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*Original Research*

# Optimal Allocation of Control Targets for $PM_{2.5}$ Pollution in China's Beijing-Tianjin-Hebei Regions

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**Abstract**

Based on the data of population size, industrial development, energy consumption and technological level from 2013 in the Beijing-Tianjin-Hebei region, the fairness of $PM_{2.5}$ pollution emissions were analyzed using Gini coefficient and contribution coefficient. In addition, a reduction allocation plan of $PM_{2.5}$ concentration by 2020 in 13 cities was determined according to a minimized model of Gini coefficient model. The results showed that: (1) Gini coefficients of industrial development and technological level were greater than 0.4, implying that the $PM_{2.5}$ pollution emissions in the region were significantly unfair from the perspective of industry and technology, especially in the aspect of technological level. (2) The spatial distribution of industrial and technological contribution coefficients presented a downward trend from Beijing and Tianjin to the periphery, and cities in Hebei Province were central to the unfairness of $PM_{2.5}$ pollution emissions across the whole region. (3) The reduction values of $PM_{2.5}$ concentration were between 16.7 1μg/m³ and 57.49 μg/m³, and a reduction allocation plan of $PM_{2.5}$ concentration could improve the overall fairness of $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region, but the unfairness of $PM_{2.5}$ pollution emissions would not change dramatically.

**Keywords**: Beijing-Tianjin-Hebei, $PM_{2.5}$ pollution emissions, Gini coefficient, contribution coefficient

## Introduction

Since the implementation of China's reform and opening-up policy, the economy has achieved rapid development, but $PM_{2.5}$ (particulate matter≤2.5μm) pollution caused by economic growth has become more serious, which is harmful to transportation, human health and industrial production [1-3]. $PM_{2.5}$ pollution episodes in China occur with high frequency, causing a heavy depth of damage with large-scale coverage since 2013, so controlling $PM_{2.5}$ pollution has become an increasing focus of research in China and worldwide [4]. A coordinated development plan of ecological and environmental protection for the Beijing-Tianjin-Hebei region released by the National Development and Reform Commission and the Ministry of Environmental Protection of the People's Republic of China in 2015 pointed out that the average $PM_{2.5}$ concentration in the

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Beijing-Tianjin-Hebei region should be controlled in the range of 64μg/m³ by 2020, a reduction of about 40% compared with 2013 levels (http://he.people.com.cn/n2/2016/0101/c192235-27446335.html).With the target set for reduction, how to allocate pollution loads of different regional units is a key factor in achieving the overall control target of pollutants [5]. Therefore, current efforts are focusing on identifying control targets of $PM_{2.5}$ concentrations in different cities.

The study of pollutant distributions by foreign scholars can be traced back to the emission trading theory proposed by Dales, an American economist, in the 1960s. Namely, the discharge amount of pollutants in internal pollution sources should be adopted in an economic method to realize environment protection targets for the whole region, where the total discharge amount would be guaranteed not to exceed the allowable emissions [6]. As research progressed, scholars gradually realized that this method of allocation ignored the inherent spatial heterogeneity of the research object itself, leading to one-sided economic benefits in the process of controlling and distributing pollutants. Therefore, some scholars began to focus on the transformation of economic benefit to fairness [7]. In 1997, Heli et al. [8] used the Gini coefficient to evaluate the fairness of carbon emissions in 135 countries worldwide from 1960 to 1990, finding that global carbon emissions were declining. Stretesky et al. [9] clearly defined the concept of environmental justice, believing that all groups and social organizations should jointly bear the adverse impacts of environmental pollutants regardless of the differences between national, ethnic and socio-economic factors. In the 21st century, the fairness of pollutant emissions gained more attention from scholars. Burn et al. [10] compared trash allocation schemes as determined by three models and concluded that a distribution plan according to the fairness principle was most reasonable. In view of the fairness of resource utilization, Druckman et al. [11] proposed a method about improving the Gini coefficient and elaborated upon its concept, methodology, application scope and policy implications in detail due to ground monitoring of $PM_{2.5}$ concentrations in China beginning in 2012, where scholars had already concentrated on the distributions of pollutants such as COD [12-13], $NH_3$-N [14], $SO_2$ [15], $CO_2$ [16-17], and so on, leading to the fact that current research on optimal distribution of $PM_{2.5}$ concentrations was rare. Meanwhile, the spatial heterogeneity of $PM_{2.5}$ pollution demonstrated that the traditional distribution method, according to economic benefit, would generate a phenomenon known as "whipping fast cattle" in the proposed reduction schemes. Therefore, it was necessary to determine the optimal target of $PM_{2.5}$ concentrations based on the principle of fairness. Scholars have adopted a variety of methods, including analytic hierarchy process [16], entropy method [18], equal proportion reduction method [19], and emission performance method [20] in the process of distributing total pollutants, but the method of combining the Gini coefficient with a linear target programming model is relatively rare. In terms of research scale, scholars have mainly conducted a few research projects from the river basin scale and diluted the scale connotation of administrative boundaries [21], while the Chinese government played a leading role in the process of controlling and distributing pollutants. There is no doubt that the dislocation between the scale and decision subject would inevitably affect implementation of allocation schemes at the watershed scale.

The Beijing-Tianjin-Hebei region lies in the North China Plain between latitudes 36°N and 43 °N and longitudes 113°E and 120°E, and its land area is 218,000 km², which includes Beijing City, Tianjin City and Hebei Province. It is worth noting that Hebei has jurisdiction over the cities of Baoding, Tangshan, Langfang, Shijiazhuang, Qinhuangdao, Zhangjiakou, Chengde, Cangzhou, Handan, Xingtai and Hengshui (Fig. 1). In 2016, the population reached 110 million, and the gross domestic product was 7,461.26 billion yuan, which played a crucial role in China's economic development pattern [22]. At the same time, the Beijing-Tianjin-Hebei region also faced a serious $PM_{2.5}$ pollution situation, with the average annual $PM_{2.5}$ concentration in the region measured at 71 μg/m³ in 2016, which was higher than the national average of

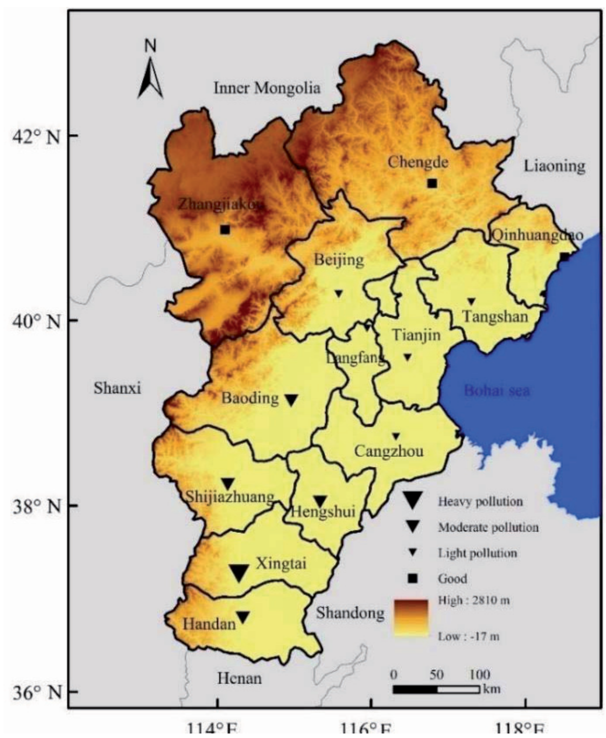


Fig. 1. Spatial distribution of $PM_{2.5}$ pollution in the Beijing-Tianjin-Hebei region in 2013.
Note: the classification of $PM_{2.5}$ pollution in 2013 is based on the National environmental air quality standards (GB3095-2012) released by the Ministry of Environmental Protection in 2012 (https://wenku.baidu.com/view/9a20c696daef5ef7ba0d3cdd.html)

24μg/m³, and was considered to be the most polluted area in China. To control or ease $PM_{2.5}$ pollution in the region, a plan for the prevention and control of air pollution in the region and surrounding areas was released by the Ministry of Environmental Protection in 2017. It defined "2 + 26" cities as air pollution control transmission channels, implying that curbing $PM_{2.5}$ pollution in the Beijing-Tianjin-Hebei region was a new situation requiring regional joint prevention (http://www.gov.cn/xinwen/2017-12/11/content_5245830.htm). Therefore, this paper used the Gini coefficient and contribution coefficient to evaluate the fairness of $PM_{2.5}$ pollution emissions in 2013 in the Beijing-Tianjin-Hebei region based on the data of population size, industrial development, energy consumption and technological level. Then, a minimized model of the Gini coefficient was built to identify an optimal allocation plan of $PM_{2.5}$ concentration in 13 cities by 2020, for the sake of providing a reference for government decision-making.

## Data and Methods

### Data Sources

To evaluate fairness of $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region using Gini coefficient, it was necessary to establish an evaluation index system. Scholars generally agree that natural factors are the external causes of $PM_{2.5}$ pollution, and human factors are the underlying factors causing $PM_{2.5}$ pollution [23]. The paper selected evaluation indexes based on human factors:

1) Population size. Areas with a large population tend to generate high demand for housing, travel and household uses, which in turn leads to $PM_{2.5}$ pollution [24]. In addition, there are usually urban problems such as traffic congestion and residential density in these areas, which are not conducive to the full burning of fossil fuels and diffusion of pollutants, worsening the level of $PM_{2.5}$ pollution.
2) Industrial development. Studies have revealed that there was a stable relationship between industrial development and energy demand [25], which indirectly affected the $PM_{2.5}$ pollution emissions. The paper selected gross value of industrial output to represent industrial development.
3) Energy consumption. Energy consumption is directly related to $PM_{2.5}$ pollution emissions. According to statistics, total coal consumption in the Beijing-Tianjin-Hebei region in 2013 was 389.61 million tons, which accounted for about 88% of total energy consumption (http://www.sic.gov.cn/News/455/6983.htm). This coal-based energy structure was undoubtedly the main cause of $PM_{2.5}$ pollution, so the GDP for each city was multiplied by the energy consumption intensity per unit GDP to calculate total energy consumption.
4) Technological level. The development of science and technology can alleviate $PM_{2.5}$ pollution through innovative production technologies and the promotion of energy conservation and environmental protection measures [24]. Therefore, the index of Research and Development (R&D) expenditures were selected to reflect technological level.

The paper selected 13 cities in the Beijing-Tianjin-Hebei region as basic research units, and the data consisted of $PM_{2.5}$ concentrations and socio-economic statistics data. Among them, the data of $PM_{2.5}$ concentration measured in 2013 came from 73 air-quality monitoring stations released by China's environmental ground monitoring station (http://www.cnemc.cn/), while social and economic data such as total population, gross value of industrial output, gross domestic product, energy consumption intensity per unit GDP and R&D expenditures were from the 2014 China statistical yearbook (http://www.stats.gov.cn/tjsj/ndsj/) and the 2014 Hebei economic yearbook (http://www.hetj.gov.cn/). We must explain that the data of population size adopted in this paper was the number of permanent residents, and the data of R&D expenditures in Hebei was derived from the statistical bulletin of science and technology expenditures in Hebei province in 2013.

### Methods

#### *Gini Coefficient*

The Gini coefficient was originally designed as an analytical tool for measuring the gap of income distribution. In recent years, the method has been widely used in the fields of resource management, environmental protection and government decision-making. Firstly, the $PM_{2.5}$ concentrations per unit index for 13 cities were sorted by an increasing order. Secondly, the cumulative proportion of $PM_{2.5}$ concentration was plotted along the vertical axis, and the cumulative proportion of each index was plotted along the horizontal axis to draw the Lorenz curve. Finally, the Gini coefficient was calculated based on the trapezoidal area method. The formula is as follows [26]:

$$G_j = 1 - \sum^{n} \left(X_{j(i)} - X_{j(i-1)}\right) * \left(Y_{j(i)} + Y_{j(i-1)}\right) \tag{1}$$

…where $j$ represents the index number and $i$ is the city unit. $G_j$ is the Gini coefficient based on index $j$. $Xj(I)$ is the cumulative proportion of index $j$ in the $i$ th city, and $Y_j(I)$ is the cumulative proportion of $PM_{2.5}$ concentration in the $i$ th city. When $i$ is equal to 1, ($X_{j(i-1)}$, $Y_{j(i-1)}$) it changes into (0,0). According to the international division standard of Gini coefficient [27], the Gini coefficient was divided into absolute fairness, relatively fair, relatively reasonable, poor and wide disparity corresponding to respective value ranges of 0~0.2, 0.2~0.3, 0.3~0.4, 0.4~0.5 and 0.5~1.0.

*Contribution Coefficient*

The Gini coefficient can reflect the overall fairness of $PM_{2.5}$ pollution emissions, but it does not reveal the underlying causes. Therefore, it is necessary to use a contribution coefficient to analyze unfair causes of $PM_{2.5}$ pollution emissions. The formula is as follows [27].

$$C_{ij} = \left(\frac{M_{ij}}{M_j}\right) / \left(\frac{W_{ij}}{W_j}\right) \tag{2}$$

…where $C_{ij}$ is the contribution coefficient for index *j*. $M_{ij}$ is the value of index *j* in the *i* th city, and $M_j$ is the sum of the index *j* for all cities. $W_{ij}$ is the $PM_{2.5}$ concentration for city *i*, and $W_j$ is the sum of $PM_{2.5}$ concentration.

*Minimized Nodel of Gini Coefficient*

Generally, the smaller the Gini coefficient, the fairer $PM_{2.5}$ pollution emissions are. This paper built a minimized model of the Gini coefficient by minimizing the sum of the Gini coefficient for each index by 2020 as an objective function, setting total, upper and lower reduction rates for each city, and using the origin Gini coefficients as constraint conditions. The formulas are as follows [28].

Objective function:

$$MinF = \sum_{j=1}^{4} G_j \tag{3}$$

Total reduction rate constraint:

$$\sum_{i=1}^{n} W_i = (1-q)x \sum_{i=1}^{n} W_{0(i)} \tag{4}$$

Gini coefficient constraint in 2013:

$$G_j \le G_{0(j)} \tag{5}$$

Upper and lower reduction rate constraints for each city:

$$P_{Min} \le \frac{W_{0(i)} - W_i}{W_{0(i)}} \le P_{Max} \tag{6}$$

*F* is the sum of the Gini coefficient for index *j*; $W_{0(i)}$ is the $PM_{2.5}$ concentration for city *i* in 2013; $W_i$ represents the control target for $PM_{2.5}$ concentrations in city *i* by 2020; *q* is the total reduction rate of $PM_{2.5}$ concentrations/%. $G_{0(j)}$ is original Gini coefficient for index *j* in 2013; $P_{Min}$ and $P_{Max}$ are upper

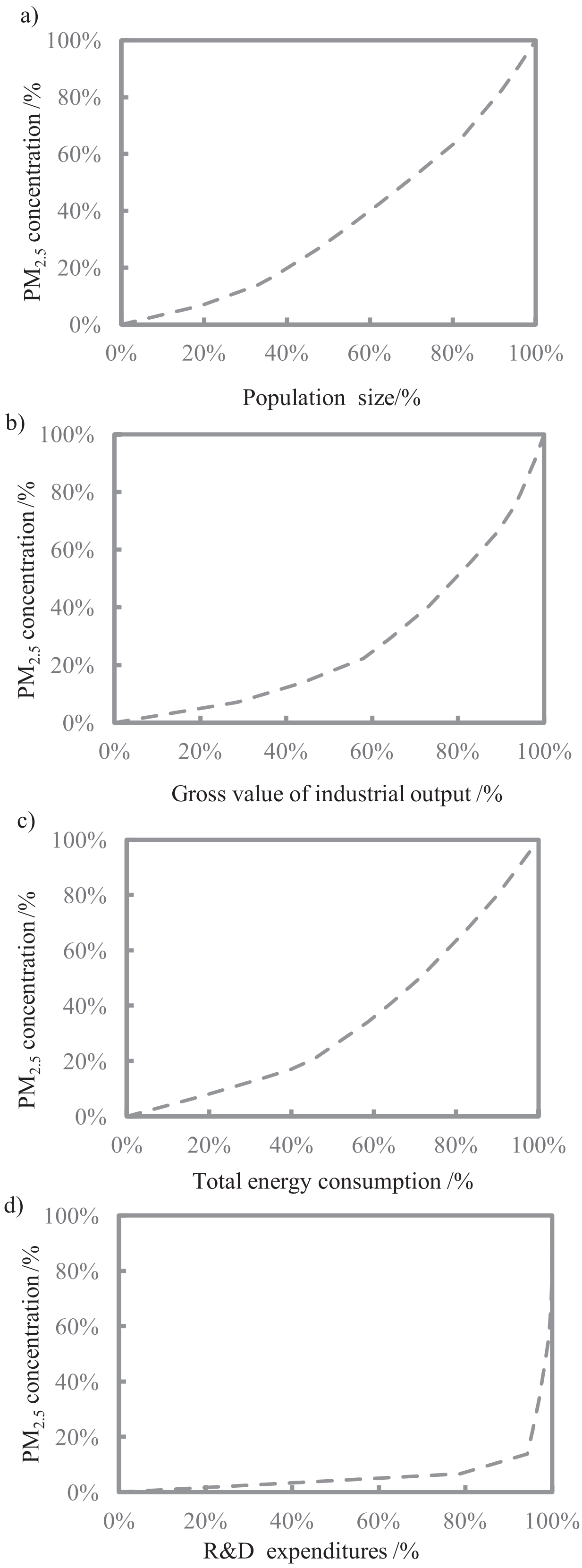


Fig. 2. Lorenz curves for $PM_{2.5}$ and four indexes in the Beijing-Tianjin-Hebei region in 2013: a) cumulative proportion of population size and $PM_{2.5}$ concentration, b) cumulative proportion of gross value of industrial output and $PM_{2.5}$ concentration, c) cumulative proportion of total energy consumption and $PM_{2.5}$ concentration, d) cumulative proportion of R&D expenditures and $PM_{2.5}$ concentration.

and lower limited $PM_{2.5}$ concentration reduction rates for city *i*.

## Results and Analysis

### Evaluating the Fairness of $PM_{2.5}$ Pollution Emissions

The control and distribution of pollutants was based on the fairness of the current situation of pollutant emissions. We took the average $PM_{2.5}$ concentrations from 13 cities in the Beijing-Tianjin-Hebei as control factors and ranked the $PM_{2.5}$ concentration per unit population size, gross value of industrial output, total energy consumption and R&D expenditures from small to large. Finally, the cumulative proportions for each index and $PM_{2.5}$ concentrations were calculated respectively, and the Lorenz curves were plotted (Fig. 2). According to formula (1), the Gini coefficients of each index were obtained (Table 1).

As shown in Table 1 and Fig. 2, the Gini coefficient for population size in 2013 was the smallest, with a value of 0.2916 and in the range of 0.2~0.3, showing that $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region was fair from the perspective of population distribution. The Gini coefficient for industrial development was 0.4566, exceeding the alert level of 0.4, indicating that the fairness of $PM_{2.5}$ pollution emissions was poor and needed to be optimized and adjusted. The Gini coefficient for energy consumption was 0.3124, indicating that energy consumption and $PM_{2.5}$ pollution emissions were somewhat compatible in terms of spatial distribution. Namely, cities with a large amount of energy consumption tended to be areas with severe $PM_{2.5}$ pollution. The Gini coefficient for technological level was the largest, with a value of 0.8729, and doubled the alert level of 0.4, showing that fairness of $PM_{2.5}$ pollution emissions in the aspects of technology were very poor due to the disparity in technological levels. It was concluded that there was a significant unfairness of $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region based on the indexes of gross value of industrial output and R&D expenditures, especially for technological level. Although the Gini coefficients for population size and energy consumption were within a relatively fair range, there was still a considerable gap between Gini coefficients and the upper limit of the absolute fairness range. The control goals of $PM_{2.5}$ concentration for each city in the future should meet the total reduction rate, and much work should be done to reduce the origin Gini coefficients for population size, industrial development, energy consumption and technological level to improve the fairness of $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region.

### Analysis of the Unfairness of $PM_{2.5}$ Pollution Emissions

Overall, $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region were not fair in the aspects of industry and technology, so it was necessary to analyze the causes of unfairness using the contribution coefficient. According to formula (2), the contribution coefficients for each city's industrial development and technological level were obtained, which were classified in the ranges of 0~0.5, 0.5~1.0, 1.0~1.5 and greater than 1.5 (Fig. 3) with the help of GIS software.

Fig. 3a) showed that the contribution coefficients of industrial development in Beijing, Tianjin and Tangshan were 4.0198, 2.2588 and 4.0198, respectively. All were greater than 1.5, meaning that gross value of industrial output in these cities was relatively high while $PM_{2.5}$ pollution was relatively low, so $PM_{2.5}$ pollution emissions of each unit gross value of industrial output was relatively small, but the cause of the phenomenon was different. Beijing, as the capital of China, has a large population and a number of enterprises that generated heavy pressure on the environment. With the acceleration of industrial transformation and the upgrades and transfer of energy-intensive industries to Hebei and the surrounding areas in recent years, $PM_{2.5}$ pollution in Beijing had been alleviated to some degree, leading to a high contribution coefficient of industrial development. Although Tianjin and Tangshan faced more serious $PM_{2.5}$ pollution than Beijing, the industrial structure of Tianjin and Tangshan prioritized heavy industry for a long time, which made up a larger proportion of the national economy. As a result, heavy industry boosted the industrial contribution coefficients for Tianjin and Tangshan. The contribution coefficients of industrial development for Chengde, Cangzhou, Shijiazhuang, Zhangjiakou, Baoding, Langfang, Qinhuangdao Handan, Xingtai and Hengshui were all less than 1, indicating that industrial production in these cities was mainly based on extensive economic growth. The industrial contribution coefficients for Langfang, Qinhuangdao, Xingtai and Hengshui were

Table 1. Gini coefficients for $PM_{2.5}$ pollution based on each index in the Beijing-Tianjin-Hebei region.

| | Population size | Industrial development | Energy consumption | Technological level |
|---|---|---|---|---|
| Initial Gini coefficient | 0.2916 | 0.4566 | 0.3124 | 0.8729 |
| Optimal Gini coefficient | 0.2846 | 0.4429 | 0.3022 | 0.8676 |
| Variation of Gini coefficient | 0.0070 | 0.0137 | 0.0102 | 0.0053 |
| Reduction rate of Gini coefficient | 2.4001% | 3.0000% | 3.2650% | 0.6072% |

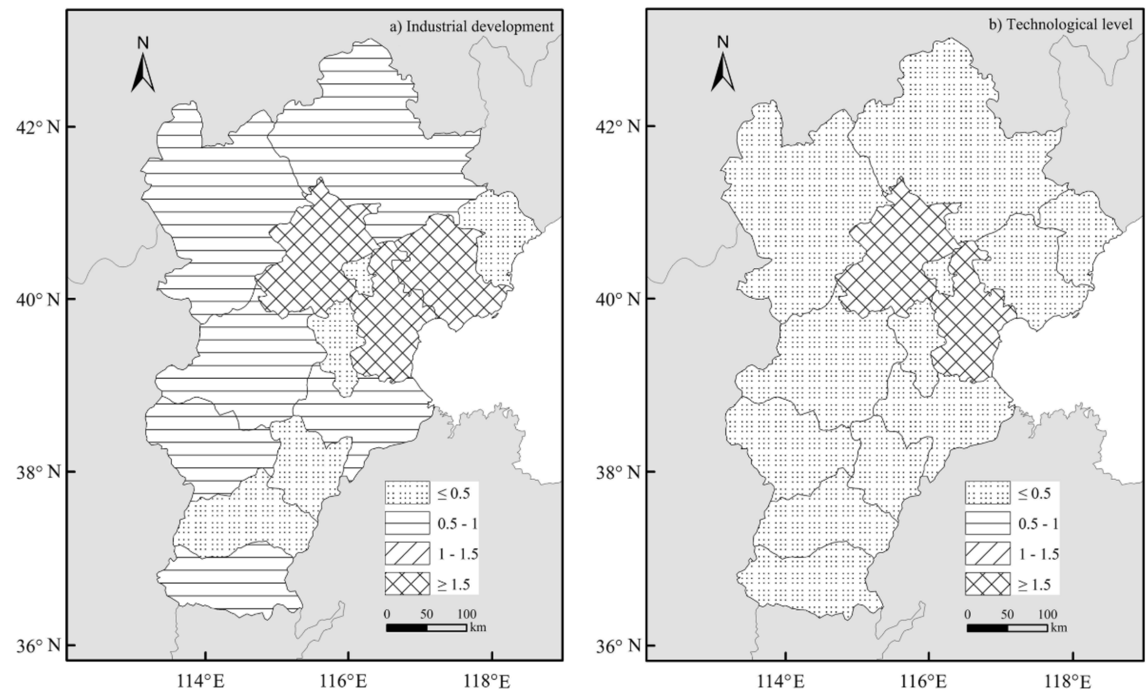


Fig. 3. Spatial distribution of contribution coefficients for industrial development and technological level.

below 0.5, which was the key factor that contributed to the unfairness of $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region. Fig. 3b) shows the spatial distribution of contribution coefficients for the technological level. We found that the contribution coefficients of technological level in Beijing and Tianjin were greater than 1.5 and had a higher fairness thanks to a good economic development foundation that made it possible to have high investments in education and technology. The technological contribution coefficients for 11 cities in Hebei province were less than 0.5 – evidence of serious unfairness. In summary, Beijing and Tianjin had better equity, and the cities in Hebei province were the main reasons for the unfairness of $PM_{2.5}$ pollution emissions in the region from the perspective of industrial development and technological level. The spatial distribution of industrial and technological contribution coefficients generally had a decreasing trend from Beijing and Tianjin to the periphery.

## Determining the Reduction Targets for $PM_{2.5}$ Pollution

The coordinated development plan of ecological and environmental protection for the Beijing-Tianjin-Hebei region in 2015 concluded that there should be a 40% reduction rate for $PM_{2.5}$ concentration in the whole region by 2020. Considering the reduction potential of $PM_{2.5}$ concentration and social economic development level for each city, the upper and lower reduction rates by 2020 were set as plus or minus 10% of the total reduction rate. The reduction scheme for $PM_{2.5}$ concentrations was obtained using Lingo11.0 software based on formulas (3) to (6) (Tables 1, 2).

Table 1 showed that the optimal Gini coefficients for population size, industrial development, energy consumption and technological level were 0.2826, 0.4429, 0.3022 and 0.2826, respectively, with reductions of 2.40%, 3.00%, 3.27% and 2.40% compared with the original Gini coefficients, indicating that the fairness of reduction plan in the Beijing-Tianjin-Hebei region by 2020 had been improved to some degree compared with 2013, especially for industrial development and energy consumption. At the same time, there was still significant unfairness in the $PM_{2.5}$ concentration reduction plan for 2020, which was mainly caused by long-term pollution emissions. Table 2 showed that the five cities with the highest reduction rates were Tangshan, Langfang, Cangzhou, Tianjin and Baoding, with corresponding cut values of $PM_{2.5}$ concentrations being 57.05, 44.04, 44.60, 57.49 and 50.85 μg/m³, implying that $PM_{2.5}$ concentration in these cities had a larger reduction potential due to local economic development. The reduction rate in Qinhuangdao was 43.14% – exceeding the overall reduction rate in the region. Although $PM_{2.5}$ pollution in Qinhuangdao was relatively low because of its good economic development foundation and relatively reasonable industrial structure, Qinhuangdao might shoulder greater responsibility for the reductions in $PM_{2.5}$ pollution emissions. Reduction rates of $PM_{2.5}$ concentrations in Hengshui, Zhangjiakou and Handan were 39.24, 38.77 and 38.21%, respectively, slightly below the overall rate cuts. The reduction rates in Chengde, Beijing, Shijiazhuang and Xingtai were 34.63, 33.89, 31.91 and 30.96%, which were also significantly

Table 2. Reduction plan for $PM_{2.5}$ concentrations in the Beijing-Tianjin-Hebei region.

| | $PM_{2.5}$ concentration in 2013 (μg /m$^3$) | Reduction value (μg /m$^3$) | Reduction rate (%) | $PM_{2.5}$ concentrations in 2020 (μg /m$^3$) |
|---|---|---|---|---|
| Beijing | 90.10 | 30.54 | 33.89 | 59.56 |
| Tianjin | 95.60 | 44.60 | 46.65 | 51.00 |
| Shijiazhuang | 148.50 | 47.38 | 31.91 | 101.12 |
| Tangshan | 114.20 | 57.05 | 49.96 | 57.15 |
| Qinhuangdao | 65.20 | 28.12 | 43.14 | 37.08 |
| Handan | 127.80 | 48.83 | 38.21 | 78.97 |
| Xingtai | 155.20 | 48.06 | 30.96 | 107.14 |
| Baoding | 127.90 | 57.49 | 44.95 | 70.41 |
| Zhangjiakou | 43.10 | 16.71 | 38.77 | 26.39 |
| Chengde | 51.50 | 17.84 | 34.63 | 33.66 |
| Cangzhou | 93.60 | 44.04 | 47.05 | 49.56 |
| Langfang | 113.80 | 50.85 | 44.68 | 62.95 |
| Hengshui | 120.60 | 47.32 | 39.24 | 73.28 |
| Sum | 1347.10 | 538.84 | 40.00 | 808.26 |

lower than the overall reduction rate. Among them, Beijing began monitoring $PM_{2.5}$ concentrations early, and efforts at curbing haze had achieved initial results. In sum, $PM_{2.5}$ pollution had been brought under effective control. If greater reductions were made, it would increase the social and economic costs of Beijing's efforts to control $PM_{2.5}$ pollution, affecting the city's initiative to reduce $PM_{2.5}$ pollution. Chengde was in the northern part of the Beijing-Tianjin-Hebei region, with a relatively small population, weak industrial base and limited energy consumption. Therefore, its $PM_{2.5}$ pollution was relatively light. In addition, the city was easily affected by the prevailing winds, which was conducive to the transmission and diffusion of $PM_{2.5}$ pollution. The lower $PM_{2.5}$ concentrations meant that Chengde was not responsible for high responsibility of reducing $PM_{2.5}$ pollution emissions. On the contrary, Shijiazhuang and Xingtai were the areas with the most $PM_{2.5}$ pollution and should have greater responsibility for reducing emissions. However, Shijiazhuang and Xingtai had heavy industry with extensive economic growth and an energy structure dominated by fossil fuels and limited technology, which severely restricted their ability to reduce $PM_{2.5}$ pollution emissions.

## Discussions

The reduction targets of $PM_{2.5}$ concentration determined in the Beijing-Tianjin-Hebei region by 2020 were of great importance in reference to reducing $PM_{2.5}$ pollution. However, the edges of urban built-up areas, small towns and rural areas had few $PM_{2.5}$ monitoring stations, leading to the fact that existing monitoring stations were difficult to fully reflect the spatial distribution of $PM_{2.5}$ pollution, so the data of $PM_{2.5}$ concentration adopted would affect the evaluation result. In addition, the fair evaluation of $PM_{2.5}$ pollution emissions and the optimal allocation of $PM_{2.5}$ concentrations was based on isolated records for each city. In fact, the study area differed in thousands of ways of social and economic factors, combined with the meteorological factors and terrain conditions, determining that $PM_{2.5}$ pollution had a strong transmission characteristic across different areas, which could affect the accuracy of the evaluation results. Finally, when we evaluated the fairness of $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region for 2020, ignoring dynamic changes in the aspects of population, industry, energy and technology, it would also eventually affect the reduction scheme of $PM_{2.5}$ concentration.

## Conclusions

1) $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region were unfair in terms of industrial development and technological level, and relatively reasonable in energy consumption, and relatively fair in population size. Gini coefficients of population size and energy consumption in 2013 were below the alert level of 0.4, but there was still a big gap between the actual Gini coefficients and the upper limit of the absolute the fair range. Gini coefficients of industrial development and technological level were 0.4566 and 0.8729, and an optimal allocation of $PM_{2.5}$ pollution emissions was urgently needed.

2) The spatial distribution of the industrial and technological contribution coefficients generally decreased from Beijing and Tianjin to the periphery; cities in Hebei Province largely led to the unfairness of $PM_{2.5}$ pollution emissions for the whole region. Industrial contribution coefficients in Beijing, Tianjin and Tangshan were greater than 1.5, and technological contribution coefficients in Beijing and Tianjin were also greater than 1.5, but industrial and technological contribution coefficients in the remaining cities were less than 1.0, which was identified as the unfair cause of $PM_{2.5}$ pollution emissions in the Beijing-Tianjin-Hebei region.
3) By 2020, the optimal reduction plan of $PM_{2.5}$ concentration in the Beijing-Tianjin-Hebei region had promoted fairness of $PM_{2.5}$ pollution emissions to some degree, but some unfairness still existed. Cities with the largest reduction rates included Tangshan, Baoding, Langfang, Cangzhou, Tianjin and Qinhuangdao, while the cities with lower reduction rates were Hengshui, Zhangjiakou, Handan, Chengde, Beijing, Shijiazhuang and Xingtai.

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## Conflict of Interest

The authors declare no conflict of interest.

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