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Article

# Spatiotemporal Assessment of PM<sub>2.5</sub>-Related Economic Losses from Health Impacts during 2014–2016 in China

Yang Yang <sup>1,†</sup>, Liwen Luo <sup>1,†</sup>, Chao Song <sup>1,2,3,\*</sup>, Hao Yin <sup>2,4</sup> and Jintao Yang <sup>1</sup>

<sup>1</sup> School of Geoscience and Technology, Southwest Petroleum University, Chengdu 610500, China; swpu\_yangy@126.com (Y.Y.); swpu\_ssdata\_lab@126.com (L.L.); believeyjt@163.com (J.Y.)

<sup>2</sup> State Key Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China; yinhao@mail.bnu.edu.cn

<sup>3</sup> Department of Geography, Dartmouth College, Hanover, NH 03755, USA

<sup>4</sup> Department of Planning, Danish Centre for Environmental Assessment, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark

\* Correspondence: songc345@163.com; Tel.: +86-28-8303-7107

† These authors contributed equally to this paper.

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**Abstract:** *Background:* Particulate air pollution, especially PM<sub>2.5</sub>, is highly correlated with various adverse health impacts and, ultimately, economic losses for society, however, few studies have undertaken a spatiotemporal assessment of PM<sub>2.5</sub>-related economic losses from health impacts covering all of the main cities in China. *Methods:* PM<sub>2.5</sub> concentration data were retrieved for 190 Chinese cities for the period 2014–2016. We used a log-linear exposure–response model and monetary valuation methods, such as value of a statistical life (VSL), amended human capital (AHC), and cost of illness to evaluate PM<sub>2.5</sub>-related economic losses from health impacts at the city level. In addition, Monte Carlo simulation was used to analyze uncertainty. *Results:* The average economic loss was 0.3% (AHC) to 1% (VSL) of the total gross domestic product (GDP) of 190 Chinese cities from 2014 to 2016. Overall, China experienced a downward trend in total economic losses over the three-year period, but the Beijing–Tianjin–Hebei, Shandong Peninsula, Yangtze River Delta, and Chengdu–Chongqing regions experienced greater annual economic losses. *Conclusions:* Exploration of spatiotemporal variations in PM<sub>2.5</sub>-related economic losses from long-term health impacts could provide new information for policymakers regarding priority areas for PM<sub>2.5</sub> pollution prevention and control in China.

**Keywords:** PM<sub>2.5</sub>; spatiotemporal assessment; health impact; economic loss; China

## 1. Introduction

Rapid industrialization and urbanization have made China one of the fastest growing economies in the world [1], although this growth is having negative effects on both the environment and public health. PM<sub>2.5</sub> refers to particulate matter suspended in the atmosphere with an aerodynamic diameter  $\leq 2.5 \mu\text{m}$ . It is suspended in the air for a long time, has a small particle size and a large surface area, is very active, carries a lot of poisonous substances, enters the body mainly through the respiratory tract, and penetrates deep into the tracheobronchial and alveolar regions [2]. Short-term and long-term exposure to PM<sub>2.5</sub> is closely correlated with a range of acute and chronic health impacts, such as respiratory diseases [3], cardiovascular diseases [4,5], lung cancer [6–8], nervous system diseases [9], and congenital heart defects [10]. These negative health effects produce a heavy economic burden, including increased health expenditure, loss of working days, and reduced labor supply [11]. Therefore,

it is important for the scientific planning of China's economic development to conduct a spatiotemporal evaluation of the health-related economic losses caused by PM<sub>2.5</sub> pollution in China.

Extensive research regarding PM<sub>2.5</sub>-related economic losses has highlighted the severity of the problem in China today. Health-related economic losses caused by PM<sub>2.5</sub> pollution totaled USD 0.76–1.04 billion in 2014 and USD 0.68–0.99 billion in 2015 in Beijing [12]. In the Beijing–Tianjin–Hebei region of China, the estimated economic losses caused by PM<sub>2.5</sub> in 2009 totaled USD 27.1 billion, or 4.7% of regional gross domestic product (GDP) [13]. The estimated economic losses in the Yangtze River Delta region in 2010 totaled USD 3.5 billion, or around 0.2% of regional GDP [14]. It is estimated that in 2013, losses of USD 4.4 billion were caused by high PM<sub>2.5</sub> pollution at the provincial level, which can be assessed as 54 percent of the total economic loss during 2001–2013 equivalently [15].

Most previous studies have examined cities and regions with high pollution, such as the Beijing–Tianjin–Hebei region [13], Beijing [12,16], The Yangtze River Delta region [14], Shanghai [17], and 74 major cities in China [18]. However, in addition to small-scale studies (big cities and areas with high pollution), it is equally important to study general trends via national-level studies. Only a few studies have analyzed China as a whole when evaluating either PM<sub>2.5</sub>-related health impacts or economic losses [15,19,20], but these have been at the provincial level, rather than the city level.

Previous studies have also examined the spatial distribution of PM<sub>2.5</sub>-related economic losses from health impacts. In Beijing, the external costs in the central and southern areas were higher than those in the northern districts [16]. In the southwest of Taiwan, the cities of New Taipei and Kaohsiung experienced the greatest numbers of deaths attributable to PM<sub>2.5</sub> [21]. Another study reported that high levels of premature mortality were found in the central and eastern parts of China, with the highest levels located in northern China and the Yangtze River Delta region [22]. However, these studies were limited to a sole space dimension in a single city or region. Moreover, some existing studies have applied time-series analyses to study changing trends in PM<sub>2.5</sub>-related health impacts on a national scale [23,24], yet few studies have examined the influence of the combination of spatial and temporal effects on PM<sub>2.5</sub>-related economic losses from health impacts at the city level.

Thus, this study aims to fill the gap in terms of the spatiotemporal evaluation of nationwide economic losses from health impacts as a result of PM<sub>2.5</sub> pollution at the city level for the period 2014–2016. Compared to previous studies focusing on provinces or a few large cities, our city-level analyses can give fine-scale spatial differences of health impacts and costs of PM<sub>2.5</sub> to facilitate policymaking. For example, we can provide detailed information by detecting and mapping highly polluted areas to mitigate air pollution. We used real-time air-quality data from 190 major Chinese cities, as well as socioeconomic and population data, from 2014 to 2016. In addition, we used log-linear (LL) exposure–response functions to evaluate long-term PM<sub>2.5</sub>-related health impacts across China at the city level, using both the value of a statistical life (VSL) and amended human capital (AHC) approaches to determine the upper and lower bounds of mortality-related economic losses from health impacts as a result of PM<sub>2.5</sub>, and cost of illness (COI) to measure morbidity-related economic losses including hospital admission costs, medical costs, and lost working days [25]. In addition, Monte Carlo simulation was used to help determine the uncertainty levels.

The study had three goals: (i) to estimate economic losses from health impacts as a result of PM<sub>2.5</sub> pollution across China in the period 2014–2016 using two different bounds; (ii) to reveal the spatiotemporal dynamics of PM<sub>2.5</sub>-related economic losses from 2014 to 2016 across China at the city level; and (iii) to quantitatively address the uncertainty of the modeling. The results provide new information for policymakers regarding priority areas in terms of air pollution prevention and control in response to the growing importance of environmental protection in China.



## 2. Materials and Methods

### 2.1. PM<sub>2.5</sub> Concentration and Socio-Economic Data

Rapid urbanization and modernization in China over the past few decades have contributed to a significant increase in both urban population and associated carbon emissions [15,19]. The average annual PM<sub>2.5</sub> concentration was more than 47 µg/m<sup>3</sup> in 2016, which was more than four times higher than the level specified in the WHO guidelines (10 µg/m<sup>3</sup>) [26,27]. In this study, monthly PM<sub>2.5</sub> concentration data were retrieved from 1566 monitoring stations in 190 cities operated by China's online air quality monitoring and analysis platform for the period from January 2014 to December 2016 (<http://www.aqistudy.cn/>). Our socio-economic data are from the 2014–2016 national economic and social development bulletins of 190 cities, including population, per capita GDP, and per capita disposable income. Since the socio-economic data is collected by year, we obtained monthly PM<sub>2.5</sub> concentration in each city due to accessibility, processed monthly the PM<sub>2.5</sub> data into the annual average to match the socio-economic data.

### 2.2. Health Impact Assessment

A recent study has reported the assessment of PM<sub>2.5</sub>-related health effects applying comprehensive meta-analysis [16]. In the analysis, the authors considered the health impact of various diseases and utilized the 10th version of the International Classification of Diseases report (ICD-10) to avoid double counting of PM<sub>2.5</sub> health impacts, and they do so because the simple sum of all health costs together without a prior proper classification will lead to overlaps and double counting. In addition, they referred to 24 research results (see Supplementary Materials S1), many of which are the latest research results. Exposure-response coefficients and baseline incidences were reviewed from these literature, giving priority to studies performed in China to improve the exposure-response accuracy. Last, both of our study areas are in China, and within similar research period. Taking the above factors into account, we applied the corresponding methodology and coefficients in this research.

Health impacts were classified into two categories: mortality and morbidity. Furthermore, they were categorized as either chronic or acute impacts. PM<sub>2.5</sub> health impacts were estimated for cardiovascular mortality, cardiopulmonary mortality, lung cancer mortality, respiratory mortality, chronic bronchitis, cardiovascular hospitalization, acute bronchitis, and asthma attacks.

The occurrence of either disease or death is a low-probability event, and exhibits a standard Poisson distribution. The risk ratio model in the Poisson regression model forms the basis of current epidemiological studies on air pollution [28]. Therefore, exposure–response functions can be represented by Equations (1) and (2):

$$E_i = E_{0i} \times e^{\beta_i(C-C_0)} \quad (1)$$

$$HI_{ij} = P_j \times (E_i - E_0) = P_j \times E_{0i} \times [e^{\beta_i(C-C_0)} - 1] \quad (2)$$

where  $HI_{ij}$  denotes the health impact  $i$  in city  $j$  under pollution level  $C$ ,  $P_j$  is the exposed population in city  $j$ ,  $E_i$  refers to the incidence of health end point  $i$  under pollution level  $C$ ,  $E_{0i}$  is the baseline incidence of health end point  $i$  of the affected population, which represents the change in incidence of a health impact per  $i$  µg/m<sup>3</sup> increments of PM<sub>2.5</sub>,  $\beta_i$  is the exposure–response coefficient of health end point  $i$ ,  $E_{0i}$  and  $\beta_i$  are derived from Yin's meta-analysis results (see Supplementary Material S1),  $C$  refers to the average annual PM<sub>2.5</sub> concentration level (µg/m<sup>3</sup>), and  $C_0$  is the baseline PM<sub>2.5</sub> concentration. We use  $C_0 = 10$  µg/m<sup>3</sup>, as recommended by the WHO [26], as the baseline concentration.

### 2.3. Economic Loss Evaluation

In this study, we applied both the VSL and AHC approaches to define the upper and lower bounds of mortality-related economic losses as a result of PM<sub>2.5</sub>, and COI was used to estimate morbidity-related economic losses. The following estimation process follows the research conducted by Yin et al [16].

The VSL refers to the benefits of risk reduction by eliciting individuals' preferences for small changes in risk and income [29]. We converted VSL for China using Equation (3) [30]:

$$VSL_j = VSL_0 \times \left( \frac{Income_j}{Income_0} \right)^{Elasticity} \quad (3)$$

where  $VSL_0$  is the threshold for the VSL and  $Income_0$  is the threshold for per capita disposable income. We selected USD 248,172, which was obtained from the latest assessment of air pollution in China, as  $VSL_0$  [31], and USD 1939, which was obtained from the National Bureau of Statistics of the People's Republic of China (NBSC), as  $Income_0$  [32].  $Income_j$  is the per capita disposable income in city  $j$ . Because the income elasticity of the VSL is a positive value, we set this to 0.8, as recommended by the Organization for Economic Co-operation and Development [33].

The AHC approach uses per capita GDP to measure the human capital loss as a result of premature death, was used based on Equation (4) [34]:

$$HCL_j = \sum_{y=1}^t GDP_{jy}^{dv} = GDP_{j0} \times \sum_{y=1}^t \frac{(1+a)^y}{(1+r)^y} \quad (4)$$

where  $GDP_{jy}^{dv}$  is the discounted value of per capita GDP in year  $y$  in city  $j$ ,  $t$  is the average number of life-years lost as a result of PM<sub>2.5</sub> pollution (assumed to be 10 years),  $GDP_{j0}$  is the per capita GDP in base year in city  $j$ ,  $a$  is the per capita GDP growth rate, and  $r$  is the social discount rate. We set  $a$  to 0.07 and  $r$  to 0.08 in accordance with the reports of the NBSC [35].

COI quantifies the cost of certain diseases in terms of medical treatment costs, hospitalization costs, and productivity loss [25]. COI is used to estimate the morbidity-related economic loss as a result of PM<sub>2.5</sub> pollution. The costs associated with asthma attacks, acute bronchitis, and cardiovascular-related hospital admissions were obtained from health and family planning career development statistical bulletin for the period during 2014–2016 [36]. We convert the costs related to the treatment of chronic diseases using disability weights. The weight of chronic bronchitis was estimated to be 0.055 of the VSL suggested by Hammitt and Zhou [37].

The total economic loss is estimated using the following equations:

$$EC_{ij} = HI_{ij} \times Cost_j \quad (5)$$

$$EC_{total} = EC_{mortality} + EC_{morbidity} \quad (6)$$

where  $EC_{ij}$  is the economic loss from health impact  $i$  in city  $j$ ,  $Cost_j$  is the economic cost per case,  $EC_{total}$  is total economic losses from health impacts, and  $EC_{mortality}$  and  $EC_{morbidity}$  are the economic losses from mortality and morbidity, respectively.

Given the upper and lower bounds of mortality-related economic losses calculated by VSL and AHC respectively, we get the range of estimates according to Equation 6. In upper bounds, the total economic loss equals to the sum of mortality-related economic losses calculated by VSL and morbidity-related economic loss. For lower bound, the total economic loss equals to the sum of mortality-related economic loss calculated by AHC and morbidity-related economic loss.

#### 2.4. Uncertainty Analysis

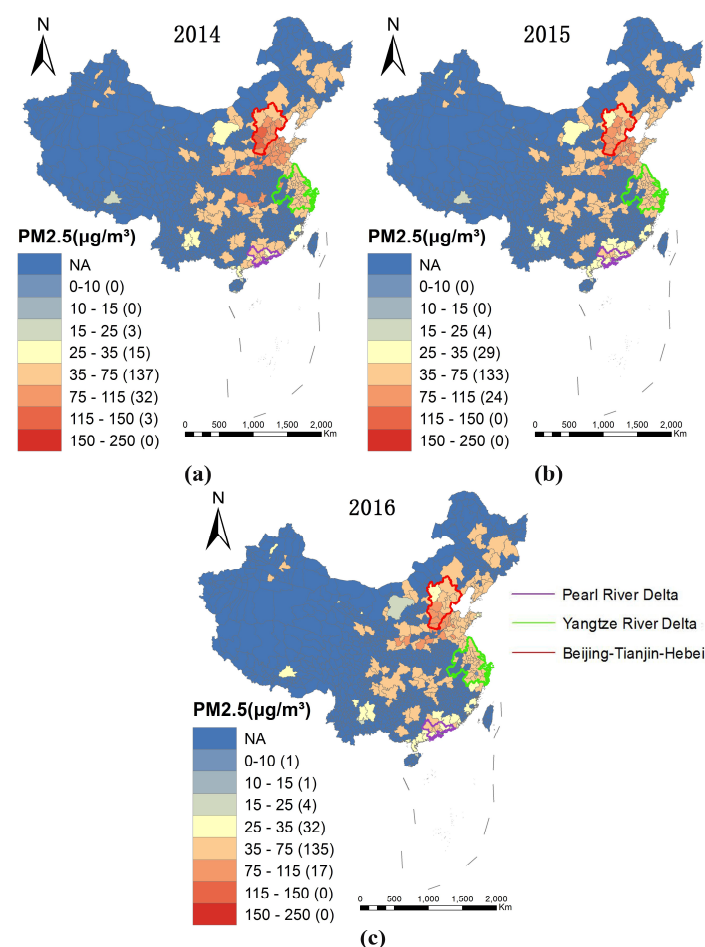
Uncertainty analysis is a measure of model performance, and Monte Carlo simulations are a way of using the probability distributions of input variables to assess the probability distributions of output variables, hence this method is widely used in probabilistic risk assessment. In this study, Crystal Ball software was used to calculate the probability distributions and confidence intervals of PM<sub>2.5</sub>-related economic losses and the Monte Carlo method was used to calculate uncertainty [38]. Uncertainty is defined as an acceptable error of  $\pm 5\%$  in relation to each output parameter (i.e., uncertainty of the equation to calculate output value within the range of 5% from the expected predicted value).

In the process of assessing PM<sub>2.5</sub>-related economic losses from health impacts, the first uncertainty arose in relation to PM<sub>2.5</sub> exposure levels, which are influenced by factors such as climate and geographic conditions. Moreover, the exposure–response coefficients were derived from the results of a meta-analysis of previous epidemiological studies, and thus we should also consider their uncertainty. In addition, health costs as a result of PM<sub>2.5</sub> exposure differ among the various studies. In terms of the medical costs of various diseases, these differences stem from the individuals’ physical condition and hospitalization costs. Regarding the VSL, the uncertainty is caused by differences in the willingness to pay for risk prevention, thus the uncertainty of economic losses per case for different health end points was also accounted for in the assessment. Therefore, the uncertainty analysis covered PM<sub>2.5</sub> exposure concentration, exposure–response coefficients, and health-related economic loss per case. In addition, AHC values were calculated based on the per capita GDP, and because the uncertainty of this estimate was unknown, the uncertainty of economic losses from mortality estimated using the AHC approach was not included in this study.

### 3. Results

#### 3.1. Spatial Distribution of PM<sub>2.5</sub>

Figure 1 shows the spatial distribution of PM<sub>2.5</sub> in 2014 (a), 2015 (b), and 2016 (c) across China. From the perspective of economic development, spatial analysis reveals that the Beijing–Tianjin–Hebei region experienced the highest levels of PM<sub>2.5</sub> pollution, followed by the Yangtze River Delta region and the Pearl River Delta region, which is consistent with the results reported in the “2016 China Environmental Status Bulletin” [27].



**Figure 1.** Spatial distribution of PM<sub>2.5</sub> in 2014 (a); 2015 (b); and 2016 (c).

PM<sub>2.5</sub> pollution areas displayed similarities across the period, high-polluted areas were concentrated in the central and eastern districts, especially in the Beijing–Tianjin–Hebei, Central Henan, Shanxi, and Western Shandong Peninsula, and less-polluted areas includes Lhasa, Chifeng, Yunnan, Pearl River Delta, and the Western Taiwan Straits. Figure 1 also indicates that the number of high pollution ( $>75 \mu\text{g}/\text{m}^3$ ) areas has declined, and “2014–2016 China Environmental Status Bulletin” has reported that the annual PM<sub>2.5</sub> concentration across China has decreased from  $62 \mu\text{g}/\text{m}^3$  in 2014, and  $50 \mu\text{g}/\text{m}^3$  in 2015, to  $47 \mu\text{g}/\text{m}^3$  in 2016 [27]. Even though the overall PM<sub>2.5</sub> pollution was being controlled, the level of pollution remained serious between 2014 and 2016, all cities exceeded WHO guidelines and approximately 71 % of the cities are  $35\text{--}75 \mu\text{g}/\text{m}^3$ .

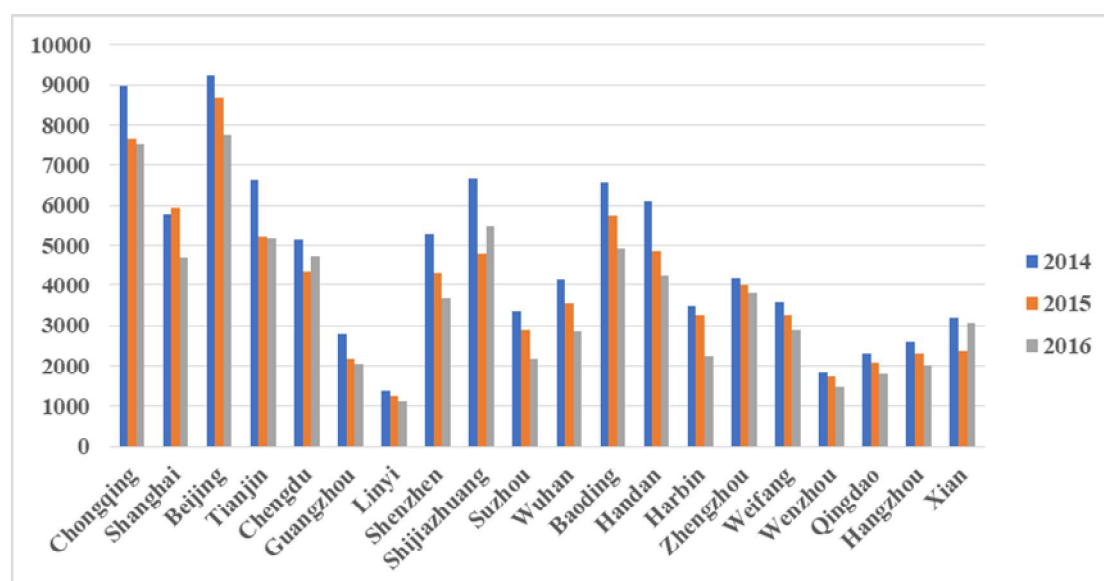
### 3.2. PM<sub>2.5</sub> Health Impact

Table 1 shows a downward trend in the overall affected population, reducing by 13.8%. The average annual decline in PM<sub>2.5</sub>-related premature deaths was 11.8%, and the incidence of asthma attacks was higher than that of other diseases.

**Table 1.** Health impacts attributed to PM<sub>2.5</sub> pollution in China during the period 2014–2016.

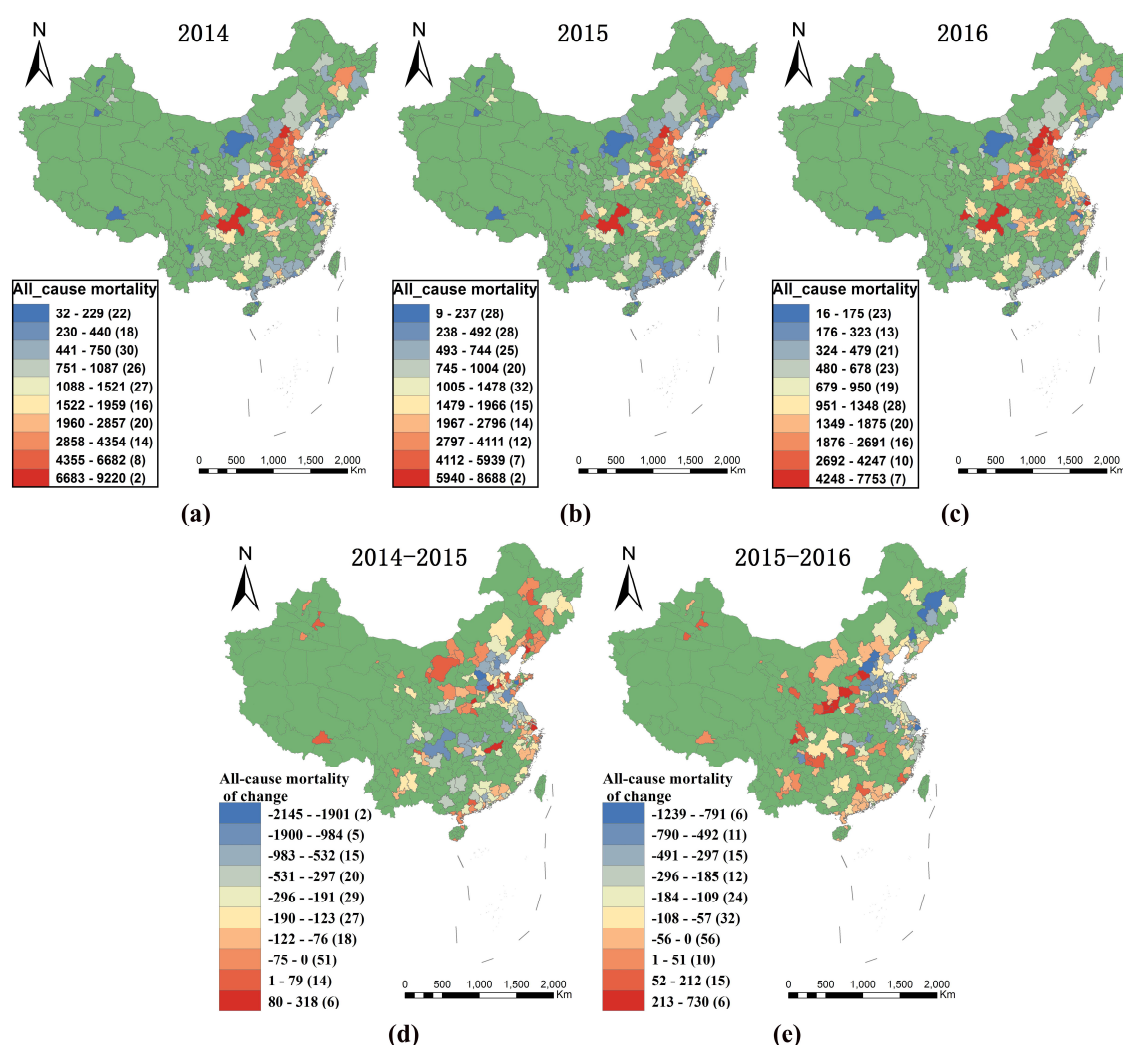
Category	2014	2015	2016
All-cause mortality	278,444	238,622	216,164
Cardiovascular mortality	71,058	60,991	55,321
Respiratory mortality	42,590	36,431	32,959
Lung cancer mortality	92,512	78,444	70,557
Cardiovascular hospitalization	1,001,233	851,497	767,387
Chronic bronchitis	185,798	159,366	144,459
Acute bronchitis	1,034,080	881,692	795,978
Asthma attack	19,197,994	15,935,983	14,130,036
Affected population	21,697,549	18,067,160	16,054,024

Figure 2 displays the PM<sub>2.5</sub>-related health impacts (all-cause mortality) in 20 major Chinese cities during the period 2014–2016. Beijing was ranked first, followed by Chongqing, Shijiazhuang, Tianjin, and Baoding. Table S3 provides more detailed information in relation to all 190 cities studied.



**Figure 2.** PM<sub>2.5</sub>-related health impacts (all-cause mortality) in 20 major cities in China during the period 2014–2016.

Figure 3 displays the distribution of PM<sub>2.5</sub>-related health impacts (all-cause mortality) during the period 2014–2016 and changes in the spatial distribution over the period. PM<sub>2.5</sub>-related premature deaths in each city characterize the health impact for that area in that year. The highest-impacted areas displayed similarities across the period and were concentrated in the central and eastern districts, especially in the Beijing–Tianjin–Hebei, Central Henan, Shanxi, Western Shandong Peninsula, Yangtze River Delta, and Chengdu–Chongqing regions, while the less-impacted areas were mainly concentrated in the northwest, including Lhasa, Inner Mongolia, Yunnan, Guizhou, and the Western Taiwan Straits, as well as in southern China. However, compared with 2014–2015 values, the areas showing the greatest improvement in 2015–2016 were concentrated in the Beijing–Tianjin–Hebei region, excluding the Shijiazhuang, Shandong Peninsula, Yangtze River Delta, and northeast regions, while the worst-impacted areas shifted from Western Inner Mongolia and the northeast, Central Henan, Western Shandong Peninsula, and Yangtze River Delta regions, to the central Shaanxi Plain, the southeast, Shanxi regions, the middle reaches of the Yangtze River, and the Western Taiwan Straits.



**Figure 3.** Spatial distribution of PM<sub>2.5</sub>-related health impacts (all-cause mortality) in 2014 (a); 2015 (b); and 2016 (c). Distribution of changes in PM<sub>2.5</sub>-related health impacts (all-cause mortality) for the periods 2014–2015 (d) and 2015–2016 (e).

### 3.3. Economic Loss of Health Impacts

Table 2 shows that overall, China experienced a slight downward trend in economic losses between 2014–2015 and 2015–2016. The average economic loss was between 0.3% (AHC) and 1% (VSL)

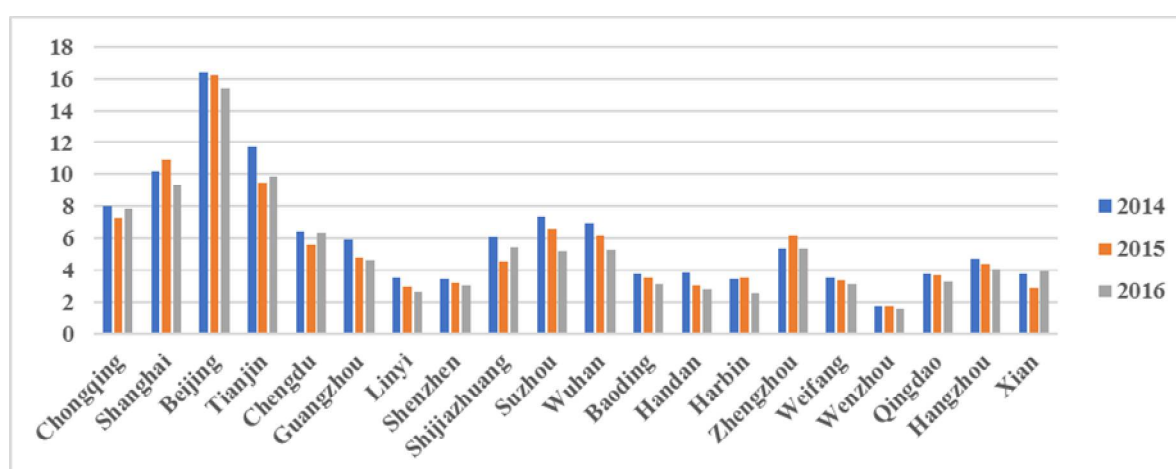


of the total GDP of 190 Chinese cities from 2014 to 2016. The economic losses estimated using the AHC method were around 26% of those estimated using the VSL method. Economic losses as a result of all-cause mortality accounted for around 80% (AHC) to 95% (VSL) of total economic losses. Table S4 shows more detailed information for the 190 cities studied.

**Table 2.** Total economic losses from health impacts as a result of PM<sub>2.5</sub> pollution during the period 2014–2016.

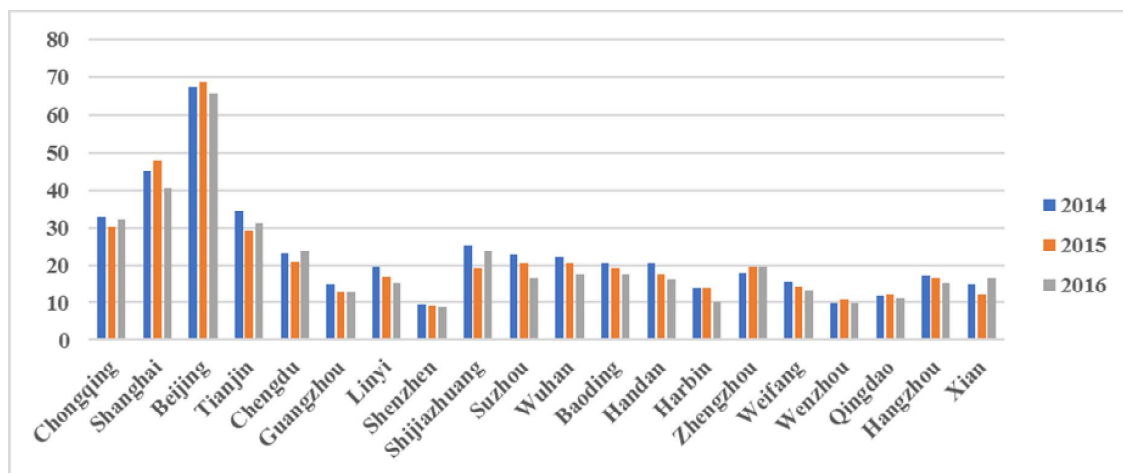
Category	The Health Economic Loss (100 Million Dollar)					
	2014 AHC	2014 VSL	2015 AHC	2015 VSL	2016 AHC	2016 VSL
All-cause mortality	256.32	1157.59	230.89	1061.69	214.16	1018.62
Cardiovascular mortality	65.46	295.48	59.03	271.44	54.84	260.75
Respiratory mortality	39.19	177	35.23	162.02	32.63	155.24
Lung cancer mortality	84.84	383.9	75.7	348.39	69.68	331.86
Cardiovascular hospitalization	12.2	12.2	10.95	10.95	10.28	10.28
Chronic bronchitis	42.48	42.48	39	39	37.44	37.44
Acute bronchitis	0.35	0.35	0.31	0.31	0.29	0.29
Asthma attack	6.57	6.57	5.8	5.8	5.4	5.4
Total economic loss (TEL)	317.93	1219.19	286.97	1117.76	267.38	1072.02
TEL/GDP	0.36%	1.36%	0.30%	1.18%	0.26%	1.06%

Figures 4 and 5 shows that, similar to the PM<sub>2.5</sub>-related health impacts, Beijing was ranked first in terms of health-related economic losses, followed by Tianjin, Shanghai, and Chongqing. From a regional perspective, of the 20 major cities that experienced the greatest economic losses, seven were in southern China and six were in northern China. However, the rankings of Guangzhou, Linyi, Shenzhen, and Wenzhou were different in two different bounds.

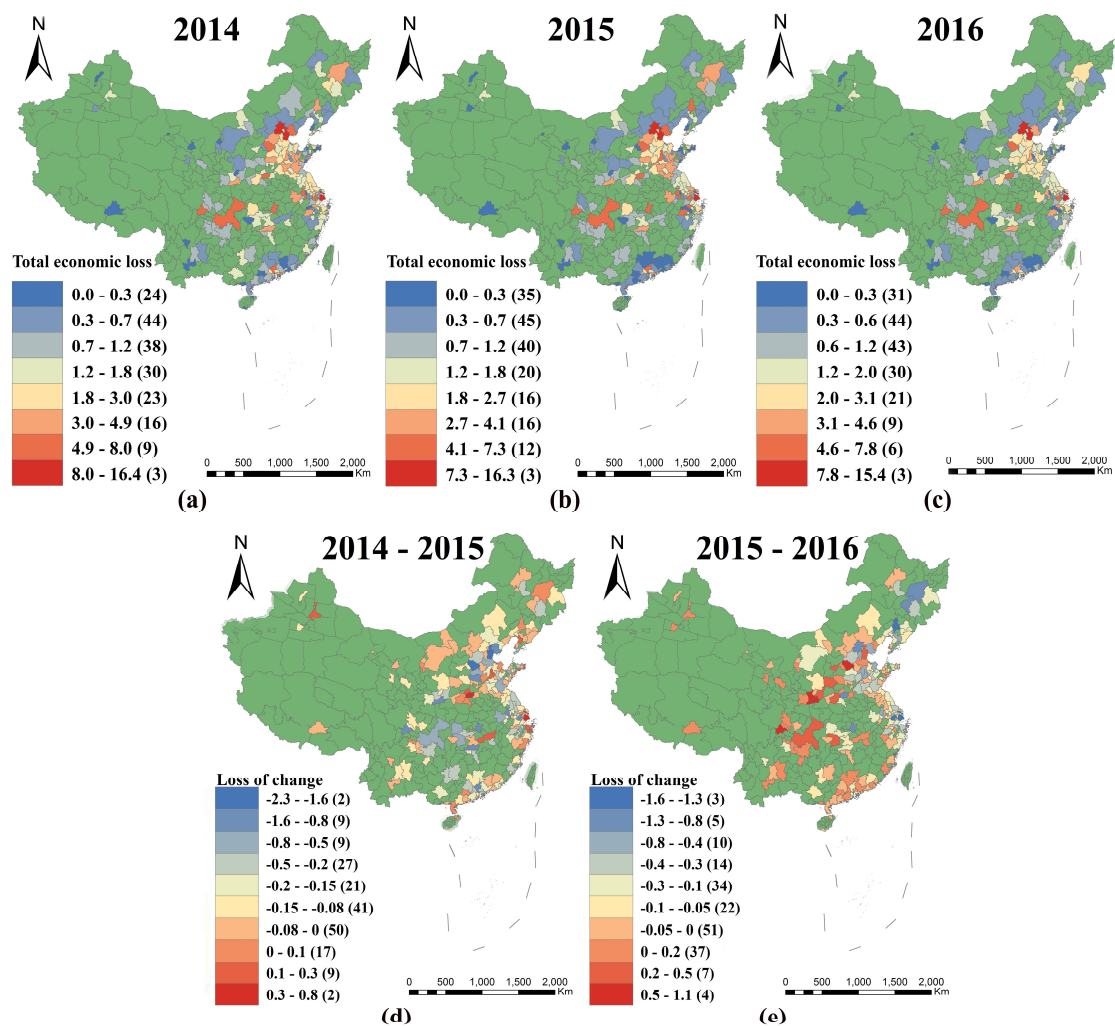


**Figure 4.** PM<sub>2.5</sub>-related economic losses as a result of health impacts in 20 Chinese major cities in the lower bounds during the period 2014–2016.

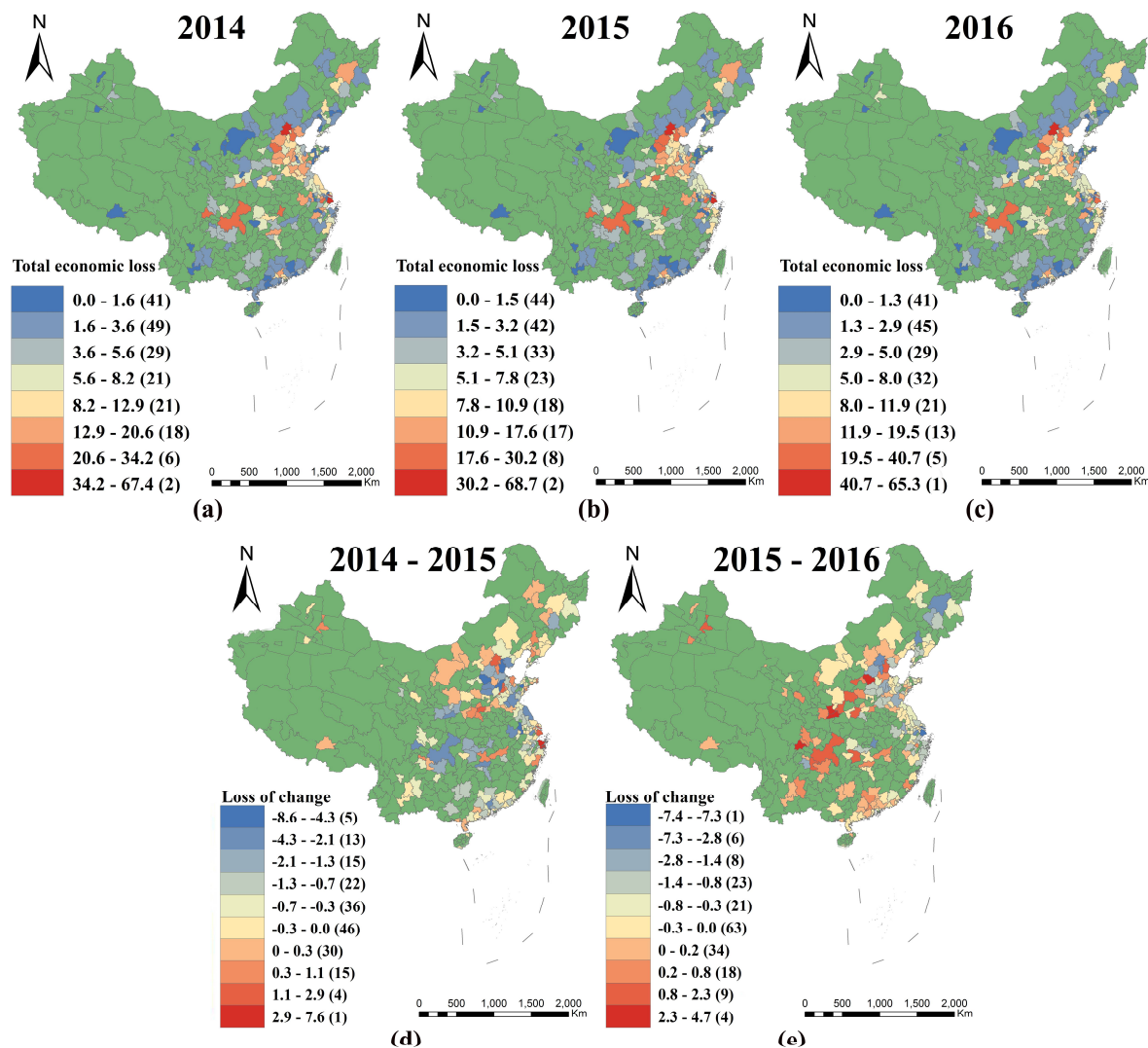
Figures 6 and 7 show the distribution of PM<sub>2.5</sub>-related economic losses during the period 2014–2016 and changes in the spatial distribution over the years, respectively. The highest-ranked areas displayed similarities across the period and were concentrated in the central and eastern districts, especially in the South Beijing–Tianjin–Hebei, Central Henan, Western Shandong Peninsula, Yangtze River Delta, and Chengdu–Chongqing regions, the middle reaches of the Yangtze River, and the Guangzhou region, while the lower-ranked areas were mainly concentrated in the northwest, Inner Mongolia, Lhasa, North Beijing–Tianjin–Hebei, Yunnan, Guizhou, southern China (excluding Guangzhou), central Shaanxi Plain, Shanxi, Eastern Shandong Peninsula, northeast, and Western Taiwan Straits regions.



**Figure 5.** PM<sub>2.5</sub>-related economic losses as a result of health impacts in 20 Chinese major cities in the upper bounds during the period 2014–2016.



**Figure 6.** Spatial distribution of PM<sub>2.5</sub>-related economic losses in the lower bounds in 2014 (a); 2015 (b); and 2016 (c). Distribution of changes in PM<sub>2.5</sub>-related economic losses in the lower bounds for the periods 2014–2015 (d) and 2015–2016 (e).



**Figure 7.** Spatial distribution of PM<sub>2.5</sub>-related economic losses in the upper bounds in 2014 (a); 2015 (b); and 2016 (c). Distribution of changes in PM<sub>2.5</sub>-related economic losses in the upper bounds for the periods 2014–2015 (d) and 2015–2016 (e).

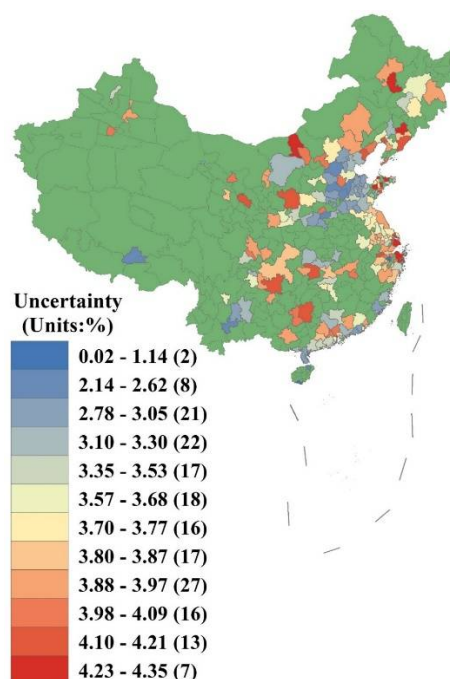
Furthermore, China experienced a downward trend in economic losses during the period from 2014 to 2016. However, compared with 2014–2015 values, the areas showing the most improvement in 2015–2016 were concentrated in the Beijing, Baoding, Chifeng, Shandong Peninsula, Yangtze River Delta, and northeast regions, while the worst-impacted regions shifted from Western Inner Mongolia, Central Henan, and the Yangtze River Delta, to Shijiazhuang, Tianjin, Henan, Shanxi, the central Shaanxi Plain, Chengdu–Chongqing, Yunnan, Guizhou, the middle reaches of the Yangtze River, the Western Taiwan Straits, and southern China.

### 3.4. Uncertainty Analysis

Figure 8 shows the spatial distribution of uncertainty in relation to the health-related economic losses calculated using the VSL method for 190 cities. It can be seen that overall uncertainty ranges from 0.02% to 4.35%. The northwest, Chengdu–Chongqing, middle reaches of the Yangtze River, Guizhou, Guangxi, Yangtze River Delta, Eastern Shandong Peninsula, Central Inner Mongolia, and northeast regions have the highest levels of uncertainty, indicating that the results in these areas are somewhat imprecise. In contrast, the Beijing–Tianjin–Hebei, Central Henan, Western Shandong Peninsula, Lhasa,



Yunnan, Pearl River Delta (excluding Guangzhou), and Western Taiwan Straits regions have lower levels of uncertainty, indicating that the results are more reliable.



**Figure 8.** Spatial distribution of uncertainty in relation to health-related economic losses using the value of a statistical life (VSL).

#### 4. Discussion

China experienced a downward trend in economic losses as a result of health impacts during the period 2014–2016, but average annual economic losses remained high, especially in the central and southern areas of China, such as the Beijing–Tianjin–Hebei, Shandong, Yangtze River Delta, and Chengdu–Chongqing regions. However, compared with 2014–2015, the areas showing the most improvement in 2015–2016 are concentrated in the Beijing, Baoding, Chifeng, Shandong Peninsula, Yangtze River Delta, and northeast regions, while the worst-impacted regions shifted from Western Inner Mongolia, Central Henan, and the Yangtze River Delta to Shijiazhuang, Tianjin, Henan, Shanxi, the central Shaanxi Plain, Chengdu–Chongqing, Yunnan, Guizhou, the middle reaches of the Yangtze River, the Western Taiwan Straits, and southern China. The reasons for this spatial distribution include pollution emissions, meteorological conditions, and population density. Meanwhile, China has experienced demographic dividend, and is now suffering low fertility and an ageing population, which is leading to a scarcity of labor, and increasing PM<sub>2.5</sub> pollution could make this situation even worse. The temporal trend indicates that overall, air pollution in China has gradually improved in recent years, thanks to a series of aggressive measures adopted by the Chinese government and the relevant urban management authorities, the implementation of measures introduced in 2016 aimed at the prevention and control of air pollution in Beijing during the period 2016–2017, and the Environmental Protection Tax Law of the People’s Republic of China introduced on 1 January 2018, whereby the tax deduction related to reductions in environmental pollution shall be USD 0.19 to USD 1.87 per pollutant equivalent. Moreover, the changes in the spatial distribution show that air pollution control measures were more effective in key cities and regions such as Beijing, Baoding, Chifeng, the Shandong Peninsula, the Yangtze River Delta, and the northeast. In contrast, regions such as Shijiazhuang, Tianjin, Henan, Shanxi, the central Shaanxi Plain, Chengdu–Chongqing, Yunnan, Guizhou, the middle reaches of the Yangtze River, the Western Taiwan Straits, and southern China

were clearly more committed to pursuing economic development while ignoring environmental governance issues.

The results of this study show that 21.7 million people suffered a health impact as a result of PM<sub>2.5</sub> pollution and there were more than 0.28 million premature deaths (about 0.03% of the total population) in China in 2014, 18.1 million people suffered a health impact and there were 0.24 million premature deaths (again, about 0.03% of the total population) in 2015, and 16.1 million people suffered a health impact and there were 0.22 million premature deaths (about 0.02% of the total population) in 2016. Acute bronchitis and asthma attacks were the health end points affecting most people. Our results are in general agreement with those of previous studies, e.g., premature deaths in the Pearl River Delta accounted for approximately 0.02% of the total population in 2012 [39], and an assessment of China's PM<sub>2.5</sub> health impacts on people of all ages indicated that premature deaths accounted for 0.09% of the total population in 2013 [40]. In addition, the results varied from country to country. In India, the average annual health burden was estimated to be 5700 premature deaths (0.16% of the total population) during the period 2001–2015 [41], while another study showed that 3300 premature deaths in Nagpur in 2013 could be attributed to ambient PM<sub>2.5</sub> pollution [42]. One study found that PM<sub>2.5</sub> pollution caused 37,000 deaths in 27 Southeast and East Asian countries in 2009 [43]. In the United States (US), premature deaths as a result of PM<sub>2.5</sub> pollution were estimated to account for 0.04% of the total population in 2005 [44]. In Sweden, a recent study estimated that there were 3500 premature deaths per year as a result of PM<sub>2.5</sub> pollution [45]. These results illustrate that the mortality rates in China and India were much higher than those in Europe and the US. We also compared the findings with those of the integrated exposure–response model in China, GBD 2015 which indicated that PM<sub>2.5</sub> pollution caused 1,108,000 deaths [46]. Total premature mortality in 190 cities in China as a result of PM<sub>2.5</sub> pollution was estimated to be 722,370 in the period 2014–2015 [47]. Another study showed that approximately 1,126,000 deaths were caused by PM<sub>2.5</sub> pollution in 2015, and that this figure fell to 1,092,000 in 2016 [24]. Our figures are lower than those presented in these studies, which indicates that the LL model may underestimate the health impacts of PM<sub>2.5</sub> pollution. In summary, PM<sub>2.5</sub> concentrations, baseline levels, exposure–response coefficients, exposure–response functions, and choice of health endpoints all influence the results found by the various studies.

The results also indicate that total economic losses as a result of PM<sub>2.5</sub>-related health impacts ranged from USD 31.79 billion (AHC) to USD 121.92 billion (VSL) or around 0.36% to 1.36% of regional GDP in China in 2014, from USD 28.7 billion (AHC) to USD 111.78 billion (VSL) or around 0.3% to 1.18% of regional GDP in 2015, and from USD 26.74 billion (AHC) to USD 107.2 billion (VSL) or around 0.26% to 1.06% of regional GDP in 2016. Similar conclusions can be found in the existing studies. One study focusing on Beijing reported that lost regional GDP as a result of PM<sub>2.5</sub> pollution was between 0.3% (AHC) and 0.9% (VSL) in 2012 [16]. Another study found that economic losses from health impacts as a result of PM<sub>2.5</sub> pollution accounted for between 0.11% (AHC) and 0.4% (VSL) of regional GDP in 2014 [48], while another study predicted future health-related economic losses and indicated that China's health expenditure will reach US\$ 25.2 billion (approximately 2% of GDP) if pollution is not controlled in 2030 [19]. Furthermore, economic losses as a result of premature deaths accounted for around 80% (AHC) to 95% (VSL) of total economic losses. Our results are in general agreement with those of previous studies, which estimated economic losses of 88.4% in 111 Chinese cities in 2004 [49], 90% in China in 2010 [50], and 80% in Beijing in 2012 [16]. In the above comparisons, we actually found that our health economic losses are slightly higher, especially those estimates calculated by VSL. Most of the above studies estimate mortality costs or morbidity related costs without focusing on the health impacts classification, and used different environmental valuation methods, which could explain this difference. Therefore, when these variations are taken into consideration, the results of this study are basically reasonable.

This study helps to fill the gap in the literature on spatiotemporal evaluation of nationwide economic losses from health impacts as a result of PM<sub>2.5</sub> pollution at the city level for the period 2014–2016. Our results provide new information for policymakers regarding priority areas in relation

to air pollution prevention and control given the trend toward increasing environmental protection in China. However, there are several areas of uncertainty. First, our evaluation was based on city-level  $PM_{2.5}$  concentrations calculated by averaging the data from all sites, which is the common method used to report daily air quality to the public. However, the uneven distribution of monitoring stations, with more in urban areas and less in suburban and rural areas, renders a simple averaging method less accurate than more complex methods [51], the spatial correlation effects between cities and peripheral areas also need to be further considered. Second, we assume the exposure population is a permanent residential population in this study, while the actual exposure of the population is dynamic. Previous studies compared the differences between dynamic and static population exposure, which illustrated that the static population exposure could underestimate the exposure level by around 20% [52]. Third, the exposure–response coefficients of  $PM_{2.5}$ , which rely on the results of epidemiology and toxicology research, require further investigation, and there are many other factors involved in the process of building the exposure–response relationship that remain unclear. Moreover, the age distribution of the population was not considered in the evaluation process. Given that previous studies have found that estimated total losses based on the VSL without considering the age distribution of the population were between 2.3 and 2.8 times greater than those obtained after taking the age structure of the population into account [15], our results might overstate the health-related economic losses. Further, the monetary evaluation method also has its limitations. Previous studies did not focus on different regional characteristics such as living habits, the economic environment, and environmental sanitation, and some health end points lack information related to medical costs, lost working time, and related contingent valuation study. Future work should focus on the promotion in these fields continuously.

Although these limitations exist, this study makes a significant contribution by exploring the spatiotemporal variations in terms of economic losses from health impacts as a result of air pollution in China. The findings of this study have important implications for policymakers regarding priority areas to be addressed in relation to the prevention and control of air pollution given the trend toward increased environmental protection in China. This study reveals the spatiotemporal dynamics of  $PM_{2.5}$ -related economic losses from health impacts during the period 2014–2016 across China at the city level. Although there is a degree of uncertainty regarding the value of these losses, this uncertainty also applies to annual assessments, hence the overall trend is not affected. Last, the long-term  $PM_{2.5}$  health impacts refer to years to decades [53]. Moreover, atmospheric pollutants have a shorter life span, and their diffusion and removal rate are fast. Therefore, our three-year study can reflect the variations of pollution and its impacts.

## 5. Conclusions

We conducted a spatiotemporal assessment of economic losses from health impacts attributed to  $PM_{2.5}$  pollution during the period 2014–2016 in 190 Chinese cities. The results provide new information for policymakers regarding priority areas to be addressed in relation to the prevention and control of air pollution in China. The results show that China experienced a decline in total economic losses from health impacts during the period 2014–2016, but average annual losses remained high, and were mainly concentrated in eastern and central districts. The three cities with the highest level of losses during the period 2014–2016 were Beijing, Chongqing, and Tianjin, which reflects the spatial distribution of  $PM_{2.5}$  pollution. Thus, these cities should be the primary focus of efforts to implement  $PM_{2.5}$  prevention and control measures. In addition, we found that China's  $PM_{2.5}$ -related economic losses of health impacts were enormous, for the reason that the average economic loss was 0.3% (AHC) to 1% (VSL) of the total GDP of 190 Chinese cities from 2014 to 2016. It suggests that  $PM_{2.5}$  reduction will have significant benefits at both the regional and national scales.

The study has some limitations. For instance, the differences between urban and rural  $PM_{2.5}$  concentrations were unclear, exposed population selected resident population without considering age structure, exposure—response coefficients were based on the results of previous meta-analyses, and not all  $PM_{2.5}$ -related health impacts were included in the evaluation. However, despite these

limitations, this study makes a significant contribution by exploring China's spatiotemporal variations in terms of economic losses from health impacts as a result of air pollution. The findings of this study have important implications for policymakers regarding the priority areas in terms of the prevention and control of air pollution given the trend toward increasing environmental protection in China.

**Supplementary Materials:** The following tables are available online at <http://www.mdpi.com/1660-4601/15/6/1278/s1>. Table S1: Source of the health impacts assessment model parameters and the disease data; Table S2: Assumption cells and forecast cells used for uncertainty analysis; Table S3: PM<sub>2.5</sub>-related health impacts and changes in all-cause mortality from 2014 to 2016 in 190 Chinese cities; and Table S4: PM<sub>2.5</sub>-related economic losses from health impacts and changes in total economic losses from 2014 to 2016 in 190 Chinese cities.

**Author Contributions:** Y.Y., L.L., C.S., H.Y., and J.Y. worked collectively. Specifically, C.S. and H.Y. developed the original idea for the study; Y.Y. and C.S. explored in depth; Y.Y. designed the procedure and provided the original data, L.L. improved data; L.L. and C.S. organized the content; L.L. conducted the experiments; Y.Y. analyzed the results, Y.Y. and L.L. drafted the article; Y.Y. and C.S. revised the article; and J.Y. provided support for the modeling and uncertainty analysis.

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