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Original Research

Research on Joint Governance Network of Regional Haze Pollution from the Perspective of Spatial Spillover

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Abstract

Haze pollution (HP), a major concern in air pollution, poses a threat to human health as well as the sustainable development of society. Due to the limitations of unilateral governance, joint governance (JG) has become a new targeted management strategy. This study aims to construct the Spatial Dubin Model (SDM) to verify the spatial spillover of HP and environmental regulation (ER). Based on this, the gravity model and social network analysis (SNA) are adopted to construct inter-provincial HP networks and JG networks. Finally, the Pan Beijing-Tianjin-Hebei and Yangtze River Deltas are selected as the representatives for a comparative analysis of the haze JG network. The findings indicate that: (1) there is a spatial spillover of haze, leading to malignant cross-pollution among regions, and the presence of a "free riding" phenomenon in environmental governance; (2) The Pan Beijing-Tianjin-Hebei and Yangtze River Delta regions exhibit higher network density (ND) compared to the national level, while the ND in JG network is significantly lower than that of HP networks across all regions; (3) The clustering trend of HP network in Pan Beijing-Tianjin-Hebei is not evident, whereas the JG network demonstrates high in-degree centralization; (4) The Yangtze River Delta has seen an accumulation of HP near Nanjing, Ma'anshan, and Chuzhou, accompanied by considerable ER disparities and an illogical layout of the JG network; (5) The prevailing disparities in endogenous power, political factors, and collaborative prospects contribute to the Pan Beijing-Tianjin-Hebei region's overall advantage in terms of network proximity and node arrangement compared to the Yangtze River Delta.

Keywords: HP, joint governance space network, Pan Beijing-Tianjin-Hebei, Yangtze River Delta, comparison

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Introduction

With accelerated industrialization and urbanization, air pollution is a frequent problem in developing countries [1]. HP is a serious environmental issue that damages air quality, climate, and human health [2, 3]. Additionally, HP has severely hindered sustainable development in China [4]. Rafaj et al. pointed out that HP causes approximately 6.5 million premature deaths each year [5]. During the first quarter of 2013, China suffered extremely severe, large-scale HP [6]. The regions with frequent HP in China are mainly distributed in economically developed, concentrated areas. For instance, the Yangtze River Delta, the Beijing-Tianjing-Heibei, the Pearl River Delta, etc. [7]. In response to the persistent HP, the Chinese government has promulgated and implemented a series of policies and regulations [8]. However, due to the high connectivity of the atmospheric environment, the HP has exceeded political and economic boundaries. The original place can affect the surrounding cities and even countries far away from the ocean [9]. Thus, it is hardly possible to achieve the goal of haze reduction by dividing the regions and administering them separately. As a result, the administrative regions that have been independent in pollution control for a long time are required for the regional JG, which becomes a new strategic decision.

The remainder of the study is structured as follows: Section 2 presents the literature review. Section 3 provides the material and methods. Section 4 explains the empirical results. Section 5 covers further discussion. The final section concludes with the main findings and policy implications.

Literature Review

The Causes of Air Pollution

The main indicators of air quality have been released to the public for scrutiny and pollution research, such as the hourly average mass concentrations of PM, SO_2, and NO_2. Among them, fine particulate matter (PM2.5) accounts for much of China's poor air quality [10]. Particulate emissions mainly come from transportation, biomass combustion, coal combustion, and dust emissions [11]. Industrial pollution emissions are the main cause of HP [12]. The proportion of coal in energy consumption and the rapid growth of economic development levels lead to the aggravation of HP [13].

The Spatial Spillover of Air Pollution

Moreover, air pollution has significant spatial spillover. Wuebbles et al. found that the air quality in parts of North America was affected by the pollutants transported from Asia [14]. Fang et al. reported that significant spatial dependence and heterogeneity existed in Air Quality Index (AQI) values [15]. Meanwhile, Asian pollutant outflows on the global general circulation and climate have a large impact [2]. Additionally, it has been found that China's dust storms and particulate pollution can even cross the Pacific Ocean, significantly affecting the air quality in Oregon and California [16].

The Governance of HP

After experiencing serious HP since 2013, individuals pay more attention to air quality and the adverse impact of $PM_{2.5}$ on their health [17]. Meanwhile, it drove the government to explore effective methods to control HP. Academics have undertaken research focusing on how the government handles HP. For instance, the regulation brought a short-term, substantial improvement in air quality in Beijing [18]. Long-term continuous supervision has the advantages of low management costs and wide management scope compared with short-term centralized supervision [19]. Besides, the choices of local government in haze governance were a process of mutual game and compromise between multiple subjects based on different value standards and interest demands [20]. The haze control index was picked as a governance tool, and the haze governance policies and measures were put forward [21].

The JG of HP

Given the limitations of unilateral governance of HP, a wave of research on the JG of HP has also emerged in recent years, such as changes in local government behavior in HP regional collaborative governance under different performance evaluation systems [22]; suggestions for public opinion monitoring of haze governance from the perspective of joint urban and regional governance [23]; and the dynamic evolution of Beijing-Tianjin-Hebei in the implementation of haze cooperative governance, depending mainly on the environmental preference coefficient and the free ratio of riding income to collective action income [24]. Cooperative governance can be carried out not only in provinces and cities but also in countries [25, 26]. However, international negotiations on cross-border environmental issues are very challenging considering the different interests of the participating countries, which leads to the complexity of cross-border environmental pollution governance.

SNA

As far as research methods are concerned, many of them have been applied in the research field of air pollution governance. For instance, case study [27], system dynamics [28], structural equation models [29], empirical research [30, 31], evolutionary games [32], etc. However, few scholars have chosen SNA to explore the spatial interaction of HP and ER. SNA is a classic method used to study interpersonal relationships [33], which is widely used in the field of social sciences. Additionally, we apply the gravity model to quantify its spatial relevance and combine the SNA to establish the interprovincial HP network and JG network. Based on the national haze spatial distribution and regional deployment of air pollution joint prevention and control policy, the Pan Beijing-Tianjin-Hebei and Yangtze River Delta are selected as the representatives to conduct a comparative analysis of the joint prevention and control network of HP, so as to explore the problems and optimization directions of the regional JG layout.

Material and Methods

Spatial Measurement Model

Firstly, the Spatial Durbin Model (SDM) [34, 35] is constructed to verify the spatial spillover of HP and ER under the premise of different degrees of geographical proximity. The formula is as follows:

$$LnPM_{it} = \beta_0 + \beta_1 Ln\sum_{j\neq i} W_{ij}PM_{jt} + \beta_2 LnER_{it} + \beta_3 Ln\sum_{j\neq i} W_{ij}ER_{jt} + \beta_4 LnX_{it} + \varepsilon_{it} \tag{1}$$

$$LnER_{it} = \beta_0 + \beta_1 Ln\sum_{j\neq i} W_{ij}ER_{jt} + \beta_2 LnX_{it} + \varepsilon_{it} \tag{2}$$

where *i* and *j* denote the regions (*i, j* = 1,2,…30); *t* denotes the period. PM_{it} or PM_{jt} is the HP degree of regions *i* or *j* in year *t*; *ER* represents the intensity of environmental regulation; W_{ij} is the spatial weight matrix composed of regions *i* and *j*. *X, β, ε* are the control variables, the parameter to be estimated, and the random error term, respectively. To avoid heteroscedasticity, all variables have been standardized.

A Modified Gravity Model

After verifying whether there is a spatial correlation between HP and ER, we need to measure and analyze the degree of correlation in order to establish the relevant network structure. The gravity model can measure the spatial forces, and the traditional gravitation model is as follows:

$$F_{ij} = K\frac{Y_i \times Y_j}{D_{ij}} \tag{3}$$

where F_{ij} represents the spatial force between region *i* and *j*, Y_i and Y_j are endogenous variables; *K* is the coefficient of gravity; D_{ij} represents the spatial distance between two regions. Combined with the research purpose, the gravity models of HP and ER are established as follows:

$$R_{ij} = \alpha_{ij}\frac{PM_i \times PM_j}{D_{ij}}, \alpha_{ij} = \frac{PM_i}{PM_i + PM_j} \tag{4}$$

$$T_{ij} = \theta_{ij}\frac{ER_i \times ER_j}{D_{ij}}, \theta_{ij} = \frac{ER_i}{ER_i + ER_j} \tag{5}$$

where R_{ij} and T_{ij} represent the connection degree of HP and ER between region *i* and *j*. α_{ij} and θ_{ij} are correction coefficients, representing the contribution rate of region *i* in the HP and ER spatial connection degree of region *i* and *j*, respectively.

SNA

SNA stands as a crucial method for quantitative research in network studies. This approach seeks to represent social networks using graphs and matrices, utilizes graph theory and algebra to analyze relationship patterns, and delves deeper into how these patterns impact insiders and the entire social network. The overall and individual network structure characteristics are explained, respectively. First, the overall network structure characteristics are described by network density (*ND*) and degree centralization (*DC*). *ND* is the ratio of the actual number of connections to the total possible number of connections between the nodes, reflecting the closeness of the spatial correlation network [36]. The higher the *ND*, the closer the relationship between the two regions. The calculation formula is as follows:

$$ND = n/[N(N-1)] \tag{6}$$

where *n* is the sum of all network connections and *N* is the number of nodes in the network. *DC* is the overall centrality of the network. The higher the *DC*, the more obvious the network clustering.

For an individual network structure, degree centrality(*De*) is the number of direct ties that a node possesses [37]. The higher the *De*, the more likely the region is the center of the network, and the more connections it has with other regions. The formula is as follows:

$$De = \frac{L}{N(N-1)-1} \tag{7}$$

where *L* stands for the number of regions directly associated with other regions. For directed networks, *De* can be divided into in-degree and out-degree. The former represents the number of received relations, and the latter represents the number of issued relations [38]. Correspondingly, *DC* includes in-degree centralization and out-degree centralization.

Main Variables and Data Sources

The sample data in this paper are the balanced panel data of 30 provinces in inland China (except Hong Kong, Macao, Taiwan, and Tibet) from 2011 to 2020. Except for pollution data and geographic data, the rest of the data comes from the China Statistical Yearbook and the China Urban Statistical Yearbook.

Haze Pollution Level (PM)

The main components of HP are PM_{10} (particulate matter smaller than 10 μm), $PM_{2.5}$ (particulate matter smaller than 2.5 μm), and other suspended particles. $PM_{2.5}$ can more accurately reflect the level of haze compared with PM_{10}. Based on the results of Van Donkelaar et al. [39], the data on HP is sourced from the annual average $PM_{2.5}$ concentration provided by the Atmospheric Composition Analysis Group of Washington University in St. Louis.

Environmental Regulation (ER)

ER can be divided into legal regulation, economic instruments, and informal ER. Given that regional JG is mainly reflected in laws and policies, *ER* in this research mainly refers to the form of legal regulation. Therefore, the pollution reduction expenditure per unit of output value of each region is picked as the representative indicator of ER [40].

Control Variables

The definitions of control variables are listed in Table 1. In addition, the descriptive statistical explanations for each variable are presented in Table 2.

Geographical Distance and Spatial Weight Matrix

Based on the longitude and latitude, the geographical distance of each city is calculated. Considering that all cities in China are located at longitude east and latitude north, the distances between the two points are calculated as follows:

$$D_{ij} = r \times \arccos\left\{ \sin\left[\left(90 - LAT_i\right) \times \frac{\pi}{180}\right] \times \sin\left[\left(90 - LAT_j\right) \times \frac{\pi}{180}\right] \right.$$
$$\left. \times \cos\left[\left(LON_i - LON_j\right) \times \frac{\pi}{180}\right] + \cos\left[\left(90 - LAT_i\right) \times \frac{\pi}{180}\right] \times \cos\left[\left(90 - LAT_j\right) \times \frac{\pi}{180}\right] \right\} \tag{8}$$

Table 1. Definitions of control variables.

Variable name	Abbreviation	Indicator	Unit
Scientific and technological level	*ST*	The number of three patent applications	-
Industrial structure	*IS*	Secondary industry accounts/GDP	%
Foreign direct investment	*FDI*	Foreign direct investment/GDP	%
Energy consumption structure	*ECS*	Coal consumption/ total energy consumption	%
Highway transportation	*TRA*	Highway mileage/ administrative area	%
City heating	*HEAT*	Proportion of collective heating area in each region	%

Note: The heating area of the city may be zero, which results in invalid value. Therefore, we use 0.0001 to replace 0 to ensure that the value is minimized as much as possible.

Table 2. Variables and descriptive statistics.

Variable	Obs	Min	Max	Mean	Std. Dev.
LnPM	390	1.938	4.406	3.395	0.549
LnER	390	-9.210	2.412	-0.853	1.155
LnST	390	-1.469	4.466	1.464	1.296
LnIS	390	-1.647	-0.527	-0.779	0.202
LnFDI	390	-3.049	1.741	-1.356	0.868
LnECS	390	-2.112	-0.063	-0.474	0.316
LnTRA	390	-3.247	0.747	-0.500	0.837
LnHEAT	390	-9.210	1.308	-5.156	3.521

where *r* represents the average radius of the earth, which is about 6,371 km. *LON* and *LAT* represent the longitude and latitude of the city, respectively. The data for *LON* and *LAT* comes from the website of the National Basic Geographic Information Center. It should be noted that the link between urban air pollution and policies frequently appears to have a diminishing effect as geographical distance grows. Consequently, a geographic distance weight matrix is employed in this research. The matrix elements are set to $1/D_{ij}$, that is, the weight values are negatively correlated with distance, and the diagonal elements are set to 0.

Results

The Spatial Spillover of HP and ER

First of all, based on the regression analysis of *SDM*, we explored the presence of inter-provincial cross-effects of HP and spatial interaction effects of ER. When the regression samples are restricted to some specific individuals, it is more reasonable to select the Fixed Effect Model (*FEM*) [41].

Table 3 shows that HP in neighboring cities contributes significantly to local cities, which verifies the spatial spillover effect of HP. The phenomenon of regional cross-pollution increases the difficulty of haze management. The improvement of ER can significantly reduce HP, and legal regulation is always necessary to mitigate air pollution. The estimated coefficient of *WGR* is significantly negative, which indicates that the local environment can be positively affected by ER in areas with high spatial proximity. Therefore, it can be considered that haze governance presents the trend of "neighbors as partners". Strict control of air pollution is responsible for local and surrounding cities.

Table 3. The spatial spillover of PH and ER.

Variable	Estimated coefficient	
	PH	ER
C	-0.120***	0.090***
LnWGR	0.380***	-0.072**
LnST	-0.186***	0.207***
LnIS	-0.062**	0.018
LnFDI	0.212***	-0.057
LnECS	0.223***	-0.037
LnTRA	0.425***	-0.060**
LnHEAT	0.035*	0.116***
R^2	0.263***	0.274
$\bar{R}^2$	0.513***	0.559
F	0.648	11.505***

Note: ***, ** and * indicates significance at the 1%, 5% and 10% levels, respectively.

All control variables significantly increase HP. First, the advanced technology level does not mitigate HP, which indicates the current low share and utilization of clean technology R&D. Besides, the negative externalities of the environment are not well controlled during technology development and production, which have a negative impact on the air. Then, the secondary industry, represented by industry and construction, is often accompanied by a large amount of industrial waste gas, smoke, and dust in its production and operation, which is the main cause of the deterioration of air quality. Moreover, the negative impact of *FDI* on the air supports the "pollution haven" hypothesis of China's haze problem, i.e., the advanced clean technology and environmental protection concepts brought by foreign investments cannot compensate for the air pollution drawbacks.

Meanwhile, owing to the energy endowment characteristics of "rich coal, little oil, and little gas" in China, the over-dependence on low-cost coal has been formed for a long time. Coal combustion products are a significant component of particulate pollution, and the use of low-quality coal further accelerates the deterioration of air quality. In addition, highway traffic intensity aggravates HP at the significance level of 1%, and automobile exhaust is one of the vital causes of air pollution. Finally, the contribution of urban central heating is outstanding; the heating demand increases local coal consumption. While non-standard heating phenomena such as small boilers and loose coal further increase the negative externality of the environment. Despite the government's policies of "coal to gas" and "coal to electricity" to strictly control the use of small boilers and loose coal, coal is still the main source of heating. Emissions from coal combustion products are affected by weather, wind speed, humidity, and other natural factors, resulting in severe winter high pressure in northern cities.

The estimated coefficient of *WGR* is significant, which verifies the spatial spillover effect of *ER*. However, the coefficient is negative; that is, the high intensity of *ER* in surrounding cities leads to a weakening of local governance. This implies that the "free-rider" phenomenon is common. Considering that enhanced environmental governance in neighboring cities can improve the air quality of local cities, local governments tend to reduce environmental interventions to save on financial expenditures. This is extremely detrimental to overall HP control. In addition, the uneven distribution of benefits and costs is one of the major reasons for the slow progress and ineffectiveness of JG.

The above empirical analysis shows that there is a significant spatial correlation of the regional HP and ER. Therefore, the regional interaction between them will be presented through network construction, so as to analyze it more intuitively and clearly.

Analysis of Regional Haze JG Spatial Network

Based on the modified gravity model and SNA, the relationship between HP and ER will be quantitatively studied.

Interprovincial HP and JG Spatial Network

Firstly, the relationship between HP and ER in 30 provinces is calculated by the modified gravity model, and a 30 * 30 matrix is established. Before constructing the network structure, the relationship matrix needs to be transformed into a 0-1 matrix. This study takes a threshold value and refers to the "threshold selection method" [42, 43]. If the matrix element exceeds this threshold value, the conversion is 1, indicating that there is a relationship between two regions; otherwise, the conversion is 0, and there is no significant relationship. The diagonal elements are set to 0. In order to make the network comparable, this study takes the common average value of elements in the HP and ER relation matrix as the threshold value. The spatial networks of interprovincial HP and ER are visualized, and the network attributes are analyzed using UCINET and NetDraw software.

Next, two indicators (*ND* and *DC*) are picked to describe the overall network structure characteristics. Fig. 1a) illustrates that all nodes are in the HP network except Xinjiang, and each province is connected to at least one province. While there are more than half of the isolated nodes in the JG network, this indicates that the spatial force of ER among provinces is intensely weak. In addition, the *ND* values in the HP network and the JG network are 0.231 and 0.031, respectively. In fact, due to the lack of internal power, the uneven distribution of interests, insufficient information sharing, etc., the performance of joint prevention and control is poor, and it is difficult to operate efficiently.

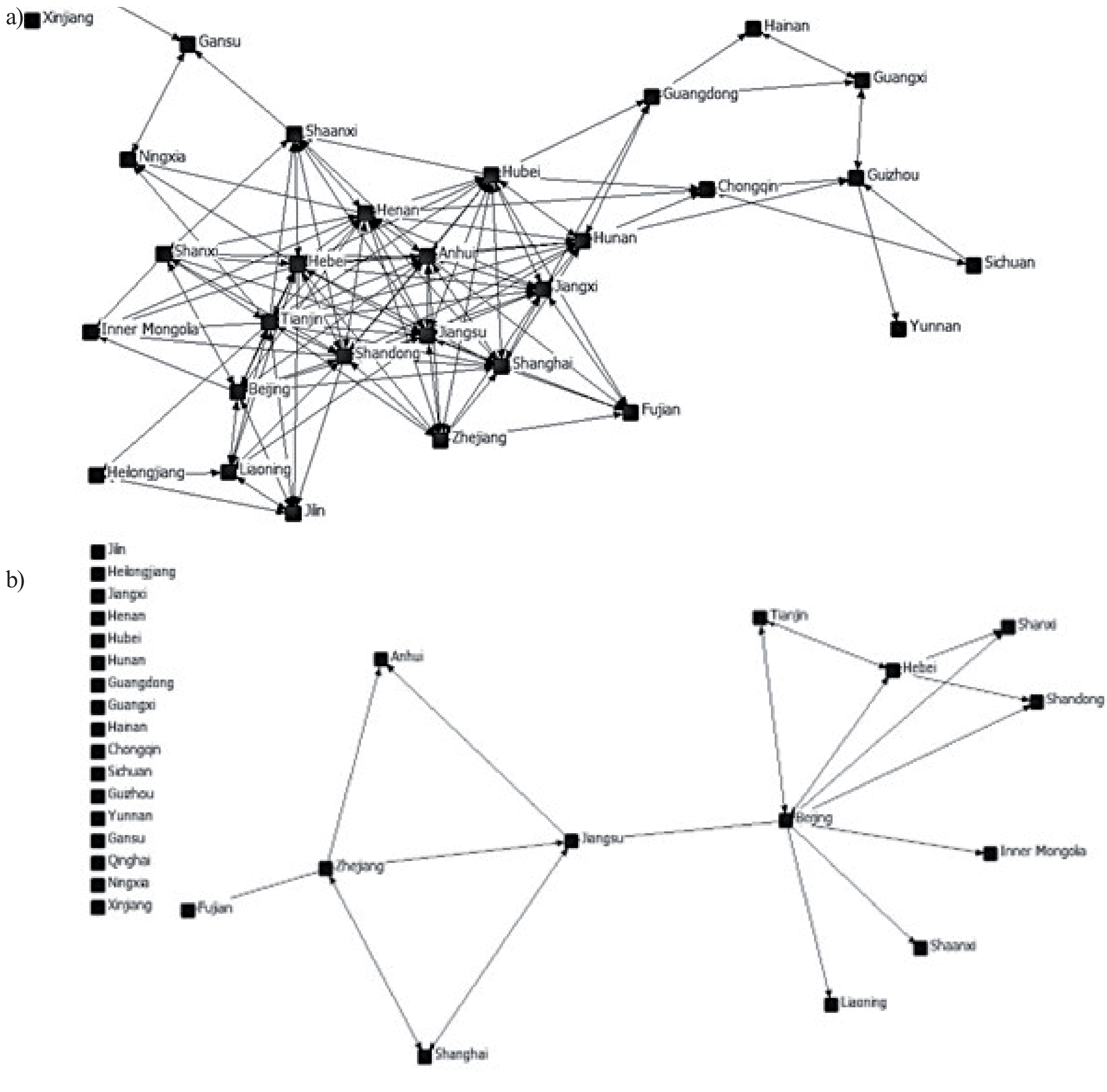

Fig. 1. National spatial network of: a) HP, b) JG.

In terms of the individual network structure, the out-degree centralization and in-degree centralization of the HP network are 40.309% and 18.906%, respectively, presenting an obvious spatial clustering of HP. Furthermore, there is a greater difference between the out-degree of nodes; that is, there are a few nodes that have a more prominent impact on other provinces. Correspondingly, the out-degree centralization and in-degree centralization in the JG network are 25.327% and 14.625%, respectively. Generally, the trend toward network centralization is not obvious.

Additionally, the spatial layout of the network combined with the node characteristics is conducive to understanding the HP and JG spatial networks. Table 4a and Table 4b list the top ten provinces of the out-degree and in-degree in the HP and JG networks, respectively. We can see that the ranking of out-degree and in-degree nodes in the HP network has great similarity by comparing two tables, which indicates that the spatial relationship of haze is manifested as bidirectional cross-pollution. Most provinces with higher centrality are Pan Beijing-Tianjin-Hebei, the Yangtze River Delta, and their surrounding areas with serious HP; that is to say, these provinces tend to have close haze connections with other areas and show a high influence in the network. Although the HP in Hunan, Hubei, and Jiangxi is relatively light, due to their central location and proximity to the HP belt, these provinces are prone to becoming recipients and disseminators of HP. From the perspective of JG, Beijing, as the capital, is clearly reflected in its network center status. Most provinces with a high ranking of *De* are still in Pan Beijing-Tianjin-Hebei and Yangtze River Delta, or close to these two regions.

Comparison of Regional HP and JG Spatial Networks

In order to get more detailed and regionally targeted research conclusions, we select the most representative regions for comparative analysis. For instance, Beijing-Tianjin-Hebei, the Yangtze River Delta, and its surrounding areas are mostly concentrated areas of serious HP. The analysis of the interprovincial JG network indicates that the current air pollution JR is mainly deployed in these two regions. Therefore, this study selects 49 cities from 6 provinces and cities, including Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Shandong, etc., which are called the Pan Beijing-Tianjin-Hebei, and 41 cities from Shanghai, Jiangsu, Zhejiang, Anhui, etc., which are called the Yangtze River Delta, so as to carry out a comparative analysis of the regional HP and JG spatial networks.

Fig. 2a) and Fig. 2b) show that there are several isolated nodes in the HP and JG spatial networks in Pan Beijing-Tianjin-Hebei, such as Hulunbuir and Tongliao, which are located in the Inner Mongolia Autonomous Region. The region has no obvious HP and is located in a remote area, so it has no haze cross-pollution with other cities or JG interaction. The *ND* values of HP and JG in Pan Beijing-Tianjin-Hebei are 0.682 and 0.517, respectively. They are both significantly higher than the national level. Although the closeness of JG has been significantly improved, it is still lower than that of HP. The out-degree centralization and in-degree centralization of HP are 28.212% and 17.578%, respectively. They are lower than the national level, especially the out-degree centralization, which reflects that HP is more balanced at the regional level, and most cities have a similar degree of cross-pollution. The out-degree centralization and in-degree centralization of JG are 21.615% and 42.882%, respectively. Among which, the trend of in-degree centralization is more obvious, which means that the level of regional ER is unbalanced and the cities are more inclined to passive benefits. This phenomenon is consistent with the behavior of "free riding" in JG.

Furthermore, the node characteristics of the spatial network in Pan Beijing-Tianjin-Hebei are analyzed as follows:

In accordance with Tables 5a) and 5b), the cities with the highest out-degree and in-degree in the HP network in Pan Beijing-Tianjin-Hebei are located in the administrative district junction of Beijing, Tianjin, Hebei, and Shandong, which have the central advantage of geographical location. Therefore, these areas play a greater role in the haze transmission process than other cities. Among which, the inward centrality of Datong is obvious, but the out-degree is low, which indicates that Datong is more likely to be a passive recipient of HP. In the JG network, Zibo, Xinzhou, and Tianjin are the network centers, and the in-degree is significantly higher than the out-degree. The gap between the in-degree and out-degree is prominent in Xinzhou, Yangquan, and Dongying, showing that these cities tend to passively absorption compared with external radiation.

The HP and JG networks of 41 cities in the Yangtze River Delta are established in the same way. The visualization results are presented in Fig. 3a) and Fig. 3b). As illustrated in two figures, all nodes are included in the HP network in the Yangtze River Delta. Besides, the network correlation degree reaches 1, that is to say, all cities have different degrees of spatial interaction, and there is no "outsider" in the term of HP. From the perspective of the JG network, there are six isolated nodes, and most of them belong to Anhui Province. In addition, the *ND* values of HP and JG in the Yangtze River Delta region are 0.462 and 0.245, respectively. Although they are significantly higher than the national level, there is an obvious gap in the closeness of environmental governance compared with Pan Beijing-Tianjin-Hebei. The out-degree centralization and in-degree centralization of HP are 34.688% and 29.563%, respectively, and the *DC* value is higher than the national level and Pan Beijing-Tianjin-Hebei. In addition, the out-degree centralization (59.372%) and the in-degree centralization (20.938%) in the JG network in the Yangtze River Delta have a significant difference, indicating that the cities have a serious spatial imbalance

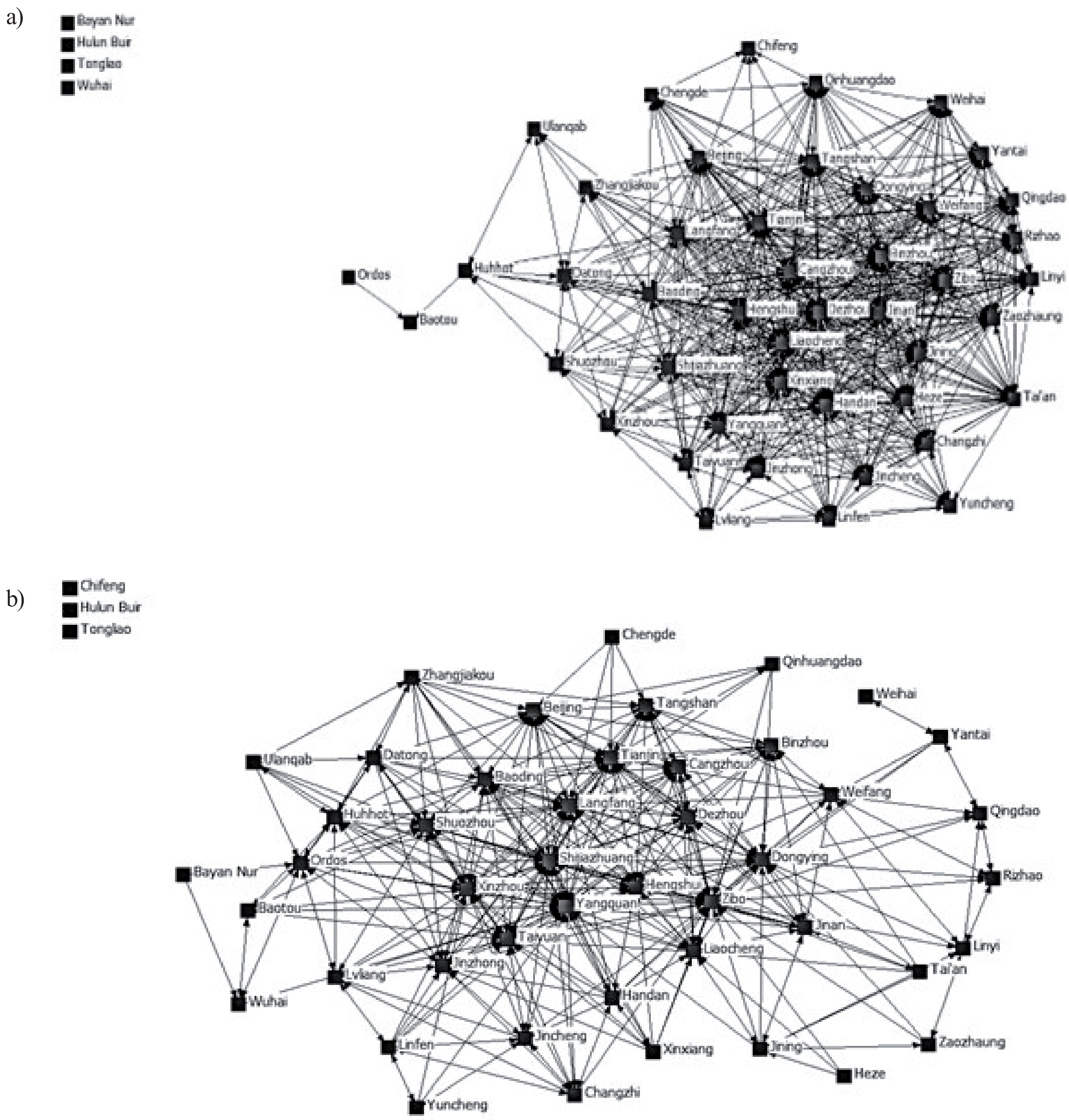

Fig. 2. Spatial network of: a) haze pollution of Pan Beijing-Tianjin-Hebei region, b) joint governance of Pan Beijing-Tianjin-Hebei region.

in the active radiation tendency of environmental governance.

Similarly, the node characteristics of the spatial network in the Yangtze River Delta are analyzed as follows:

From the perspective of in-degree and out-degree (Table 6a), the cities in the center of the HP network in the Yangtze River Delta are Jiangsu and Anhui Province, and they are mainly concentrated in Nanjing, Ma'anshan, and Yangzhou. In addition, most nodes in Zhejiang Province have a low *De*. This may be related to the edge location and the lower value of HP in Zhejiang Province compared with the other three provinces. For the JG network (Table 6b), some cities in Jiangsu and Zhejiang Province have the most prominent centrality. However, the out-degree and in-degree are not symmetrical. As proof, Changzhou and Zhenjiang have obvious outward centrality, but the in-degree is not prominent. Shaoxing and Nanjing have the opposite performances.

Discussion

The structural attribute data of the above spatial networks is summarized in Table 7. Based on the comparative analysis of the network attributes at the provincial level, Pan Beijing-Tianjin-Hebei, and the Yangtze River Delta, the following findings can be obtained:

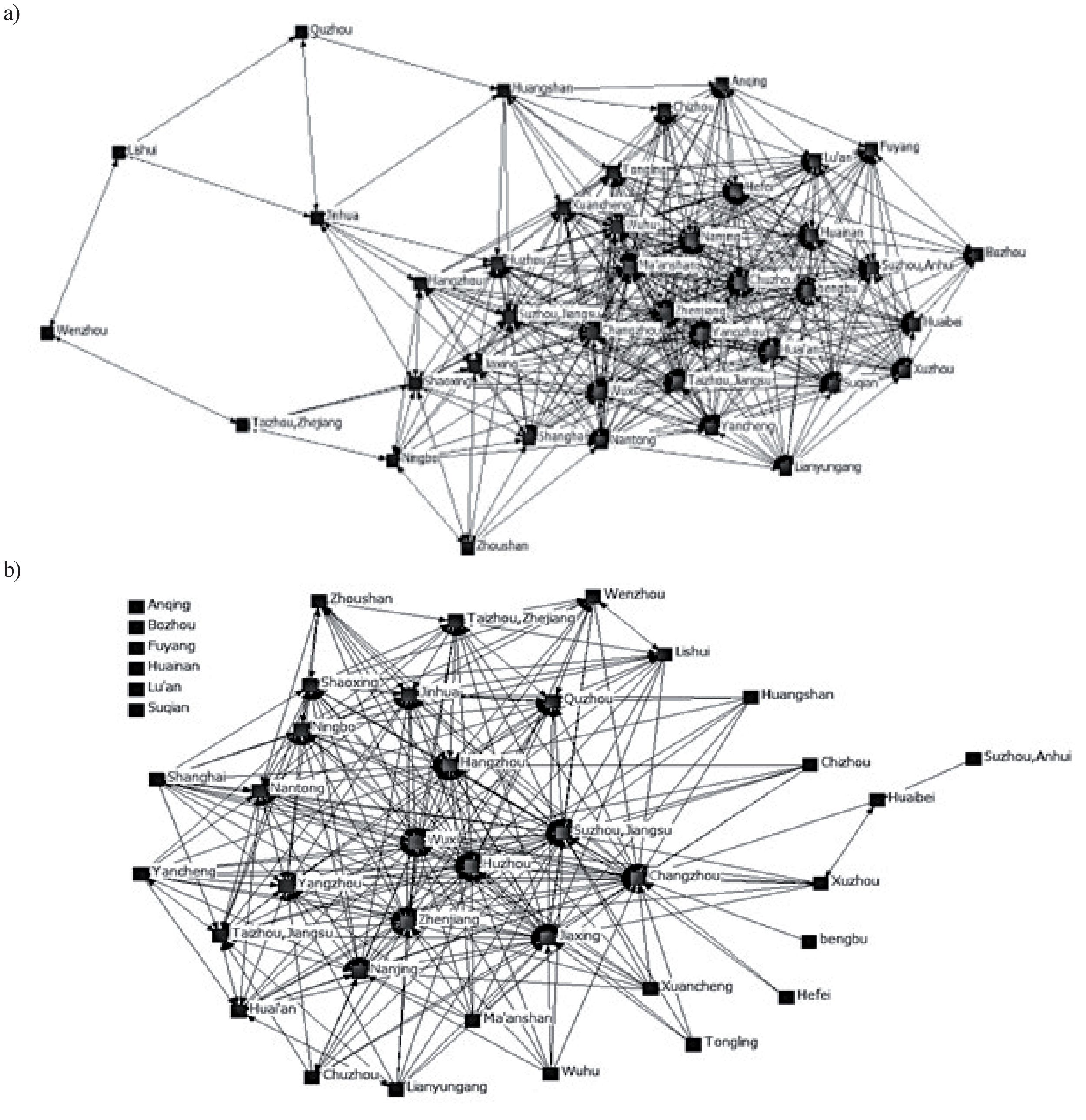

Fig. 3. Spatial network of: a) haze pollution of Yangtze River Delta region, b) joint governance of Yangtze River Delta region.

(1) For HP, the *ND* values of Pan Beijing-Tianjin-Hebei and the Yangtze River Delta are higher than those of the whole country, and the spatial interaction of HP is more obvious in small-scale regions. In addition, the out-degree centralization of the national network is higher in the Yangtze River Delta than in Pan Beijing-Tianjin-Hebei; for JG, the *ND* values in all regions are significantly lower than HP. Among which, the gap at the national level is the most obvious. Besides, the closeness of environmental governance in Pan Beijing-Tianjin-Hebei is the highest.

(2) From the perspective of the spatial layout of the JG network, the phenomenon of nationwide agglomeration is not obvious, which may be related to the lack of connected nodes in the network. The Pan Beijing-Tianjin-Hebei region has a relatively high in-degree centralization, indicating the serious phenomenon of "free riding" in individual cities. Meanwhile, the Yangtze River Delta has a relatively high out-degree centralization, showing a "central-marginal" network structure radiating from some core nodes to the surrounding areas.

(3) Comparing the central node layout of the HP network with the JG network, the whole country and Pan Beijing-Tianjin-Hebei both show a high similarity, while the Yangtze River Delta presents a low consistency in the node layout of the two networks. Additionally, the core leading position of Shanghai and provincial capitals has not been reflected, thus there is a possibility of an unreasonable layout.

Table 4a. The ranking of De in interprovincial HP network.

Out-degree			In-degree		
Ranking	Province	Absolute value	Ranking	Province	Absolute value
1	Tianjin	18	1	Henan	12
2	Hebei	17	2	Tianjin	11
3	Henan	16	3	Hebei	11
4	Shandong	16	4	Shandong	11
5	Jiangsu	15	5	Jiangsu	11
6	Anhui	14	6	Anhui	11
7	Hubei	14	7	Shanghai	11
8	Shanghai	12	8	Jiangxi	11
9	Beijing	11	9	Hubei	10
10	Hunan	9	10	Beijing	10

Table 4b. The ranking of De in interprovincial JG network.

Out-degree			In-degree		
Ranking	Province	Absolute value	Ranking	Province	Absolute value
1	Beijing	8	1	Beijing	5
2	Hebei	4	2	Hebei	3
3	Zhejiang	4	3	Jiangsu	3
4	Jiangsu	3	4	Zhejiang	2
5	Tianjin	2	5	Shanxi	2
6	Shanxi	2	6	Shanghai	2
7	Shanghai	2	7	Shandong	2
8	Inner Mongolia	1	8	Anhui	2
9	Shandong	1	9	Inner Mongolia	1
10	Other	0	10	Liaoning	1

Table 5a. The ranking of De in HP network in Pan Beijing-Tianjin-Hebei.

Out-degree			In-degree		
Ranking	Province	Absolute value	Ranking	Province	Absolute value
1	Dezhou	46	1	Langfang	41
2	Liaocheng	46	2	Baoding	41
3	Hengshui	46	3	Beijing	41
4	Langfang	46	4	Hengshui	40
5	Tianjin	45	5	Tianjin	40
6	Cangzhou	45	6	Xingtai	40
7	Handan	45	7	Shijiazhuang	40
8	Baoding	45	8	Datong	40
9	Beijing	45	9	Dezhou	39
10	Xingtai	45	10	Liaocheng	39

Table 5b. The ranking of De of JG network in Pan Beijing-Tianjin-Hebei.

Out-degree			In-degree		
Ranking	Province	Absolute value	Ranking	Province	Absolute value
1	Hengshui	35	1	Zibo	45
2	Shijiazhuang	35	2	Xinzhou	45
3	Liaocheng	34	3	Tianjin	45
4	Zibo	33	4	Langfang	45
5	Beijing	33	5	Yangquan	45
6	Tianjin	33	6	Dongying	45
7	Dezhou	32	7	Shijiazhuang	44
8	Langfang	32	8	Hengshui	42
9	Cangzhou	32	9	Baoding	42
10	Baoding	32	10	Beijing	42

Table 6a. The ranking of De in HP network in Yangtze River Delta.

Out-degree			In-degree		
Ranking	Province	Absolute value	Ranking	Province	Absolute value
1	Nanjing	32	1	Chuzhou	30
2	Ma'anshan	32	2	Nanjing	29
3	Yangzhou	31	3	Ma'anshan	29
4	Zhenjiang	31	4	Yangzhou	26
5	Chuzhou	30	5	Zhenjiang	26
6	Taizhou	29	6	Wuhu	26
7	Heifei	27	7	Taizhou	25
8	Wuxi	27	8	Heifei	25
9	Changzhou	27	9	Changzhou	25
10	Huai'an	26	10	Xuancheng	25

Table 6b. The ranking of De in JG network in Yangtze River Delta.

Out-degree			In-degree		
Ranking	Province	Absolute value	Ranking	Province	Absolute value
1	Changzhou	33	1	Hangzhou	18
2	Suzhou	31	2	Ningbo	18
3	Jiaxing	30	3	Shaoxing	18
4	Huzhou	30	4	Suzhou	17
5	Wuxi	29	5	Jiaxing	17
6	Hangzhou	25	6	Jinhua	17
7	Zhenjiang	24	7	Huzhou	16
8	Ningbo	20	8	Wuxi	16
9	Jinhua	20	9	Taizhou	15
10	Yangzhou	20	10	Nanjing	15

Table 7. The comparison of regional HP and JG network characteristics.

Region	Network	Node	ND	Out-degree Centralization (%)	In-degree Centralization (%)
Whole country	HP	30	0.231	40.309	18.906
	JG	30	0.031	25.327	14.625
Pan Beijing-Tianjin-Hebei	HP	49	0.682	28.212	17.578
	JG	49	0.517	21.615	42.882
Yangtze River Delta	HP	41	0.462	34.688	29.563
	JG	41	0.245	59.372	20.938

Generally, the environmental governance of Pan Beijing-Tianjin-Hebei is better than that of the Yangtze River Delta in terms of the degree of closeness and the rationality of the spatial layout of network nodes. In view of this phenomenon, it can be analyzed from the following points:

(1) Endogenous power. Owing to the industrial structure, winter heating, and seasonal sandstorms, the HP in Pan Beijing-Tianjin-Hebei and its surrounding areas is particularly serious. Except for the national policy pressure, the poor air quality makes the region have greater endogenous power, which urges Pan Beijing-Tianjin-Hebei to make greater efforts in environmental governance and unite the surrounding cities to carry out joint prevention and control.

(2) Political factors. As the capital of China, serious HP has a negative impact on Beijing's international image to a large extent. Relatively, Pan Beijing-Tianjin-Hebei have faster response speeds and stricter implementation standards for the relevant policies of joint prevention and control of HP. Moreover, Beijing, as the political center that contributes to the Pan Beijing-Tianjin-Hebei region, establishes close political ties in daily governance and promotes the development of regional joint prevention and control.

(3) Joint opportunity. Pan Beijing-Tianjin-Hebei and surrounding areas have achieved a "political blue sky" in the short term during the Beijing Olympic Games, the military parade, the APEC meeting, and the "two sessions". Although this centralized supervision mode guided by short-term goals is not worth advocating, it does provide more opportunities and lays a foundation for joint prevention and control in Pan Beijing-Tianjin-Hebei to some extent.

Conclusions and Policy Implications

This study empirically analyzes the spatial spillover effects of regional HP and ER. By establishing a national spatial network for HP and ER and selecting the Pan Beijing-Tianjin-Hebei and Yangtze River Delta regions as representatives, a comparative analysis of the regional network is conducted, and the following conclusions and inspirations are obtained:

(1) The spatial spillover of haze results in malignant cross-pollution among regions. The ER of local and surrounding areas both has a significant increase in local HP, but the high-intensity regulations of surrounding areas will inhibit local environmental governance. Besides, the "free riding" phenomenon exists in environmental governance. China still needs to strengthen ER, which is not only reflected in the strength of legislation, but also in the improvement of law enforcement.

(2) The comparison between the spatial networks of HP and JG implies that the *ND* values in Pan Beijing-Tianjin-Hebei and the Yangtze River Delta are higher than the national level. Besides, the interaction between haze cross-pollution and ER is more obvious in two regions. The density of the JG network in all regions is significantly lower than that of the HP network. Among which, the regulatory interaction in Pan Beijing-Tianjin-Hebei is relatively obvious.

(3) From the perspective of spatial network layout, the national network centers of HP and JG are mostly occupied by Pan Beijing-Tianjin-Hebei and the Yangtze River Delta or their surrounding areas. The trend of HP network clustering in Pan Beijing-Tianjin-Hebei is not obvious, while the JG network has a high in-degree centralization. A few nodes, represented by Zibo, Xinzhou, and Tianjin, are more prominent in passive reception spillover; that is, the behavior of "free riding" appears easily. In the Yangtze River Delta, the HP has gathered around Nanjing, Ma'anshan, and Chuzhou. Besides, the imbalance of ER is significant, and the current layout of the JG network is unreasonable due to the obvious gap between in-degree centralization and out-degree centralization in the JG network.

(4) The performance of Pan Beijing-Tianjin-Hebei is better than that of the Yangtze River Delta in general, according to the closeness of the network and node layout. The reasons for the differences can be summarized as endogenous power, political factors, and joint opportunities.

In light of the above analysis, it can be known that the current JG network of HP has not achieved the desired effect. Some suggestions targeted at this problem are given as follows:

Firstly, the central government should break the limitation of traditional administrative region division in terms of concept and policy, based on the spatial structure characteristics of HP, combined with political factors, geographical location, natural climate, etc., to divide the cross-region. Moreover, deploying joint prevention and control of HP involves two aspects: increasing the closeness of JG and reasonably adjusting the spatial layout. Meanwhile, the central government should take the achievements of haze control as a crucial indicator of the local government's performance and strengthen the supervision of the local government's haze control behavior. Additionally, enhancing the power of awards and punishments and optimizing the implementation path of laws and policies so as to effectively play the functions of leadership, supervision, and coordination. Finally, the gap in the intensity of environmental governance among areas can be narrowed, and the phenomenon of "free riding" can be avoided.

Secondly, the Yangtze River Delta region should take Pan Beijing-Tianjin-Hebei as a reference, improve endogenous power, and actively carry out joint prevention and control of HP. Due to the political center characteristics of Beijing, the political ties between Pan Beijing-Tianjin-Hebei are closely connected. Thus, the Yangtze River Delta should also rely on its internal close economic exchanges to quickly establish the political ties of haze governance. Meanwhile, combined with the spatial distribution characteristics of HP, making a reasonable layout for regional collaborative governance and defining the leading role of key cities, which are conducive to good radiation and drive for the surrounding cities.

Finally, in the long-term planning, the temporary regional haze JG practices such as the Beijing Olympic Games, the military parade, the APEC conference, and the Shanghai World Expo can be regarded as an opportunity for regional cooperation. However, the shortsighted behavior is not desirable. Gaining insights from past experiences and progressively refining them is crucial for establishing a robust, enduring, and intimate regional HP and JG network.

The conclusion of the study recognizes its unique limitations. This article merges the geographical spread of haze with the implementation of combined air pollution management strategies, focusing exclusively on the Yangtze River Delta and the Pan Beijing-Tianjin-Hebei area for network evaluation. Subsequent studies might utilize alternative regional segmentation techniques to broaden the research range and undertake comprehensive investigations.

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Data availability

Data used in this manuscript is available from https://sites.wustl.edu/acag/data-sets/surface-pm2-5/, https://www.ngcc.cn/ngcc/html/1/index.html, http://www.stats.gov.cn/t-jsj/ndsj and https://navi.cnki.net/knavi/yearbooks/YZGCA/detail.

Conflict of Interest

The author declares no conflict of interest.

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