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RESEARCH ARTICLE

Effects of shared governance and cost redistribution on air pollution control: a study of game theory–based cooperation

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Abstract
This study seeks cost-effective strategies for PM2.5 reduction to generate insights into minimizing pollution abatement costs subject to different scenarios. This study theorizes that the cooperation of PM2.5 abatement has potential gains for participants and develop an empirical way to compare the costs and efficiency of PM2.5 abatement involving the variation of environmental conditions. This study revises the cooperative game model in the context of threshold effects using data obtained from the Beijing-Tianjin-Hebei metropolitan cluster in China. In general, the results support the key assertion that cooperation in the metropolitan cluster plays a vital role in optimizing the efficiency and costs of PM2.5 abatement. In addition to extending the application of the revised model, this study provides a way to estimate the costs and the mitigation benefits of meeting the pollution targets for each coparticipant and take the scenario of multiparty cooperation into account as well as the scenarios involving other types of pollutants. The empirical findings have important policy implications for regional shared governance, decentralization, and resource reallocation. Economic incentive-based shared governance and cost reallocation work better than traditional regulations.

Keywords Air pollution control · Cooperative game · Shared governance · Cost–benefit analysis

Introduction

Rapid industrialization and urbanization brought impressive economic growth, scientific progress, and good infrastructure, but it also brought fine particulates, causing significant economic loss and health outcomes (Han et al. 2016; Chai et al. 2014; Chen et al. 2016; Richter et al. 2005). As a regional economic growth pole, the Beijing-Tianjin-Hebei (BTH) region has for years suffered from some of the worst air pollution in China. Meteorology plays a significant role in air pollution formation; fine particulates are easily exported by one city and imported by another, affected by transport, deposition, transformation, and adverse meteorological conditions (Gui et al. 2019). Due to the transboundary air pollution, it is difficult to control air pollution only through the efforts of a single region. Especially, fine particulate pollution in Beijing mainly comes from regional transport, such as Hebei (Zhang et al. 2021). For example, severe air pollution events still occurred although anthropogenic emissions from Beijing and Tianjin have decreased since the initial outbreak of coronavirus disease (COVID-19) (Zhao et al. 2020). Therefore, the cross-regional diffusion of fine particulates triggers local government concerns, as it is difficult for individual local governments to achieve their targets of environmental quality through their own efforts if they are in the vicinity of the origin (Akimoto 2003). To sum up, it is meaningful and typical to study the shared governance and cost redistribution on air pollution control of the Beijing-Tianjin-Hebei (BTH) region. The research results can yield a more general reference for other countries or regions to reduce the costs of air pollution abatement.

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Previous studies explain that PM2.5 in China is mainly composed of primary particles (BC, OC, and elemental carbon), secondary aerosols, including secondary inorganic aerosols (SNA: sulfate, nitrate, and ammonium), and secondary organic aerosols (Li et al. 2017; Song et al. 2017). PM2.5 abatement refers to any measure taken to reduce, control, or eliminate PM2.5 pollution from a given environment. Abatement measures can be regulatory, technological, or behavioral. Abatement costs are government expenditures to reduce the pollution created by industrial enterprise. Over the past decades, scholars in the field of the environment have examined the topic of shared governance related to air pollution from a variety of different perspectives (Chan and Yao 2008). A mainstream conclusion of prior studies is that acting independently would easily lead to a tragedy of the commons in the absence of adequate incentives. It has been posited that the local governments in polluted regions try to cooperate in governance, but cooperation often ends in failure because they are unable to find a no-loser solution (Wang et al. 2020).

The cost allocation of shared governance is the focus of the current debate on how and by how much to abate fine particulate pollution beyond this. It helps the highest incremental gain for the fully cooperative coalition if each region agreed to negotiate (Shi et al. 2016), but estimating the costs of fine particulate abatement varies from one city to another. Thus, the optimization of fine particulate abatement is a rewarding goal of governance policy and improves coherence in economic and environmental objectives. Game theory is generally employed to study such problems because it permits the analysis of the strategies and behaviors of different agents under certain behavioral assumptions (Zara et al. 2006; Sumaila et al. 2009; Wei et al. 2010; Madani 2010; Shi et al. 2016; Fathi and Bakhshoodeh 2021).Considering the potential importance of shared governance in the context of air pollution control, this study explores and empirically demonstrates the costs and benefits of shared governance on fine particulate reduction, especially PM2.5. This model consists of nonlinear programming revised by threshold effects for minimizing the aggregate costs of fine particulate abatement in metropolitan areas. This study identified feasible Pareto-dominant strategies in the specific context of how to cooperate in governance. The variation in environmental conditions and possible scenarios were manipulated in this model, and their effects on pollution control and costs of abatement were examined, which enables comparisons of the costs and the efficiency in differentiated emission strategies.

Prior studies have shown that air pollution is a typical case of negative externality: the city of air pollutant origin may have little motivation to concern itself with the emissions from production and daily life, except to the extent that public pressure and legislation force the local government to take into account air pollution (Zhang et al. 2016). Some studies have positioned cooperation as a key factor mitigating pollution (Li et al. 2019; Zhu et al. 2020). There have been very few attempts to bring shared governance theories into practice to quantify the benefits and costs of cooperation in governance. The current study contributes to this intractable issue by providing a PM2.5 mitigation strategy to internalize the environmental externalities equitably and cost-effectively.

Transregional externalities imply that potential benefits can be realized through shared governance. Nonetheless, this study still needs the legislation of the national government to enforce cooperation. The required targets of emission reduction and the corresponding expense vary among cities, and the city required to bear the large expense may be reluctant to pay, especially when the benefits tend to be realized from the efforts of other cities. To this end, this study adopted game theory to find a cost-equals-benefit agreement by explicitly linking preventing free riders with the Shapley value.

Most existing shared governance research elaborates on how institutional structure facilitates cooperation agreements rather than empirically evaluating whether cost-effectiveness–based cooperation works better than regulations in pollution reduction at the source (Berman and Keita 2020; Chen et al. 2020). Building on the shared governance framework, this study extends the literature by proposing cost-effective, socially acceptable, and administrative-feasible cooperation strategies for PM2.5 emission reduction and comparing the marginal reduction costs between cities in the same metropolitan cluster.

In addition to the literature on the shared governance of pollution, this study contributes to the fast-growing research on fine particulates. No research, at least thus far, has examined the equitable allocation of PM2.5 emissions and abatement costs using the threshold effect–based game model across cities in metropolitan areas. Moreover, most prior studies rely on correlation analysis or the input–output approach. This study is among the first to systematically analyze the efficiency and costs of cooperative PM2.5 removal based on nonlinear programming from the perspective of metropolitan areas. One surprising finding from the construction of the threshold effect–revised game model is that the aggregate costs of cooperative governance are approximately 1/10 less than the costs of independent territory governance. To reconcile the costs and benefits of abatement, the Shapley value was employed to allocate the reduction costs for each city according to their abatement contribution. In particular, this study finds that the most polluted city in a metropolitan area is likely to realize the maximum abatement and bear the largest proportion of costs along with the highest levels of subsidies and tax benefits. Shared governance would greatly improve the utilization efficiency of resources, funds, talent, and energy and reduce the costs of governance through cooperation in sharing information, resources, and technology.

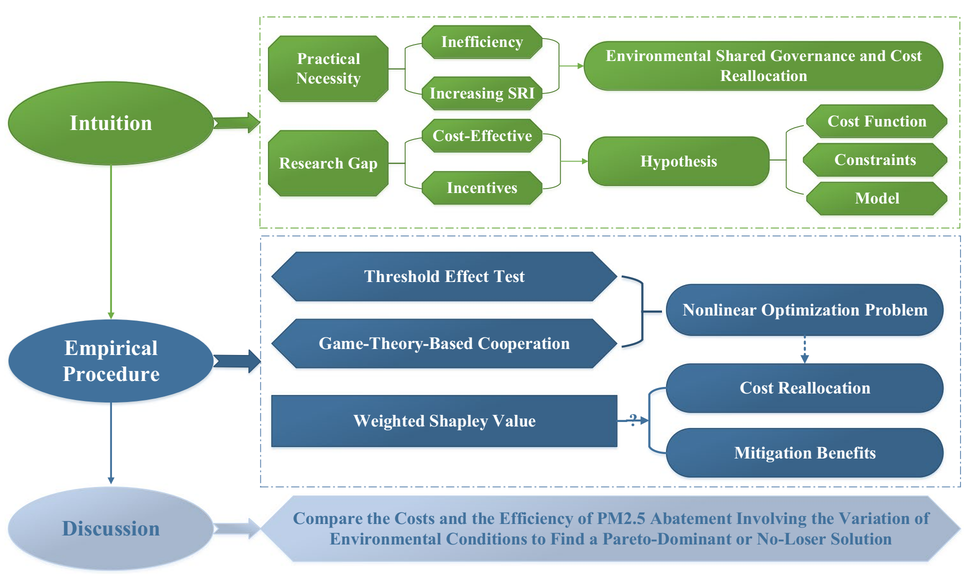
The rest of the paper is structured as follows. The "Literature review" section surveys the related literature about shared governance responses to pollution control. The "Data and methodology" section discusses the data and methodology. The "Empirical results" section documents the estimation results. The "Conclusions and policy implications" section concludes. Figure 1 presents the outline of this research.

Literature review

Scholars have made several contributions to the effective treatment of environmental pollution by game theory. Kilgour et al. (1988) first used game theory to study the transboundary pollution problem for regulating chemical oxygen demand (COD). Since then, game theory is used by other researchers to analyze the cost/gain effectiveness of pollutant reduction and cost/gain allocations, especially water pollution abatement (Shi et al. 2016; Augeraud-Véron et al. 2022). Petrosyan and Yeung (2020) developed a new class of cooperative dynamic games, which could be used to study the regulation of pollutant emissions. GHG (greenhouse gas) emissions between regions are different. Fathi and Bakhshoodeh (2021) investigated the losses (benefits) of GHG emissions in the Iranian meat market by the policy of removing energy subsidy. Gu et al. (2022) proposed an evolutionary game model of government and enterprises controlled by a third party. Zheng and Yu (2022) studied the subsidy strategy of carbon-sink fishery by a three-party evolutionary game model of fishermen, consumers, and the government. Cost redistribution on air pollution control is the essential question of shared governance, but previous research did not pay attention to it.

Transboundary pollution conflicts tend to become common with economic growth (Gu et al. 2022). For air pollution, fine particulates have been transported to different cities and the dynamics of the concentration vary extremely over time as well as by location, resulting in the absence of certain fundamental externalities. Cooperation among regions is an economic way to control the emission of pollutants (Shi et al. 2016). Shared governance refers cooperative game among different subjects or regions. Shared governance in air pollution control is exercised in two ways: direct regulatory instruments and economic instruments (Hutton and Halkos 1995). Direct regulations are described as "command and control," including a set of enforcement mechanisms, such as environmental quality standards and fine particulate emission regulations. On the other hand, economic instruments work more straightforwardly than enforcement policies by taxing and charging based on Pigou's theory to internalize the environmental externality. The economic mode of governance reflects the comprehensive cost of environmental damage activities (Pope Iii et al. 2020). Shi et al. (2016) find that the fully cooperative coalition yielded the highest incremental gain for regions willing to cooperate. Previously, most research to control air pollution involved only emission reduction targets. However, bottom-up competition among local governments makes it difficult to focus on reduction targets alone. In reduction-target-driven strategies,

Fig. 1 Research outline



some fundamentals of fine particulates are ignored. The implementation of reduction-target-driven strategies is challenging as a consequence of the uncertainty in finding appropriate reduction targets. Given that each participant benefits differently from the shared governance, it is essential to reallocate the surplus from the cooperation to improve the incentive for cooperation. In view of the spatial heterogeneity of PM2.5 and the dependence of global-optimum-based optimization approaches, the tricky part in an economic way is that the government needs to know the cost functions of the corresponding abatement to set the appropriate rate of taxes and charges. Pollution control cost of a transboundary river basin was tested by using game theory (Shi et al. 2016), but there have been few relevant empirical studies for air pollution at least thus far.

More recently, various modeling studies associated with the evaluation of cost-efficient PM2.5 abatement approaches have been undertaken since air pollution control is cost intensive (Gupta et al. 2021). From the perspective of sensitivity analysis, optimal cooperation could abate pollutant emissions to a level around the critical load (Vareda et al. 2019). In addition, the local governments in cooperation tend to fall into the prisoner's dilemma without constraints. Nonetheless, the introduction of constraints is likely to facilitate Pareto improvement. Therefore, a classic model in the pollution control literature often contains the maximization of the aggregate reduction from all participants and two constraints. The first one sets the bounds on the reduction level for each participant, and the second one sets the financial constraints of abatement. In this case, reduction-target-driven strategies are more prevalent to be used in identifying the upper bound of fund support for the corresponding targets. An alternative type of model in pollution control does not take the financial constraints into account because critical loads are considered more appropriate to fix reduction targets.

In light of the critical importance of costs and the requirements of large integrated modeling, it is necessary to fit the abatement costs to every individual city, whereas the high dispersibility would increase costs to achieve the reduction targets. This study not only fits the reduction costs to each city but also grounds in metropolitan areas instead of countries to alleviate the high dispersibility problem. Most of the positivist studies in this field aim for an effective frontier based on a minimal cost to identify the optimal aggregate cost function (Acar and Ibrahim 2019). It has been proven that the maximum reduction under any arbitrary fund constraint may not be applicable to derive the cost functions for individual participants (Halkos 1993). Furthermore, quite a few cost-effective strategies are confronted with the problem that the theoretical reduction targets tend to be undervalued compared to the incremental abatement costs because of the unevenly distributed or negative net benefits.

To avoid the "noncooperative" Nash equilibrium, the status quo is regarded as the benchmark to evaluate the gains of cooperation based on game theory. Taking Halkos's research as this departure point, this study revised the nonlinear programming by threshold effects to better fit the true cost curve of fine particulate abatement based on cities from metropolitan areas, as well as estimate further numerical costs and potential benefits from shared governance. Following the call for estimating environmental damage indirectly, this study hypothesizes the corresponding parameters by assuming that the marginal cost of environmental damage equals the marginal cost of fine particulate abatement. As we shall show, the threshold revised functions of nonlinear programming have far-reaching implications for multiparty cooperation scenarios and fiscal decentralization.

Data and methodology

In view of the nonlinear correlation between PM2.5 reduction and abatement costs, this study tests the threshold effect through a nonlinear programming problem. The data were obtained city by city, sector by sector, and year by year from the statistical yearbook and annual environmental quality bulletin of a classic instance of metropolitan clusters, Beijing-Tianjin-Hebei.

Game theory points out that the optimum reallocation is cost-equals-benefit and Pareto-efficient, which means that all of the participants benefit from cooperation. To simplify the research, this study focuses on PM2.5 pollution, which has been the main pollutant of concern in quite a few countries for a long time. Moreover, the long-range transmission of PM2.5 makes it a good example to explore shared governance. This study employed the threshold effect–improved game model to determine a cost-effective PM2.5 reduction strategy in a metropolitan cluster, which minimizes the aggregate cost of pollution control subject to meeting corresponding constraints in each participant simultaneously. The constraints for each city imply the minimum PM2.5 abatement to secure air quality targets derived from the threshold regression model. The objective function, which is the aggregate cost of PM2.5 abatement in the shared governance, is a convex upward sloping curve suggesting an increasing marginal cost, offering the costs of realizing different PM2.5 abatement targets employing pollution control approaches available for fine particulate abatement. To reconcile the costs and benefits of abatement, the Shapley value was employed to allocate the reduction costs for each city according to their abatement contribution. The variable definitions are shown in Table 1.

Table 1 Variable definitions

Parameter type	Parameters	Meaning
Players	B	Beijing
	T	Tianjin
	H	Hebei
PM2.5 parameters	D_i	PM2.5 abatement rate in province i
	PM_i^*	Optimal PM2.5 concentration in province i
	I_i	Initial PM2.5 concentration in province i
	RPM_i	Real PM2.5 concentration in province i
	PM_i	Simulated PM2.5 concentration in province i
	PMS	National PM2.5 abatement standard
	I_{it}	The threshold of PM2.5 concentration in province i
Cost parameters	TC	The total cost of PM2.5 abatement
	C_i	The cost of PM2.5 abatement in province i
	CB	The cost function of PM2.5 abatement
	PI_i	The proportion of environmental investment compared to GDP in province i
Instrumental parameters	β_{ij}	The coefficients to be estimated
	θ_i	Constant term
	W	Weighting factor

This study begins by constructing the cost function of PM2.5 abatement as Eq. (1).

$$C_i = f(D_i, I_i, PI_i) \tag{1}$$

The cost function is convex with constraints $\{\mathrm{PM}_i \geq / \leq / = \delta\}$. The coefficient matrix of constraints is estimated by the threshold model using stepwise regression or derived from the air quality targets.

Then, the Pareto-efficient or no-loser equilibrium is given by Eqs. (2) and (3).

$$\min_{D_B, D_T, D_H,} \mathrm{TC} = C_B + C_T + C_H \tag{2}$$

$$s.t.\left\{\mathrm{PM}_i \geq / \leq / = \delta\right\} \tag{3}$$

Accordingly, to distribute the abatement costs equitably, this study employs the Shapley value to compute the following cost reallocation plan by Eqs. (4) and (5).

$$C_i = \Sigma W(|s|)\left[\underset{s\subset\{B,T,H\}}{CB(s)} - CB(s-i)\right] \tag{4}$$

where

$$W(|s|) = \frac{(3-|s|)(|s|-1)!}{3!} \tag{5}$$

The fixed elastic function is adopted for a better fitting effect as Eq. (6).

$$lnC_i = \beta_{1i} lnD_i + \beta_{2i} lnI_i + \beta_{3i} PI_i + \beta_{4i} PM_i + \theta_i \tag{6}$$

where $\beta_{1i}, \beta_{2i}, \beta_{3i}, \beta_{4i}$ are the coefficients to be estimated, and θ_i is a constant term. Equation (6) can be rewritten as Eq. (7).

$$C_i = e^{\theta_i} \cdot D_i^{\beta_{1i}} \cdot I_i^{\beta_{2i}} \cdot \mathrm{PI}_i^{\beta^{3i}} \cdot \mathrm{PM}_i^{\beta_{4i}} \tag{7}$$

The total cost (TC) of PM2.5 abatement aggregating costs of participants in the shared governance, including Beijing, Tianjin, and Hebei (C_B, C_T, C_H), is given by Eq. (8).

$$\begin{aligned} &\underset{PM_B,PM_T,PM_H}{Min} TC = \sum_{i\subset\{B,T,H\}} C_i = e^{\theta_B} \cdot D_i^{\beta_{1B}} \cdot I_i^{\beta_{2B}} \cdot PI_i^{\beta_{3B}} \cdot PM_i^{\beta_{4B}} \\ &+ e^{\theta_T} \cdot D_i^{\beta_{1T}} \cdot I_i^{\beta_{2T}} \cdot PI_i^{\beta_{3T}} \cdot PM_i^{\beta_{4T}} \\ &+ e^{\theta_H} \cdot D_i^{\beta_{1H}} \cdot I_i^{\beta_{2H}} \cdot PI_i^{\beta_{3H}} \cdot PM_i^{\beta_{4H}} \\ &s.t. \sum_{i\subset\{B,T,H\}} \mathrm{PM}_i \leq \sum_{i\subset\{B,T,H\}} \mathrm{RPM_i}; \mathrm{PM}_i \leq I_{it}; \mathrm{PM}_i \leq 75 \end{aligned} \tag{8}$$

The formulation of this mathematical programming problem can be regarded as a way to incorporate cost–benefit analysis based on target constraints. In other words, this study tries to find an efficient and minimal cost envelope to derive the optimal cost function of PM2.5 abatement. The procedure is to construct a total cost function exhibiting nondecreasing marginal costs by excluding any choices that yield the nonconvex cost curve. To generate a minimum cost curve for a metropolitan area, the curves of each participant are aggregated.

It is clear that multilateral cooperation is more prevalent in air pollution control (Akimoto 2003). Therefore, to explore the no-loser solution that involves more participants, this study rewrites the model in a more flexible form. In the case of multilateral corporative governance, this study assumes that the number of participants is n, and the cost function of PM2.5 abatement for partner i is $lnC_i = \beta_{1i}lnD_i + \beta_{2i}lnI_i + \beta_{3i}PI_i + \beta_{4i}PM_i + \theta_i$ $,i \subset [1, 2, \cdots, n]$. The cooperative game model of multilateral PM2.5 abatement is shown in Formula (9).

$$\underset{PM_1,PM_2,\cdots,PM_n}{Min} TC = \sum_{i\subset\{1,2,\cdots,n\}} C_i = \sum_{i\subset\{1,2,\cdots,n\}} e^{\theta_i} \cdot D_i^{\beta_{1i}} \cdot I_i^{\beta_{2i}} \cdot PI_i^{\beta_{3i}} \cdot PM_i^{\beta_{4i}} \\ s.t. \sum_{i\subset\{1,2,\cdots,n\}} \mathrm{PM}_i \le \sum_{i\subset\{1,2,\cdots,n\}} \mathrm{RPM}_i ; \mathrm{PM}_i \le I_{it} ; \mathrm{PM}_i \le \mathrm{PMS} \tag{9}$$

The variable definitions are shown in Table 1. Similarly, this study employs the Shapley value to redistribute the abatement costs by Eq. (10).

$$C_i = \sum W(|s|)[\underset{s\subset\{1,2,\cdots,n\}}{CB(s)} - CB(s-i)] \tag{10}$$

where

$$W(|i|) = \frac{(n-|i|)!(|i|-1)!}{n!} \tag{11}$$

Table 2 gives the computation procedure of the Shapley value–based cost redistribution of partner I, which derives from the abatement contribution in PM2.5 corporative governance.

For partner i, the PM2.5 abatement cost in a state of equipoise is given in Eq. (12):

$$C_i = \sum W(|s|)[\underset{s\subset\{1,2,\cdots,n\}}{CB(s)} - CB(s-i)] \\ \sum_{a\subset[1,2,\cdots,n],a\neq i} \frac{1}{n\cdot(n-1)} \cdot CB(2)_a + \cdots + \frac{1}{n} \cdot \left[CB(n) - CB(n-1)_i\right] \tag{12}$$

The above equations provide a theoretical game model for multilateral cooperation scenarios of PM2.5 abatement. This cooperative game model adjusted by the threshold effect is also applicable to other pollutants, such as sulfur dioxide, nitrogen oxides, ozone, carbon emissions, water pollutants, and solid waste. By applying this adjusted game model, this study can systematically analyze the efficiency and costs of shared governance based on nonlinear programming and reconcile the costs and benefits of abatement according to their abatement contribution.

Table 2 Computation procedure of Shapley value–based cost redistribution of partner I

s	$\{i\}$	$\{i,a\}_{a,i\subset[1,2,\cdots,n],a\neq i}$	$\{i,a,b\}_{a,b,i\subset[1,2,\cdots,n],a\neq b\neq i}$	…	$\{1,2,\cdots,n\}$
$CB(s)$	0	$CB(2)_a$	$CB(3)_{ab}$	…	$CB(n)$
$CB(s-\{i\})$	0	0	0	…	$CB(n-1)_i$
$CB(s)-CB(s-\{i\})$	0	$CB(2)_a$	$CB(3)_{ab}$	…	$CB(n)-CB(n-1)_i$
$\mid s \mid$	1	2	3	…	n
$W(\|s\|)$	$\frac{1}{n}$	$\frac{1}{n\cdot(n-1)}$	$\frac{2}{n\cdot(n-1)\cdot(n-2)}$	…	$\frac{1}{n}$
$W(\|s\|)[CB(s)-CB(s-\{i\})]$	0	$\frac{1}{n\cdot(n-1)} \cdot CB(2)_a$	$\frac{2}{n\cdot(n-1)\cdot(n-2)} \cdot CB(3)_{ab}$	…	$\frac{1}{n}\cdot[CB(n)-CB(n-1)_i]$

Empirical results

Threshold effect test

In requiring estimations for the coefficient matrix of constraints, this study examines the threshold effect to address the critical pollution control issue: specifically, what PM2.5 abatement or emission standards need to be applied. It is evident that the coefficient matrix varies with time because of meteorological variations and technological progress. The introduction of the threshold effect can mitigate this problem and fit the coefficient matrix closer to reality, but it still does not fit the reality precisely. To reduce estimation bias, the panel threshold model is employed by this study combined with bootstrap sampling (Boos 2003) to determine the number of thresholds. Table 3 presents the testing results of the multi-threshold effect.

As seen in Table 3, the coefficient estimates of the thresholds corresponding to the real PM2.5 concentration and the total cost are statistically significant, especially when compared to other driving factors of PM2.5 abatement, suggesting that there exists a nonlinear relationship between the PM2.5 abatement cost and the abatement efficiency. More interestingly, the coefficients of multiple thresholds are almost all significant for the total cost and vary from each other, implying that the variation of their relationship is large and that there may exist an inflection point in the sample period. Therefore, the estimates of thresholds and the coefficients are applied to revise the cooperative game models. Furthermore, the estimated coefficients of R&D are negative for all the above regressions, indicating that there is still substantial potential for abating PM2.5 in terms of improving R&D. This result is similar to that of Berman and Keita (2020), who employ a shorter sample period than this study.

Pareto-dominant solutions

To construct a cost-effective PM2.5 abatement strategy in China, a mathematical programming problem has been applied, which minimizes the aggregate abatement cost subject to meeting the national PM2.5 emission standards for each province

Table 3 Multi-threshold effect test by panel regressions with bootstrap sampling

Threshold variable	Proportion of tertiary industry	Fuels	RPM_i	TC	Energy elasticity	Environmental investment	Energy efficiency	R&D
Proportion of tertiary industry	-	1.201	0.079	0.224	0.518	−0.437	−0.167	0.455
	-	(0.216)	(0.915)	(0.797)	(0.584)	(0.600)	(0.870)	(0.621)
Proportion of secondary industry	0.107	0.577	−0.026	0.004	0.139	−0.397	−0.300	0.054
	(0.865)	(0.390)	(0.964)	(0.995)	(0.829)	(0.507)	(0.669)	(0.932)
Energy consumption	0.444	-	0.322	−0.096	0.362	0.764	0.283	0.616
	(0.559)	-	(0.636)	(0.916)	(0.662)	(0.356)	(0.744)	(0.420)
Economic structure	0.444	-	0.322	−0.096	0.362	0.764	0.283	0.616
	(0.559)	-	(0.636)	(0.916)	(0.662)	(0.356)	(0.744)	(0.420)
Traffic	1.419*	1.934**	2.012***	1.330*	1.196	1.235	1.372*	1.712**
	(0.079)	(0.017)	(0.005)	(0.083)	(0.161)	(0.140)	(0.090)	(0.044)
R&D	−1.105	−1.225*	−1.087*	−0.934	−1.031	−0.503	−0.790	-
	(0.132)	(0.074)	(0.086)	(0.191)	(0.167)	(0.460)	(0.252)	-
Environmental investment	−0.042	0.003	-	−0.116	0.013	−0.028	−0.101	−0.049
	(0.817)	(0.988)	-	(0.527)	(0.944)	(0.878)	(0.595)	(0.795)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Threshold-0	−0.145	1.453*	−0.612**	−0.483	3.391	−0.515	−0.077	−1.786
	(0.873)	(0.093)	(0.040)	(0.450)	(0.105)	(0.424)	(0.891)	(0.148)
Threshold-1	0.493	0.693	6.444**	1.309*	0.392	−2.458	0.164	−1.139
	(0.588)	(0.329)	(0.015)	(0.070)	(0.211)	(0.314)	(0.800)	(0.131)
Threshold-2	−0.148	1.305	−0.065	0.485**	1.200	0.226	0.218	−1.970*
	(0.878)	(0.129)	(0.949)	(0.021)	(0.105)	(0.372)	(0.676)	(0.081)
Threshold-3	1.477	−0.030	0.113	1.118**	0.410	−0.469	−0.658	−0.551
	(0.208)	(0.971)	(0.542)	(0.018)	(0.568)	(0.264)	(0.263)	(0.442)
R^2	0.671	0.709	0.742	0.678	0.653	0.672	0.658	0.662

The sample contains city-years from 2013 to 2019 with non-missing values for all the control variables. The *p* values are reported in parentheses based on standard errors clustered by both city and time. Year-fixed effects are included in all regressions. The variables are defined in Table 1

*Statistical significance at 10%

**Statistical significance at 5%

***Statistical significance at 1%

simultaneously. Each of the constraints implies the minimum abatement of PM2.5 to secure targeted national PM2.5 emission standards for each province. The aggregate abatement cost, which is the threshold adjusted objective function, is a convex upward sloping curve, implying increasing marginal costs with the abatement level. To solve the optimization problem, the panel data is used from the Beijing-Tianjin-Hebei region. Based on the above estimation results of the thresholds, the piecewise cost functions of PM2.5 abatement are obtained by stepwise regressions. Table 8 in Appendix 1 shows the stepwise regression results of PM2.5 abatement cost functions in Beijing, Tianjin, and Hebei.

One of the closest progenitors to the application of cooperative game theory is industry analysis based on a cooperative game setting (Brandenburger and Harborne 1996), which calls attention to the virtually unquestioned evaluation of pollution abatement efficiency with the pollution control cost. Then, this study explored the optimal control targets and the optimal abatement costs of PM2.5 in Beijing, Tianjin, and Hebei. The threshold-adjusted game theory model does not seek abatement benefits with any precision. Nonetheless, it is sensible to examine corporative benefits in the developing PM2.5 abatement standards to guarantee that the abatement costs of PM2.5 are used in an optimal cost-effective way. In effect, game theory analysis seeks to achieve cost-effective PM2.5 abatement; thus, it is critical to improve PM2.5 reduction strategies to ensure pollution control improvements in cooperative partners that would cost the least and benefit the most (Liu et al. 2020a, b). The results are shown in Table 4, which is solved by

Table 4 Optimal targets and abatement costs of PM2.5 in Beijing-Tianjin-Hebei adjusted by threshold effect

Province	Actual annual average concentration of PM2.5 (μg/m^3)	Optimal annual average concentration targets of PM2.5 (μg/m^3)	Actual abatement costs of PM2.5 (million yuan)	Total optimal abatement cost of PM2.5 (million yuan)	Percentage change in total abatement costs before and after cooperative governance
Beijing	73	62	945.99	6056.08	−10.78%
Tianjin	69	68	683.73		
Hebei	70	69	5158.16		
Total	212	199	6787.88		

Lingo, and the solution details are attached in Appendix Figs. 2, 3, 4, and 5.

Table 4 presents the results of the game theory model adjusted by the threshold effect. From a cost-effective perspective, cooperative governance begins with the deployment of environmental resource combinations. When a metropolitan area is abating PM2.5, it enjoys the advantage of bundling resources. In turn, the cooperative governance contributes to reducing PM2.5 by 6.13% and the abatement cost by 10.78% when the marginal cooperation gains are positive. Additionally, the PM2.5 reduction effects for Tianjin and Hebei are moderate, and Beijing experiences a substantial gain in PM2.5 reduction. Thus, cooperative governance tends to occur when the abatement efficiency or cost has the potential to improve while maintaining or improving the corporative gain margins. By acting cooperatively rather than independently, the abatement efficiency and costs are optimized when a metropolitan area shares the resource among the participants so that the efficiency among the participant's abatement and the costs paid by local governments are optimized. These findings are consistent with the fact that shared governance improves the utilization efficiency of resources, funds, talent, and energy and reduces the costs of governance through cooperation in sharing information, resources, and technology (Mayer 1999). However, it is far more difficult to achieve the theoretical scenario and targets because of the immature corporative mechanism.

Shapley value–based cost redistribution

Although the game theory model described above gives the optimal targets and total abatement costs of PM2.5 in the corporative governance scenario, it does not examine the abatement costs of PM2.5 for each corporative participant. To date, most PM2.5 abatement strategies have tended to take a holistic approach to environmental investment, focusing on the extent to which the abatement costs of PM2.5 are invested across all cities of an area as well as across areas (Pope Iii et al. 2020). By ignoring the potential existence of different marginal gains for different areas, many of the PM2.5 abatement strategies may seem monolithic. However, some policy suggestions are intuitively appealing; it may be unsuitable to simplify the nature of environmental investments and conjecture that there exists a single optimal level of abatement cost for managing all areas. Rather, it is believed that the most appropriate mode of investment in PM2.5 abatement will vary for different areas. In practice, the abatement costs of PM2.5 discriminate against the cities that are polluted. If the abatement costs are not redistributed after the corporation, the corporative benefits could be negative for some of the participants, and these participants should be compensated to encourage cooperation. Therefore, it is extremely important to fairly allocate abatement costs based on their contribution to corporative pollution control. Because of the difficulty in measuring such contributions, this study employed the Shapley value to make this analysis practicable.

To redistribute the abatement costs of PM2.5, first, the abatement costs are examined if they act independently by achieving the same PM2.5 abatement targets as acting cooperatively. The second is to establish a cost-redistribution corporation among participants and to create a regional fund for PM2.5 pollution control, which could redeploy the resources from member cities in proportion to corporative contributions along with gains and then redistribute the resources and subsidies among participants to encourage cost-effective abatements as well as avoid distributional egalitarianism. More specifically, by comparing the difference in different modes of governance in Beijing-Tianjin-Hebei, including territorial governance, bilateral cooperative governance, and trilateral cooperative governance, this study employs the Shapley value to weight the abatement contributions of each province under cooperative governance.

The first is to solve the PM2.5 abatement costs in different cooperative modes of governance among Beijing, Tianjin, and Hebei. The game model adjusted by the threshold effect of Beijing-Tianjin cooperative governance is shown in Formula (13). Similarly, the game models of Beijing-Hebei and Tianjin-Hebei are shown in Formula (14) and Formula (15), respectively. The coefficients in Formulas (13), (14), and (15) are estimated in Table 3.

$$\underset{PM_B,PM_T}{Min}\ TC = \sum_{i \subset \{B,T\}} C_i = e^{\theta_B} \cdot D_i^{\beta_{1B}} \cdot I_i^{\beta_{2B}} \cdot PI_i^{\beta_{3B}} \cdot PM_i^{\beta_{4B}} + e^{\theta_T} \cdot D_i^{\beta_{1T}} \cdot I_i^{\beta_{2T}} \cdot PI_i^{\beta_{3T}} \cdot PM_i^{\beta_{4T}}$$
$$\text{s.t.} \sum_{i \subset \{B,T\}} PM_i \le \sum_{i \subset \{B,T\}} \text{RPM}_i; \text{PM}_i \le I_{it}; \text{PM}_i \le 75 \tag{13}$$

$$\underset{PM_B,PM_H}{Min}\ TC = \sum_{i \subset \{B,H\}} C_i = e^{\theta_B} \cdot D_i^{\beta_{1B}} \cdot I_i^{\beta_{2B}} \cdot PI_i^{\beta_{3B}} \cdot PM_i^{\beta_{4B}} + e^{\theta_H} \cdot D_i^{\beta_{1H}} \cdot I_i^{\beta_{2H}} \cdot PI_i^{\beta_{3H}} \cdot PM_i^{\beta_{4H}}$$
$$\text{s.t.} \sum_{i \subset \{B,H\}} \text{PM}_i \le \sum_{i \subset \{B,H\}} \text{RPM}_i; \text{PM}_i \le I_{it}; \text{PM}_i \le 75 \tag{14}$$

$$\underset{PM_T,PM_H}{Min}\ TC = \sum_{i \subset \{T,H\}} C_i = e^{\theta_T} \cdot D_i^{\beta_{1T}} \cdot I_i^{\beta_{2T}} \cdot PI_i^{\beta_{3T}} \cdot PM_i^{\beta_{4T}} + e^{\theta_H} \cdot D_i^{\beta_{1H}} \cdot I_i^{\beta_{2H}} \cdot PI_i^{\beta_{3H}} \cdot PM_i^{\beta_{4H}}$$
$$\text{s.t.} \sum_{i \subset \{T,H\}} \text{PM}_i \le \sum_{i \subset \{T,H\}} \text{RPM}_i; \text{PM}_i \le I_{it}; \text{PM}_i \le 75 \tag{15}$$

The solution results calculated by Lingo are shown in Appendix Figs. 2, 3, 4, and 5. The optimal corporative abatement costs of PM2.5 for Beijing-Tianjin, Beijing-Hebei, and Tianjin-Hebei are RMB 201.04 million, RMB 4744.38 million, and RMB 4462.62 million, respectively. The optimal corporative abatement costs of PM2.5 for Beijing-Tianjin-Hebei are shown in Table 4. For the trilateral cooperative governance of Beijing-Tianjin-Hebei, the above solutions are close to Nash solutions. Therefore, the primary data required by the Shapley value are prepared, and then the abatement costs could be redistributed to each participant.

Table 5 shows the computation procedure of the Shapley value in Beijing by the abatement contribution in PM2.5 corporative governance. The redistributed PM2.5 abatement cost in Beijing is $C_B = 0 + 33.51 + 790.73 + 531.15 = 1355.39$ million RMB. In contrast, the PM2.5 abatement cost of Beijing in the noncooperative scenario is RMB 945.99 million, which implies that Beijing would take on more abatement costs in corporative governance resulting from the higher marginal efficiency of PM2.5 abatement. In other words, Beijing is more cost-effective in PM2.5 abatement than other participants, and an RMB 409.4 million (43.28%) increase in Beijing's PM2.5 abatement cost could achieve better abatement results in corporative governance, while the total abatement cost in Beijing-Tianjin-Hebei is 10.78% less than that in the noncooperative scenario. Meanwhile, Beijing is the largest gainer from cooperative PM2.5 reductions, as the average concentration of PM2.5 is reduced by 15.07% compared to the noncooperative scenario.

Table 6 shows the computation procedure of the Shapley value in Tianjin by the abatement contribution in PM2.5 corporative governance. The redistributed PM2.5 abatement cost in Tianjin is $C_T = 0 + 33.51 + 743.77 + 437.23 = 1214.51$ million RMB. In contrast, the PM2.5 abatement cost of Tianjin in the noncooperative scenario is RMB 683.73 million, which implies that Tianjin would also take on more abatement cost in corporative governance because of the higher marginal efficiency of PM2.5 abatement, and RMB 530.78 million increased in Tianjin's PM2.5 abatement cost could also achieve better abatement results in corporative governance. However, even in the trilateral corporation, Tianjin benefits less than Beijing. The reason is that Tianjin gains little from other participants' abatement, while its higher marginal abatement effect mitigates the increase in PM2.5 (although the PM2.5 abatement rate decreases proportionately).

Table 7 shows the computation procedure of the Shapley value in Hebei by the

Table 6 Computation procedure of the Shapley value–based cost redistribution in Tianjin

s	T	B, T	T, H	B, T, H
CB(s)	0	201.04	4462.62	6056.08
CB(s −)T	0	0	0	4744.38
CB(s)−CB(s − T)	0	201.04	4462.62	1311.7
($\|s\|$)	1	2	2	3
W($\|s\|$)	1/3	1/6	1/6	1/3
W($\|s\|$)[$CB(s) - CB(s - \{T\})$]	0	33.51	743.77	437.23

Table 5 Computation procedure of the Shapley value–based cost redistribution in Beijing

s	B	B, T	B, H	B, T, H
CB(s)	0	201.04	4744.38	6056.08
CB(s − B)	0	0	0	4462.62
CB(s)−CB(s−B)	0	201.04	4744.38	1593.46
$\|s\|$	1	2	2	3
$W(\|s\|)$	1/3	1/6	1/6	1/6
$W(\|s\|)$[CB(s)−CB(s−B)]	0	33.51	790.73	531.15

Table 7 Computation procedure of the Shapley value–based cost redistribution in Hebei

s	H	B, H	T, H	B, T, H
CB(s)	0	4744.38	4462.62	6056.08
CB(s −)H	0	0	0	201.04
CB(s)−CB(s − H)	0	4744.38	4462.62	5855.04
($\|s\|$)	1	2	2	3
W($\|s\|$)	1/3	1/6	1/6	1/3
W($\|s\|$)[$CB(s) - CB(s - \{H\})$]	0	790.73	743.77	1951.68

abatement contribution in PM2.5 corporative governance. The redistributed PM2.5 abatement cost in Hebei is $C_H = 0 + 790.73 + 743.77 + 1951.68 = 3486.18$ million RMB. In contrast, the PM2.5 abatement cost of Hebei in the noncooperative scenario is RMB 5158.16 million, which means that Hebei could save RMB 1671.98 million in the trilateral PM2.5 abatement. In other words, Hebei is less cost-effective in PM2.5 abatement than other participants, and it benefits greatly from the abatement cost redistribution. It is worth noting that the trilateral gains of Hebei are much greater than its bilateral gains. Accordingly, the PM2.5 abatement cost of Hebei is subsidized from the extra costs of its neighbors, Beijing and Tianjin, while it is intrinsically difficult to negotiate a trilateral agreement because of the generous side payments from Beijing and Tianjin.

This study examines the reallocation of PM2.5 abatement costs in a way that the participants whose abatement costs are cheaper need to undertake more PM2.5 abatements. By comparing the corporative costs and benefits, Tianjin benefits less than Beijing and Hebei in each case, and the trilateral loss is relatively greater, whereas Beijing benefits a lot in PM2.5 reduction and Hebei gains in subsidies in corporative governance. This demonstrates the difficulty and necessity in encouraging the trilateral corporation since an individual participant has less effect than the corporation of all participants because of policy interdependence. The trilateral corporation leads to a more than 6% reduction in PM2.5 across the area compared to acting independently. It is clear, therefore, that a 10% reduction in the abatement cost could achieve a 6% reduction in PM2.5 if a cost-effective reallocation is adopted. This is because the wide adherence to a combination of regulatory approaches and economic instruments in corporative governance, such as the "polluter pays" principle, could enhance the abatement efficiency and the equality promotion among participants to obtain wide support. Harmonizing standards in PM2.5 control could push manufacturers throughout the region to make more environmentally friendly products instead of simply transferring the pollution industry to neighbors (Wang et al. 2020).

Discussion

This study focuses on seeking cost-effective strategies for PM2.5 reduction to generate insights into minimizing pollution abatement costs subject to different scenarios. The results from the Beijing-Tianjin-Hebei metropolitan cluster in China show that cooperation in the metropolitan cluster plays a vital role in optimizing the efficiency and costs of PM2.5 abatement, which is similar to the research results of Shi et al. (2016) and Fathi and Bakhshoodeh (2021). Besides, this study provides a way to estimate the costs and the mitigation benefits of meeting the pollution targets for each coparticipant and take the scenario of multiparty cooperation into account as well as the scenarios involving other types of pollutants.

Game theory is generally employed to study governance or pollution control since Kilgour et al. (1988). Scholars have explored the pollution control of transboundary river basin (Shi et al. 2016), the energy subsidy (Fathi and Bakhshoodeh 2021), the subsidy strategy of carbon-sink fishery (Zheng and Yu 2022), the behavioral game of additional supervision (Gu et al. 2022), and so on. Different from the existing game theory studies, this study first focuses on the cost redistribution on air pollution control. By applying the threshold effect–adjusted game model, this study extends the literature (Zara et al. 2006; Sumaila et al. 2009; Wei et al. 2010; Madani 2010; Shi et al. 2016; Fathi and Bakhshoodeh 2021; Gu et al. 2022; Zheng and Yu 2022) by proposing cost-effective, socially acceptable, and administrative-feasible cooperation strategies of PM2.5 mitigation to internalize the environmental externalities equitably as well as cost-effectively. This study is among the first to revise the nonlinear programming by threshold effects to better fit the true cost curve of fine particulate abatement based on cities from metropolitan areas, as well as estimate further numerical costs and potential benefits from shared governance. To reconcile the costs and benefits of abatement, this study employs the Shapley value to allocate the reduction costs for each city according to their abatement contribution. The empirical findings have important policy implications for regional shared governance, decentralization, and resource reallocation. Economic incentive-based shared governance and cost reallocation work better than traditional regulations.

Certainly, there are some shortcomings in this study. First, the pollution control cost is a systematic project, including subsidies, supervising cost, governance cost, and so on. In the future, all kinds of cost should be included. Second, this study only tests the Beijing-Tianjin-Hebei (BTH) region; other regions should be further studied by the above method.

Conclusions and policy implications

Conclusions

Cooperation among regions is an economic way to control air pollution. This study theorizes that the cooperation of PM2.5 abatement has potential gains for participants and develop an empirical way to compare the costs and efficiency of PM2.5 abatement involving the variation of environmental conditions. This study revises the cooperative game model in the context of threshold effects using data obtained from the Beijing-Tianjin-Hebei metropolitan cluster in China. The conclusions are as follows.

First, the results support the key assertion that cooperation in the metropolitan cluster plays a vital role in optimizing the efficiency and costs of PM2.5 abatement. Cooperative solutions can achieve air quality targets in a more cost-effective way. The aggregate costs of cooperative governance are approximately 1/10 less than the costs of independent territory governance.

Second, this study also finds that the most polluted city in a metropolitan area is likely to realize maximum abatement and bear the largest proportion of costs along with the highest levels of subsidies and tax benefits. In the case study, a 10% reduction in the abatement cost could achieve a 6% reduction in PM2.5 if a cost-effective reallocation is adopted.

Third, Tianjin benefits less than Beijing and Hebei in each case, and the trilateral loss is relatively greater, whereas Beijing benefits a lot in PM2.5 reduction and Hebei gains in subsidies in corporative governance.

The results support the key assertion that cooperation in the metropolitan cluster plays a vital role in optimizing the efficiency and costs of PM2.5 abatement. To summarize, shared governance would greatly improve the utilization efficiency of resources, funds, talent, and energy and reduce the costs of governance through cooperation in sharing information, resources, and technology.

Policy recommendations

Urban air pollution affects residents' behaviors, such as their willingness to pay for green space (Liu et al. 2020a, b). Therefore, the empirical findings have far-reaching policy implications for regional shared governance, fiscal decentralization, and resource reallocation. Based on the above conclusions, this study puts forward the following policy recommendations.

First, this study needs a mechanism for transregional transfers to motivate participants to cooperate because some participants may be unwilling to cooperate in governance and therefore attach a low priority to cooperating in governance or trying to free ride on the efforts of other participants to abate pollution. Beijing-Tianjin-Hebei coordinated development strategy by China government makes shared governance and cost redistribution a reality.

Second, the strong agreement of cooperative governance must be reached to ensure strict government supervision so that each participant can share cooperation benefits. Actions to reduce greenhouse gas emissions often lead to co-benefits for ambient air quality (West et al. 2013). To enable cooperative governance between regions, supply-side policies could realize environmental targets in a more effective way, such as fuel substitution in electricity generation and new abatement technology.

Third, cooperative reallocation mainly relies on the sufficient sharing of talent, funds, resources, and technology. The reallocation of costs and resources ignores different environmental impacts between different regions. Various optimal abatement strategies should exist due to various economic incentives and different reduction costs. Additionally, this study also needs tradable emission permits to avoid the underestimation of abatement costs, whereas the emission standards are maintained.

Fourth, the wide adherence to a combination of regulatory approaches and economic instruments in corporative governance, such as the "polluter pays" principle, could enhance the abatement efficiency and the equality promotion among participants to obtain wide support. Furthermore, the harmonizing standards in PM2.5 control could push manufacturers throughout the region to make more environmentally friendly products instead of simply transferring the pollution industry to the neighbors.

Appendix 1

Table 8 The cost functions of PM2.5 abatement by stepwise regressions in Beijing-Tianjin-Hebei

Models	(1)	(2)	(3)
Province	Beijing	Tianjin	Hebei
lnPM	−2.331*	-	−2.114***
lnPI	1.846*	0.610*	-
lnI	-	−2.765***	-
lnD	-	0.621***	-
Constant	28.27***	28.20***	21.97***
Adjusted R^2	0.751	0.676	0.423

The sample contains city-years from 2013 to 2019 with non-missing values for all the control variables. The variables are defined in Table 1

Appendix 2

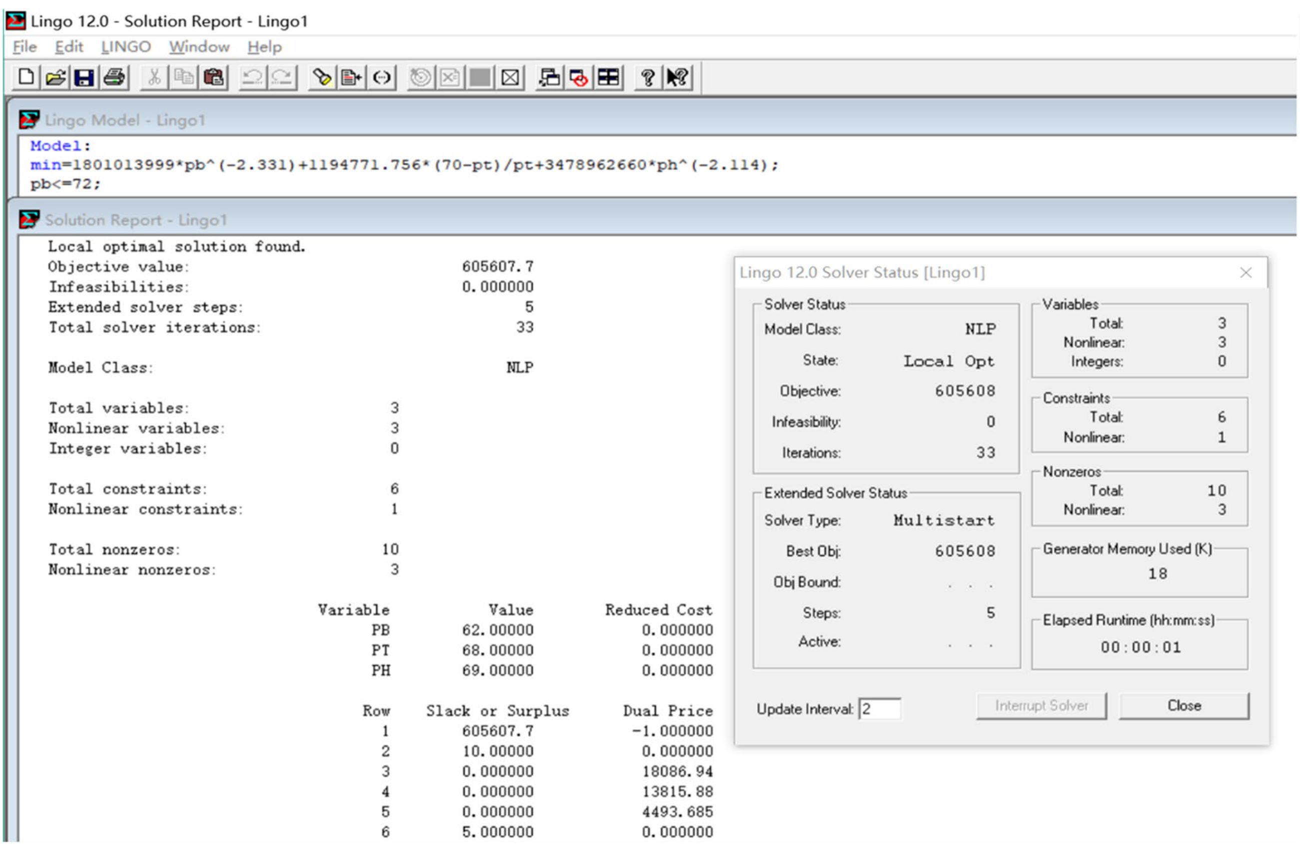


Fig. 2 The game model solution of PM2.5 abatement in Beijing-Tianjin-Hebei adjusted by threshold effect

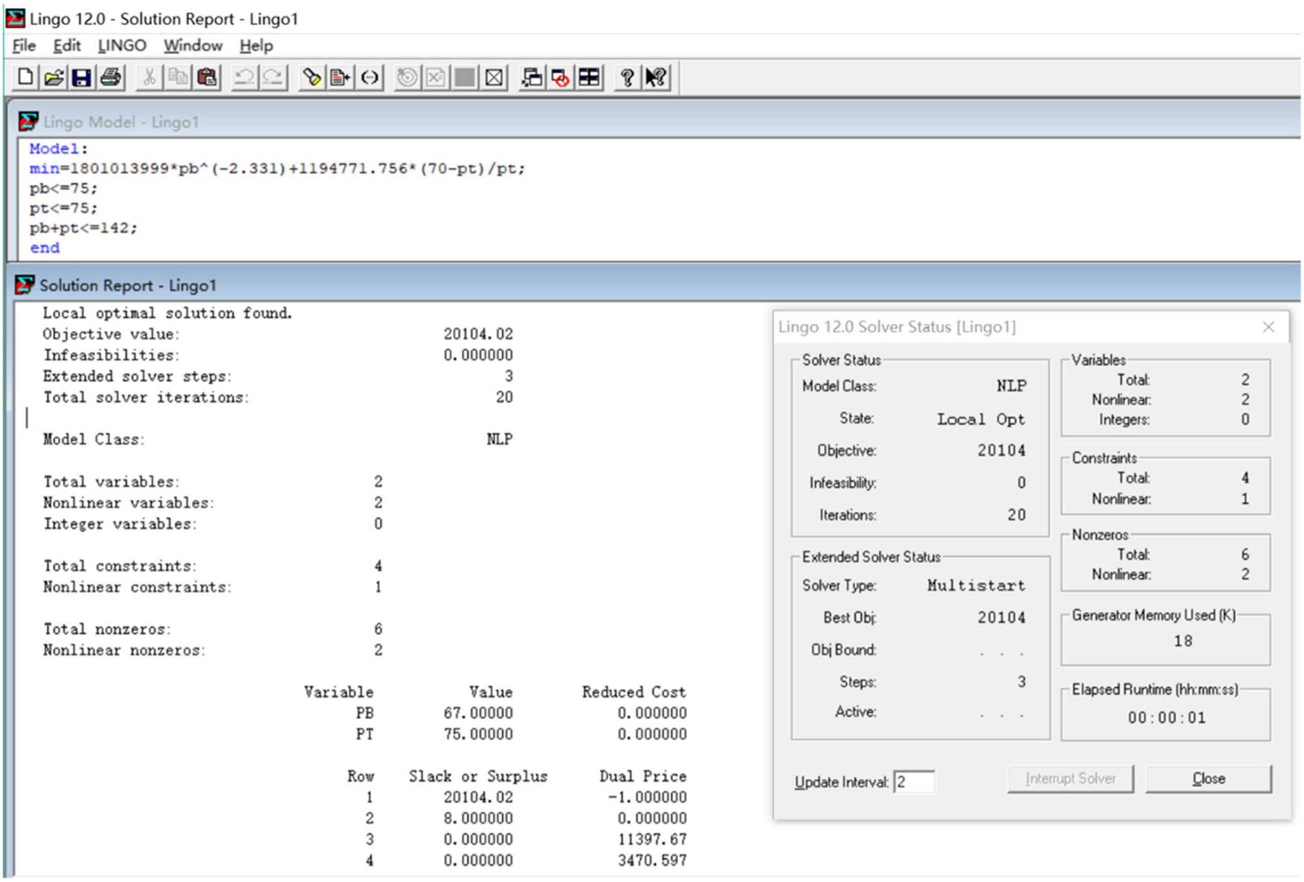


Fig. 3 The game model solution of PM2.5 abatement in Beijing-Tianjin adjusted by threshold effect

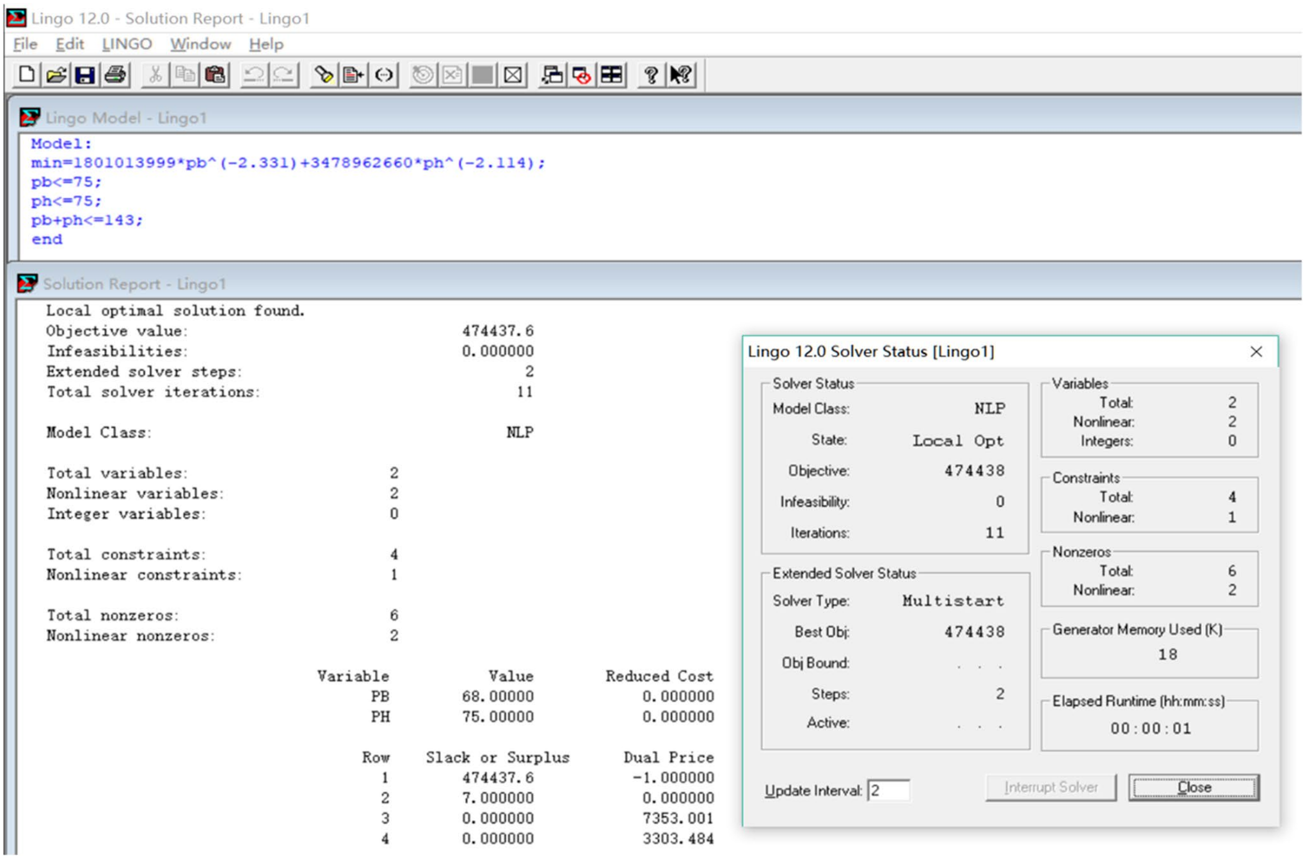


Fig. 4 The game model solution of PM2.5 abatement in Beijing-Hebei adjusted by threshold effect

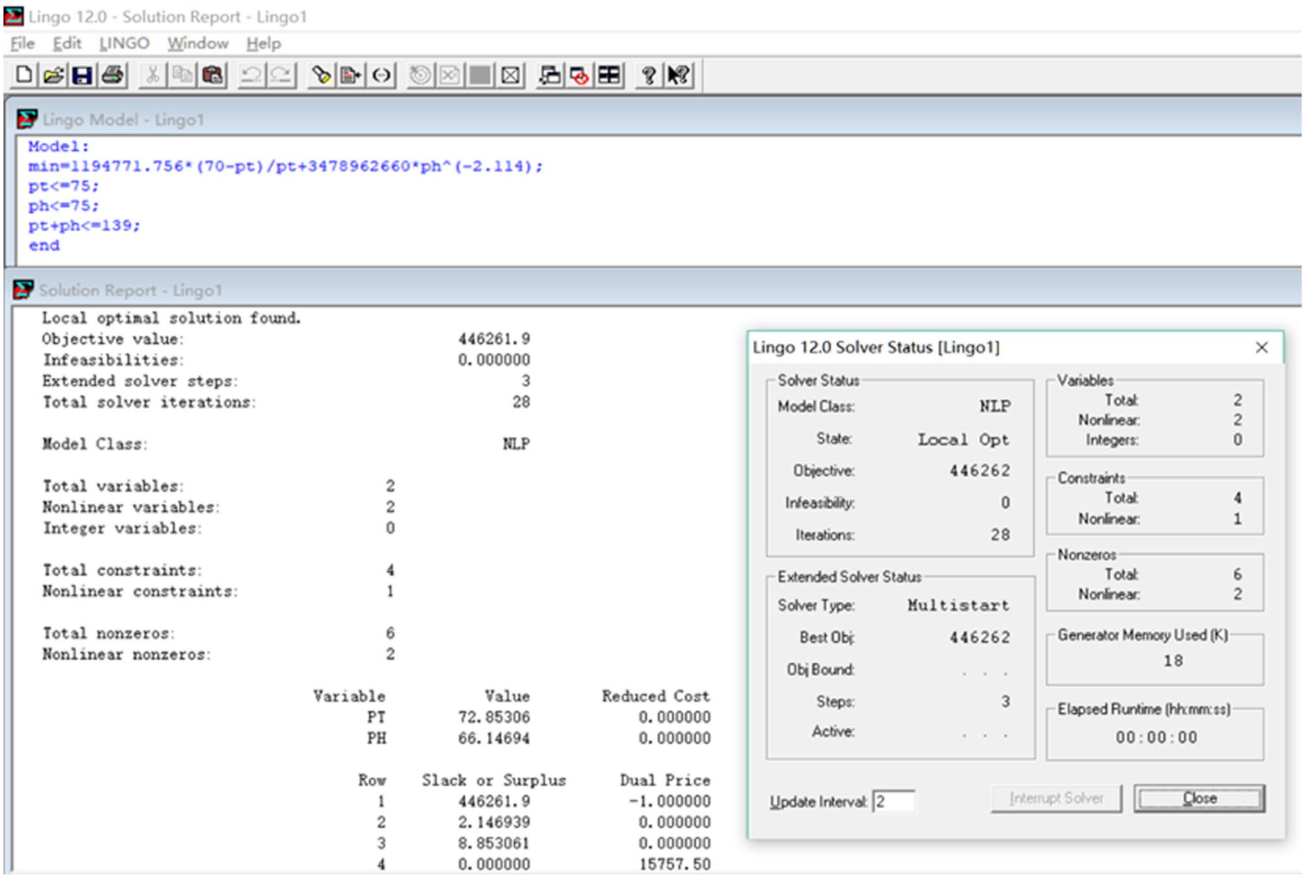


Fig. 5 The game model solution of PM2.5 abatement in Tianjin-Hebei adjusted by threshold effect

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Data availability The datasets used and analyzed during the current research are available from the corresponding author on request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Acar C, Ibrahim D (2019) Review and evaluation of hydrogen production options for better environment. J Cleaner Prod 218:835–849
Akimoto H (2003) Global air quality and pollution. Science 302:1716–1719
Augeraud-Véron E, Choquet C, Comte É et al (2022) A game theory approach for the groundwater pollution control[J]. Siam J Control Optim 60(3):1667–1689
Berman JD, Keita E (2020) Changes in us air pollution during the COVID-19 pandemic. Sci Total Environ 739:139864
Boos DD (2003) Introduction to the bootstrap world. Statist Sci 18(2):168–174
Brandenburger AM, Harborne WSJ (1996) Value-based business strategy. J Econ Manag Stra 5:5–24
Chai F, Gao J, Chen Z, Wang S, Zhang Y, Zhang J, Zhang H, Yun Y, Ren C (2014) Spatial and temporal variation of particulate matter and gaseous pollutants in 26 cities in China. J Environ Sci 26(1):75–82
Chan CK, Yao X (2008) Air pollution in mega cities in China. Atmos Environ 42:1–42
Chen J, BoShuoMalin WHGS (2020) The influence of increased population density in China on air pollution. Sci Total Environ 735:139456
Chen X, Zhang L-W, Huang J-J, Song F-J, Zhang L-P, Qian Z-M, Trevathan E, Mao H-J, Han B, Vaughn M (2016) Long-term exposure to urban air pollution and lung cancer mortality: a 12-year cohort study in Northern China. Sci Total Environ 571:855–861
Fathi F, Bakhshoodeh M (2021) Economic and environmental strategies against targeting energy subsidy in Iranian meat market: a game theory approach[J]. Energy Policy 150:112153
Gu Q, Hang L, Sun S (2022) Behavioral game theory model in pollution control with additional supervision[J]. Algorithms 15(5):137
Gui K, Che H, Wang Y, Wang H, Zhang L, Zhao H, Zheng Y, Sun T, Zhang X (2019) Satellite-derived PM2.5 concentration trends over Eastern China from 1998 to 2016: relationships to emissions and meteorological parameters. Environ Pollut 247:1125–1133
Gupta A, Hemant Bherwani SG, Saima A, Kavya M, Narendra K, Avneesh Al, Rakesh K (2021) Air pollution aggravating COVID-19 lethality? Exploration in Asian cities using statistical models. Environ Develop Sustain 23(4):6408–6417
Halkos GE (1993) Sulphur abatement policy: implications of cost differentials. Energy Policy 21:1035–1043
Han R, Wang S, Shen W, Wang J, Wu K, Ren Z, Feng M (2016) Spatial and temporal variation of haze in China from 1961 to 2012. J Environ Sci 46:134–146
Hati SK, Rao SS (2001) Game theory approach for the design of an optimal air pollution control system for thermal power plants[J]. Int J Environ and Pollut 15(5):505–516
Hutton JP, Halkos GE (1995) Optimal acid rain abatement policy for Europe: an analysis for the year 2000. Energy Econ 17:259–275
Kilgour DM, Okada N, Nishikori A (1988) Load control regulation of water pollution: an analysis using game theory. J Environ Manag 27:179–194
Li L, Tan Q, Zhang Y, Feng M, Qu Y, An J, Liu X (2017) Characteristics and source apportionment of PM2.5 during persistent extreme haze events in Chengdu, Southwest China. Environ Pollut 230:718–729
Li X, Jin L, Kan H (2019) Air pollution: a global problem needs local fixes. Nature 570(7762):437–439
Liu NM, Lisa M, Barbara AM, Graham M, Carolyn JPJ, Benjamin B, Shakila T, Vassil K, Imad AA, Zabeada A (2020a) Evidence for the presence of air pollution nanoparticles in placental tissue cells. Sci Total Environ 751:142235. https://doi.org/10.1016/j.scitotenv.2020.142235
Liu Z, Hanley N, Campbell D (2020b) Linking urban air pollution with residents' willingness to pay for greenspace: a choice experiment study in Beijing. J Environ Econ Manag 104:102383
Madani K (2010) Game theory and water resources. J Hydrol 381:225–238
Mayer H (1999) Air pollution in cities. Atmos Environ 33:4029–4037
Petrosyan LA, Yeung DWK (2020) Cooperative dynamic games with durable controls: theory and application. Dyn Games Appl 10:872–896
Pope Iii CA, Nathan C, Pond ZA, Burnett RT (2020) Fine particulate air pollution and human mortality: 25+ years of cohort studies. Environ Res 183:108924
Richter A, Burrows JP, Nüß H, Granier C, Niemeier U (2005) Increase in tropospheric nitrogen dioxide over China observed from space. Nature 437(7055):129–132
Shi G, Wang J, Zhang B et al (2016) Pollution control costs of a transboundary river basin: empirical tests of the fairness and stability of cost allocation mechanisms using game theory[J]. J of Environ Manag 177:145–152
Song C, He J, Wu L, Jin T, Chen X, Li R, Ren P, Zhang L, Mao H (2017) Health burden attributable to ambient PM2.5 in China. Environ Pollut 223:575–586
Sumaila UR, Dinar A, Albiac J (2009) Game theoretic applications to environ- mental and natural resource problems. Environ Dev Econ 14:1–5
Vareda JP, Artur JMV, Luisa D (2019) Assessment of heavy metal pollution from anthropogenic activities and remediation strategies: a review. J Environ Manage 246:101–118
Wang P, Chen K, Zhu S, Wang P, Zhang H (2020) Severe air pollution events not avoided by reduced anthropogenic activities during COVID outbreak. Resour Conserv Recycl 158:104814
Wei S, Yang H, Abbaspour K, Mousavi J, Gnauck A (2010) Game theory based models to analyze water conflicts in the middle route of the south-to-north water transfer project in China. Water Res 44:2499–2516
West JJ, Smith SJ, Silva RA, Naik V, Zhang Y, Adelman Z (2013) Cobenefits of global greenhouse gas mitigation for future air quality and human health. Nat Clim Change 3:885–889
Zara S, Dinar A, Patrone F (2006) Cooperative game theory and its application to natural, environmental, and water resource issues.

Application to natural and environmental resources, 2nd edn. World Bank, Washington, D.C. (working paper)
Zhang H, Wang S, Hao J, Wang X, Wang S, Chai F, Li M (2016) Air pollution and control action in Beijing. J Clean Prod 112:1519–1527
Zhang Z, Wang X, Zhang H, Guan P, Wang C, Tang G (2021) PM2.5 transport characteristics of typical cities in Beijing-Tianjin-Hebei region in autumn and winter. China Environ Sci. 41(3):993–1004
Zhao N, Wang G, Li G, Lang J, Zhang H (2020) Air pollution episodes during the COVID-19 outbreak in the Beijing-Tianjin-Hebei region of China: an insight into the transport pathways and source distribution. Environ Pollut 267:115617
Zheng S, Yu L (2022) The government's subsidy strategy of carbon-sink fishery based on evolutionary game[J]. Energy (oxford) 254:124282
Zhu Y, Xie J, Huang F, Cao L (2020) Association between short-term exposure to air pollution and COVID-19 infection: evidence from China. Sci Total Environ 727:138704. https://doi.org/10.1016/j.scitotenv.2020.138704