

Spatial-Temporal Dynamics of Disease Burden Attributable to Pm2.5 Exposure in China From 2000 to 2016

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Research Article

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Spatial-temporal dynamics of disease burden attributable to PM_{2.5} exposure in China from 2000 to 2016

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Abstract

In recent years, long-term exposure to ambient fine particulate matter (PM_{2.5}) has slowly increased both morbidity and mortality for Chinese people, becoming a leading problem for public health efforts. However, spatial-temporal dynamics of disease burden attributable to PM_{2.5} exposure still lacks a comprehensive evaluation so as to provide inadequate supports for policy making and improvement. Here, we used the exposure-response function to derive the spatial-temporal dynamics of disease burden attributable to PM_{2.5} pollution in China. We found the fact that economic loss attributable to PM_{2.5} increased by 93% from 35 billion Chinese Yuan (95% CI: 14-52) to 536 billion Chinese Yuan (95%CI: 236-753) during the period of 16 years. Digging further, we discovered a substantiate level of regional differences, with the disease burden being the most severe in East China and the least severe in the Northwest China. Other than that, there existed a spatial aggregation of health-related economic losses among Chinese cities. Our paper made an evaluation on the spatial-temporal dynamics of health effects attributed to PM_{2.5}, an evaluation that could provide more insights to future policy making of the air pollution control for China and other developing countries.

Keywords: health effects; PM_{2.5}; exposure-response assessment;China

1. Introduction

Exposure to fine particulate matter is a world's leading health risk, and long-term exposure to ambient fine particle air pollution (PM_{2.5}) caused global 4.2 million deaths and 103.1 million lost years of healthy life in 2015, accounting for 7.6% of total mortality, making it the fifth-ranked global risk factor (1-3). Since 2013, China has experienced massive smog pollution, affecting about 8 million people. The concentration of PM_{2.5} per hour in Beijing reached an astonishing figure of 1000 μ g/m³. The first-level PM_{2.5} concentration standard set by the World Health Organization (WHO) is 10 μ g/m³, which has been overly exceeded by most Chinese cities (4,5). As a representative of high-concentration PM_{2.5} pollution, cities in China have far more cases of disease (premature death) due to PM_{2.5} than those in most other countries. In order to effectively improve the problem of PM_{2.5} pollution and to protect more urban residents from being harmed by PM_{2.5} pollution, the Chinese government has formulated a series of corresponding policies

and measures. For example, China promulgated the tougher-ever “Air Pollution Prevention and Control Action Plan” in 2013.

A systematic assessment on the burden of air pollution in China could help to develop optimized control policies based on health effects, which would be more effective. Therefore, research on the disease burdens of PM_{2.5} in China deserves more attention. The exposure-response model has been widely adopted among the scholars. Plugging in pollutants and health effects, this model estimates the health effects (premature death or illness) attributed to fine particulate pollution (6-11). Cohen et al. (2017) estimated through the integrated exposure-response that the long-term exposure to outdoor PM_{2.5} in 2015 attributed to more than 42 million cases of death worldwide, and noted that there is currently no large-scale study of PM_{2.5} and mortality in the most polluted areas. Yet higher levels of exposure-response coefficient should be used in areas exposed to high concentrations of PM_{2.5}. China, with a relatively high level of pollution, has also studied the burden of disease caused by air pollution (12-15). However, most studies on the health effects of air pollution in China are based on globally consistent epidemiological exposure-response coefficients, which may not be appropriate for estimating the disease burden in Chinese cities². Additionally, high emissions of primary particles, gaseous PM_{2.5} precursors from multiple sources and efficient secondary PM_{2.5} formation have cause regional differences of PM_{2.5} pollution. But previously published studies are restricted to a single region, which did not deal with regional diversity of PM_{2.5} among Chinese cities. Also, current studies mainly focus on a short-scale evaluation, a scale that cannot provide a comprehensive overview of spatial-temporal dynamics in the burden of disease attributable to PM_{2.5} pollution in China. What’s more, PM_{2.5} has cross-regional transmission characteristics, and the regional economies also interact with one another. As a result, economic losses attributable to the health effects of PM_{2.5} among regions are also interconnected. However, there is not any discussion of the spatial correlation of economic losses attributed to the health effects of PM_{2.5} in China. Our goal is to address several shortcomings on the studies about the burden of disease attribute to PM_{2.5} in China.

We obtained the exposure-response coefficient from Chinese epidemiological studies. Combined with the exposure-response coefficient and the data of PM_{2.5} in Chinese cities from 2000 to 2016, we used the exposure-response function to estimate the amount of disease burden attributed to PM_{2.5} during 2000-2016, and thus quantified the health effects of PM_{2.5} pollution on Chinese cities and the corresponding economic losses. Secondly, we took the Huai River and Qinling Mountain as the boundary to compare the north-south regional division of Chinese cities. We discovered that the burden of disease attributed to PM_{2.5} pollution was higher in the northern cities than the southern ones in a long-term scenario, which was consistent with previous research (16,17). Furthermore, based on the geographical area of each city, this study divided Chinese cities into seven regions. By quantifying the burden of disease caused by PM_{2.5} pollution this way, we noticed some regional differences in the losses caused by PM_{2.5} pollution. Assessment of long-term changes in the burden of disease attributed to PM_{2.5} exposure in these areas, we found the

spatial-temporal dynamics of the burden of disease attributable to PM_{2.5} exposure in China. In the long-term, the burden of disease has improved in some regions (Central China), but in some regions the burden has been more severe (Northeast China). In order to investigate the regional aggregation of economic loss of health effects attributed to PM_{2.5} pollution, we also explored the spatial distribution of economic losses due to health effect. By describing the situation of economic loss at the spatial level, we found that pollution loss of PM_{2.5} is polarly concentrated in spatial distributions. Through the spatial-temporal dynamic assessment of disease burden attributed to PM_{2.5} in Chinese cities from 2000 to 2016, we can then provide a basis for the design and improvement of policies to control the pollution in China.

2. Methodology and data

2.1. Data

2.1.1. PM_{2.5} concentration

The PM_{2.5} concentration data obtained from the National Aeronautics and Space Administration (NASA) medium resolution imaging spectrometer (MODIS), multi-angle imaging spectrometer (MISR) and ocean observation wide field sensor (SeaWiFS) inversion global annual PM_{2.5} raster data of aerosol optical thickness(AOD) , and use ArcGIS software to parse it into specific values of the average annual PM_{2.5} concentration in 210 Chinese cities from 1998 to 2016 (if necessary, you can obtain it from the author). According to the WHO air quality guidelines, when the PM_{2.5} concentration is less than 10ug/m³, it is a safe value. Therefore, the threshold of PM_{2.5} selected in this paper is 10ug /m³

2.1.2. The exposure-response coefficient and baseline incidence

The assessment of the health loss of atmospheric pollution is widely used for quantitative analysis of the exposure-response coefficient between particulate matter and the end of the health effect. Considering that the globally consistent epidemiological exposure-response coefficient is mostly under the condition of low concentration of PM_{2.5} pollution, it cannot be directly applied to the high PM_{2.5} concentration in China as a whole (5,14). Therefore, this paper comprehensively selects the exposure-response coefficients obtained from the comprehensive analysis of the Chinese epidemiological cohort(Supplementary Table 1). The base incidence rate of different health endpoints in Chinese cities comes from the statistical yearbooks of various cities and the China Health Statistical Yearbook. Among them, due to the lack of data in the yearbook for the baseline incidence of asthma and acute bronchitis, reference was made to the baseline incidence in the study by Huang et al.(2013) (14).

2.1.3. Unit values for health endpoints

For the economic loss caused by premature death, this study uses the willingness to pay method (WTP) to evaluate. The statistical life value (VSL) can be used to express the willingness of individuals to pay. In this paper, the benefit conversion method is used to adjust different VSL values caused by city differences, and the corresponding VSL values

of various cities in China are obtained. The harm of PM_{2.5} to the human body mainly affects the respiratory system and the cardiovascular system (20-22), so this article selects the death of respiratory disease and death of cardiovascular disease as the research object for the end point of death.

For the economic loss caused by disease, this study adopts the cost of disease method (COI). According to the "China Health Statistics Yearbook" of each year, the per capita hospitalization cost, per capita outpatient cost and average hospitalization days were obtained, and the average hospitalization day was taken as the time of lost work. Among them, the unit economic loss due to asthma and acute bronchitis was not available in the yearbook. Therefore, referring to the unit economic value of asthma and acute bronchitis in Beijing in 2009, which was studied by Huang et al. (2013) (14), after income adjustment, the unit economic loss of disease end points in various cities was obtained. For chronic bronchitis, it is difficult to determine the time of illness, so it is difficult to use the disease cost method to evaluate. This article refers to the research results of Magat & Huber (1991) (23) and Viscusi & Aldy (2003) (24). There is a risk trade-off between inflammation and premature death. The unit economic loss of chronic bronchitis is 32% of the statistical life value. Based on the above method, this paper concludes that the unit economic losses of different health end points in Chinese cities from 2005 to 2016 are limited to space. This paper only lists the relevant data of the first ten cities in 2016. See Supplementary Table 2 for details.

2.1.4. Exposure population and economic data

This article selects the population of the city districts at the end of each year as the exposed population data. At the end of the year, the population and per capita GDP data are derived from the "China City Statistical Yearbook", and the per capita disposable income data comes from the statistical yearbook of each city (if necessary, you can obtain it from the author).

2.2. Methodology

2.2.1 Health effect assessment

Epidemiological studies often use exposure-response models to assess the effects of air pollution on poor health. The Global Burden of Disease (GBD) and the World Health Organization (WHO) (10) use the exposure-response models as a basis for estimating the burden of disease caused by PM_{2.5}. Based on the exposure-reaction relationship between PM_{2.5} pollution concentration and health effects obtained by Chinese epidemiological studies, the change of health effect is calculated by using the relative risk model of Poisson regression. The basic model sets the health risk (mortality or morbidity) of the population of the actual concentration of PM_{2.5} for a selected health terminal as:

$$I = \exp(\beta \times (C - C_0)) \times I_0$$

where C is the actual PM_{2.5} concentration, C_0 is the threshold level of PM_{2.5} (10 $\mu\text{g}/\text{m}^3$), I is the health risk of the population at PM_{2.5} at C concentration, I_0 is the health risk of the population at C_0 concentration, and β is the corresponding exposure-reaction coefficient.

The change in health risk attributable to PM_{2.5} contamination is:

$$\Delta I = I - I_0 = I(1 - 1/\exp(\beta \times (C - C_0)))$$

Thus, the health effects from PM_{2.5} are calculated as:

$$E = P \times \Delta I = P \times I(1 - 1/\exp(\beta \times (C - C_0)))$$

Where P is the number of exposed people.

2.2.2. Economic assessment of health losses caused by PM_{2.5}

Methods commonly used to assess the health values of the environment include Willingness of payment (WTP) and Cost of Disease (COI). WTP effectively measures the amount of money people are willing to pay to improve their own health and that of others, with the advantage of reflecting the personal wishes and preferences of the measured population, as well as the negative effects of economic loss and suffering to individuals as a result of illness or premature death (16,17); COI measures the total cost of diseases imposed on society, including the value of loss of productivity (loss of income) from diseases, medical expenses such as hospital care, medicine, medical and nursing services, and other related out-of-pocket costs(18).

Statistical Life Value (VSL) is a society's marginal willingness to pay to reduce the risk of death from pollution (17). At present, there have been many studies to investigate the level of payment intention in various regions and calculate the corresponding VSL, this paper takes the 2010 VSL research results (19) in Beijing as the benchmark VSL, and uses the benefit conversion method to calculate the annual VSL in Chinese cities.

$$VSL_n = VSL_{BJ} \times \left(\frac{I_n}{I_{BJ}} \right)^e$$

where VSL_n and VSL_{BJ} are VSL values for city n and Beijing respectively, I_n and I_{BJ} are per capita disposable income of city n and *Beijing*, respectively, and e is income elasticity (generally take $e=1$).

The basic formula for COI defined as:

$$C_i = (C_{pi} + GDP_p \times T_{Li}) \times E_i$$

where C_i is the total cost of additional health expenditure for PM_{2.5} to health endpoint i , C_{pi} is the unit economic loss of health endpoint i , GDP_p is the daily average of GDP per city, T_{Li} is the number of days of missed work due to health endpoint i , and E_i is calculated as a health effect related to PM_{2.5}.

2.2.3. Spatial correlation analysis of health-related economic loss

Spatial correlation analysis focuses on the degree of correlation between observations in geospatial space. The global Moran's I index describes the average correlation between the overall spatial objects in the study area, with Moran's I values ranging from -1 to 1.

Space is positively correlated between the space units if Moran's $I > 0$ is anything to go by. If Moran's $I < 0$ is, there is a spatial negative correlation between the space units. If Moran's $I = 0$ indicates that there is no spatial correlation. The global Moran's I index formula is defined as:

$$I = \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^n \sum_{j=1}^n w_{ij}}$$

where X_i is the value of the health economic loss of region i , the mean of health economic loss for all regions, n is the number of cities, S^2 is the sample variance, W_{ij} is the (i,j) element of the spatial weight matrix, which is used to measure the distance between region i and region j .

The local Moran's I index can examine the spatial concentration around a single city i and describe spatial correlations in different spatial locations. The local Moran's I value > 0 indicates that a high value is surrounded by a high value or a low value is surrounded by a low value. The local Moran's I value < 0 indicates that the high value is surrounded by a low value or a low value is surrounded by a high value. The local Moran's I index formula defined as:

$$I_i = \frac{x_i - \bar{x}}{S^2} \sum_{j=1}^n w_{ij} (x_j - \bar{x})$$

Measuring spatial correlation requires selecting the appropriate spatial weight matrix W . In this paper, W is constructed to measure the spatial distance between regions, and W can be defined as:

$$W_{ij} = \begin{cases} 1/d_{ij} & d_{ij} \geq d \\ 0 & d_{ij} \leq d \end{cases}$$

where d_{ij} is the geographic distance measured according to the latitude and longitude of the area.

3. Results

3.1. Health effects

We estimated the health effects (and 95% CI) of $PM_{2.5}$ exposure in Chinese cities from 2000 to 2016 (Table 1), compared the proportion of these cases on the total urban population, and discovered that the proportion of premature deaths increased gradually in 2000-2010 (from 0.004% to 0.0082%), while decreased in 2015 (0.0075%) and then climbed a little bit (0.0087%) in 2016. Meanwhile, the proportion of disease kept increasing during 2000-2015 (from 0.489% to 1.451%) and encountered drop in 2016

(1.445%). This paper ranked the estimated number of health effects for each city, and found out that the cities with the highest number of health effects attributed to PM_{2.5} were not the cities with the highest concentrations of PM_{2.5} (such as, the cities with the highest number of health effects due to PM_{2.5} in 2000 were Tianjin and in 2016 were Shanghai). In 2016, although the principal one in the 210 cities' ranking of PM_{2.5} concentration was Langfang with 79.2ug/m³, as compared to the 61.07ug/m³ in Shanghai, Langfang has a population of only 0.86 million people while Shanghai has 14.5 million. As a result, the health effects caused by PM_{2.5} pollution in Shanghai far exceed those in Langfang City. It can be found that the health effects caused by PM_{2.5} were not only related to the PM_{2.5} concentration of each city, but also to the economic development of each city and the density of the exposed population.

Table 1

Estimated number of cases (and 95% CI) attributable to PM_{2.5}

Health endpoints	2000	2005	2010	2015	2016
Mortality					
Respiratory Mortality	4257.62 (2562,5981)	8783.71 (5311,12285)	10894.38 (6591,15228)	11508.28 (6923,15984)	12181.36 (7328,16918)
Cardiovascular mortality	4705.19 (1338,7959)	10100.36 (2881,17037)	14927.42 (4259,25169)	15777.76 (4513,26655)	21241.82 (13502,28900)
Total	9015.49 (3900,13940)	18931.41 (8192,29322)	25821.79 (10850,40397)	27286.04 (11436,42639)	33423.18 (20830,45818)
Disease					
Respiratory hospital admission	46875.28 (0,94421)	112316.19 (0,224269)	130996.18 (0,261285)	138408.06 (0,276465)	146504.79 (0,290246)
Cardiovascular hospital admission	55944.94 (35684,76748)	134489.76 (85968,184155)	156918.75 (100325,214807)	165841.63 (106281,227482)	138020.07 (39185,231456)

Internal medicine	464773.60 (258236,666 293)	1078418.24 (60329,15436 01)	1689000.19 (940389,2416 983)	2670036.28 (1480936,52 21147)	2826287.77 (1564535,40 79874)
pediatrics	118390.01 (42702,1906 62)	324926.49 (117553,5219 23)	654743.17 (236896,1051 087)	1155173.01 (419076,185 8508)	1222771.26 (440009,195 1274)
Acute bronchitis	104233.39 (37912,1636 18)	237019.77 (89704,35892 0)	274809.13 (104438,4144 21)	289243.63 (110497,436 146)	306098.00 (116002,457 679)
Chronic bronchitis	237572.11 (92876,3490 32)	531705.05 (218115,7523 64)	615435.09 (253722,8671 75)	647110.85 (268449,912 899)	684774.22 (281634,956 696)
Asthma attack	72994.94 (51665,9513 1)	173499.79 (122023,2250 16)	202164.79 (142231,2619 68)	213466.68 (150604,277 157)	225946.69 (158117,296 965)
Total	1100784.27 (518475,163 5904)	2592375.29 (1232069,380 5004)	3724067.29 (1775908,548 1116)	5279280.13 (2515098,77 29216)	5550402.81 (2599483,81 98193)

Note: Each cell in the table represents the estimated numbers of health effects and the 95% confidence interval caused by PM_{2.5} at various health endpoints in 2000-2016, including respiratory mortality, cardiovascular mortality, respiratory hospital admission, cardiovascular hospital admission, internal medicine, pediatrics, acute bronchitis, chronic bronchitis and asthma attack.

Inspired by studies of Chen et al. (2013) (16) and Ebenstein et al. (2017) (17), China's Huai River Policy, which provides free or heavily subsidized coal for indoor heating during the winter to cities north of the Huai River but not to those to the south resulted in significant differences in air pollution levels between north and south cities in China. Therefore, residents in northern cities are particularly affected by air pollution. Our paper divided the Chinese cities into north and south with the Huai River and Qinling Mountain

as the boundary, and compared the differences in various health effects caused by PM_{2.5} in the northern and southern cities (Supplementary Table 3). From 2000 to 2016, various health effects caused by PM_{2.5} in northern cities were higher than those in the southern cities (For example, the loss of premature death caused by PM_{2.5} in northern cities will be 5,910 cases more than that in southern cities and the loss of diseases caused by PM_{2.5} was higher than that in the southern cities of 966,000 cases in 2016). By observing the data, we can find the pattern that, except in 2005 that the PM_{2.5} concentration in some southern cities (Shanghai, Guangdong, Hangzhou, Wuhan, etc.) increased significantly, resulting in relatively few differences in the health effects of the north and south cities. In other years, the health effects of northern cities are higher than those of southern cities. Further, we used the Mann-Whitney U test to compare the health effects of PM_{2.5} in northern and southern cities (Table 2) and noticed a significant difference between the north and south health effects of a 5% level. The average rank of North in the test is higher than that of South, which means the number of health effects in north is higher than that in south.

Table 2

Mann-Whitney U test for health effects in north and south

Index	N	Average rank	Sum of ranks
South	99	95.62	9466.00
North	111	114.32	12689.00
Z value		-2.003	
Sig		0.045**	

Note: **Significant at 5%.

Mann-Whitney U test tests whether there is a significant difference in health effects between North and South. A high average rating means a greater number of health effects, and a significance value means at what level there is a significant difference.

PM_{2.5} pollution shows significant regional pollution characteristics. In order to better compare the characteristics of PM_{2.5} pollution in Chinese cities, this paper divided 210 cities into 7 groups, with each representing northeast, north, east, south, midlands, northwest and southwest, based on the seven geographical regions of China's eight administrative regions (excluding Hong Kong, Macao, and Taiwan) (the results are listed in Supplementary Table 4 and SupplementaryTable5). We demonstrated the total death losses due to PM_{2.5} in each region from 2000 to 2016 (Supplementary Table 4). It can be noted that there are a relatively higher number of death losses due to PM_{2.5} in the east and midlands. Nevertheless, the density of the exposed population in each region is also an indispensable factor that affects the number of health effects. Taking the population density into our consideration, as a consequence, Figure 1 shows the proportion of premature death losses caused by PM_{2.5} as a percentage of the population density. After comparison, we

discovered that the regions with higher proportions in 2000 and 2010 are the north, midlands and east. However, the regions with higher proportions in 2015 and 2016 became the north, east, and northeast. This is caused by the decrease in the proportion of death losses due to PM_{2.5} in the midlands to the population density of the region. Death from PM_{2.5} in the east, north, south, and northwest are increasing gradually each year, while the number of deaths and losses in midlands and southwestern decreased in 2015, implying the effectiveness of the two regions in combating PM_{2.5} pollution. This paper illustrated the number of disease losses due to PM_{2.5} in each region (Supplementary Table5). Regions with large disease losses are east and midlands. The proportion of the number of disease losses in each region to the regional population density is illustrated in Figure 2. It can be noted that the regions with a large proportion of disease losses in 2000-2010 are east, midlands, and north. The loss of disease due to PM_{2.5} pollution in the northeast increased, with the proportion of disease losses in the northeast surpassing that of the midlands in 2015 and 2016. We used the Kruskal-Wallis test to compare the health effects of PM_{2.5} in seven regions (Supplementary Table 6) and found significant differences in the health effects of the seven regions at the 1% level, indicating that the health effects of PM_{2.5} in seven regions were significantly different with the east has the highest average rating, followed by the south and the lowest in the northwest.

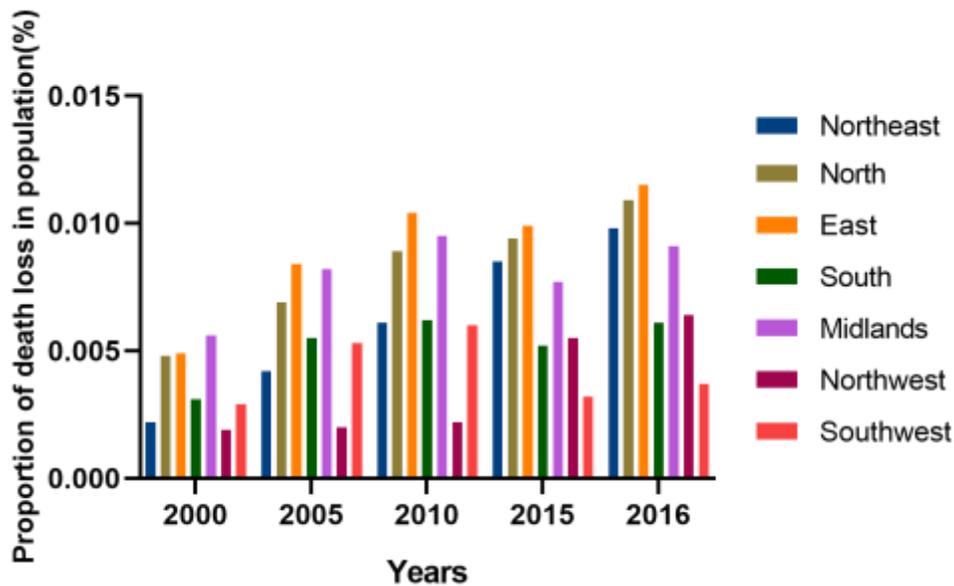


Fig. 1. Between 2000 and 2016, the number of premature deaths attributed to PM_{2.5} exposure in different regions as a proportion of the total annual exposure population in

the region. Different colors represent the northeast, north, east, south, midlands, northwest and southwest.

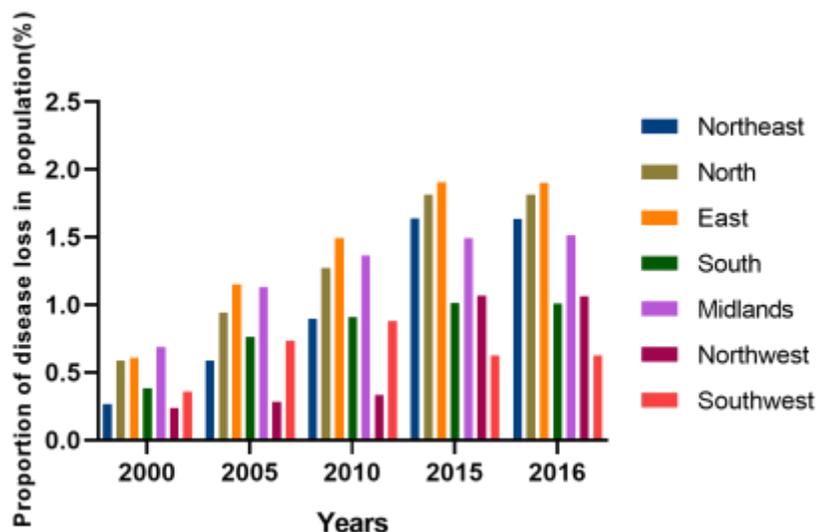


Fig. 2. Between 2000 and 2016, the number of diseases attributed to PM_{2.5} exposure in different regions as a proportion of the total annual exposure population in the region. Different colors represent the northeast, north, east, south, midlands, northwest and southwest.

3.2. Economic assessment of health effects

Economic losses from the health effects of PM_{2.5} pollution in Chinese cities from 2000 to 2016 are given in Supplementary Table 7. We also made an estimation regarding the proportion of the economic losses in terms of each year's gross domestic product (GDP). The economic losses as a share of GDP increased in 2005(1.62%) compared to 2000(0.87%), it declined in 2010-2015 (1.27%) and slightly increased in 2016(1.33%). The spatial distribution of the economic losses caused by PM_{2.5} pollution in 210 Chinese cities from 2000 to 2016 is illustrated in Figure 3 (blank areas are cities other than 210 cities). By observing the changes in the spatial distribution of health-related economic losses in different years, we can see that the economic losses of most cities have gradually increased over the years. In 2000, the maximum total economic loss of each city did not exceed 3.3 billion Chinese Yuan (CNY), but in 2016, 36 cities will have an economic loss of more

than 3.3 billion CNY, with a highest economic loss (Shanghai) exceeding 50.5 billion CNY.

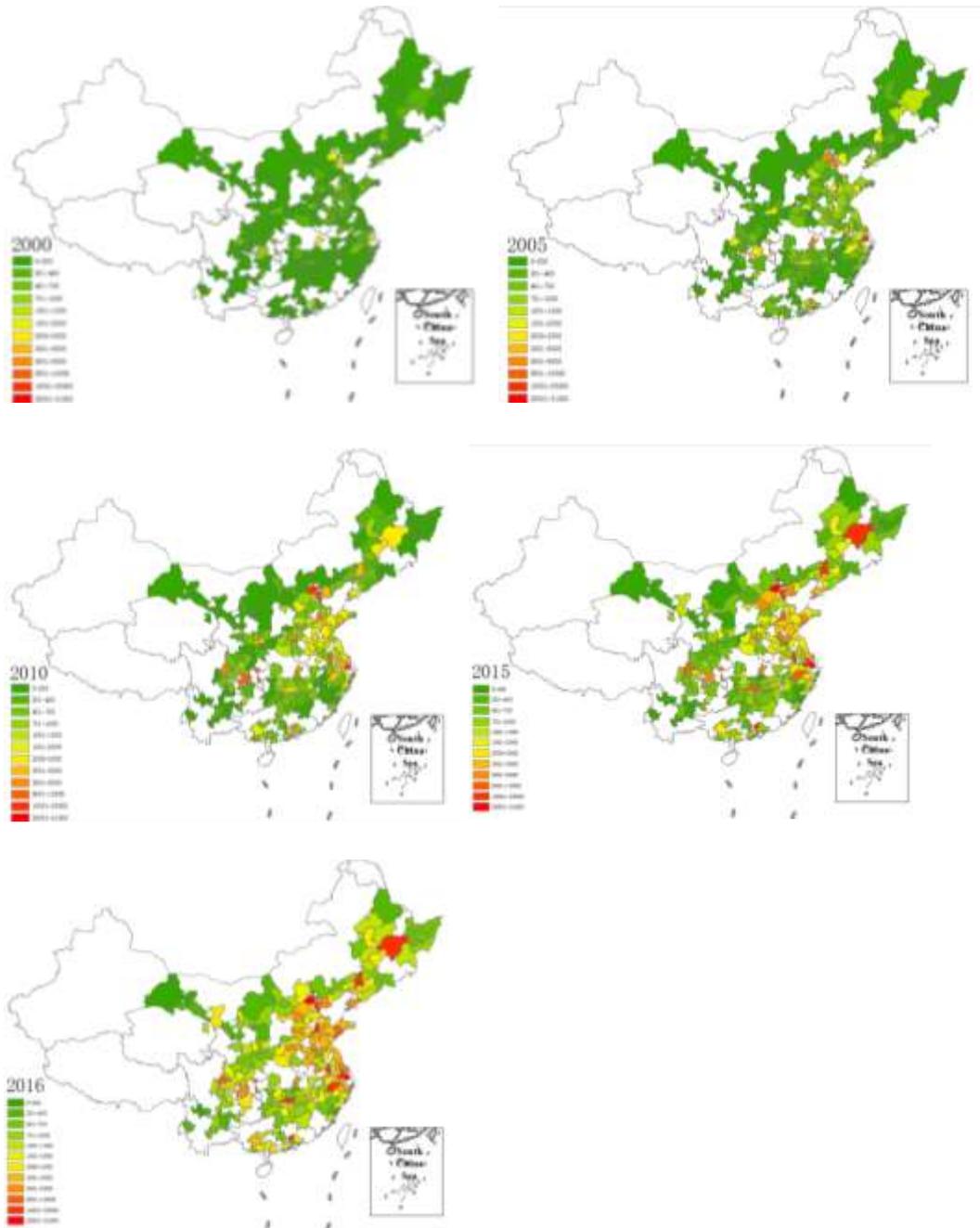


Fig. 3. The health-related economic losses (CNY¥) attributed to PM_{2.5} exposure are distributed in Space in China. The coloring corresponds to the degree of economic loss in 210 cities, where green, yellow and red indicate relatively low economic loss, medium and higher areas, respectively. Areas left in white are not within an acceptable range of any station. Figure (1)-(5) corresponds to spatial distribution for the years 2000-2016.

We compared the health-related economic losses caused by PM_{2.5} pollution in north and south (Supplementary Table 8). From the data we can conclude that except in 2005 (the reason is that the PM_{2.5} concentration in some southern cities began to increase significantly in 2005), the health-related economic loss caused by PM_{2.5} pollution in the north is greater than that in the south, and the difference in economic loss between the north and south keeps increasing every year. However, the Mann-Whitney U test for the economic losses attributed to PM_{2.5} from the north to south (Supplementary Table 9) shows that the difference between the economic losses is not significant at 5% level. The reason may underlie in the gap between the north and south economic development. The economic level of northern cities falls behind that of the southern cities. Because the unit economic losses spent on health effects may differ (although the health effects caused by PM_{2.5} are significantly different), the difference in economic losses is not notable.

This paper listed the economic loss related to PM_{2.5} pollution from 2000 to 2016 for the seven regions (Supplementary Table 10). Because economic growth among regions is quite different, the unit economic loss of health effect cannot be treated as the same. In order to make a further comparison among different regions, this paper calculated the loss as a proportion of the local GDP (Fig. 4). After calculation, we can find that the total loss of the northeast region (56.7 billion Yuan) was less than the east, north, and midlands in 2016. Yet the loss-to-GDP ratio of the northeast (1.92%) outweighed that of the east, north, and midlands. Also, although the northwest region suffered only 5.3 billion losses, the less proportion of this region was not that low (1.41%). The same pattern could still be found in the south and southwest by having a relatively high loss amount but low loss ratio of 0.61% and 0.79%, respectively. According to the proportion of health-related economic losses caused by PM_{2.5} in the region's GDP for that year can be found, In 2000, the regions with the largest proportion of the economic losses due to PM_{2.5} in GDP were north, midlands, and east; 2005 and 2010 were east, midlands, and southwest; and 2015 and 2016 were northeast, east and north. In the figure, the proportion of economic losses in midlands and southwestern has decreased since 2010, while the proportion of economic losses in northeastern and northwestern regions has increased, especially the northeast region is surpassing other regions in 2016 to become the region with the largest proportion of health-related economic losses in GDP. The Kruskal-Wallis test was conducted on health-related economic losses due to PM_{2.5} in seven regions (Supplementary Table 11). The results were consistent with the health effects in seven regions, and there were significant differences

in health-related economic losses at the 1% level. The average rank is the highest in the east, followed by the south and the lowest in the northwest.

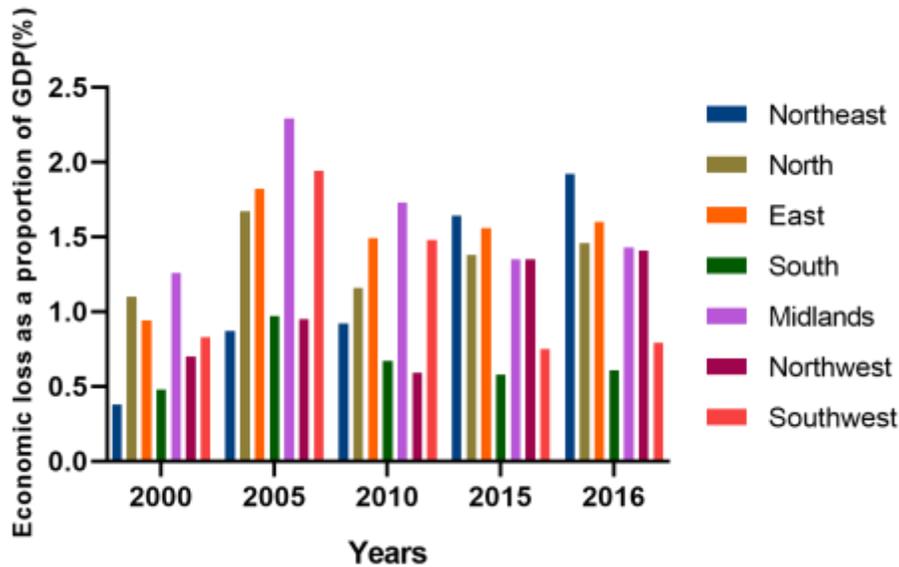


Fig. 4. In 2000-2016, the economic losses caused by PM_{2.5} exposure accounted for the proportion of GDP in each region. The different seven colors correspond to seven areas, the same as Figure 1.

3.3. Spatial auto-correlation analysis of health economic loss

We measured the global Moran's I index of the health-related economic losses attributed to PM_{2.5} in Chinese cities (Supplementary Table 12). The global Moran's I index is 0.225, significant at 1% level, indicating that 210 Chinese cities have a significant positive spatial correlation of health-related economic losses due to PM_{2.5}. Furthermore, the partial Moran's I index of the economic loss due to PM_{2.5} in 210 Chinese cities is estimated. The local Moran scatter plot (Fig. 5) divided the spatial distribution of the economic losses into four parts. The first quadrant is "H-H": it means that the city itself and surrounding cities have higher economic losses; the second quadrant is "L-H" : indicates that the city itself has lower economic losses, but the surrounding cities have higher economic losses; the third quadrant is "L-L": indicates that the city itself and surrounding cities have lower economic losses; the fourth quadrant is "H-L": it means that the city itself has a higher economic loss, but it is surrounded by surrounding cities with lower economic loss. It can be found from the figure that most cities fall in the first and third quadrants, indicating that the economic loss of PM_{2.5} pollution in Chinese cities has a more obvious bipolar aggregation phenomenon. In terms of spatial distribution, the "H-

H" and "L-L" distribution are the main types, of which areas with high economic losses gather together, and areas with low health economic losses gather together.

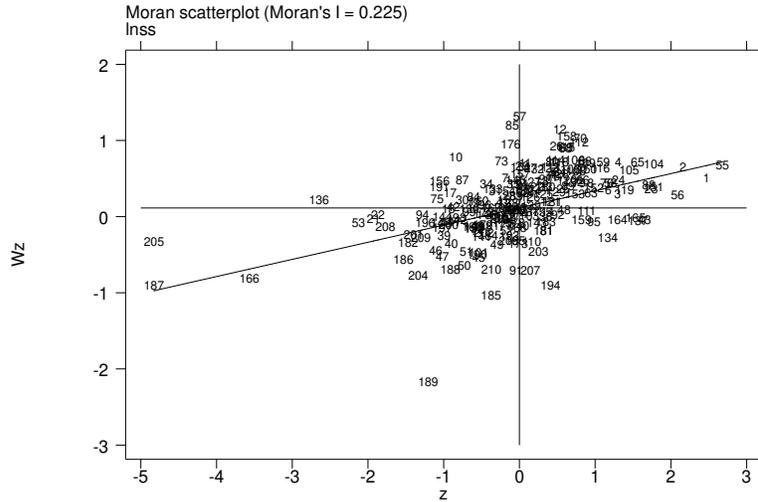


Fig. 5. The Moran scatter plot is used to describe the spatial distribution of economic losses attributed to PM_{2.5} exposure in Chinese cities. This Moran scatter plot of economic losses in 2016.

4. Discussion

Our study provided quantitative assessment on the burden of disease attributed to PM_{2.5} exposure across Chinese cities from 2000 to 2016 by the exposure-response model to provide a more comprehensive estimate of the disease burden attributed to PM_{2.5} in Chinese cities. From 2000 to 2016, the disease burden attributed to PM_{2.5} in Chinese cities has dynamic changes in the spatial-temporal level. The economic loss from the health effects of PM_{2.5} increased from 35.7 billion Yuan in 2000 to 538 billion Yuan in 2016, and the city with the highest disease burden changed from Tianjin in 2000 to Shanghai in 2016.

Our findings here were subject to several limitations and uncertainties. Firstly, although we adopted Chinese exposure-response coefficients, these coefficients are still uncertain. And all cities use the same exposure-response coefficients, which can cause some error in the results. Similarly, the average value used in estimating the unit economic loss of the health effect (e.g., average hospitalization cost, the average outpatient cost, the average hospital stays, etc.) can also result in errors in the estimated unit economic loss. Secondly, currently there are only 210 out of 293 prefecture-level cities that were evaluated, which might have underestimated the total health effect. We might further measure the rest cities to create a more systematic evaluation in the future. Thirdly, the city's value of a statistical life (VSL) is estimated by the benefit conversion method based on the 2010 Beijing's VSL. In order to ensure the validity of VSL, our study randomly selected 9 cities (Beijing, Nanjing, Xuzhou, Xi'an, Nanchang, Jinan, Taiyuan, Harbin and Dalian) from 210 cities to conduct a questionnaire survey on willingness to pay (WTP) (18). Compared the theoretical results with the survey results to test the effectiveness of

the VSL in this paper (Supplementary Figure 1), and found that the survey results was close to the theoretical results (no more than 5% error between survey value and theoretical value), so it is feasible to use theoretical VSL values. However, the VSL obtained from the questionnaire still has some shortcomings. Owing to the different design methods of the conditional value method (CVM) questionnaire, the result of respondent's choice will be different. The difference in the socioeconomic characteristics of the respondent will cause the respondent to have an extreme value in the amount of willingness to pay, so the VSL calculated, which based on the average WTP, will produce a certain error. In the future, we will may go further and make more precise investigations to fill these shortcomings.

This study compared the health effects proportion of different annual urban populations and economic losses proportion of the city's annual GDP. Compared with that before 2010, the proportion of health effect due to PM_{2.5} pollution in 2015 and 2016 has not significant increased. And the proportion of economic losses declined during the 2010-2016. This shows that China's disease burden due to PM_{2.5} has improved during recent years, and China's implementation of the "Air Pollution Prevention Action Plan" in 2013 has played its role in PM_{2.5} pollution control (22-25). The realization of the policy requires a medium- and long-term process. Especially for the pollution factor of PM_{2.5}, which is composed of both multiple and wide sources. China needs to formulate a more systematic control strategy and to establish a comprehensive prevention and control system for PM_{2.5} pollution. Considering heterogeneity between regions (e.g., industrial structure, policy, geographical characteristics, etc.), we divided Chinese cities into north and south which is defined by the line formed by the Huai River and Qinling Mountain range, and we noted that the health effects and economic losses caused by PM_{2.5} in the North were mostly higher than those in the South, which was consistent with the results of previous studies on North-South air pollution (16, 17, 26-28). In order to alleviate the serious air pollution problems in the north, it is necessary to effectively control the burning of residents' coal and use clean energy to replace coal. Clean domestic heating fuel has now become part of China's northern policy, which is now gradually being implemented throughout the country for heating and cooking solid fuel(13). Secondly, China's PM_{2.5} pollution has obvious cross-border transport and multi-scale propagation characteristics (29, 30). In this regard, we divided Chinese cities into seven regions, and found that the disease burdens due to PM_{2.5} pollution were different in the seven regions. The disease burden due to PM_{2.5} in East is the most serious (loss of premature death in 2016 of 120,000 cases, with 2.18 million patients, and economic losses exceeding 483.2 billion Yuan). Comparing the regional disease burden in different years, we can find the loss caused by PM_{2.5} pollution in the central and southwest regions was significantly reduced, but the loss caused by PM_{2.5} pollution in the northeast and northwest regions was increased. The Ministry of Environment of China promulgated the "Twelfth Five-Year Plan" for the Prevention and Control of Atmospheric Pollution in Key Areas in 2012, emphasizing the regional joint prevention and control mechanism for key areas, and tailoring pollution control policies to the characteristics of some key areas. However, this paper found that such policies cannot

be implemented in different regions for a long time. The improvement of pollution in the central and southwestern regions has proved the effectiveness of the national air pollution control policy, in order to enable the same improvement in pollution in regions such as northwest and northeast. China must establish and improve a more rationalized, refined and differentiated air pollution intervention and control policy in conjunction with the current regional air pollution control mechanism. Last but not least, we conducted a spatial auto-correlation analysis of the economic losses due to the health effects of PM_{2.5} in Chinese cities. The results show that the economic losses due to the health effects of PM_{2.5} in Chinese cities have a significant positive spatial correlation. In terms of spatial distribution, health-related economic losses are mainly dominated by bipolar aggregation, the "H-H" and "L-L" distribution are the main types, of which areas with high economic losses gather together, and areas with low health economic losses gather together. The economic loss caused by the health impact of PM_{2.5} in a region will not only affect itself, but also further affect the neighboring cities. Therefore, China should strengthen the implementation of the joint regional defense and control mechanism, and improve the policy guarantee of the joint regional defense and control mechanism. The spatial-temporal dynamic assessment of the burden of disease attributed to PM_{2.5} exposure may be valuable to Chinese policy makers and other developing countries. The results reported here may be improving the understanding of health effect due to PM_{2.5} pollution.

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Figures

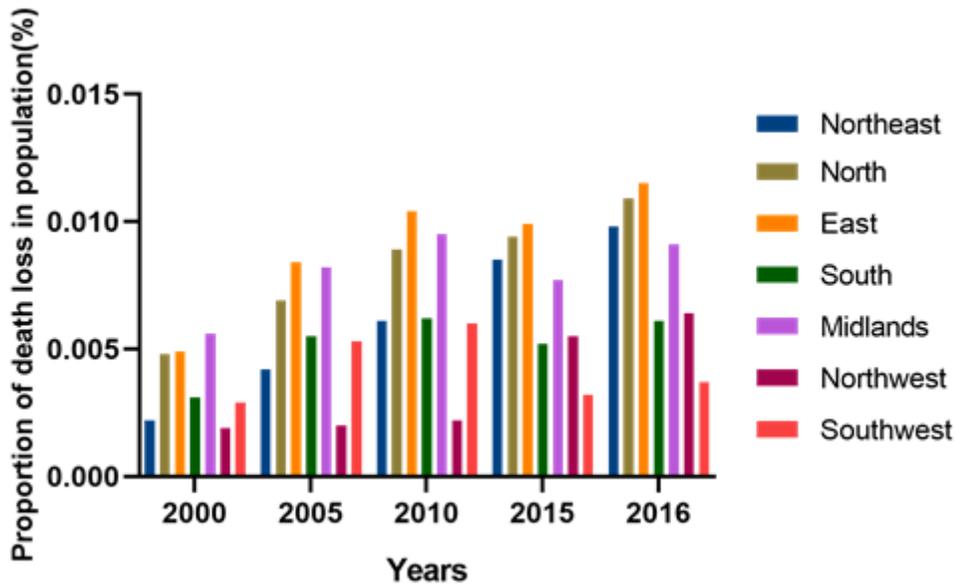


Figure 1

Between 2000 and 2016, the number of premature deaths attributed to PM2.5 exposure in different regions as a proportion of the total annual exposure population in the region. Different colors represent the northeast, north, east, south, midlands, northwest and southwest.

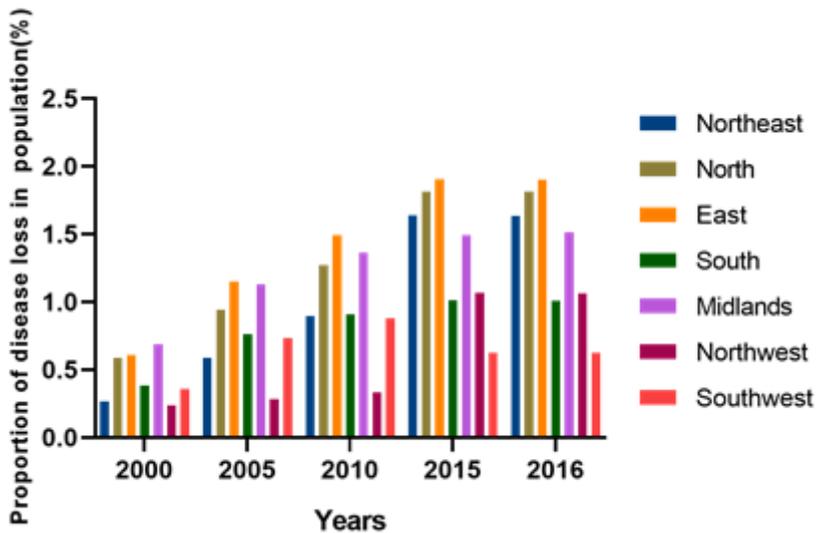


Figure 2

Between 2000 and 2016, the number of diseases attributed to PM2.5 exposure in different regions as a proportion of the total annual exposure population in the region. Different colors represent the northeast, north, east, south, midlands, northwest and southwest.

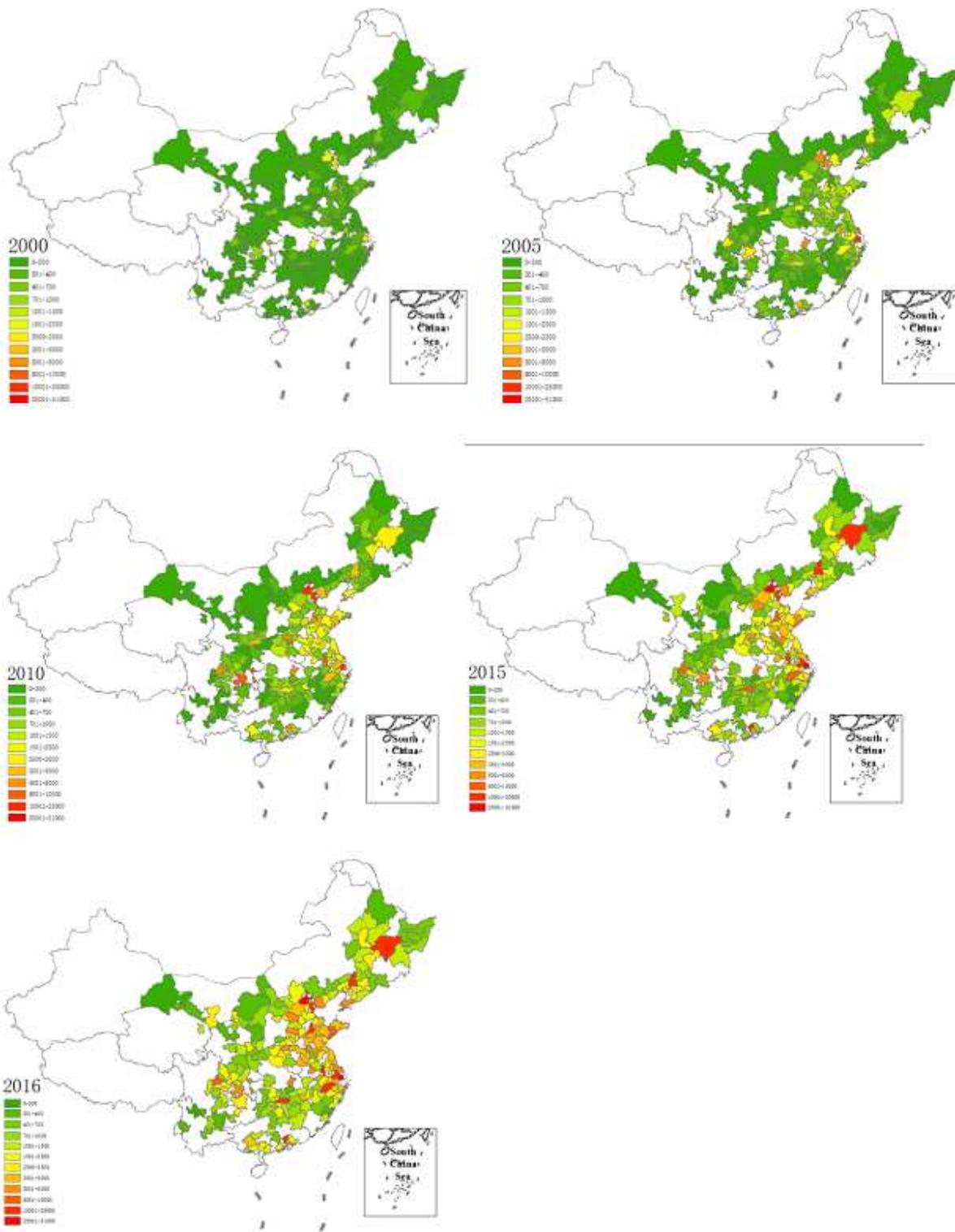


Figure 3

The health-related economic losses (CNY¥) attributed to PM_{2.5} exposure are distributed in Space in China. The coloring corresponds to the degree of economic loss in 210 cities, where green, yellow and red indicate relatively low economic loss, medium and higher areas, respectively. Areas left in white are not within an acceptable range of any station. Figure (1)-(5) corresponds to spatial distribution for the years 2000-2016. Note: The designations employed and the presentation of the material on this map do not

imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

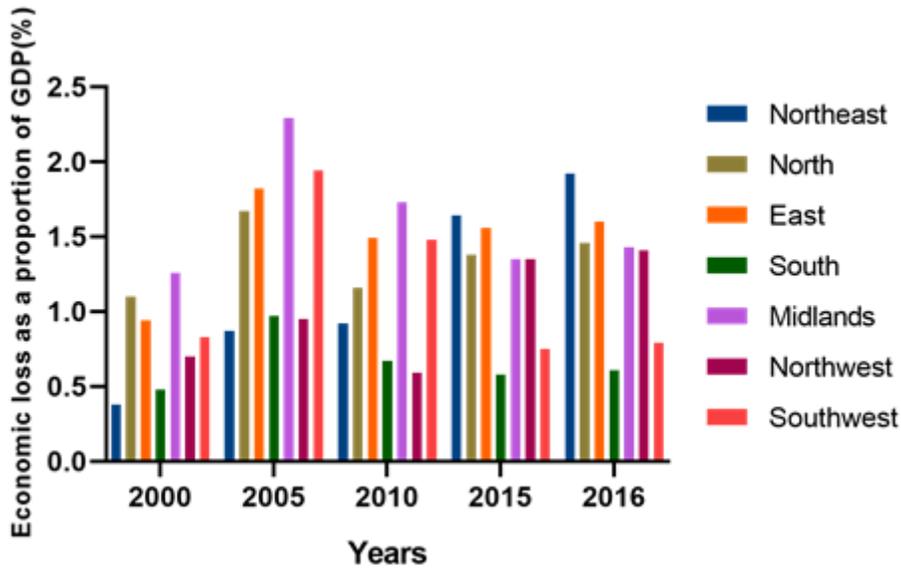


Figure 4

In 2000-2016, the economic losses caused by PM2.5 exposure accounted for the proportion of GDP in each region. The different seven colors correspond to seven areas, the same as Figure 1.

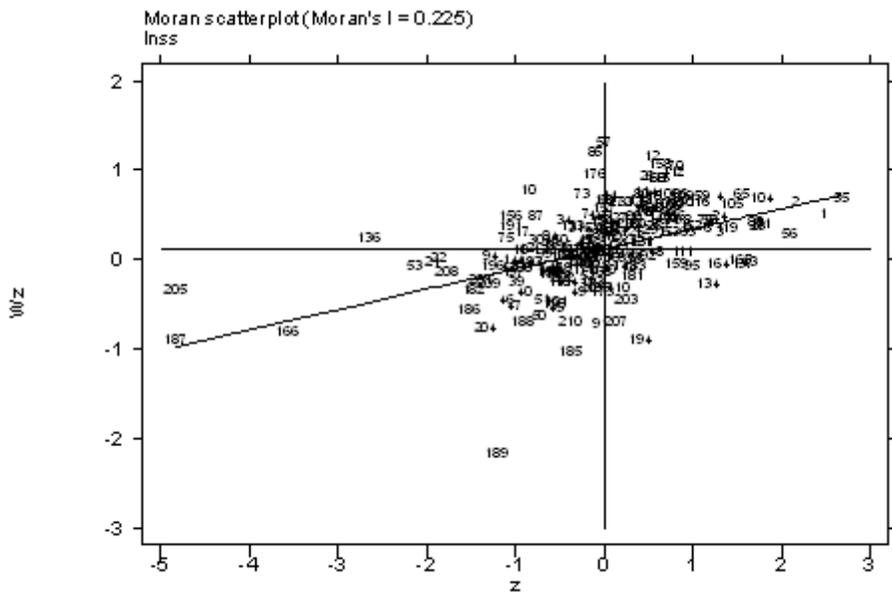


Figure 5

The Moran scatter plot is used to describe the spatial distribution of economic losses attributed to PM2.5 exposure in Chinese cities. This Moran scatter plot of economic losses in 2016.

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