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Original Research Paper

Spatial Distribution of Haze Pollution in China and Eco-compensation Measures

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ABSTRACT

Serious haze pollution is harming public health and life in many provinces in China. The spatial distribution characteristics of haze pollution in 30 provinces, including cities and municipalities, in China were further analysed. The possible existence of spatial club convergence tendency among different provinces was explored, enabling the implementation of customized governance measures according to eco-compensation. First, spatial autocorrelation of the haze was calculated using Moran's I index based on the annual data of haze pollution over the study area from 2003-2014. Spatial error panel data model was used to analyse the presence of spatial club convergence of haze pollution. Finally, related policy suggestions to manage haze pollution were proposed based on eco-compensation. Results demonstrated that China's key monitored provincial capitals and municipalities had suffered very serious haze pollution. All 30 provinces could generally be divided into light, middle, relatively high, and high haze regions. The provinces exhibited strong spatial autocorrelation. Spatial concentration presented continuous distribution and increasing spatial dependency. Several regional provinces presented spatial club convergence based on haze pollution. Empirical results provided certain references to further understand the spatial distribution of haze pollution in China, explore eco-compensation measures against haze pollution, and relieve the effect of haze on social and economic development.

INTRODUCTION

Haze is one of the atmospheric pollution which contribute abundant air particulates, such as dust, smoke, dust, etc. These particulates will degrade air quality and reduce horizontal visibility to less than 10km. Some particles can directly enter the human body through the respiratory tract, resulting in serious damages to human health. Haze mainly includes sulphuric acids and carbon particles. Haze generally presents an orange or yellow appearance because of its abundant visible light with long scattering wavelength. Orange-gray air pollution has been observed in most cities in China, primarily because black charcoal is one of main air pollutants in the country. Haze covers a large area and persists, contrary to other severe weather conditions.

Haze is mainly concentrated over Beijing-Tianjin-Hebei, Yangtze River Delta, and middle region between these two economic entities, suggesting a non-equilibrium and heterogeneous spatial distribution. East China has experienced serious haze in the first six months of 2015 according to the PM2.5 concentration monitoring in key provincial capitals and municipalities in China in 2014 (Fig. 1). Many monitored sites have exceeded the standard of air quality, indicating that these cities have been suffering very serious air pollution. Haze often occurs under general atmospheric circulation conditions with weak cold air and strong moisture. Gentle air activities exist in the horizontal and vertical directions because calm wind or breeze in places near the ground is influenced by static stable weather. These activities reduce atmosphere diffusivity. Pollutants caused by consumption of energy sources for transport and production activities accumulate continuously at low altitude in big and small cities. Thus, enhancing collaborative administration in the region is an important method to control haze. Different provinces and cities also have diverse haze control abilities and practical applications because of their diverse levels of economic development, technological conditions, and energy structures. Therefore, an empirical study on the spatial pattern evolution and club convergence of haze in China by exploring the haze convergence system in different provinces is significant. Such study is beneficial for the formulation of scientific and reasonable regional haze control policies based on ecological management.

RESEARCH PROGRESS

Spatial distribution and control measures of haze have been extensively investigated worldwide. Eldred conducted the first analysis of the haze distribution in the US and concluded that the level of inhalable particle pollutants in the east was higher than that in the west (Eldred et al. 1997). Motallebi discovered seasonable trends of inhalable particle pollution.

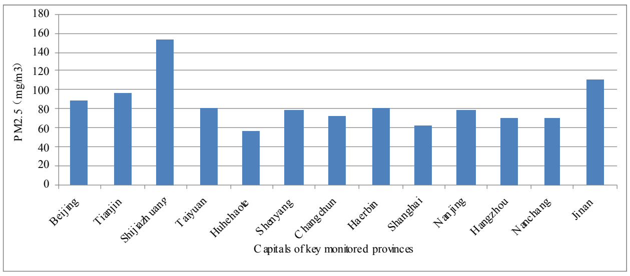

Fig.1: PM2.5 concentrations in key monitored provincial capitals and municipalities in 2014.

They reported that different seasonable and climatic conditions could significantly influence pollutant concentration (Motallebi 1999). Anselin, who is an internationally recognized expert in spatial measurement, discussed the significance of spatial factors on environmental economic issues (Anselin 2001). Rupasingha first implemented this method to discuss the relationship between per capita income and atmospheric pollution in 3,029 counties in the US. He concluded that the introduction of spatial variables significantly increased the accuracy of the measurement model (Rupasingha et al. 2004). Maddison analysed European countries and discovered the overflow effect in pollution among countries and pollution control using pollutants (e.g., SO_2) as the measurement index of environmental quality (Maddison 2007). Poon studied the effect of energy sources, traffic, and foreign trade on the atmosphere over China using spatial measurement. He mainly focused on SO_2 and smoke and confirmed the existence of overflow effect among provinces in the country (Poon et al. 2006). Dinda analysed the possible presence of spatial overflow effect between two major air pollutants using the environmental curve (Dinda 2004). Hosseini established six spatial models with six types of weight matrices, which confirmed the existence of spatial overflow effect based on pollution and environmental policies between different countries (Hosseini et al. 2013). Hueglin discovered a decreasing trend of trace elements in the haze from city streets to city suburbs and then to rural regions, which implied that road traffic, may be the main source of these trace elements, to a certain extent (Hueglin et al. 2005). Gehrig measured PM.5 and PM10 in seven points in Switzerland and analysed distribution variations of haze (Gehrig et al. 2003). Li analysed the mass concentration of PM2.5 and distribution of 20 polycyclic aromatic hydrocarbons in Guangzhou City (Li et al. 2005). Guo performed three analyses of PM2.5 samples collected from Qingdao City, China and discussed the spatial distribution of total suspended particulates (Guo et al. 2004). Querol analysed the distributions of PM10, PM2.5, and PM1 of total suspended particulates in urban areas in Barcelona as well as their relationships with urban traffic (Querol et al. 2001).

We reviewed the literature and found that environmental problems and social effect caused by spatial distribution of haze have attracted attention from all sectors. China's economic scale has continuously expanded with the rapid economic development and technological reform in China. Meanwhile, haze pollution in China has intensified. In particular, accidents and deteriorating vents caused by air pollution have increased continuously in economically and industrially developed cities. However, most studies on haze have focused on the spatial-temporal distribution in one city, one region, or one haze. Few studies have conducted spatial-temporal distribution of haze around China. Therefore, spatial distribution of haze in China was explored in this study using the haze data from 30 cities and municipalities in the country. The possible presence of spatial club convergence of haze pollution was analysed using spatial error panel data model (SEPDM). Finally, related policy suggestions for haze control were proposed based one co-compensation.

MODEL INTRODUCTION AND DATA SPECIFICATION

Model Introduction

Moran's I index: Regions were grouped to study the spatial club convergence. This process required the calculation and testing of spatial autocorrelation of carbon emission. Spatial autocorrelation (dependence) of carbon emission behaviour over the geographic space of one region is often measured by Moran's I index. Therefore, Moran's I was used to group the endogenous region.

$$Moran's \quad I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(Y_i - \bar{Y})(Y_j - \bar{Y})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \qquad ...(1)$$

Where $S^2 = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{Y})^2$ and $\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i$. i is the observed value in Y_i (urban haze quantity $y_{i,t}$ in this paper), n is number of provinces, and W_{ij} is the neighbouring space weight matrix of the binary system.

The space weight matrix W is defined as follows:

$$\ln(y_{it}/y_{i,t-1}) = \alpha_{it} + \beta \ln(y_{i,t-1}) + \rho W \ln(y_{it}/y_{i,t-1}) + \mu_{it} \qquad ...(2)$$

SLPDM: The spatial panel model of haze convergence in China was established based on the theoretical model of carbon emission convergence proposed by Jobert (Jobert et al. 2010). The spatial lag panel data model (SLPDM) is expressed as follows:

$$\ln\left(\frac{y_{it}}{y_{i,t-1}}\right) = \alpha_{it} + \beta \ln(y_{i,t-1}) + \rho W \ln\left(\frac{y_{it}}{y_{i,t-1}}\right) + \mu_{it} \quad ...(3)$$

Equation (1) is the SLPDM, where β is the convergence coefficient, W is the spatial weight matrix, and ρ is the spatial correlation coefficient. This model is used to measure the spatial overflow effect of carbon emission in one region on the carbon emission in surrounding regions.

$$\ln\left(\frac{y_{it}}{y_{i,t-1}}\right) = \alpha_{it} + \beta \ln(y_{i,t-1}) + \mu_{it} \quad ...(4)$$

$$\mu_{it} = \lambda W \mu_{it} + \varepsilon_{it} \quad ...(5)$$

Equations (2) and (3) describe the SEPDM, where β is the convergence coefficient, and W is the spatial weight matrix. Λ is used to measure the overflow effect on the region caused by observed values of errors of samples.

Data Specification

Statistical data on PM2.5 concentration in China started from 2003. PM2.5 concentrations in different provinces were replaced by data from the provincial capitals because of the limited statistical data. Data from 30 provinces, excluding Tibet, Hong Kong, Macao, and Taiwan, were collected from the China Statistical Yearbook during 2004–2015. The unit of PM2.5 concentration was in milligram per cubic meter (mg/m^3).

EMPIRICAL STUDY

Estimation of Moran's I: Moran's I values of the 30 provinces from 2003–2014 were estimated from Equations (1) and (2). The results are listed in Table 1.

The data in Table 1 show that the data pass the 1% significance level when all global values are positive. This value indicates that haze pollution in China has evident positive spatial correlation among different provinces. Thus, a region with high level of haze pollution often has one or more regions with the same level of haze pollution as neighbours. This phenomenon reflects that haze pollution among the 30 provinces has relatively stable positive spatial correlation, which is correlated with industrial and economic development in recent years. Central China has begun to undertake industrial transfers, mainly industries with high pollution and energy consumption, from the developed eastern China because of the national promotion of developing central China since 2006. Industrial transfer from eastern China to the middle and western China has become an important strategic deployment of coordinated regional balanced development in the country. This development conforms to the fact that industrial transfer direction is difficult to change in a short time because of the industrial development law. Moreover, central China, which is adjacent to developed regions with serious pollution, is easy to be the concentrated region of high levels of haze pollution. The global correlation analysis disclosed positive correlation and significant overflow effect of haze pollution. Developed regions with excellent resources in China could not acquire all benefits of local industrial structural optimization because they are adjacent to central China. Economically developed regions have difficulty in improving local environmental quality when such "overflow effect of pollution" is higher than the "local optimization effect".

Table 1: Moran's I values of 30 provinces in China from 2003-2014.

Year	Moran's I	P value	Year	Moran's I	P value
2003	0.514	0.001	2009	0.516	0.001
2004	0.521	0.001	2010	0.526	0.002
2005	0.498	0.001	2011	0.539	0.001
2006	0.478	0.002	2012	0.496	0.001
2007	0.465	0.001	2013	0.487	0.001
2008	0.496	0.001	2014	0.478	0.001

(Note: P value is the accompanying probability of index)

Spatial club convergence analysis of haze pollution: The Moran's I values show the presence of spatial autocorrelation of haze pollution level among 30 provinces in China, and this pollution level has been intensifying gradually. China's industrialization and urbanization based on the extensive economic development will increase the rigid demands of China's development on fossil energies. This phenomenon will result in serious haze pollution with the rapid economic development. This characteristic has been represented in the spatial distribution pattern of haze over these cities. In addition, haze pollution in urban areas has entered the fast differentiation stage because of the increasing economic and geographic difference among the various regions. This pollution will intensify continuously if previous economic development mode will incessantly be adopted. This characteristic also reflects that the spatial distribution of haze over urban areas in China is correlated with the regional economic development pattern to a certain extent. Spatial club convergence analysis considers the urban haze over a group of regions with similar initial haze pollution levels, and spatial economic structural characteristics converge to the same steady state. This group of regions is called the spatial convergence club. Spatial endogenous grouping of these study areas was implemented using Moran's I index to further analyse the spatial distribution pattern of haze pollution in 30 provinces in China. The study areas were mainly divided into light, middle, relatively high and high haze regions.

Table 2 shows positive coefficients of relatively high and high haze regions according to the estimated spatial club convergence, but these coefficients are not significant. Thus, the target region with high haze pollution level will cause negative overflow effect to neighbours. This characteristic may increase the gap of carbon emission between regions and contrary to convergence. This behaviour fully reflects the demonstration effect of regions during these two short periods which could not be ignored in low-carbon economic development. The coefficient in the light haze region is negative, showing spatial club convergence. Thus, haze growth in the light haze region has positive impacts on the haze growth of other regions, regardless of whether the value is significantly positive or not. Haze pollution in a region has certain demonstration effect to neighbours with high or low haze pollution levels through spatial interaction when haze pollution in the target region is relatively low. This phenomenon facilitates the convergence of urban haze levels. Spatial club convergence exists in low-concentration regions. Therefore, establishing a low-carbon economy demonstration region in a regional club will lead to positive impacts to its neighbours and can narrow the haze gap among different cities in the region. Spatial overflow effect is evidently one form of regional interaction.

ECO-COMPENSATION MEASURES FOR HAZE CONTROL

Environmental legislation should be strengthened, and eco-compensation laws for haze pollution should be refined: China's laws and regulation on atmosphere pollution control should be refined according to the international experiences in haze control and China's practical needs. A series of problems caused by current haze management requires corresponding legal basis. The existing version of laws and regulations does not consider atmosphere environmental protection at the desired height. This discrepancy provides opportunities of interested parties to exploit weaknesses in laws because of the conflict between atmosphere protection and economic development. Therefore, promoting the revision of Atmosphere Pollution Control Act is an urgent concern for effective atmosphere pollution management in China. Revising laws and regulations not only can provide more safeguards to various environmental rights and interests of the public, but such revision also offers stronger support to atmospheric environmental protection for the public. Moreover, revised laws provide the environmental protection department more executive powers. Such empowerment will enable the department to strengthen executive efforts and impose heavier punishment to practices that violate laws and cause considerable atmospheric pollution.

Eco-compensation mechanism should be established, and the transaction mechanism of emission rights should be improved: Eco-compensation mechanism is an environmental economic policy that targets the protection of ecological environment and promotes harmonious human–nature development. This mechanism adjusts the interest relationship between ecological environmental protection and related construction parties using administrative and market measures comprehensively according to the service value of the ecosystem, ecological protection cost, and development opportunity cost. Establishing regional eco-compensation mechanism can reduce cost for regional pollution management. Formulating such mechanism initially requires the determination of the producer, victims, and benefited party of the pollution. Thus, responsibilities, powers, and obligations shall be redefined. The mechanism should stick to the principle that "pollution producers are held responsible, and the benefited party undertakes management cost." Different parties undertake distinct responsibilities in pollution control using various environmental resources equally. The transaction mechanism of emission rights can reduce emission costs of enterprises in the region while maintaining total emissions and equivalent pollution control effect, thereby minimizing the influence of environmental protection on the regional economy. The transaction mechanism of emission rights is also beneficial to unify pollutant emission standards, which is the foundation to further implement pollution control and finally achieve collaborative pollution control in a region. The Chinese government shall refine corresponding mechanisms, reinforce monitoring of pollution sources, and train high-quality professionals positively during the

Table 2: SEPDM regression results of the four types of haze regions.

Regions	Variable	Coefficient	P value	Regions	Variable	Coefficient	P value
High	α	0.016	0.396	Middle	α	0.017	0.001
haze region	β	0.014	0.236	haze region	β	0.013	0.460
	ρ	0.386	0.0010		ρ	0.271	0.003
Relatively high	α	0.025	0.165	Light	α	0.024	0.002
haze region	β	0.017	0.515	haze region	β	-0.013	0.121
	ρ	0.249	0.024		ρ	0.141	0.000

promotion of the transaction mechanism of emission rights.

Economic growth method should be altered, and eco-compensation should be realized through industrial upgrading: Current energy consumption structure in China is dominated by coal which is the main cause of haze pollution. A balance between coal consumption limit and development of clean energy and renewable energy sources should be explored. Limiting coal consumption requires cooperation from the government at all levels, forming an upper-bottom control system. The goal of limiting coal consumption can only be realized gradually by administrative and economic measures with the cooperation of related departments and positive support from the public. The key to achieve this goal is to reduce the production cost of the energy sources. Only technological progress can reduce production cost of clean and renewable energy sources for long-term sustainable development. Such development shall restrict the application of tener construction of traditional industrial enterprises and expansion of production scale as well as promote elimination of traditional industrial enterprises with surplus productivity. Increasing the difficulty of acquiring approval for constructing traditional industrial enterprises with high pollution and high energy consumption has been suggested. Moreover, further production expansion of existing ones from capitals, policy, and taxation are to be restricted, and existing traditional enterprises are encouraged to reform production technologies to reduce pollutant emissions. Industrial enterprises with surplus productivity shall be eliminated through powerful administrative means. Furthermore, the state government shall give more support to enterprises using clean and renewable energy sources and encourage the development of enterprise that adopts environmental-friendly technologies and materials. Additionally, approval procedure of these enterprises shall be simplified and certain capital support shall be provided. Technologies and products of these enterprises shall be promoted positively when solving various construction problems.

Haze control technologies should be formulated, and environmental education should be enhanced: Ongoing urbanization, transformation of industrial enterprises, rapid development of urban transportation facilities, and continuous construction of residential houses and supporting facilities in China present good opportunities for using energy-saving environmental-friendly new technologies and energy sources. This phenomenon results in the formation of a set of relatively mature technological and energy system at the end of urbanization. Such system will hamper the use of energy-saving environmental-friendly new technologies and energy sources. Consequently, the Chinese government shall enhance the promotion of energy-saving environmental-friendly new technologies and energy sources to realize more extensive application of these technologies and sources. Values created per unit energy consumption will increase accordingly and the total energy consumption is reduced with the increasing application of these technologies and energy sources. Additionally, the Chinese government shall offer more fiscal subsidies to users of these technologies and energy sources, which are difficult to generalize because of their high cost. Therefore, high fiscal subsidies can promote these resources to some extent. Production technology will be improved significantly when these new technologies and energy sources are widely accepted, resulting in reduced production cost and sales price. The government shall enhance the sense of social responsibility of citizens through extensive social propaganda and encourage the citizens to establish a joint haze control with enterprises and other groups. This setup is also conducive to increase the awareness of citizens on environmental protection, enabling the citizens to choose green lifestyle to improve the environmental protection level in their region.

CONCLUSIONS

Haze pollution in China has caused damages, and environmental pollution control should be implemented. Club convergence of haze pollution in one region is explored. Specific eco-compensation measures against haze pollution are proposed to further analyse the spatial distribution of haze pollution in China. Spatial autocorrelation of haze pollution among 30 provinces in China is calculated through Moran's I, and spatial distribution of haze in China is analysed. Spatial club convergence of haze pollution is discussed using SEPDM. Results from the empirical study show that haze pollution in the key monitored provincial capitals and municipalities in China is very serious. Strong spatial autocorrelation of haze pollution exists among the study areas. Spatial concentration presents characteristics of continuous distribution and increasing spatial dependency. Several regional provinces exhibit spatial club convergence based on haze pollution. Results provided certain references to further understand the spatial distribution of haze pollution in China and explore eco-compensation measures against this phenomenon. This paper only discussed a short period because of the short history of haze pollution statistical system in China. Additional studies can increase the length of the time sequence of haze pollution data and explore the spatial correlation between economic development and haze pollution, as well as eco-compensation measures, to limit haze pollution.

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