e., $\delta = 10.7\%$, from the giver to receiver (Fig. 6d).

In summary, the upper and lower bounds of the emission reduction rate in the CRG model constraints will not affect the final transferred compensation results within a certain range, but will affect the results beyond this range. The parameter setting range is supposed to make reasonable trade-offs between various targets. In setting the parameters of the cooperative game model, the government should not only fully assess the cost-effectiveness of the whole region and each region, but also pay attention to the changes in the gap of transferred compensation for each region. For example, when governments across North China increase their upper bounds of emission reduction rate, the total regional cost savings rise significantly. This could provide an impetus for active cooperation across regions. However, the attendant widening gap in transferred compensation funds among regions is likely to hinder cooperation without a well-established benefits allocation mechanism. Furthermore, raising the upper bounds of local emission reduction capacity blindly and indiscriminately will not consistently lead to higher cooperation benefits.

5. Conclusions

In order to minimize the NO_x reduction cost, the cooperative reduction game (CRG) model was employed in this paper to demonstrate the positive effect of cooperative game and incentive mechanism on pollutant reduction in future scenarios. Compared with the baseline scenarios, the total cost of NO_x reduction in North China will be saved by 20.36% and 13.71% under the CRG model in 2025 and 2035, respectively.

As an incentive for cooperation, the benefits allocation mechanism ensured that the reduction cost of each region participating in the

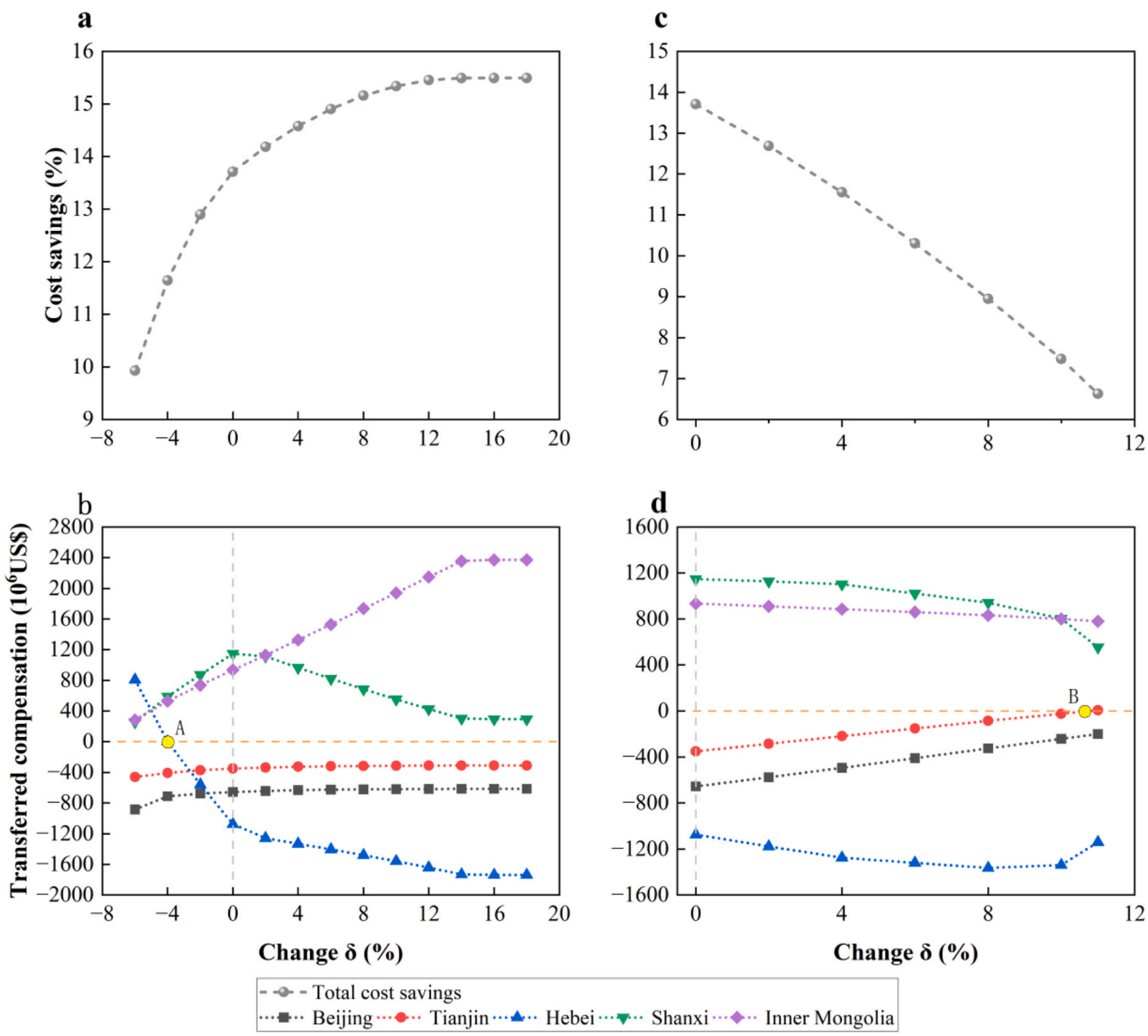

Fig. 6. The effect of changing the upper bounds of emission reduction rates in 2035 scenario on (a) total regional cost savings and (b) transferred compensation (TC_i) under the CRG model. The effect of changing the lower bounds of emission reduction rates in 2035 scenario on (c) total regional cost savings and (d) transferred compensation (TC_i) under the CRG model.

cooperation was reduced. We have integrated the consumption responsibility principle with the Shapley value method to provide a new approach to ensure fair allocation of cooperation benefits among participating regions. After inter-regional transferred compensation, the reduction cost will be lowered by 4.01–59.51% and 5.25–29.94% among these five regions in 2025 and 2035, respectively.

In response to the above findings, the proposals are as following.

(1) In order to minimize the cost of air pollution reduction, it is necessary to encourage local governments to carry out regional joint reduction of air pollution, coupled with a reasonable benefits allocation mechanism. Regions with lower marginal cost, such as Shanxi and Inner Mongolia, should be actively encouraged to share the burden of emission reduction tasks in those regions with high marginal reduction cost as much as possible within the limits of their own emission reduction capacity. Taking on more emission reduction tasks means that these regions reduce more emissions at the level of their own emissions, rather than transferring pollutants from high-cost cities to be emitted in these regions. It will bring greater economic benefits to low-cost regions by receiving substantial transferred compensation. Regions with high marginal reduction cost, such as Beijing and Tianjin, should not only reduce their reduction cost by engaging in cooperation, but also strengthen their technological innovations for emission reduction in order to decrease the high marginal reduction cost. Similarly, this model of regional cooperative game for air pollution reduction can be generalized for application in other regions with cost differences.

(2) The combination of market mechanisms and government instruments for the purpose of transferred compensation is a desirable approach. The inter-regional transferred compensation based on the consumption responsibility principle can be achieved by incorporating transferred compensation into the price of goods in circulation, or by market instruments such as trading of emission rights. Transferred compensation based on the Shapley value method can be realized through government instruments, such as the central government regulating taxes or conducting financial appropriations. However, if the market mechanism is used alone, it can effectively moderate the post-cooperation cost gap among regions, but it may not fully compensate for the increased cost. On the other hand, if the administrative instrument is employed alone, it can directly enable each participant to obtain the benefits of cooperation that they deserve, but it may face extreme disparities in the regulation of funds among the participants. Therefore, it is essential to combine market

mechanisms and administrative means to ensure that each participant can gain benefits from the cooperation.

(3) It is crucial to establish a dynamic regional cooperative system for air pollution reduction. The reduction cost is dynamic and is affected by many factors, such as the level of pollutant tax rate, the development of pollution control technology, economic level, and policy implementation. Therefore, it is necessary to couple the cooperative game model with the reduction cost model to establish a dynamic regional cooperation analysis system.

There are some limitations in this study. The CRG model constructed in this paper is a static cooperative game model of local governments. It mainly focuses on the effect of environmental governance after the cooperative game among multiple participants. However, the model does not consider the cost and contribution of the central government in coordinating the cooperation among local governments. The evolutionary game model, as another game model widely used in the environment field, is primarily used to analyze and explain the process of reaching equilibrium in the game among multi-stakeholders in environmental governance, including the central government and local governments. In the future, we can consider combining the two game models to study the contribution of the central government in coordinating the cooperation of different local governments.

CRediT authorship contribution statement

Tingyu Wang: Conceptualization, Methodology, Data curation, Visualization, Writing – original draft. **Yuan Wang:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Zengkai Zhang:** Methodology, Formal analysis. **Chen Liang:** Investigation, Validation. **Mei Shan:** Formal analysis, Data curation. **Yun Sun:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118949.

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