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Spatial Inequality of Haze Pollution in China's Urban Regions and Coordinated Prevention and Control Countermeasures

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ABSTRACT

The haze pollution issue in China has been widely paid attention among the social public recently. It is significant to analyse the spatial inequality of haze pollution in different urban regions of China objectively for providing corresponding efficient coordinated prevention and control countermeasures. Based on the PM2.5 data of China's 187 urban regions with data availability, this study adopted Gini coefficient decomposition and polarization measurement to analyse the spatial inequality of haze pollution in China's urban regions from 2013 to 2015. Results showed that the spatial inequality of haze pollution in China's urban regions was displaying a growth trend. The changing trends of the polarization index *LU* and the national overall Gini coefficient are basically consistent with each other, both indicating an increasing trend. Moreover, the spatial inequality of China's urban regions in the haze pollution level was mainly displayed as the intra-regional inequality within eastern, middle and western regions of China. The contribution of intra-regional Gini coefficient accounted for over 55% of the overall Gini coefficient, while the contribution of inequality within themselves accounted for less than 45%. There were existing five kinds of urban regions in total, by using k-means algorithm clustering, according to the haze pollution levels of them. As a result, coordinated haze pollution prevention and control countermeasures were provided in this study. The conclusions suggest that finding of this study is of certain theoretical value and practical significance for the coordinated treatment of haze pollution in different urban regions of China.

INTRODUCTION

The major component of urban haze pollution is PM2.5 (suspended particulate matters with a diameter smaller than 2.5μm). Since Ambient Air Quality Standard (AAQS) was re-issued in China on October 11^{th}, 2012, PM2.5 has been officially included into ambient air quality monitoring as one index. In recent years, the haze pollution issue in China has been widely paid attention among the social public. However, it is necessary to look into the spatial inequality of haze pollution in different regions to realize coordinated treatment across the country.

Gini coefficient decomposition and polarization measurements are used popularly in the field of spatial inequality measurement at present. Gini coefficient decomposition has been widely applied into inequality measurement between regions and groups (Dagum 1997, Rey 2013, Teng et al. 2014). Liu examined the evolution of economic gap between different regions in China during 1996-2007 using Gini coefficient decomposition method (Liu 2011). And using the same method, Chi measured the income gap between different regions in China (Chi et al. 2012). The research regarding polarization measurement is originally applied into income distribution (Esteban et al. 1994). Now more and more scholars adopt this method in studying inequality issue of other areas (Maza 2014, Kobus 2015). Jin Fenghua analysed the polarization trend of innovation capacity in the metropolitan area of Shanghai (Jin Fenghua et al. 2013). Zhao Lei analysed the spatial imbalance and polarization trend of Chinese tourism development (Zhao et al. 2014). However, through bibliographic retrieval, it is found out that there has been no literature that jointly adopts Gini coefficient decomposition and polarization measurement for analysing the spatial inequality of haze pollution in China's urban regions.

Hence, this paper proposes to adopt Gini coefficient decomposition and polarization measurement to measure and analyse the spatial inequality of haze pollution in 187 urban regions with data availability across the country during 2013-2015. The research results are of certain theoretical value and practical significance for the coordinated treatment of haze pollution.

MATERIALS AND METHODS

Gini coefficient decomposition: Gini coefficient decomposition is a relatively popular kind of spatial inequality measurement method at present, and it has been widely applied into inequality measurement between regions and groups. The calculation formula for overall Gini coefficient of the haze pollution level in urban regions is:

$$G = \frac{\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i}^{n_j}\sum_{r}^{n_h}\left|y_{ji} - y_{hr}\right|}{2N^2 u} \quad ...(1)$$

Where, G represents general Gini coefficient, y_{ji} represents the haze pollution level of urban regions i in region j (hereby, j=1,2,3, representing the eastern, middle and western regions respectively; The regional classification of urban regions: western region includes 12 provinces, namely Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Sichuan, Chongqing, Yunnan, Guizhou, Tibet, Guangxi and Inner Mongolia; the middle region includes 8 provinces, namely Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan; and the eastern region includes 11 provinces, namely Liaoning, Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong and Hainan); n_h represents the number of urban regions in region h; N is the total number of urban regions; u is the average haze pollution level in 187 urban regions across China.

The overall Gini coefficient value can be obtained through formula (1). The overall inequality in the haze pollution level among urban regions can be judged directly, but group decomposition cannot be done. To this end, a decomposition method is proposed to decompose it into the contribution G_w of intra-regional inequality to overall inequality and the contribution G_b of inter-regional inequality to overall inequality (Dagum 2001), namely $G = G_w + G_b$, in which, the Gini coefficient within region P_j is:

$$G_{jj} = \frac{\sum_{i=1}^{n_j}\sum_{r=1}^{n_j}\left|y_{ji} - y_{jr}\right|}{2n_j^2 u_j} \quad ...(2)$$

The contribution of intra-regional inequality to overall Gini coefficient is:

$$G_w = \sum_{j=1}^{k} G_{jj} P_j s_j \quad ...(3)$$

Where, $p_j = \frac{n_j}{N}$, $s_j = \frac{n/u_j}{Nu}$

The Gini coefficient calculation formula between region j and h is:

$$G_{jh} = \frac{\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}\left|y_{ji} - y_{hr}\right|}{n_j n_h \left(u_j + u_h\right)} \quad ...(4)$$

Then the contribution of inter-regional inequality to overall Gini coefficient is:

$$G_b = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}\left(p_j s_h + p_k s_j\right) \quad ...(5)$$

Based on the above, the Gini coefficient is within 0-1, and a larger value indicates a bigger inequality.

Polarization measurement: The inequality of Chinese urban regions in terms of the haze pollution level can be measured with Gini coefficient, but it is difficult to make accurate judgment upon its polarization tendency. This is because polarization not only reflects the distribution of all members in deviating from the overall situation, but also emphasizes that all members are distributed in cluster surrounding the local sample. Polarization index analyses can more objectively understand the spatial inequality of Chinese urban regions in the haze pollution level.

In polarization analyses, research object must contain some subpopulations of a certain scale; and there must be high heterogeneity between them and high homogeneity inside them. To the heterogeneity between subpopulations and the homogeneity inside them, Esteban & Ray (1994) defined the inter-subpopulation alienation function and intra-subpopulation identification function for measurement. They gave out the alienation function $AL_{ij} = \left|u_i - u_j\right|$ between the i^{th} sub-population and the j^{th} sub-population. Polarization index can be obtained by multiplying each function and summing up all subpopulations after weighting.

$$ER = K\sum_{i=1}^{s}\sum_{j=1}^{s} p_i p_j p_i^{\alpha}\left|u_i - u_j\right| \quad ...(6)$$

Where, K is a constant larger than 0, and in formula it works for standardization; α is a polarization sensitive parameter, with its value ranging from 1 to 1.6.

ER index requires the condition that population members have the sense of identification to complete consistency, but the intra-population identification has a close relationship with subpopulation formation means and intra-population inequality. Larger intra-population inequality indicates smaller clustering force. Hence, the above condition does not establish itself in most cases. Based on the above, an improved method (De La Vega et al. 2014) is proposed:

$$LU = K\sum_{i=1}^{s}\sum_{j=1}^{s} p_i p_j p_i^{\alpha}\left(1 - G_i\right)^{\beta}\left|u_i - u_j\right| \quad ...(7)$$

Where, G_i is the Gini coefficient inside sub-population i, and the parameter β>0. After the measurement of G_i, the

Table 1: Statistical analysis result of haze pollution conditions of 187 urban regions (2013-2015).

Statistics	N	Minimum	Maximum	Average	Standard deviation
PM2.5 in 2013	187	11	209	102	44.44
PM2.5 in 2014	187	18	123	61	19.80
PM2.5 in 2015	187	17	104	54	18.12

polarization index *LU* can be measured and analysed with the formula (7).

SPATIAL DIFFERENCE ANALYSES RESULTS OF HAZE POLLUTION IN CHINA'S URBAN REGIONS

Data source: China's urban regional haze pollution data were obtained from China air quality online monitoring platform (https://www.aqistudy.cn/). The results of descriptive statistical analysis of the haze pollution level of 187 urban regions from 2013 to 2015 are given in Table 1. From 2013 to 2015, the maximum and average PM2.5 value of urban regional haze pollution both showed a gradual declining tendency. All units of the 187 urban regions are included in Table 3.

Analyses results based on Gini coefficient decomposition: According to Gini coefficient measurement and decomposition formula (1)-(5), the spatial inequality of the haze pollution level of Chinese urban regions is measured, and their inequality is decomposed as per eastern, middle and western regions. The measurement results are given in Table 2. From the measurement results, the national overall Gini coefficient showed a growth trend from 0.163 in 2013 to 0.204 in 2015, indicating that the overall inequality was expanding. From contribution of Gini coefficient, the inequality of Chinese urban regions in the haze pollution level was mainly displayed as the intra-regional inequality within eastern, middle and western regions. The contribution of intra-regional Gini coefficient accounted for over 55% of the overall Gini coefficient, while the contribution of inequality within themselves accounted for less than 45%.

Seen from the Intra-regional Gini coefficient of the haze pollution level within the three regions, the inequality inside eastern, middle and western regions is close. The annual average Gini coefficients in eastern, middle and western regions were 0.209, 0.17 and 0.191, respectively. In addition, the growth of Gini coefficient within western and eastern regions were both slower than that for middle region, registering an average annual growth of 13.65% and 4.82%; and that for middle region is higher at 17.06%. Seen from the inter-regional Gini coefficient of the haze pollution level between the three regions, the inequality between middle and western regions is largest, with the annual average of Gini coefficient reaching 0.207. Then the inequality between eastern and middle regions followed, with the average Gini coefficient reaching 0.20; and the smallest inequality existed between eastern and western regions, reaching 0.067.

Analyses results based on polarization measurement: This research adopted polarization index calculation formula (7) to further reveal spatial inequality of the haze pollution level of Chinese urban regions. To ensure that the obtained polarization index is within 0-1, this paper in the empirical process refers to the parameter setting in relevant literature, and sets K= 0.1, ∂= 0.5, β= 2.

From the measurement results, the polarization index *LU* changing trend of spatial polarization of Chinese urban regions in terms of the haze pollution level is basically consistent with the changing trend of the national overall Gini coefficient, both displaying a growth trend. From 2013 to 2015, the polarization index increases from 0.388 to 0.412, an increasing rate of 5.95% as given in Table 2. As for the reasons behind, the clustering degree inside the three regions is weakening, and the regional confrontation displayed an enhancing trend. As given in Table 2, whether for intra-regional Gini coefficient or inter-regional Gini coefficient, it is increasing. And the spatial polarization of the haze pollution level of Chinese 187 urban regions is also increasing, in general.

Clustering analysis of haze pollution in 187 urban regions: Considering the obvious spatial inequality of different regions in haze pollution, this paper conducted clustering analyses of haze pollution according to the pollution level of different regions (as per the average haze pollution data of 187 urban regions in three years) using k-means algorithm. The basic approach of k-means algorithm was as follows: first of all, randomly choose K objects with each representing the centroid of one cluster; for the remaining objects, assign them into corresponding similar cluster according to the distance between the object and clustering centroid; then, calculate the new centroid of each cluster; repeat the above steps until the criterion function converges, and the normally adopted criterion function is square error criterion function (Macqueen 1967). The clustering results are as presented in Table 3 (with 5 clusters in total).

***Urban regions with the most serious haze pollution*: The** haze pollution of 11 urban regions, including Jining, Linyi,

Table 2: Analyses results based on Gini coefficient decomposition and Polarization measurement.

	Intra-regional Gini coefficient and its contribution						Inter-regional Gini coefficient and its contribution					
Year	Overall Gini coefficient	Gini coefficient within eastern region	Gini coefficient within middle region	Gini coefficient within western region	Contribution of intra -regional Gini coefficient to overall Gini coefficient	Ratio of Contribution in overall Gini coefficient	Gini coefficient between eastern and middle regions	Gini coefficient between eastern and western region	Gini coefficient between middle and western region	Contribution of inter-regional Gini coefficient to overall Gini coefficient	Ratio of Contribution in overall Gini coefficient	The polarization index *LU*
2015	0.204	0.234	0.266	0.259	0.114	55.65%	0.255	0.081	0.265	0.091	44.35%	0.412
2014	0.156	0.192	0.114	0.161	0.088	56.57%	0.169	0.060	0.174	0.068	43.43%	0.398
2013	0.163	0.200	0.130	0.153	0.092	56.24%	0.177	0.061	0.183	0.071	43.76%	0.388
Annual average	0.174	0.209	0.170	0.191	0.098	56.15%	0.200	0.067	0.207	0.077	43.85%	0.399

Zaozhuang, Shijiazhuang, etc. was the most serious, and all of them fell into the eastern region, accounting for 9.32% of all the sampled urban regions in the eastern region.

***Urban regions with relatively serious haze pollution*:** There were 22 urban regions, including Binzhou, Weifang, Changzhou, Nanjing, etc., located in the regions with relatively serious haze pollution. Among them, the urban regions in the eastern region took the largest share (13 in number), accounting for 11.02% of all the sampled urban regions in the eastern region. It was followed by the urban regions in the central region (5 in number), accounting for 16.13% of all the sampled urban regions in the central region. And the western region had the least (4 in number), accounting for 10.53% of all the sampled urban regions in the western region.

***Urban regions with normal haze pollution*:** There were 51 urban regions, including Liuzhou, Ningbo, Fuyang, Pingdingshan, etc., located in the regions with normal haze pollution. Among them, the urban regions in the eastern region took the largest share (29 in number), accounting for 24.58% of all the sampled urban regions in the eastern region. It was followed by the urban regions in the central region and western region (both 11 in number), accounting for 35.48% of all the sampled urban regions in the central region and 28.95% of all the sampled urban regions in the western region.

***Urban regions with relatively sound air conditions*:** There were 60 urban regions, including Yixing, Qingyuan, Dandong, Dongguan, etc., located in the regions with relatively sound air conditions. Among them, the urban regions in the eastern region took the largest share (38 in number), accounting for 32.20% of all the sampled urban regions in the eastern region. It was followed by those in the central region (12 in number), accounting for 38.71% of all the sampled urban regions in the central region. And the western region had the least (10 in number), accounting for 26.32% of all the sampled urban regions in the western region.

***Urban regions with the best air conditions*:** There were 43 urban regions, including Erdos, Lhasa, Jiayuguan, Chifeng, etc., located in regions with the best air conditions. Among them, the urban regions in the eastern region took the largest share (27 in number), accounting for 22.88% of all the sampled urban regions in the eastern region. It was followed by those in the western region (13 in number), accounting for 34.21% of all the sampled urban regions in the western region. And the central region had the least (3 in number), accounting for 9.68% of all the sampled urban regions in the central region.

From the above analyses, it can be seen that in the eastern region, the urban regions with sound air conditions accounted for the largest proportion (32.20%), followed by the urban regions with normal haze pollution (24.58%) and the urban regions with the best air conditions (22.88%); and the urban regions with relatively serious haze pollution only accounted for a small proportion (11.02%). In the central region, the urban regions with relatively sound air conditions accounted for the largest proportion (38.71%), followed by the urban regions with normal haze pollution (35.48%) and the urban regions with relatively serious haze pollution (16.13%); and the urban regions with relatively sound air conditions were the least (9.68%). In the western region, the urban regions with the best air conditions accounted for the largest proportion (34.21%), followed by

Table 3: Clustering results of haze pollution in 187 urban regions

Type	Cities
Urban regions with the most serious haze pollution	Jining, Linyi, Zaozhuang, Shijiazhuang, Hengshui, Liaocheng, Texas, Xingtai, Handan, Heze, Baoding
Urban regions with relatively serious haze pollution	Binzhou, Weifang, Changzhou, Nanjing, Wuxi, Jingzhou,Mianyang, Baoji, Cangzhou,Harbin, Weinan, Tai'an, Huai'an, Xianyang, Tangshan, Hefei, Zhengzhou, Langfang, Jinan, Wuhan, Laiwu, Zibo
Urban regions with normal haze pollution	Liujiang, Yancheng, Shouguang, Anyang, Changzhi, Jiaxing, Shenyang, Xi'an, and so on. It is located in the city of Changjiang, Changchun, Yibin, Tongchuan, Pingdingshan, Shanghai, Quzhou, Urumqi, Urumqi, Zhuzhou, Luzhou, Luzhou, Luzhou, Luoyang, Guilin, Yichang, Deyang, Xuzhou, Suzhou, Chengdu, Jiujiang, Yangzhou, Changsha, Lianyungang, Jurong, Suqian, Huzhou, Taizhou, Jinhua, Tianjin, Dongying
Urban regions with relatively sound air conditions	Yantai, Qingyuan, Dandong, Dongguan, Hohhot, Jiangmen, Wendeng, Luoyang, Yangjiang, Guangzhou, Shaoguan, Wafangdian, Guiyang, Lishui, Qinhuangdao, Wujiang, Kunshan, Yantai, Sanmenxia, Yinchuan, Huludao, Panjin, Qiqihar, Zhaoyuan, Taicang, Wenzhou, Maoming, Changshu, Foshan, Zhaoqing, Kaifeng, Jiaozuo, Jinzhou, Xining, Lanzhou, Taizhou, Lacey, Nanchang, Zunyi, Baotou, Nanning, Jiaozhou, Qingdao, Yueyang, Changde, , Korla, Yangquan, Jieyang, Laizhou, Chaozhou, Zhangjiajie, Yiwu, Jintan, Jiaonan, Chongqing, Taiyuan, Haimen, Linfen
Urban regions with the best air conditions	Zhaoyuan, Zhaoshan, Panzhihua, Jilin, Huizhou, Benxi, Heyuan, Shizuishan, Yingkou, Fushun, and so on. It is located in the city center, Rongcheng, Shenzhen, Shantou, Beihai, Meizhou, Zhuhai, Mudanjiang, Qujing, Yan'an, Datong, Jimo, Yunfu, Penglai, Zhongshan, Rushan, Karamay, Dalian

the urban regions with normal haze pollution (28.95%) and the urban regions with relatively sound air conditions (26.32%); and the urban regions with relatively serious haze pollution were the least (10.53%).

COORDINATED PREVENTION AND CONTROL COUNTERMEASURES OF HAZE POLLUTION IN CHINA'S 187 URBAN REGIONS

Establishing trans-regional haze joint prevention and control mechanism: First of all, the regions need to sign a binding trans-regional haze prevention and control cooperation agreement, which will specify the leading organ, responsibilities, obligations, monitoring system, complete evaluation index system with evaluation held regularly to assess the pollution treatment performance of local governments. Besides, trans-regional responsibility sharing mechanism needs to be built to share the cost of haze treatment. Differentiated responsibilities should be borne according to the contribution of different regions to haze pollution with the gap in economic development taken into consideration. If economically backward regions are asked to undertake the major cost, their economic development will be strained, so trans-regional cooperation should be established where the regions jointly share the cost under explicit responsibilities.

Taking the corresponding measures according to the features of different regions: At present, the focus of coordinated treatment of haze should be placed into the 11 urban regions with the most serious haze pollution, including Jining, Linyi, Zaozhuang, Shijiazhuang, Henghsui, Liaocheng, Dezhou, Yingtai and so on. Meanwhile, due to the influences of industrial structure, energy structure and environmental protection upon haze pollution as well as varied influencing factors of haze pollution in different regions, measures need to be adjusted for different urban regions so as to formulate suited haze prevention and control policies. For example, for small and medium-sized urban regions like Jining and Hengshui, unreasonable industrial structure and energy structure may be the major reasons for serious haze pollution, so attention should be paid to structural transformation and upgrading, develop the tertiary industry, and enhance input into science and technology. For super-large developed urban regions like Beijing and Shanghai, population density and vehicle exhaust emission may be the major reasons for serious haze pollution, so excessive population growth needs to be curbed; and vehicle exhaust should be strictly controlled through forcibly installing filter in diesel-driven vehicles, and developing electric-driven automobiles and bicycles. And meanwhile, the influence of vehicle exhaust emission upon haze pollution should be eased through vigorously developing public traffic and promoting green commuting.

CONCLUSIONS

Relying on the PM2.5 data of China's 187 urban regions obtained from China air quality online monitoring platform, this paper adopted Gini coefficient decomposition and polarization measurement to measure and analyse the spatial inequality of haze pollution in China's urban regions from 2013 to 2015. The research results showed that the spatial inequality of haze pollution in China's urban regions displayed a growth trend recently. The changing trend of polarization index *LU* was basically consistent with the changing trend of the national overall Gini coefficient, both displaying an increasing trend. Moreover, the spatial inequality of China's urban regions in the haze pollution level was mainly displayed as the intra-regional inequality within eastern, middle and western regions of China. The contribution of intra-regional Gini coefficient accounted for over 55% of the overall Gini coefficient, while the contribution of inequality within themselves accounted for less than 45%. Seen from the intra-regional Gini coefficient of the haze pollution level within the three regions, the spatial inequality inside eastern, middle and western regions is close. Seen from the inter-regional Gini coefficient of the haze pollution level between the three regions, the spatial inequality between middle and western regions was the largest. Then the inequality between eastern and middle regions followed, and the smallest spatial inequality existed between eastern and western regions. Clustering analysis of haze pollution in 187 urban regions using k-means algorithm showed that there were existing five kinds of urban regions in total: Urban regions with the most serious haze pollution (including 11 urban regions); urban regions with relatively serious haze pollution (including 22 urban regions); urban regions with normal haze pollution (including 51 urban regions); urban regions with relatively sound air conditions (including 60 urban regions); urban regions with the best air conditions (including 43 urban regions). Consequently, coordinated prevention and control countermeasures were provided for coping with the spatial inequality of haze pollution in different urban regions of China efficiently.

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