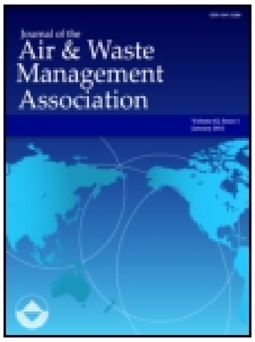

Journal of the Air & Waste Management Association

ISSN: 1096-2247 (Print) 2162-2906 (Online) Journal homepage: https://www.tandfonline.com/loi/uawm20

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To cite this article: Laijun Zhao, Jian Xue, Huaizhu Oliver Gao, Changmin Li & Rongbing Huang (2014) A model for interprovincial air pollution control based on futures prices, Journal of the Air & Waste Management Association, 64:5, 552-560, DOI: 10.1080/10962247.2013.873091

To link to this article: https://doi.org/10.1080/10962247.2013.873091

TECHNICAL PAPER

A model for interprovincial air pollution control based on futures prices

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Based on the current status of research on tradable emission rights futures, this paper introduces basic market-related assumptions for China's interprovincial air pollution control problem. The authors construct an interprovincial air pollution control model based on futures prices: the model calculated the spot price of emission rights using a classic futures pricing formula, and determined the identities of buyers and sellers for various provinces according to a partitioning criterion, thereby revealing five trading markets. To ensure interprovincial cooperation, a rational allocation result for the benefits from this model was achieved using the Shapley value method to construct an optimal reduction program and to determine the optimal annual decisions for each province. Finally, the Beijing–Tianjin–Hebei region was used as a case study, as this region has recently experienced serious pollution. It was found that the model reduced the overall cost of reducing SO_2 pollution. Moreover, each province can lower its cost for air pollution reduction, resulting in a win–win solution. Adopting the model would therefore enhance regional cooperation and promote the control of China's air pollution.

Implications: The authors construct an interprovincial air pollution control model based on futures prices. The Shapley value method is used to rationally allocate the cooperation benefit. Interprovincial pollution control reduces the overall reduction cost of SO_2. Each province can lower its cost for air pollution reduction by cooperation.

Introduction

With the rapid growth of urbanization, industrialization, and ownership of private vehicles in China, coupled with massive increases in energy consumption and pollutant emissions, complex air pollution problems such as particulate matter (PM) and ozone are causing severe health and environmental impacts in major urban clusters. Air pollution is reportedly one of the most urgent issues in many Chinese cities, especially the industrialized regions such as the Beijing–Tianjin–Hebei region, the Yangtze River Delta, and the Pearl River Delta. In addition to technical solutions, many market-based approaches have been proposed for cost-effective air pollution control (e.g., emission taxes and environmental taxes; Fenger, 2009; Muller and Mendelsohn, 2009). Recently, financial futures theory has been proposed for use in pollution control (Wen and Wu, 2010). Financial futures (futures contract, or more colloquially futures), as an effective tool for risk control under uncertainties, are standardized contracts between two parties to buy or sell an asset of specified quantity and quality at a price agreed upon today (the futures price or strike price), with delivery and payment scheduled at a given future date, the delivery date (Brigham and Ehrhardt, 2011). The United States was the first to have a marketplace, the Chicago Climate Futures Exchange (CCFE), for environmental derivatives and financial instruments, with underlying values based on tradable environmental assets. The CCFE has provided trading in futures and options contracts for sulfur dioxide (SO_2) and nitrogen oxide emission rights since 2003. In 2008, the European Climate Exchange started trades of carbon dioxide (CO_2) emissions in Europe and internationally. In pursuit of various emission reduction approaches, China has also actively explored emissions trading systems and operated a few exchanges, such as the Shanghai Environment and Energy Exchange, the Beijing Environment Exchange, and the Tianjin Climate Exchange, since 2008. Although it has been gaining momentum, there are important fundamental methodological questions yet to be answered regarding the mechanism and functional design of a trading system for successful implementation of emissions trading. This research need is particularly urgent in China—despite various efforts, the air quality in many Chinese cities such as Beijing, Tianjin, and Jinan became unacceptably bad, culminated with smog/haze episodes in January 2013 and more recently.

Recognizing the grand challenge and the complexity of environmental pollution, the Chinese governments of various levels (e.g., the central and provincial governments) has been striving to develop pollution control policy gradually. Prior to 1983, China's government used to adopt direct regulations for pollution control. Due to its nature of excessive government intervention, this approach failed. Subsequently, the policy focus shifted

Journal of the Air & Waste Management Association, 64(5):552–560, 2014. Copyright © 2014 A&WMA. ISSN: 1096-2247 print
DOI: 10.1080/10962247.2013.873091 Submitted July 19, 2013; final version submitted October 18, 2013; accepted November 22, 2013.

to a hybrid of regulation and emission taxes, which proved more effective. In July 2003, for example, the Chinese government announced regulations to tax sewage discharges. Under this scheme, the pollution control structure has evolved from focusing solely on concentration control to addressing a combination of concentrations and total "comprehensive control units." The economic instrument used has also evolved from total charges for excessive emissions to per-unit charges, and from single-factor charges to multifactor charges.

The concept of tradable emission permits was first proposed by Dales (1968), with applications to attaining water quality targets. Halkos (1993, 1994, 1996) was the first researcher to apply game theory to developing cost-effective emission control strategies for minimizing sulfur abatement costs in Europe. Jorgensen and Zaccour (2001) constructed a dynamic game model in which two countries or regions can coordinate their policies to reduce downstream pollution. Germain et al. (2003) developed credit transfer schemes that achieve both individual and collective rationality in the design of international agreements that seek to achieve global optimality in pollutant control problems, based on the assumption that these agreements can, at least in principle, be negotiated at each point in time. Krawczyk (2005) studied a pollution game problem with coupled constraints for the cases of static and dynamic equilibria. Paolella et al. (2008) analyzed CO_2 trading permits in the United States and SO_2 trading permits in Europe. They applied generalized autoregressive conditional heteroskedasticity to compute the permit prices. By combining theoretical analysis with numerical simulation, Rosendahl (2008) described the trading motivations and the resulting prices in a trading system where permit allocations are based on updated baseline emissions data. Sauma (2011) estimated the impact of different initial emission permit allocations and formulated a three-period model to study how the market powers of oligopolistic firms affect investment in pollution control technology.

Weishaar et al. (2012) conducted an empirical study of emission rights auction in Germany. Their study revealed the important issues related to profits distribution policy tend to emerge at the end of the auction. Based on market price analysis, Boutabba et al. (2012) examined the correlations between long-term and short-term SO_2 pricing, industrial production, and weather conditions. Ghosh and Shortle (2012) constructed two models and compared their predictive capabilities in stochastic, independent, and unmeasurable cases. Milunovich et al. (2007) found that, by sharing information efficiently, the spot and futures markets both contributed to price discovery in the European Union carbon futures market. Their study also shed light on the evidence of bidirectional volatility that transferred between the spot price and various futures contracts. Carmona et al. (2009) rigorously analyzed a simple risk-neutral reduced-form model for allowance futures prices, and showed how to price European call options written on these contracts in reality.

In China, emissions trading permits have also been emerging as a hot topic. Hu (2007) used transaction-cost theory to study the operational mechanism of an emissions trading market. Fang and Ma (2008) introduced the successful American experience to China to investigate the characteristics of China's SO_2 emission reduction and associated issues. They suggested that emissions trading could be an effective policy instrument for controlling SO_2 emissions. Wu (2007) proposed that a trading system of pollution discharge rights would allow win–win solutions and help readjust the balance between government intervention and a market-oriented system. He argued that this is both a trend and an inevitable result of the development of a modern market economy.

Although there has been encouraging progress, China is yet to develop a comprehensive workable trading system for the regulation of air pollutant emissions. Especially, very few studies have explored the opportunities of interprovincial cooperation for air pollution control using financial futures. Existing literature mainly focused on normative exploration and control mode trials, targeting solely at carbon emissions. For example, Wang et al. (2009) explored eight carbon financing modes and found that financial innovation can introduce new financial products and control modes that would change the current passive situation for China's carbon trading and promote both energy conservation and China's industrial restructuring. Huang et al. (2007) attempted to create a time decision model for the efficiency of a SO_2 emission trading market. Zhuang et al. (2008) discussed in depth such key issues as the purpose of the trading, allocation of emission quotas, and competitive mechanisms for successful emissions trading mechanism design for China's power industry.

The scope of this work focuses on China's territorial management system, where the central government sets the total maximum quantity of air pollutant emissions and allocates the allowances or budgets to each province according to the province's actual economic situation such as economic potential, industrial structure, and the reported quota. Each province must then conform to the central government's regulation and, currently, complete the task of pollution control individually. Under the current regulatory framework in China, in this study we propose a cooperative interprovincial air pollution control model. For the sake of brevity, our model in this study focuses the interprovincial interactions, although the model framework can be easily expanded to also consider intraprovincial decisions such as assignment of emission permits among enterprises in each province. Numerical results are derived from the model to show that interprovincial emissions trading markets facilitate coordinated pollution control efforts among provinces in the region, leading to more cost-effective air pollution control and win–win solutions for the individual participating provinces as well as the whole region.

Materials and Methods

The goal of this paper is to provide scientific and modeling support for the design of successful market-based trading mechanisms that help the Chinese government (at both regional and provincial levels) with cost-effective solutions to the country's severe air pollution problems. Due to geographical variations in local economy, production activities, technologies, and meteorological/environmental conditions, there exists significant cost differentiation in emission reduction and pollution control across provinces. Such cost differentiation provides opportunities for cross-provincial cooperation in emission control, although the intricacies of the interactions among participating provinces must be fully accounted for in exploiting the cooperation. After all, the individual provinces in a region, although sharing similar environmental concerns and pollution control goals, have separate economic, financial, budgetary, and technological objectives/constraints. That is, the design of a trading system for emission rights futures among provinces involves the process of solving systems optimization problems, defined for specific objectives and subject to various constraints, for the best design option/policy over a set of decision variables. Such optimization problems are not uncommon in environmental studies, and they often, when the objective function and/or the constraints are not linear in terms of the decision variables (Bertsekas, 1999), lead to nonlinear optimization. Further, cross-provincial interactions in air pollution control introduce cooperative games, where players can coordinate their strategies and share the payoff. In particular, sets of players, called coalitions, can make binding agreements about joint strategies, pool their individual agreements, and redistribute the total in a specified way (Curiel, 1997). Aiming to fully account these intricacies, in this paper we adopted the nonlinear optimization theory to propose an interprovincial emissions trading model based on environmental futures prices for air pollution control in China. For illustration, we used empirical data from the Beijing–Tianjin–Hebei region for a case study.

Assumptions, variables, and parameters

We first introduce basic assumptions and variables used in this paper.

Assumption 1: Cooperative provinces consist of a big "bubble." "Bubble policy" is a well-known environmental management policy that was developed in 1979 by the U.S. Environmental Protection Administration (EPA) (EPA, 1979). For a big regional bubble that consists of multiple participating provinces in the "bubble policy" in this study, one province can increase its emissions of a pollutant so long as other provinces can reduce their emissions, at more economical cost, to achieve no net change or the given budget of the total emission amount for the whole region. Interprovincial cooperation to reduce air pollution can therefore add value because it allows a transfer of emission permits among cooperating provinces to achieve cost-effectiveness in meeting the total regional emission reduction requirements set by the central government.

Assumption 2: The maximum environmental capacity of a province is indicated by the emission quota assigned to the province. If the pollutants emitted by a province are within this limit, it meets the environmental quality standards.

Assumption 3: Each province has a capacity range for emission reduction. The maximum pollutant reduction quantity can be achieved when all pollutant treatment facilities work at their full capacity. However, even at maximum capacity, it is still not possible to completely eliminate all the pollutants produced by a province. Therefore, there is an upper limit for each province's pollutant reduction capacity. On the other hand, the pollutant treatment facilities will always be able to remove at least some of the air pollutants produced in this province. There is hence a lower limit for each province's pollutant reduction capacity.

Assumption 4: For China's emission rights futures market in consideration, only traders representing the N *participating provinces, but no other investors, can participate and carry out transactions. This futures market is a no-friction market.* Table 1 summarizes the variables and parameters used in our model.

Cost function for emission reduction

For province $i = 1, 2, \ldots, N$, the environmental reduction cost function π_i contains three parts: the pollutant reduction cost, the

Table 1. Definitions of the variables and parameters

Variables and Parameters	Definition
R_i	Annual air pollution reduction quantity for province; $i = 1, 2, \ldots, N$
R_{0i}	Annual air pollutant quantity produced by province; $i = 1, 2, \ldots, N$
R_{1i}	Annual industrial air pollutant quantity produced by province; $i = 1, 2, \ldots, N$
Q_i	Air pollutant quota set by the government for province; $i = 1, 2, \ldots, N$
S	Spot price of annual air emission rights
h_i	Air pollutant reduction quota set by the government for province; $i = 1, 2, \ldots, N$; $h_i = P_{0i} - E_i$
π_i	Total environmental cost, including the pollutant reduction cost, environmental damage cost, and the transfer tax paid for province; $i = 1, 2, \ldots, N$
AC_i	Cost of air pollutant reduction for province; $i = 1, 2, \ldots, N$; units: 10^4 USD.
W_i	Volume of emissions for province; $i = 1, 2, \ldots, N$
α_i	Multiplier for the upper limit of the air pollutants emission for province; $i = 1, 2, \ldots, N$
β_i	The upper limit of the pollutant reduction capacity for province; $i = 1, 2, \ldots, N$
γ_i	The lower limit of the pollutant reduction capacity for province; $i = 1, 2, \ldots, N$

environmental damage cost EC_i due to the gap to meeting the reduction requirement, and the transfer fee that is paid. That is:

$$\pi_i(R_i) = AC_i(R_i) + EC_i(R_i) + (h_i - R_i)S \tag{1}$$

Based on Assumption 2, if a province i achieves its required environmental quality standard, we do not need to consider the cost of environmental damage, thus $EC_i = 0$. Thus, the environmental reduction cost becomes

$$\pi_i(R_i) = AC_i(R_i) + (h_i - R_i)S \tag{2}$$

The SO_2 reduction quantity, for example, has been considered mainly as a regional pollution control measure. Based on previous research on pollution cost function (Zhao, 2009; Zhao et al., 2012; Cao et al., 2009), we constructed the SO_2 reduction cost function as below:

$$\ln(AC_i) = \sigma_0 + \sigma_1 \ln(W_i) + \mu \ln(\eta_i) + \sigma_2 \ln(X_{ri}) \tag{3}$$

where σ_0, σ_1, σ_2, and μ are structural parameters determined using curve fitting from historical data, W_i is the volume of emissions for province i , $\eta_i = G_i/I_i$ is the average reduction rate for a pollutant for province i that exports an average concentration of G_i and imports an average concentration of I_i, and X_{ri} reflects the structure of the regional industrial structure, enterprise ownership, pollution control technology, and the level of regional economic factors for province i.

To better represent the relationship between quantity of pollutant reduction and the reduction cost, we replaced reduction rate (η_i) with $(I_i - G_i)/Q$ in eq 3. By mathematical transformation, we can then express the pollutant reduction cost function as a function of the variable pollutant emissions (W_i) and the annual air pollution reduction quantity (R_i):

$$AC_i = \theta_i \cdot W_i^{\varphi_i} \cdot R_i^{\mu_i} \tag{4}$$

where θ_i, φ_i, and μ_i are constants for each province i.

Model development

We developed the pollutant reduction function, which is nonlinear with respect to the pollutant reduction. Hence, we could use nonlinear optimization tools to develop our model. Our model consists of three parts: (I) calculating the spot price for emission rights; (II) partitioning between the buyer group and the seller group in the emission rights trading market; and (III) determining optimal reduction quantities.

(I) Spot price for emission rights. Since the middle of last century, many theories and methods in financial engineering have been widely used in studying social and economic activities (Okay and Akman, 2010). The application of futures pricing theory has been particularly prominent (Talinli et al., 2010). Futures pricing theory is not only used for hedging and speculative arbitrage due to its ability to more accurately reflect the expected spot price, but is also increasingly used for commodity pricing. Cornell and French (1983) first proposed a pricing formula for frictionless market futures. In this paper, we use their classic futures pricing formula to describe the relationship between the spot price (S) and the futures for air pollutant emission rights:

$$S = F e^{r(t-T)} \tag{5}$$

where F is the emission rights price for the first year, r is the annual continuously compounded interest rate for risk-free investment, t is the current time (years), and T is the futures contract expiration time (years).

Each cooperative province in a region will synchronously conduct emission rights trading based on our Assumption 1. There is no sequence of trading whether for buyers or sellers under a certain futures price.

(II) Partitioning the buyer and seller groups in the emission futures market. Based on the futures price F of pollutant emission rights in the futures market, province i can calculate its optimal pollutant reduction $\hat{R}_i$ (first assuming no cooperation with other provinces) to minimize its emission reduction cost using the following program:

$$\min_{R_i} AC_i(R_i) + (h_i - R_i) \cdot S \tag{6}$$

$$\boldsymbol{s.t.}\ R_i \geq 0 \tag{7}$$

$$R_{0i} - \gamma_i Q_i \leq R_i \tag{8}$$

$$\alpha_i R_{1i} \leq R_i \leq \beta_i R_{1i} \tag{9}$$

$i = 1, 2, \ldots, N.$

The province can then compare the resulting value of $\hat{R}_i$ with the reduction quota h_i it is assigned. If the optimal reduction $\hat{R}_i$ is greater than its allocation, province i can afford extra reduction capability $(\hat{R}_i - h_i)$ than required and can hence be a seller in the market (province i helps other provinces to fulfill their quota requirements). Otherwise, province i can be a buyer in the market and purchase a quantity of $h_i - \hat{R}_i$. Without loss of generality, we can suppose that there are m buying provinces in the buyer group Ω_b and n selling provinces in the seller group Ω_s; $m + n = N$.

As a result, there are five possible cases for the emission rights trading market:

(a) If the futures price is too high, all of the provinces would like to sell.
(b) If the futures price is too low, all of the provinces would like to buy.
(c) For a given futures price, the total emission rights demanded by the buyers group equals the total from that of the seller group in the market.

(d) For a given futures price, the total emission rights demanded by the buyer group is greater than that from the seller group in the market.
(e) For a given futures price, the total emission rights demanded by the buyer group is less than that for the seller group in the market.

We will continue on to discuss the five market cases in next section.

(III) Determining the optimal reduction. Neither case a nor b constitutes a trading market, since each province would then independently meet the reduction target imposed by the state's quota, h_i. Cases c–e can lead to trading markets where each province can determine its individual optimal reduction and trading quantity that can be achieved through cooperation with other provinces.

For case c, balancing the total emission rights for the buyer group and those of the seller group in the market gives

$$\sum_{i\in\Omega_s}(\hat{R}_i - h_i) = \sum_{j\in\Omega_b}(h_i - \hat{R}_j) \tag{10}$$

The optimal reduction R_i* for province i is equal to $\hat{R}_i$ when no cooperation opportunity is identified.

In case d, where the total emission rights demanded by the buyer group is greater than that of the seller group:

$$\sum_{i\in\Omega_s}(\hat{R}_i - h_i)\rangle\sum_{j\in\Omega_b}(h_i - \hat{R}_j) \tag{11}$$

The optimal own reduction quantity for buying province j is equal to its optimal reduction under noncooperation, $R_i{*}{=}\hat{R}_j$. After determining the buyers' demand, the n sellers allocate their optimal level of pollutants through alliance reductions, which result from cooperative alliances among provinces, to achieve their pollutant quotas by using the following interprovincial seller cooperative game model:

$$\min_{R_i}\sum_{i\in\Omega_s}[AC(R_i) + (R_i - h_i)\cdot S] \tag{12}$$

$$\boldsymbol{s.t.}\ h_i \le R_i \tag{13}$$

$$\alpha_i\ R_{0i} \le R_i \le \beta_i R_{0i} \tag{14}$$

$$R_{0i} - \gamma_i Q_i \le R_i \tag{15}$$

$$\sum_{i\in\Omega_s} R_i = \sum_{i\in\Omega_s} h_i + \sum_{j\in\Omega_b}(h_j - \hat{R}_j) \tag{16}$$

$i = 1, 2, \ldots, n.$

Suppose that the optimal solution for the cooperative game model for provincial sellers is R_i*, with optimal reduction cost Y, this model ensures that the overall seller group achieves its minimum cost. However, this group optimum may not represent economically rational behavior for individual provinces. Therefore, designing a mechanism that governs effective implementation within the seller group is critical.

In a noncooperative mode, provinces use up their reduction quota assigned by the government, then sellers begin to sell additional emission rights in a fair and competitive market. As a result, the total emission reduction quantity for a selling province will be

$$R_i = h_i + [\sum_{j\in\Omega_b}(h_j - \hat{R}_j)]\cdot(\hat{R}_i - h_i)/\sum_{i\in\Omega_s}(\hat{R}_i - h_i) \tag{17}$$

Suppose that in the noncooperative mode, the total cost for all the sellers is X. X is usually not equal to Y. Then, the allocation the discrepancy ($X - Y$) among selling provinces has to consider fairness, understanding that each selling province wants to maximize its own benefit. This is important, because otherwise there is no incentive for actors to collaborate. In this paper, we used the Shapley value method to allocate the benefit ($X - Y$). Shapley value is a robust method for fair distribution of both gains and costs to several players working in a coalition. It ensures that each actor gains as much as or more than they would get from acting independently (Roth, 1988). The method has been applied primarily in situations when the contributions of each player are unequal in a cooperative game (Narayanam and Narahari, 2010).

Let all selling provinces comprise a collection $N = \{1, 2, \ldots, n\}$. If, for any subset s of N, there exists a real-valued function $V(s)$ such that $V(\varphi) = 0$, $V(s_i \bigcup s_j) \ge V(s_i) + V(s_j)$, where $s_i \bigcap s_j = \Phi$, then $[N, V]$ is called the cooperative game for n provinces, V is called the characteristic function of countermeasures, and $V(s)$ is called the benefit from the provincial alliance. The Shapley value $X = (X_1, X_2, \ldots, X_n)$ is determined by the characteristic function V as below:

$$X_i(V) = \sum_{S_i\subset S} W(|s|)[V(s) - V(s - i)] \tag{18}$$

$$W(|s|) = \frac{(n - |s|)!(|s| - 1)!}{n!} \tag{19}$$

where s represents all subsets that contain selling province i, $|s|$ is the number of provinces in s, $W(|s|)$ is the weighting factor, and $V(s - i)$ is the benefit for seller group s, excluding province i.

In case e, the total amount of emission rights for the buyer group is less than that of the seller group in the market; that is, $\sum_{i\in\Omega_s}(\hat{R}_i - h_i)\langle\sum_{j\in\Omega_b}(h_j - \hat{R}_j)$. Then, the optimal reduction for selling province i is $R_i{*} = R_i$. In this case, the selling quantity is determined easily. The m buyer provinces, through alliances, need to allocate the optimal quantity to buy and their own pollutant reductions to help the buyers minimize the cost of the overall environmental conformity. The cooperative interprovincial buying model is as follows:

$$\min_{R_j} \sum_{j \in \Omega_b} [AC(R_j) + (h_{j_i} - R_j) \cdot S] \tag{20}$$

$$\boldsymbol{s.t.}\ h_j \leq R_j \tag{21}$$

$$\alpha_j\ R_{1j} \leq R_j \leq \beta_j\ R_{1j} \tag{22}$$

$$R_{0j} - \gamma_j Q_j \leq R_j \tag{23}$$

$$\sum_{j \in \Omega_b} R_j = \sum_{j \in \Omega_b} h_j - \sum_{i \in \Omega_s} (\hat{R}_i - h_i) \tag{24}$$

$j = 1, 2, \ldots, m.$

Through this model, we can obtain the optimal quantity of reductions for all the buying provinces after accounting for their permit purchases. Similar to the case for interprovincial seller cooperation, we can use the Shapley value method to ensure that all buyers can cooperate in an equitable way.

Results and Discussion

The air quality statistics collected by the China National Environmental Monitoring Center show a remarkable episode of air pollution in the Beijing–Tianjin–Hebei region in January 2013, with half of the region's counties severely impacted. Therefore, we chose SO_2 emission control in this region for a case study to illustrate how our model works. Based on the data availability in the China Environment Statistical Yearbook, we chose the period from 2003 to 2009 for our study.

The SO_2 reduction cost functions for the Beijing–Tianjin–Hebei region was calculated using eq 4, with the estimated coefficients reported in Table 2.

Spot price for emission rights

Assuming that the observed emission right price of SO_2 futures on the futures market is \$408.91/t and the benchmark interest rate was $r = 2.25\%$ in 2010, eq 5 gives a spot price for emission rights of \$382.22/t in 2013.

Partitioning the buyer and seller groups

Under noncooperation, the optimal SO_2 reductions in Beijing, Tianjin, and Hebei can be calculated as follows:

Table 2. Beijing, Tianjin, and Hebei SO_2 reduction cost functions

Province	Reduction Cost Function
Beijing	$AC_1 = 35.19{R_1}^{1.835}$
Tianjin	$AC_2 = 4.13{R_2}^{2.323}$
Hebei	$AC_3 = 72.77{R_3}^{1.251}$

Notes: The unit for AC_i is 10^4 USD; that for R_i is 10^4 t.

Beijing: $$\min_{R_1} 35.19 \cdot R_1^{1.835} + (7.2 - R_1) \cdot 382.22 \tag{25}$$

$$\boldsymbol{s.t.}\ 2.4 \leq R_1$$

$$6.9 \leq R_1 \leq 15.5$$

Tianjin: $$\min_{R_2} 4.13 \cdot R_2^{2.323} + (24.8 - R_2) \cdot 382.22 \tag{26}$$

$$\boldsymbol{s.t.}\ 17.5 \leq R_2$$

$$17.2 \leq R_2 \leq 38.7$$

Hebei: $$\min_{R_3} 72.77 \cdot R_3^{1.251} + (117.5 - R_3) \cdot 382.22 \tag{27}$$

$$s.t. 78 \leq R_3$$

$$91.2 \leq R_3 \leq 205.2$$

By solving these three optimization problems, we can obtain $\hat{R}_1 = 8.41 \times 10^4$ t, $\hat{R}_2 = 17.5 \times 10^4$ t, $\hat{R}_3 = 205.2 \times 10^4$ t, $h_1 = 7.2 \times 10^4$ t, $h_2 = 24.8 \times 10^4$ t, and $h_3 = 117.5 \times 10^4$ t. Then, $\hat{R}_1 - h_1 = 1.21 \times 10^4$ t, $h_2 - \hat{R}_2 = 7.3 \times 10^4$ t, and $\hat{R}_3 - h_3 = 87.7 \times 10^4$ t.

Determining the optimal reductions

Based on the calculations in partitioning between the buyer and seller groups, $(\hat{R}_1 - h_1) + (\hat{R}_3 - h_3) = 1.21 \times 10^4\ \text{t} + 87.7 \times 10^4\ \text{t} > h_2 - \hat{R}_2 = 7.3 \times 10^4$ t. According to the partitioning criterion described earlier, Beijing and Hebei belong to the seller group and Tianjin belongs to the buyer group. Therefore, the optimal reduction for Tianjin is $R_2^* = \hat{R}_2 = 17.5 \times 10^4$ t. Beijing and Hebei will need to jointly accomplish the task of reducing $h_1 + h_3 + (h_2 - \hat{p}_2) = 132 \times 10^4$ t according to the following cooperative game model:

$$\begin{aligned} \min_{R_1, R_3} [&35.19 \cdot R_1^{1.835} + (R_1 - 7.2) \cdot 382.22 \\ &+ 72.77 \cdot R_3^{1.251} + (R_3 - 117.5) \cdot 382.22] \end{aligned} \tag{28}$$

$$\begin{aligned} &\boldsymbol{s.t.}\ 7.2 \leq R_1 \\ &117.5 \leq R_3 \\ &2.4 \leq R_1 \\ &6.9 \leq R_1 \leq 15.5 \\ &78 \leq R_3 \\ &91.2 \leq R_3 \leq 205.2 \\ &R_1 + R_3 = 132 \end{aligned}$$

Solving the above model, we obtain $R_1{}^* = 7.2 \times 10^4$ t and $R_3{}^* = 124.8 \times 10^4$ t for reductions under cooperation, compared with the reductions 7.3×10^4 and 124.7×10^4 t for Beijing and Hebei, respectively, under noncooperation.

Table 3. Benefit allocation to Beijing in 2013

S	Beijing	Beijing, Hebei
$V(S)$	0	3.19
$V(S - \{\text{Beijing}\})$	0	0
$V(S) - V(S - \{\text{Beijing}\})$	0	3.19
$\|S\|$	1	2
$W(\|S\|)$	1/2	1/2
$W(\|S\|)[V(S) - V(S - \{\text{Beijing}\})]$	0	1.60

To ensure fair cooperation between Beijing and Hebei, we used the Shapley value method described in eqs 7 and 8 for allocation. Tables 3 and 4 summarize the results.

Tables 3 and 4 suggest that, in order to guarantee fairness, the benefits that should be allocated to Beijing and Hebei from cooperation are both \$1.60 × 10^4.

To summarize, we can see that under the assumption that the futures price is \$408.91/t, the optimal reductions for Beijing, Tianjin, and Hebei are 7.2 × 10^4, 17.5 × 10^4, and 124.8 × 10^4 t, respectively, under cooperation. We can compute the optimal reductions for Beijing, Tianjin, and Hebei under any given SO_2 futures price at a given time following a similar process.

Cost analysis

Currently, China uses a territorial management model in which the central government assigns each province an emission quota. Reduction efforts are then carried out separately by individual provinces. Table 5 shows the current reductions and the corresponding costs for Beijing, Tianjin, and Hebei under this quota system. The total environmental cost for the Beijing–Tianjin–Hebei region is \$36.77 × 10^7 under noncooperation, versus \$35.01 × 10^7 under cooperation according to our model. This suggests that a modified practice based on our model can help reduce the environment abatement cost by \$1.76 × 10^7, a 4.8% savings. In our model, Hebei and Beijing represent a group that can help Tianjin reduce its pollutants by 7.3 × 10^4 t. Although Beijing did not directly help Tianjin to control its air pollution, it can earn \$8.73 × 10^4 from the cooperation between Hebei and Beijing. Actually, a 4.8% savings is not very promising in case study of the Beijing–Tianjin–Hebei region in comparison with other studies that modeled emissions trading at an enterprise level and used process-based cost functions to estimate emission control costs. How much is saving in new approach depends on differences of the SO_2 reduction cost function and the market structure of emission rights trading among provinces. More money may be saved if the new approach is applied to other regions.

Table 4. Benefit allocation to Hebei in 2013

S	Hebei	Hebei, Beijing
$V(S)$	0	3.19
$V(S - \{\text{Hebei}\})$	0	0
$V(S) - V(S - \{\text{Hebei}\})$	0	3.19
$\|S\|$	1	2
$W(\|S\|)$	1/2	1/2
$W(\|S\|)[V(S) - V(S - \{\text{Hebei}\})]$	0	1.60

Futures price is the key input in the model for the interprovincial air pollution control. Therefore, we conducted a sensitivity analysis of the model with changes in the different futures prices. The robustness of the model forecast was further examined by conducting the sensitivity analysis with respect to futures price. As shown in Table 6, the total environment abatement cost for the Beijing–Tianjin–Hebei region remains almost unchanged when futures price changed from minus to plus 20% of \$408.91/t.

Conclusion

In this paper, we developed a futures pricing model for interprovincial cooperation to decrease pollutant emissions. Applying the model in a case study of the severely polluted Beijing–Tianjin–Hebei region of China, we found that results of our model can help reduce environmental costs for the entire region and for each of the three provinces. A regulatory mechanism based on the interprovincial cooperation model will achieve improved cost-effectiveness through coordinated efforts. Compared with the current territorial approach, our model can more effectively reallocated the environmental and social resources by taking the advantage of a futures market, leading to a win–win solution. At present, China is vigorously promoting energy conservation and striving to improve air quality. China's central government has clearly defined these tasks for each province. The model we developed can potentially help provinces to achieve those emission reduction targets through cooperation. If possible, some pilot projects could be implemented following this new model approach in the Beijing–Tianjin–Hebei region, the Yangtze River Delta, and the Pearl River Delta. The approach and models develop in the paper are aims for application in emissions trading at the provincial level at this point. Future work will consider adding a lower layer of

Table 5. Comparison of the pollutant (SO_2) reduction costs in 2009

Parameter	Beijing	Tianjin	Hebei	Total
Current reduction (h_i; 10^4 t)	7.2	24.8	117.5	149.5
Current environmental reduction cost (A; 10^4 \$)	1317.08	7168.77	28287.06	36772.90
Optimal reduction in our model (p_i*; 10^4 t)	7.2	17.5	124.8	149.5
Environmental reduction cost in the present model (B; 10^4 \$)	1308.35	6174.47	27526.13	35008.95
A − B (10^4 \$)	8.73	994.30	760.93	1763.95

Table 6. Sensitivity analysis for futures price

Futures Price Volatility	Futures Price ($/t)	Beijing (10^4 t)	Tianjin (10^4 t)	Hebei (10^4 t)	Total (10^4 $)	Saving
−20%	327.13	7.17	17.5	124.83	35008.07	4.80%
−10%	368.02	7.2	17.5	124.8	35008.95	4.80%
0.00%	408.91	7.2	17.5	124.8	35008.95	4.80%
10%	449.80	7.2	17.5	124.8	35008.95	4.80%
20%	490.69	7.2	18.59	123.71	35156.65	4.40%

intraprovincial decisions such as assignment of emission permits among enterprises in each province.

Funding

This study was funded by the National Natural Science Foundation of China (project nos. 71373155 and 90924030), by the Program for New Century Excellent Talents in Universities of China (project no. NCET-10-0938), and by the Program of Social Development of Metropolis and Construction of Smart City (project no. 085SHDX001), and the Chinese Ministry of Education, Humanities and Social Sciences (project nos. 13YJC630196 and 13YJC630072).

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