

Article

Health Impact Attributable to Improvement of PM_{2.5} Pollution from 2014–2018 and Its Potential Benefits by 2030 in China

Yu Ma ^{1,2}, Deping Li ^{1,2,*} and Liang Zhou ^{1,2}

¹ Hunan Key Laboratory of Geospatial Big Data Mining and Application, Hunan Normal University, Changsha 410081, China; mayu0411@hunnu.edu.cn (Y.M.); zhouliang@hunnu.edu.cn (L.Z.)

² School of Geographic Sciences, Hunan Normal University, Changsha 410081, China

* Correspondence: lideping106@aliyun.com; Tel.: +86-130-5518-4008

Abstract: With the advancement of urbanization and industrialization, air pollution has become one of the biggest challenges for sustainable development. In recent years, ambient PM_{2.5} concentrations in China have declined substantially due to the combined effect of PM_{2.5} control and meteorological conditions. To this end, it is critical to assess the health impact attributable to PM_{2.5} pollution improvement and to explore the potential benefits which may be obtained through the achievement of future PM_{2.5} control targets. Based on PM_{2.5} and population data with a 1 km resolution, premature mortality caused by exposure to PM_{2.5} in China from 2014 to 2018 was estimated using the Global Exposure Mortality Model (GEMM). Then, the potential benefits of achieving PM_{2.5} control targets were estimated for 2030. The results show that premature mortality caused by PM_{2.5} pollution decreased by 22.41%, from 2,361,880 in 2014 to 1,832,470 in 2018. Moreover, the reduction of premature mortality in six major regions of China accounted for 52.82% of the national total reduction. If the PM_{2.5} control target can be achieved by 2030, PM_{2.5}-related premature deaths will further decrease by 403,050, accounting for 21.99% of those in 2018. Among them, 87.02% of cities exhibited decreases in premature deaths. According to the potential benefits in 2030, all cities were divided into three types, of which type III cities should set stricter PM_{2.5} control targets and further strengthen the associated monitoring and governance. The results of this study provide a reference for the formulation of air pollution control policies based on regional differences.

Keywords: PM_{2.5}; health impact; spatiotemporal changes; potential benefits; GEMM; China



Citation: Ma, Y.; Li, D.; Zhou, L. Health Impact Attributable to Improvement of PM_{2.5} Pollution from 2014–2018 and Its Potential Benefits by 2030 in China. *Sustainability* **2021**, *13*, 9690. <https://doi.org/10.3390/su13179690>

Academic Editors: Eduardo Missoni, Samantha Pegoraro and Marc A. Rosen

Received: 8 June 2021

Accepted: 24 August 2021

Published: 29 August 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In recent decades, the world has experienced rapid and widespread urbanization and industrialization [1]. Although this process has brought economic development and social progress, it has also led to ambient air pollution [2–5]. Among all types of air pollutants, PM_{2.5} (particulate matter with an aerodynamic diameter of 2.5 μm or less) poses significant harm to human health [6–9]. A great deal of epidemiological research has shown that long-term exposure to high concentrations of PM_{2.5} can lead to cardio-cerebrovascular diseases [10–12] and respiratory diseases [13–15]. Among all deaths caused by PM_{2.5}, ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD), lower respiratory infection (LRI), and lung cancer (LC) account for 36, 21, 20, 16 and 7%, respectively, according to the 2015 Global Burden of Disease (GBD) research report [16].

The World Health Organization (WHO) has established an air quality guideline (AQG) for PM_{2.5} concentration and has stipulated an annual average concentration limit of 10 μg/m³. Furthermore, three interim target values (IT-1, IT-2 and IT-3) have also been established, encompassing annual average concentration limits of 35, 25 and 15 μg/m³, respectively. In China, the guidelines for PM_{2.5} in secondary environmental standards use the WHO IT-1 standard. The Ministry of Ecological Environment of the People's Republic of China has noted that 265 of 338 cities nationwide exceeded ambient air quality

standards in 2015, accounting for 78.4% [17]. Most urban residents in China have been experiencing long-term exposure to high concentrations of PM_{2.5} causing premature deaths, which accounted for more than a quarter of the global deaths attributable to ambient PM_{2.5} pollution [16,18]. In order to control and reduce air pollution, the Chinese government has established a series of measures. For example, the Air Pollution Prevention and Control Action Plan launched by the State Council of China in 2013, the Law of the People's Republic of China on the Prevention Control of Atmosphere Pollution amended in 2015 and the 'Healthy China 2030 Planning Outline', released by the State Council of China in 2016 [19–21]. Meanwhile, some studies have found that meteorological conditions have a significant impact on PM_{2.5} concentration, and that their impacts have large spatial variations [22,23].

The size of the health burden attributable to PM_{2.5} is the result of the combined effect of PM_{2.5} concentration and population density, requiring PM_{2.5} and population data to correspond as exactly as possible at a given time and location [24–26]. Despite the fact that some studies have assessed the health burden attributable to PM_{2.5} in China [27–30], there are limitations in terms of the spatial scale of both PM_{2.5} and population data. The PM_{2.5} concentration and population density used in previous studies were usually statistical values associated with a city or a county [31–33], or spatial data with coarse resolution (e.g., 36 or 10 km) [34,35]. However, these studies largely ignored the spatial heterogeneity of PM_{2.5} concentration and population density [36], which may result in biased health burden assessments. Using PM_{2.5} and population data with high spatial resolution, Wu et al. [37] estimated the premature deaths caused by PM_{2.5} pollution in the Beijing–Tianjin–Hebei region of China, but only data in a specific region in 2015 were analyzed. Therefore, there is a lack of nationwide assessments of health loss attributable to ambient PM_{2.5} using high spatial-resolution data. Meanwhile, the status of PM_{2.5} pollution in China has been greatly improved in recent years, and it is necessary to analyze the annual change of health loss caused by PM_{2.5} pollution.

For an exposure–response model describing the relationship between PM_{2.5} concentration and excess relative risk, the Integrated Exposure Response (IER), proposed by Burnett et al. [38], has mostly been used [39]. One limitation of the IER model is a lack of cohort studies with high PM_{2.5} exposure levels, such that it is unable to account for the relative risk in high PM_{2.5} concentrations [40]. To overcome the above limitations of the IER model, the Global Exposure Mortality Model (GEMM), with the inclusion of Chinese cohort information, has been proposed by Burnett et al. [41], which is able to account for the excess relative risk due to the high PM_{2.5} concentration range in China. Using the GEMM method, Burnett et al. [41] estimated 1.946 million deaths in China from five diseases caused by PM_{2.5}, instead of the 1.108 million deaths reported in the GBD 2015 [16]. In this regard, using new health burden assessment models to update the premature death numbers caused by PM_{2.5} is necessary and urgent.

In this study, using PM_{2.5} and population data with a 1 km resolution, we first analyze the spatial distribution of PM_{2.5} concentration and its relationship with population density. Combined with disease-specific baseline mortality data, the health burden attributable to PM_{2.5} from 2014 to 2018 was obtained through use of the GEMM. Finally, the reduction potential of health burden by 2030 was estimated based on future population distribution data and PM_{2.5} control targets in 2030. The results of this study can serve to update the spatiotemporal changes of the health burden in Mainland China, and to estimate the potential benefits of achieving the PM_{2.5} control targets by 2030.

2. Materials and Methods

2.1. Data Sources

The data involved in this study mainly included PM_{2.5} concentration, population density, baseline mortality, and other related data.

The PM_{2.5} concentration data from 2014 to 2018 were obtained from the Atmospheric Composition Analysis Group of Dalhousie University and estimated by a geographically

weighted regression algorithm integrating satellite observation data, a chemical transport model, and ground monitoring station data with 0.01-degree (~1 km) resolution [42]. These data were subsequently resampled at 1 km spatial resolution.

The population density data from 2014 to 2018 were obtained from the LandScan™ data set provided by Geographic Information Science and Technology (GIST), from Texas A&M University, with a 1 km resolution [43]. The spatial population distribution data for 2030 were obtained from Chen et al. [44], which also had a spatial resolution of 1 km.

The national disease-specific baseline mortality was obtained from the GBD database [45], and the baseline mortality rates of each province (municipality, autonomous region) were obtained from a survey of causes of death in various regions of China conducted by Zhou et al. [46]; however, this only provided data for 2013. Therefore, we combined these two databases to derive the provincial baseline mortality from 2014 to 2018.

In addition, administrative boundary data were obtained from the Resource and Environment Science and Data Center (RESDC), Chinese Academy of Sciences [47].

2.2. Assessment of Health Burden

2.2.1. Global Exposure Mortality Model (GEMM)

In order to assess the health burden attributable to PM_{2.5} in China from 2014 to 2018, we used the GEMM method to predict relative risk (RR). GEMM is the first exposure–response model using Chinese cohort data, and has a large range of observed concentrations (2.4–84.0 µg/m³) [41]. The formula for calculating the RR is as follows:

$$RR_i = \exp\{\beta \log(\Delta C_i / \alpha + 1) / (1 + \exp\{-(\Delta C_i - \mu) / \nu\})\},$$

$$\Delta C_i = \max(0, C_i - C_0),$$
(1)

where RR_i is the RR of premature mortality due to PM_{2.5} exposure in grid i ; β is the exposure–response model coefficient; C_i is the annual PM_{2.5} concentration in grid i ; C_0 indicates the theoretical minimum risk exposure level, which is 2.4 µg/m³; and α , μ , and ν determine the curved form of the exposure–response relationship in GEMM. The values of the model parameters for this study are given in Table 1.

Table 1. Parameter estimates for the Global Exposure Mortality Model (GEMM).

Cause of Death	β	α	μ	ν	References
IHD	0.2969	1.9	12.0	40.2	Burnett et al. [41]
Stroke	0.2720	6.2	16.7	23.7	
COPD	0.2510	6.5	2.5	32.0	
LC	0.2942	6.2	9.3	29.8	
LRI	0.4468	6.4	5.7	8.4	

2.2.2. Estimation of Premature Mortality

Based on the GEMM, the premature mortality caused by PM_{2.5} pollution can be estimated using Equation (2):

$$M_i = [(RR_i - 1) / RR_i] \times B_i \times P_i,$$
(2)

where M_i is the premature mortality caused by PM_{2.5} pollution in grid i ; RR_i is the RR of IHD, stroke, COPD, LC, and LRI in grid i ; B_i is the baseline mortality rate of IHD, stroke, COPD, LC, and LRI in grid i ; and P_i is the exposed population in grid i .

2.3. Sensitivity Analysis

Changes in premature deaths were associated with the variations in PM_{2.5} concentration, baseline mortality, and population density. In order to quantify the impact of each driving factor, we performed a sensitivity analysis where only a single factor was allowed to change from 2014 to 2018 (as a variable), while the other two factors were kept

at their 2014 levels (as constants). Here, the difference between the results of the sensitivity analysis and the results of the 2014 baseline scenario (where 2014 values were used for all driving factors) was used to represent the relative contribution of each driving factor to premature deaths.

2.4. Health Benefits by 2030

In recent years, the Chinese government has taken several measures to promote PM_{2.5} emissions reduction with the aim to reach the WHO IT-1 standard (35 µg/m³) nationwide by 2030 [48]. In order to understand the reduction potential of health burden, the health benefits of achieving the PM_{2.5} control target by 2030 were assessed. At the moment, there exist few evaluations of the health benefits associated with the current planning goals. Some studies have mainly used the future population data at the city or county level, which were obtained through the divisional statistics of the future population scenario data from the Shared Socioeconomic Pathways (SSPs) Public Database [49]. These data do not consider China's specific population policies (e.g., the two-child policy and population ceiling policy), or low spatial precision, as a recent study has found that the spatial resolution could significantly influence the results of air pollution on health impacts [50].

In this study, the spatial population distribution data for 2030 were gridded population data considering the specific population policy of China, with a spatial resolution of 1 km. Moreover, taking the annual mean PM_{2.5} concentration in 2015 as the baseline concentration, regions with an annual mean PM_{2.5} concentration more than 35 µg/m³ will reach the PM_{2.5} control target value by 2030, while regions in which the annual mean PM_{2.5} concentration is less than or equal to 35 µg/m³ will maintain the baseline concentration as the PM_{2.5} control target [33]. The spatial distribution of population density and PM_{2.5} concentration in 2030 are presented in Figure S1. As for the baseline mortality rate, according to the 'Healthy China 2030 Planning Outline', the mortality rate of diseases in China will drop by 30% in 2030 compared to 2015 [51].

3. Results

3.1. Spatial Distribution of PM_{2.5} Pollution and Its Relationship with Population Density

The spatial distribution of PM_{2.5} in China was highly similar from 2014 to 2018, although the overall PM_{2.5} concentration exhibited a decreasing trend (see Figure 1). High-value areas were mainly concentrated in the Beijing–Tianjin–Hebei region and surrounding areas (BTHS), the Yangtze River Delta (YRD), the Fenhe and Weihe Plain (FWP), the Chengdu–Chongqing region (CYR), and the Triangle of Central China (TCC) (see Table S1 and Figure S2), as well as in Xinjiang. The lower-value areas were distributed in the western plateau and southeast coastal areas. However, the spatio-temporal changes of PM_{2.5} significantly differed in China from 2014 to 2018. The PM_{2.5} concentration in the eastern part of China decreased obviously, especially in the areas of high concentration (Figure 2). The PM_{2.5} concentration in the BTHS decreased from 73.55 µg/m³ in 2014 to 49.49 µg/m³ in 2018, accounting for a 32.71% reduction in five years. The PM_{2.5} concentrations in YRD, FWP, CYR, and TCC decreased significantly, with a mean concentration of more than 10 µg/m³. Moreover, that in the Pearl River Delta (PRD) also decreased by 9.38 µg/m³, which was greater than the national mean (5.56 µg/m³). While the western part of China was generally in a rising state, especially in the Taklimakan Desert in southern Xinjiang (with the maximum value of 20 µg/m³; Figure 1f), more notably, the PM_{2.5} concentration was slowly declining before 2018. This is because the Taklamakan Desert in Xinjiang is a major dust source [52]. The Aerosol Optical Depth (AOD) over Taklimakan showed a decreasing trend from 2014 to 2017, while the AOD value significantly increased in 2018 [53,54]. This may be also linked to natural soil characteristics, drought, and atmospheric dynamics in central Asia and West China [55].

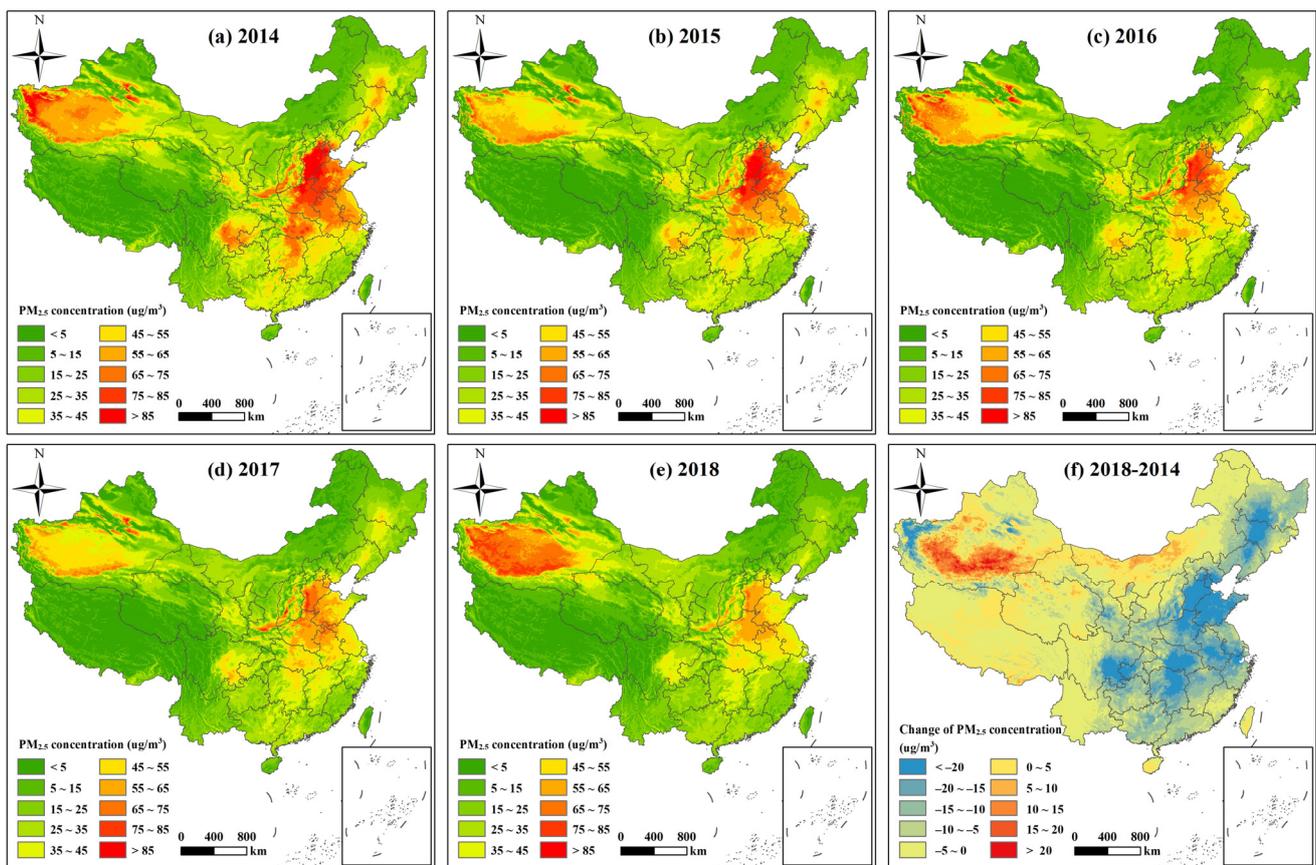


Figure 1. Spatial distribution of annual averaged $PM_{2.5}$ concentrations in China from 2014–2018 and changes from 2014–2018.

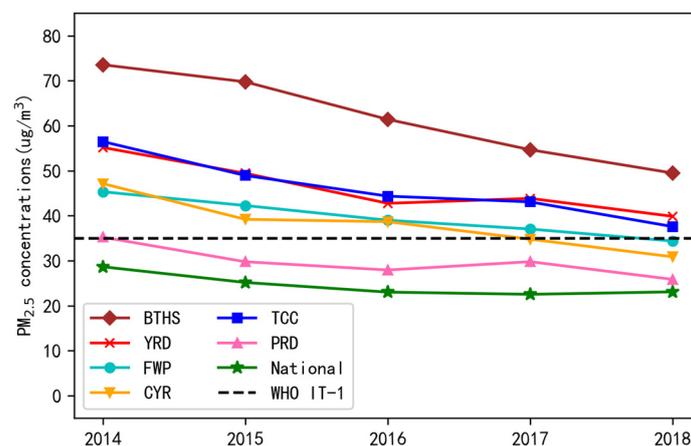


Figure 2. Interannual variations of $PM_{2.5}$ concentrations in major regions from 2014–2018.

At the provincial level, only two out of 31 provinces exhibited increased $PM_{2.5}$ concentrations from 2014 to 2018: Hainan and Xinjiang. Among the remaining 29 provinces, Beijing, Tianjin, Hebei, and Shandong in the North China Plain exhibited the most obvious decreases in $PM_{2.5}$ concentrations (Table S2). At the city level, the $PM_{2.5}$ concentrations in almost all (95.87%) cities decreased, among which Shijiazhuang, Xingtai, Langfang, and Hengshui in Hebei Province experienced the most significant decreases (more than $30 \mu\text{g}/\text{m}^3$). In addition, the $PM_{2.5}$ concentration in 4.13% of cities increased by less than $10 \mu\text{g}/\text{m}^3$, among which 12 cities exhibited an increase in $PM_{2.5}$ concentration of $0\text{--}5 \mu\text{g}/\text{m}^3$ (Figure S3).

Changes in PM_{2.5} concentrations are largely influenced by human activities [56,57] and, to analyze the relationship among these two factors, we fitted the PM_{2.5} concentration with the population density (Figure 3). Overall, there was a certain correlation between PM_{2.5} concentrations and population density, where the value of the coefficient of determination (R^2) was about 0.1 from 2014–2018, meaning that most cities with severe pollution also had a concentrated population distribution. The average concentration of PM_{2.5} from 2014–2018 was divided into low and high concentrations, for a more in-depth analysis of the effect of population density on PM_{2.5} concentration (Figure 4). The correlation between PM_{2.5} and population was more significant at high than at low concentration, with determination coefficients (R^2) of 0.095 and 0.053, respectively. The reason for this is that the cities with high population density were different: some of them were facing problems relating to PM_{2.5} pollution, but some cities had lower PM_{2.5} concentrations. In the early stage, population clustering further expanded the demand for necessities such as clothing, food, shelter and transportation, resulting in the use of more fossil fuels and the creation of more construction/domestic dust [58]. However, studies have pointed out that when socio-economic development reaches a higher stage the effect of human agglomeration on the environment can be mitigated through technological innovation and industrial transformation, as well as other approaches [59].

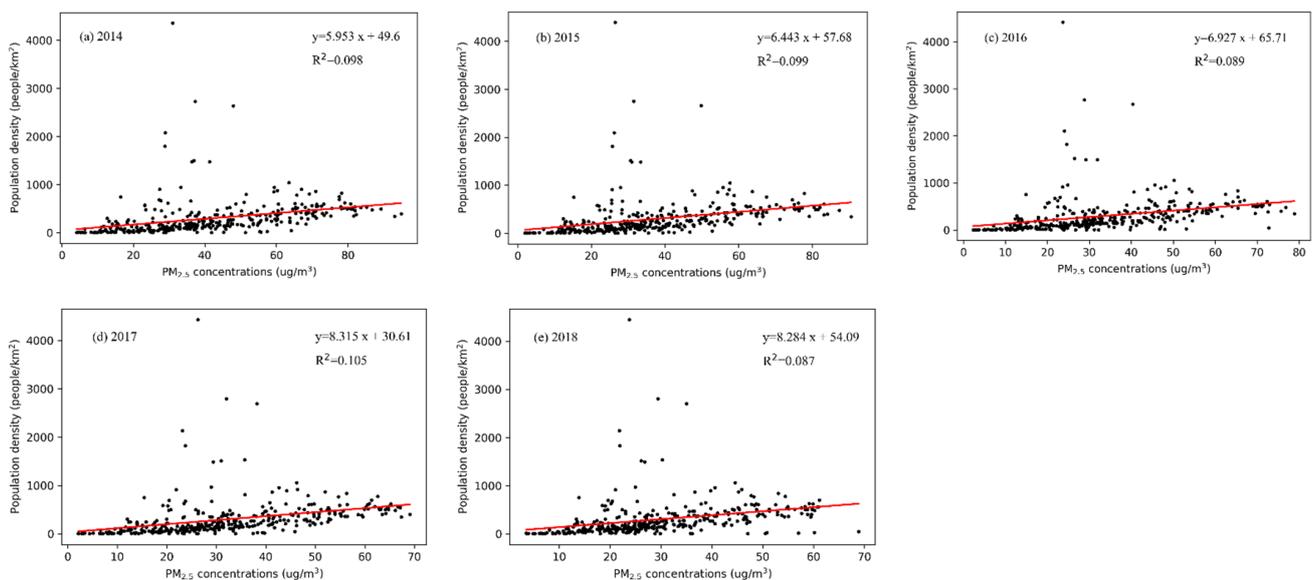


Figure 3. Fitting relationship between PM_{2.5} concentration and population density from 2014–2018.

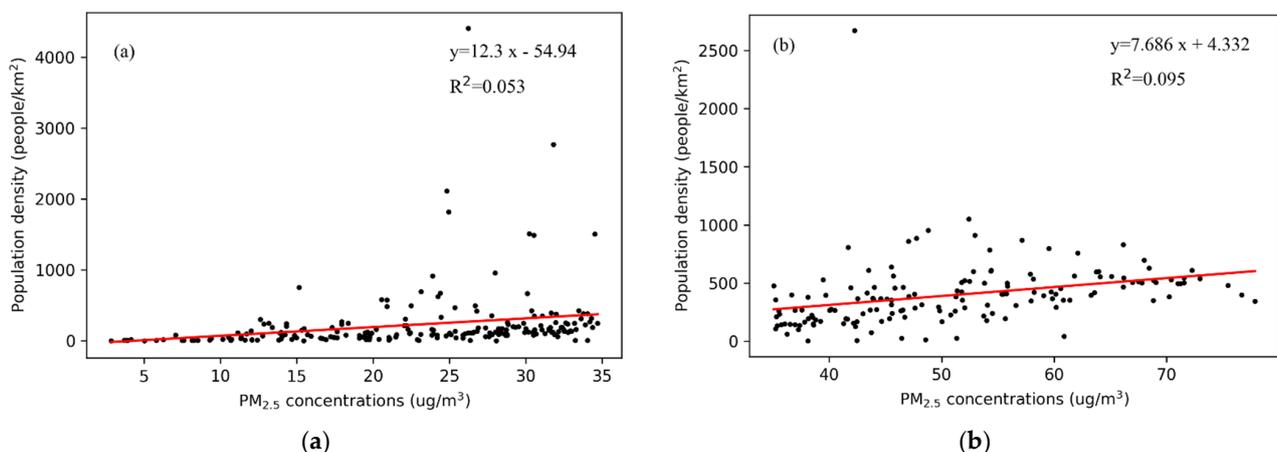


Figure 4. Population density–PM_{2.5} concentration fitting relationships, considering: (a) low and (b) high concentrations.

3.2. Health Burden Attributable to PM_{2.5} and Factor Contribution Analysis

The total premature mortality caused by PM_{2.5} pollution was calculated using the PM_{2.5} concentration, population density, and baseline mortality in China from 2014 to 2018 (Figure 5a). In general, PM_{2.5}-related premature deaths decreased each year in China, with a decrease of 529,410 from 2014–2018. The continuous decline in PM_{2.5} concentration was the main reason for the decrease in deaths [34]. Specifically, the premature deaths caused by IHD, stroke, COPD, LC, and LRI decreased by 145,840, 207,880, 104,770, 39,240 and 31,680, respectively. The relative percentage of premature deaths caused by PM_{2.5} were calculated, as shown in Figure 5b. Among all PM_{2.5}-related deaths in 2018, IHD and stroke were the two most important causes, accounting for 36.52 and 32.86%, respectively; followed by COPD, LC, and LRI, accounting for 14.41, 10.12 and 6.09%, respectively. Compared to 2014, the relative percentage of premature deaths by IHD, LC, and LRI increased by 5.82, 6.41 and 0.50%, while that caused by stroke and COPD decreased by 4.20 and 7.75%, respectively. This also demonstrated the improving PM_{2.5} pollution at the present stage is more helpful to alleviate stroke and COPD.

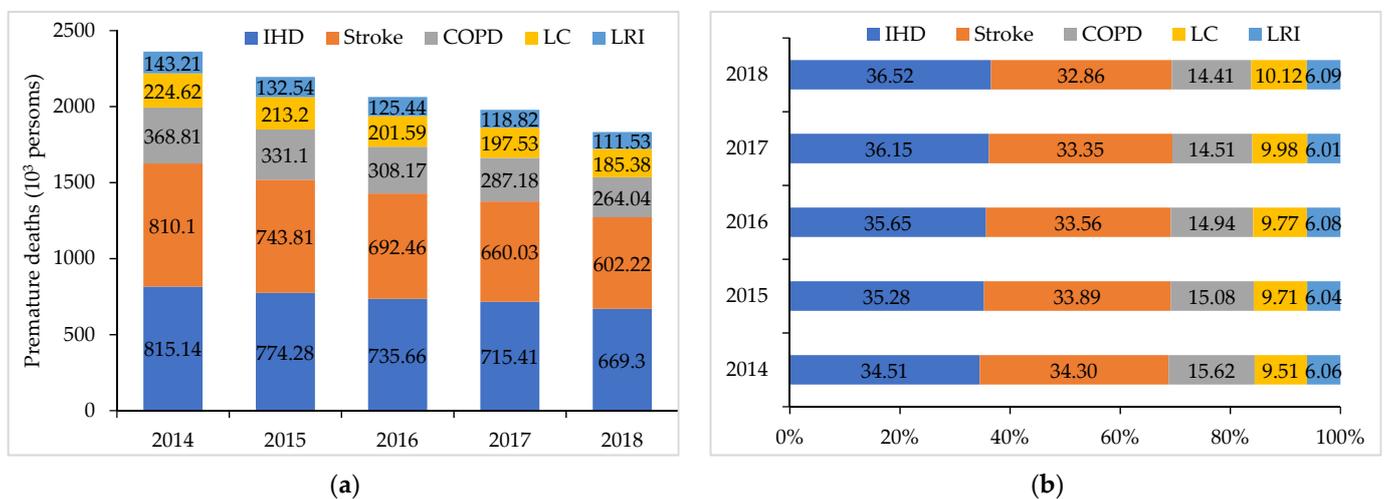


Figure 5. Statistical analysis of premature deaths caused by PM_{2.5} pollution in China from 2014 to 2018: (a) number of premature deaths, and (b) relative percentage in number of premature deaths.

Table 2 shows the PM_{2.5}-related premature deaths in six major regions of China. The reduction in premature deaths in six major regions accounted for 52.82% of the total reduction in the whole country from 2014–2018. As the most polluted region in China, BTHS experienced the highest decrease in premature deaths (by 86,520). Similar to BTHS, the premature deaths in YRD, CYR, and TCC, along the Yangtze River, decreased by 68,360, 48,050 and 44,880, respectively. Compared to other regions, the decline in premature deaths of FWP and PRD was obviously lower, only 15,740 and 16,080. From 2014–2018, except for FWP, the premature deaths in BTHS, YRD, CYR, TCC, and PRD decreased by more than 20%, which also showed that PM_{2.5} pollution improvement had achieved remarkable results within the five years.

Table 2. Premature deaths caused by PM_{2.5} pollution in major regions of China from 2014 to 2018.

Year	Premature Deaths (10 ³ Persons)						Decline in Premature Deaths (%)					
	BTHS	YRD	FWP	CYR	TCC	PRD	BTHS	YRD	FWP	CYR	TCC	PRD
2014	414.49	315.88	97.08	180.39	182.21	77.75	0	0	0	0	0	0
2015	397.61	295.33	90.39	160.69	166.51	69.20	4.07	6.51	6.89	10.92	8.62	11.00
2016	377.39	270.92	90.36	156.26	156.19	64.88	8.95	14.23	6.92	13.38	14.28	16.55
2017	351.19	265.01	87.79	144.28	150.88	66.59	15.27	16.10	9.57	20.02	17.19	14.35
2018	327.97	247.52	81.34	132.34	137.33	61.67	20.87	21.64	16.21	26.64	24.63	20.68

Meanwhile, the reduction of PM_{2.5}-related premature deaths exhibited obvious differences among provinces (Figure 6). Among the 31 provinces, Shandong exhibited the largest decrease in premature deaths due to the five diseases (47,040), while Tibet exhibited the smallest decrease (520). In the remaining provinces, those with the most significant decreases in deaths were Henan (40,250), Sichuan (37,630), Hebei (36,860), Hunan (30,160), Guangdong (28,480), and Hubei (25,360). In contrast, Hainan (620), Ningxia (1640), Qinghai (2440), Shanghai (4920), Tianjin (5590), and Xinjiang (6140) had smaller decreases in deaths. Moreover, Jilin, Heilongjiang, Chongqing, Guizhou, Zhejiang, and Liaoning were the six provinces with the largest percentage decline (by 32.37, 31.04, 28.73, 27.87, 27.67 and 26.01%, respectively).

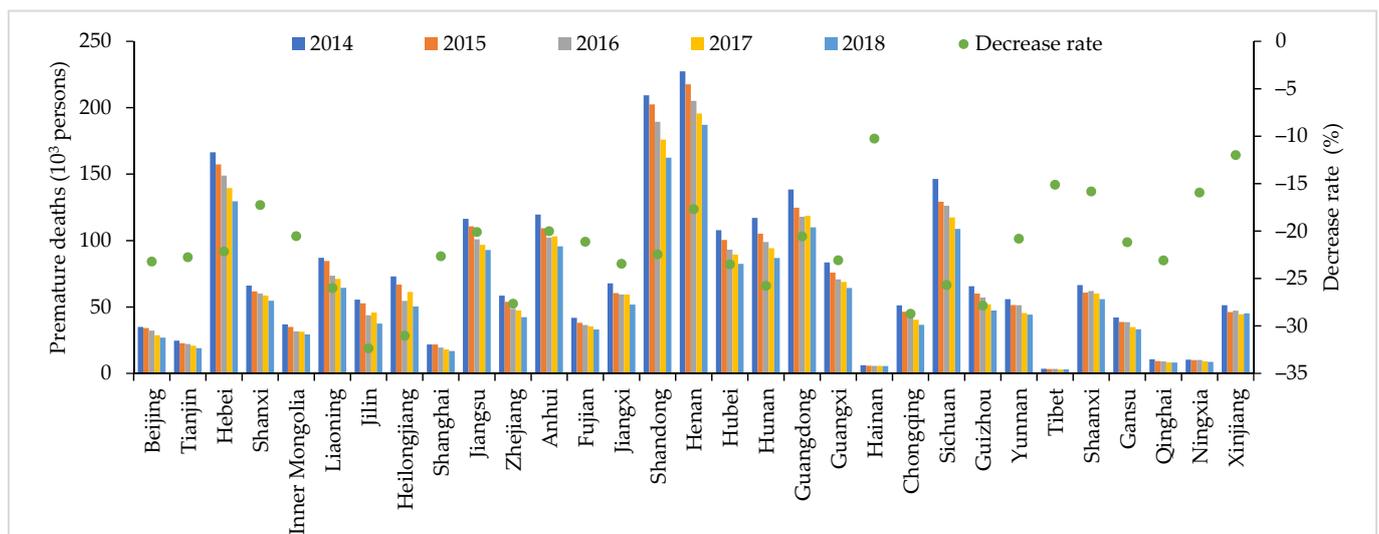


Figure 6. Premature deaths caused by PM_{2.5} pollution in different provinces of China from 2014 to 2018.

The relative change of premature deaths attributable to PM_{2.5} concentration, baseline mortality, and population density between 2014 and 2018 were quantified through the use of a sensitivity analysis (Figure 7). Overall, the PM_{2.5} concentration reduction was the main reason for the decline in premature deaths; concretely, premature deaths declined by 393,460 (16.66%) due to PM_{2.5} reduction from 2014–2018. The baseline mortality reduction contributed to the decline in premature deaths significantly, resulting in a 208,150 (8.81%) reduction in premature deaths. Conversely, changes in population density resulted in an increase by 49,240 (2.08%) in premature deaths. From 2014 to 2018, the total population of mainland China increased from 1367.82 million to 1395.38 million, an increase of only 2.01%, which greatly weakened the increase attributed to changes in the population density. At the provincial level, Shandong had the most significant decline in premature mortality due to PM_{2.5} reduction, with a value of 36,170, while Sichuan, Hebei, Henan, Hunan, and Guangdong each exhibited decreases in premature mortality of more than 20,000. Meanwhile, the premature deaths caused by changes in population density also increased by more than 2500 in each of the aforementioned provinces. The impact of PM_{2.5} reduction on premature deaths was greater than that of baseline mortality reduction in most provinces. However, the relative changes in premature deaths caused by baseline mortality reduction were greater than that caused by PM_{2.5} reduction in Hainan and Xinjiang, with differences of 320 and 2190, respectively.

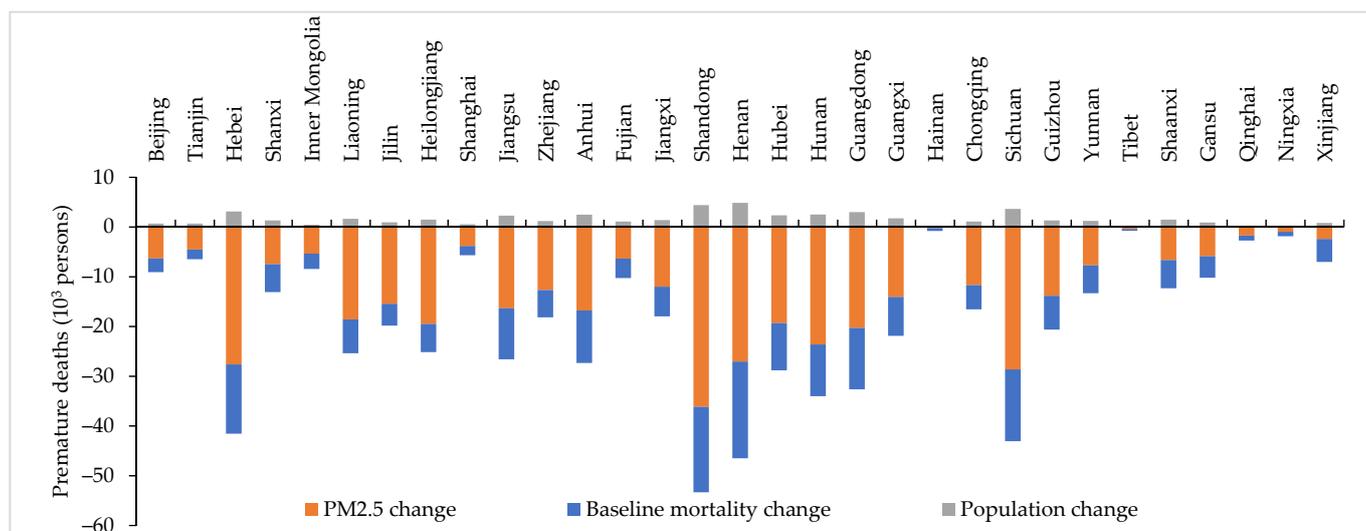


Figure 7. Relative change of premature deaths, attributable to three factors (PM_{2.5}, baseline mortality, and population).

3.3. Changes in Health Burden at the City Level

As shown in Figure 8a, the spatial distribution of premature mortality caused by PM_{2.5} pollution across Mainland China from 2014–2018 exhibited the pattern of “high in the south and low in the north, high in the east and low in the west”. The PM_{2.5}-related premature mortality northwest of the Heihe–Tengchong Line (as known as the Hu Line and is an imaginary empirical line that divides the population distribution in China) was lower, with less than 10 deaths per 100 km² in most areas. To the southeast of the Hu Line, BTHS, YRD, FWP, CYR, TCC and PRD were the main regions affected by high health burden attributed to PM_{2.5} pollution. In particular, the premature mortality in cities with large population density, or high concentration of PM_{2.5}, was more than 100 deaths per 100 km². Over the considered five years (i.e., 2014–2018), the health burden attributable to PM_{2.5} pollution decreased in most areas (Figure 8b). In addition, note that the areas with increased premature mortality were scattered throughout the whole country, but the reasons in the southeast and northwest of the Hu Line were different. The main reason in the southeast was that the relative changes of premature mortality due to population increases were greater than those caused by the decrease in PM_{2.5} concentration [34], such as in parts of Jiangsu and Henan. The main reason in the northwest was that the PM_{2.5} concentration had experienced an increasing trend, such as in parts of Inner Mongolia and Xinjiang.

The changes of PM_{2.5}-related premature mortality in Chinese cities from 2014 to 2018 were calculated; the results are presented in Figure 9 and Table S3. Western China had lower PM_{2.5} concentrations and population density, and the cities had smaller decreases in premature mortality. Cities with a high population density and high decline in PM_{2.5} concentration, such as those in BTHS, had a larger decrease of premature mortality (see Figure 9a). In BTHS, cities which experienced a large decrease of premature deaths were Beijing (8110), Baoding (6050), Tianjin (5590), and Shijiazhuang (5300). The premature deaths in the megacities Chongqing, Chengdu, Wuhan, and Shanghai decreased by 14,680, 7000, 5430, and 4920, respectively. In Northeast China, the large cities with large decreases in premature deaths were Harbin (7670), Changchun (6080), and Shenyang (5120). The cities of Linyi, Tangshan, Weifang, and Handan also had high decreases in premature deaths (4980, 4680, 4550 and 4490, respectively). In terms of the percentage change, cities in northeast and southwest parts of China exhibited the largest declines in premature mortality (Figure 9b). Specifically, the premature deaths in 33.92% of the cities decreased by 0 to 20%, while that in 59.59% of the cities decreased by 20 to 30%. Moreover, the premature deaths in other cities decreased by more than 30%.

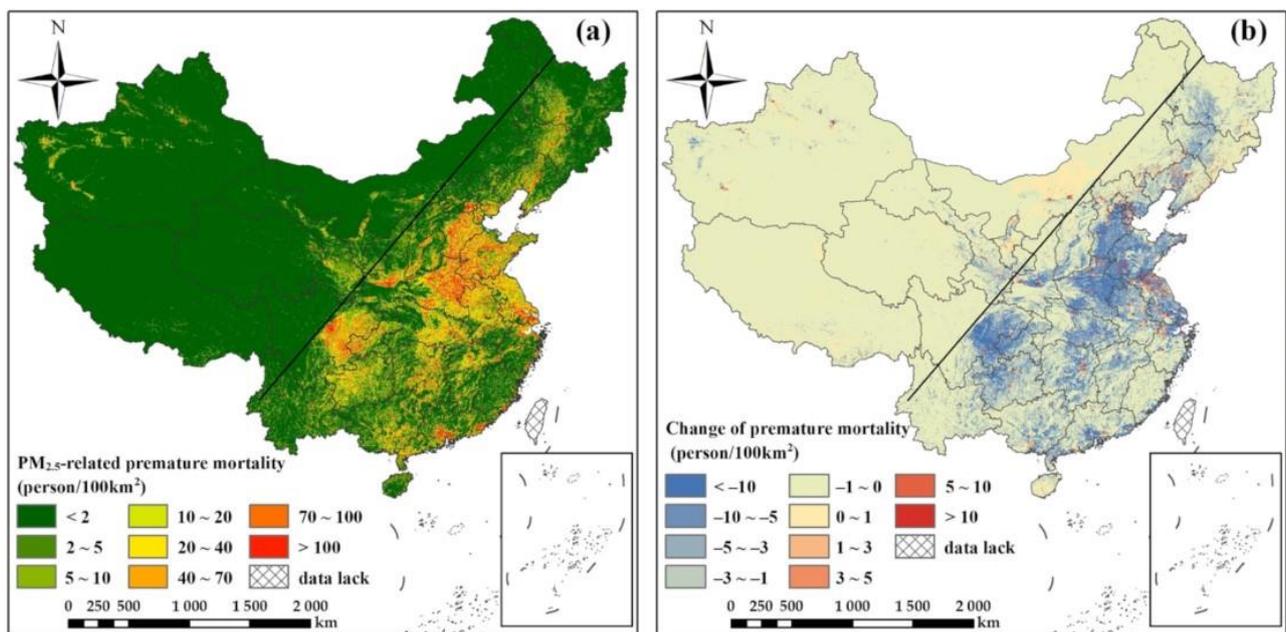


Figure 8. Spatial distribution of premature deaths caused by $PM_{2.5}$ pollution in China: (a) average premature deaths from 2014–2018; and (b) change of premature deaths from 2014 to 2018. The northeast–southwest black line represents the ‘Heihe–Tengchong Line’.

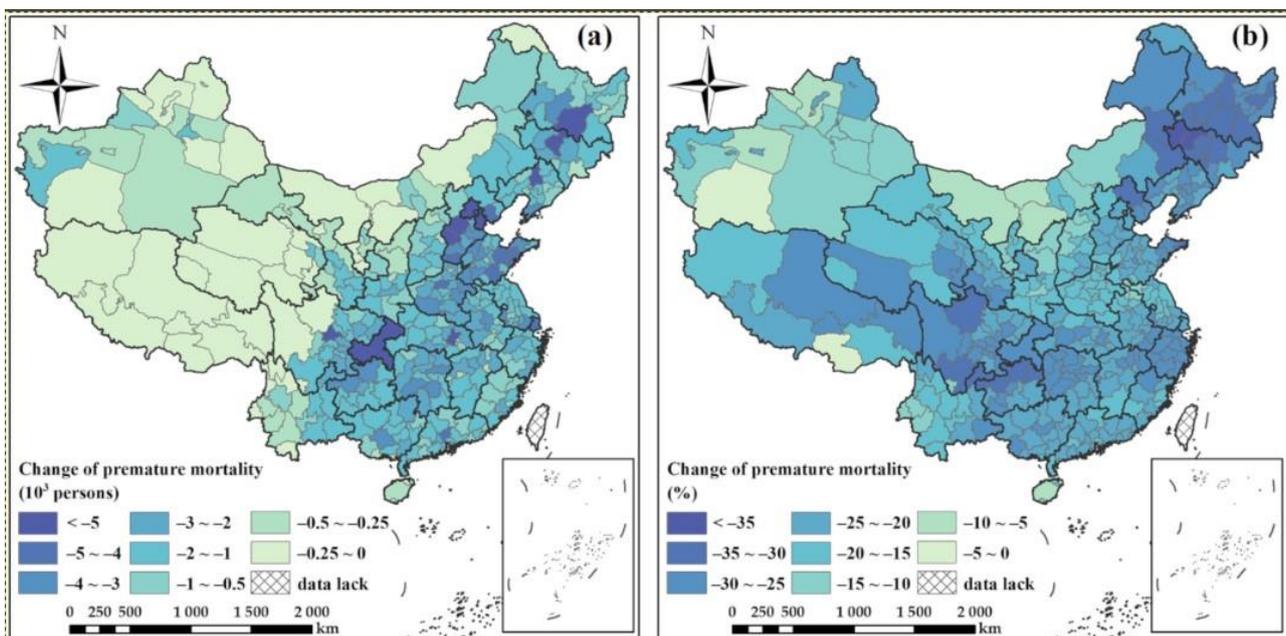


Figure 9. Distributions of changes in premature deaths caused by $PM_{2.5}$ pollution in Chinese cities: (a) change in number of deaths from 2014 to 2018, and (b) percentage change in number of deaths from 2014 to 2018.

3.4. Potential Benefits from Achieving $PM_{2.5}$ Control Targets by 2030

Figure 10 presents the premature mortality caused by $PM_{2.5}$ pollution in China, under the circumstance that the target of $PM_{2.5}$ concentration control in 2030 could be achieved. Compared to 2018, the premature deaths could be decreased by 403,050, accounting for 21.99% of those in 2018. In terms of $PM_{2.5}$ -related premature deaths in 2030, IHD and stroke were still the two most important causes, accounting for 35.22 and 32.31%, respectively; followed by COPD, LC, and LRI, accounting for 16.24, 9.01, and 7.21%, respectively.

Compared to 2018, the relative contribution of premature deaths caused by IHD, stroke, and LC decreased by 3.56, 1.67 and 10.97%, respectively, while those caused by COPD and LRI increased by 12.70 and 18.39%, respectively. At the provincial level (Figure 11), Henan exhibited the largest decreases in premature deaths (64,500), while Shandong, Hebei, Anhui, Jiangsu, Sichuan, and Hubei each decreased in premature deaths by more than 20,000 deaths, accounting for 67.96% of the national mortality decline. In contrast, the premature deaths in Guizhou and Yunnan increased by 11.81 and 1.33%, respectively. These were mainly because the PM_{2.5} concentrations in 2015 had almost approached the PM_{2.5} control target in 2030, such that the relative changes in premature mortality from the decrease in PM_{2.5} were smaller than that caused by population increases.

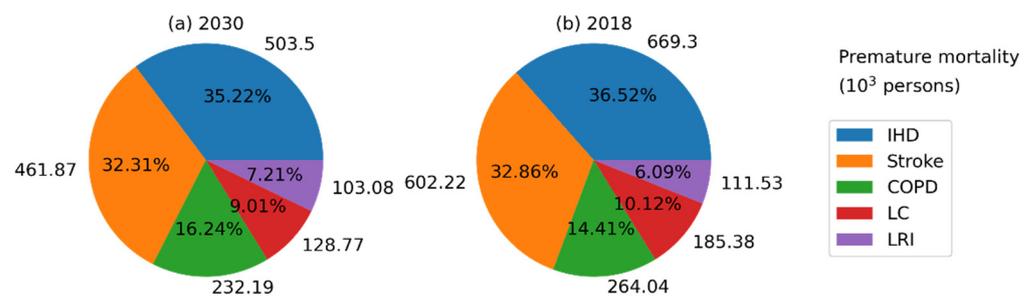


Figure 10. Premature deaths caused by PM_{2.5} pollution across China in 2018 and 2030. The external value of the pie chart represents the number of deaths, while the internal value represents the proportion.

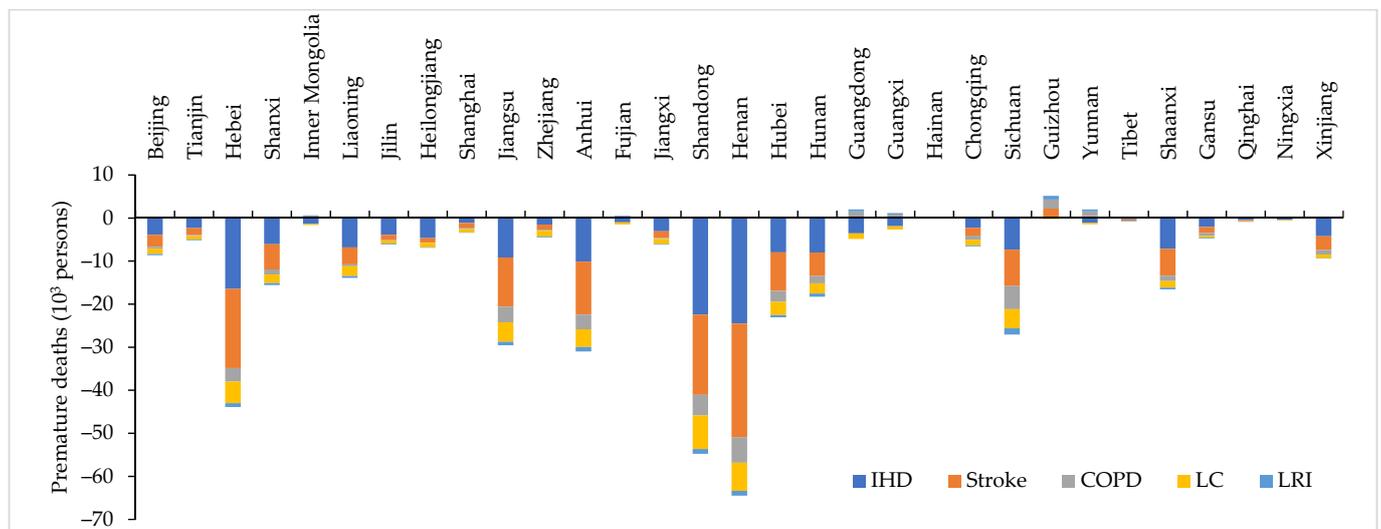


Figure 11. Changes in premature deaths caused by PM_{2.5} pollution in different provinces from 2018 to 2030.

The changes of PM_{2.5}-related premature mortality in Chinese cities from 2018 to 2030 were calculated; the results are presented in Figure 12 and Table S3. Among them, 87.02% of cities exhibited decreases in premature mortality caused by PM_{2.5}. BTHS, YRD, FWP, CYR, and TCC would be the main contributors to the reduction in premature deaths. From 2018–2030, the premature mortality caused by PM_{2.5} in BTHS, YRD, FWP, CYR, and TCC exhibited decreases of 106,440 (32.45% reduction), 68,360 (27.62% reduction), 23,490 (28.88% reduction), 28,620 (21.63% reduction), and 26,690 (19.44% reduction), respectively. The number of premature deaths in the megacities Beijing, Chongqing, Tianjin, and Shanghai decreased by 8660, 6570, 5160 and 3400 thousand, respectively. The cities Heze, Nanyang, Zhoukou, Baoding, and Cangzhou also had high decreases in premature deaths of 8700, 8690, 7620, 7560 and 7160, respectively. However, note that 12.98% of cities exhibited increases in premature mortality caused by PM_{2.5} pollution. These cities should further

strengthen their monitoring and governance with the aim of reaching the PM_{2.5} control target. Specifically, PM_{2.5}-related premature deaths in the PRD experienced a 9804 increase (15.95% growth), with Guangzhou and Shenzhen experiencing increases of 7000 and 5200, respectively. In addition, some provincial capital cities also experienced increases in premature deaths. Guiyang, Kunming, Nanning, and Nanchang were the top four cities, with the most obvious increases of 5260, 5060, 4030 and 2830, respectively.

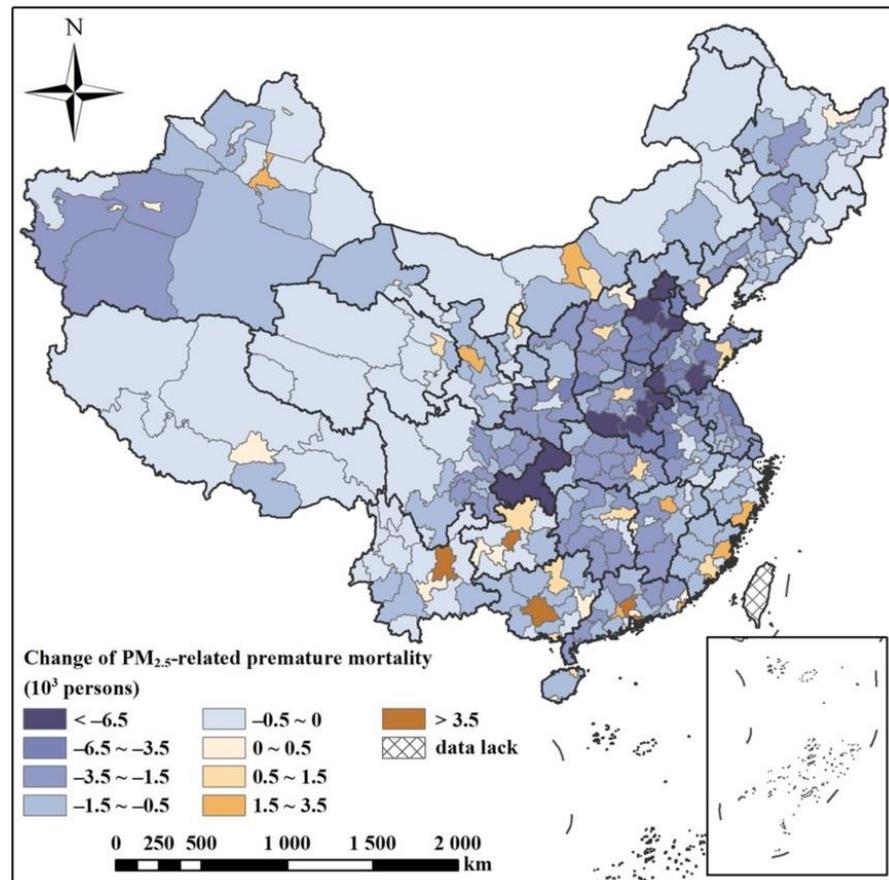


Figure 12. Distributions of changes in premature deaths caused by PM_{2.5} pollution in Chinese cities from 2018–2030.

3.5. Classification of Potential Benefits and Policy Recommendations

A recent study has shown that age structure change may still increase premature mortality by about 30%, under the condition of reaching the PM_{2.5} control target by 2030 [60]. As the population distribution data used in this study had no age structure, cities with less than 30% reduction in health burden were associated with uncertainty. In order to further explore the health benefits of achieving PM_{2.5} control targets by 2030, taking PM_{2.5}-related premature deaths in 2018 as the horizontal axis and the change of premature deaths from 2018 to 2030 as the longitudinal axis, all cities were divided into three types, as shown in Figure 13a. Type I represents areas where the reduction in health burden was more than 30%; Type II represents areas where the reduction in health burden was less than 30%; and Type III represents areas where the health burden exhibits increased compared that in 2018. For a more intuitive observation and analysis, the classification results of potential benefits are shown in Figure 13b.

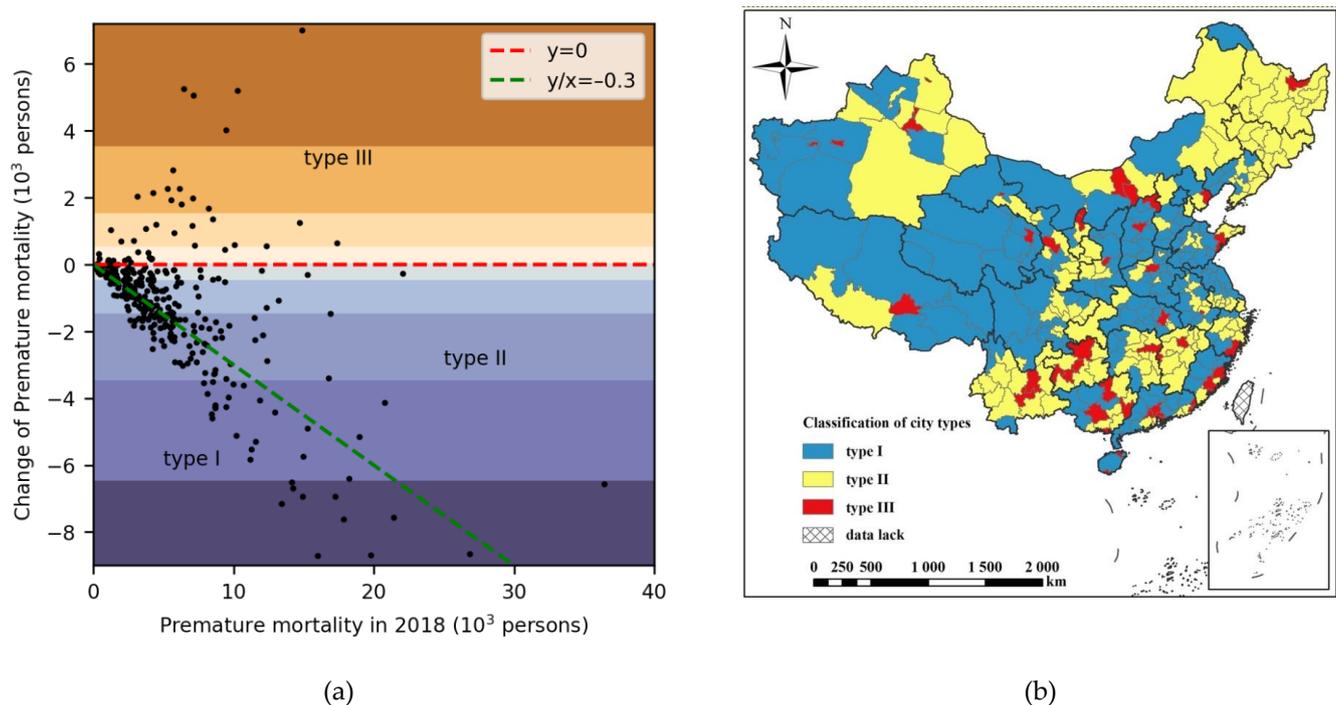


Figure 13. Classification of potential benefits for Chinese cities: (a) classification results of different cities, and (b) spatial distribution of different cities.

Type I consisted of 148 cities, accounting for 43.66% of the total number of cities, and was the most widely distributed across China. Under the circumstance that the target of $PM_{2.5}$ concentration control in 2030 could be achieved, type I cities are expected to experience reductions in health burden by more than 30%. Even considering the increase of health burden caused by age structure change, the potential benefits of type I cities are still positive. Therefore, the $PM_{2.5}$ control target of these cities should not need to be changed and implementing the current emission reduction policies would be sufficient.

Type II accounted for 43.36% of the total number of cities and had a relatively concentrated distribution across China. Type II cities are expected to experience reductions in health burden by less than 30% under the circumstance that the target of $PM_{2.5}$ concentration control in 2030 is achieved. Considering the age structure change, it is difficult to determine whether the potential benefits of type II cities are positive or negative benefits. Thus, these cities should adapt to local conditions and adjust the $PM_{2.5}$ control target rationally, based on their own age structure characteristics.

Type III accounted for 12.98% of the total number of cities, having a scattered distribution across China and being relatively small in number: mainly provincial capitals, subprovincial cities, and other cities with good socio-economic development. Under the circumstance that the target of $PM_{2.5}$ concentration control in 2030 could be achieved, type III cities are expected to experience increases in health burden in varying degrees. In order to make the potential benefits of these cities positive in 2030, type III cities should set stricter $PM_{2.5}$ control targets and further strengthen monitoring and governance.

4. Discussion

In this study, the health burden attributed to $PM_{2.5}$ pollution was assessed. Compared with existing studies on the mortality burden of long-term exposure to $PM_{2.5}$, one advantage of this study is the high spatial resolution of the data used. Hu et al. [61] pointed out that using coarse-scale data may affect the accuracy of assessment with respect to $PM_{2.5}$ pollution, and that using fine-scale data can provide more comprehensive information. However, previous studies mostly evaluated the premature mortality caused by $PM_{2.5}$ pollution using coarse-scale $PM_{2.5}$ and population data [31–35]. A recent study also noted

the limitations of using county-level population data to estimate premature deaths [62]. To solve this problem, we used PM_{2.5} and population data with finer resolution (1 km), in order to assess the health burden attributed to PM_{2.5} pollution. This considered the spatial heterogeneity of PM_{2.5} concentration and population distribution, and greatly improved the accuracy of estimation.

On the other hand, the latest exposure–response model (GEMM) was used to assess the relative risk (RR) of five diseases (including IHD, stroke, COPD, LC, and LRI) under different concentrations of PM_{2.5}, as shown in Figure 14. Overall, the RR of PM_{2.5} to different diseases increased with the PM_{2.5} concentration. The curves of stroke, COPD, and LC were roughly straight lines, indicating that the RR increased evenly with the PM_{2.5} concentration. As for the IHD curve, the RR increased rapidly when the concentration of PM_{2.5} was lower than 20 µg/m³, then increased steadily in a straight line. For the LRI curve, the RR increased rapidly when the concentration of PM_{2.5} was below 40 µg/m³ then the growth rate slowed down. In this study, the estimated premature mortality caused by PM_{2.5} pollution was higher than that in past studies [32–34,63]. The main reason may be that the exposure–response model used was different, whereas previous studies mostly used the integrated exposure–response (IER) model for estimation. The results of the study by Burnett et al. [41] showed that the global estimates of mortality attributable to ambient fine particulate air pollution by the GEMM method were 120% larger than that estimated by the IER model. Meanwhile, another study pointed out that the estimation results of the GEMM method may be more applicable to high pollution areas such as China [64].

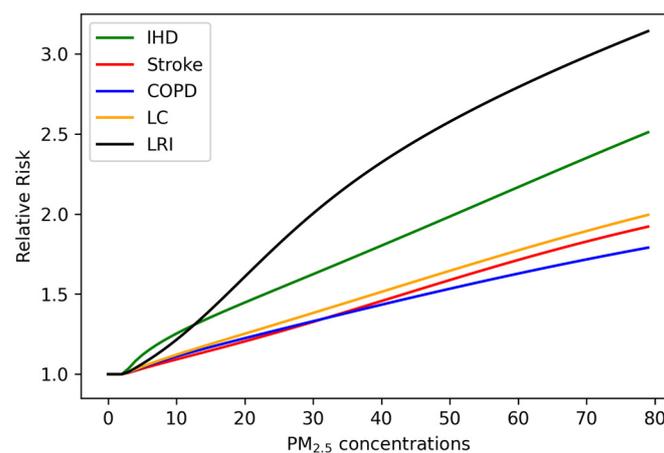


Figure 14. Relationships between the relative risk (RR) of five diseases calculated by the GEMM method and the PM_{2.5} concentration.

However, this study had some limitations. First, as baseline mortality rate and population density data with a 1 km resolution for different age ranges are difficult to obtain, all-age population density and baseline mortality were used to estimate premature mortality. Related studies have shown that the RR of PM_{2.5} pollution on cardio-cerebro-vascular diseases in different age ranges may significantly differ [41], causing uncertainty in the health burden assessment. Second, for the low-concentration regions (PM_{2.5} concentrations lower than or equal to 35 µg/m³), we assumed that the air quality was maintained at the baseline concentration. However, PM_{2.5} concentrations might increase in low-concentration regions due to economic development by 2030. Meanwhile, the PM_{2.5} concentration in low-concentration regions may also be considerably lower than 35 µg/m³ when emissions in high-concentration regions are further controlled. Third, the GBD database does not provide baseline mortality data for future years, and no data are available for the future baseline mortality of each disease (at the country or provincial level). According to the ‘Healthy China 2030 Planning Outline’, we assumed that the baseline mortality in China will drop by 30% in 2030 compared to 2015. However, substantial spatial disparities exist in the baseline mortality of each disease due to the differences in socio-economic contexts,

environments, and health services. Fourth, we assumed that all chemical species in PM_{2.5} have equivalent toxicity, whereas the effects of different chemical species on human health are different [65]. It is generally believed that black carbon and organic carbon in PM_{2.5} are more harmful to humans [66], which also leads to uncertainty in the health burden assessment.

5. Conclusions

In summary, with the aid of high spatial resolution PM_{2.5} concentration and population density data, we assessed the health burden attributed to PM_{2.5} pollution in China. The results show that premature mortality caused by PM_{2.5} pollution in China decreased by 529,410 from 2014–2018, including decreases of 145,840, 207,880, 104,770, 39,240, and 31,680 in the number of premature deaths caused by IHD, stroke, COPD, LC, and LRI, respectively. In addition, the reduction of premature mortality in six major regions (BTHS, YRD, FWP, CYR, TCC, and PRD) of China accounted for 52.82% of the total national reduction from 2014–2018. If the PM_{2.5} control target can be achieved by 2030, PM_{2.5}-related premature deaths will decrease by 403,050, accounting for 21.99% of those in 2018. Among them, 87.02% of cities exhibited decreases in premature deaths. According to the potential benefits in 2030, all cities were divided into three types, namely type I, type II, and type III. For type I cities, achieving the current PM_{2.5} control target will be sufficient. Although the health burden in Type II cities experienced reductions, they still need to adjust the PM_{2.5} control target according to local conditions, especially in cities with an aging age structure. Type III cities, with increases in health burden, should set stricter PM_{2.5} control targets and further strengthen the associated monitoring and governance. We suggest that the relevant Chinese government departments pay attention to regional differences, as well as formulate differentiated air pollution control policies according to the specific circumstances.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/su13179690/s1>. Figure S1: Spatial distribution of population density (a) and PM_{2.5} concentration (b) across China in 2030. Table S1: List of the cities and division basis of six major regions in China. Figure S2: Geographical locations of Chinese provinces and the six major regions. Table S2: Annual averaged PM_{2.5} concentrations in 31 provinces of China from 2014–2018 and changes from 2014 to 2018. Figure S3: Changes of annual averaged PM_{2.5} concentrations in Chinese cities from 2014 to 2018. Table S3: Premature mortality caused by PM_{2.5} in Chinese cities from 2014–2030.

Author Contributions: Conceptualization, Y.M. and D.L.; methodology, Y.M. and L.Z.; data collection and analysis, Y.M.; writing—original draft, Y.M.; writing—review and editing, D.L. and L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Scientific Research Project of Hunan Education Department (No.18A014).

Institutional Review Board Statement: No applicable.

Informed Consent Statement: No applicable.

Data Availability Statement: No applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fu, B.; Zhuang, X.; Jiang, G.; Shi, J.; Lu, Y. Environmental problems and challenge in China. *Environ. Sci. Technol.* **2007**, *41*, 7597–7602. [[CrossRef](#)] [[PubMed](#)]
2. Aghion, P.; Durlauf, S.N. *Handbook of Economic Growth*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2005; pp. 1559–1560.
3. Liang, W.; Yang, M. Urbanization, economic growth and environmental pollution: Evidence from China. *Sustain. Comput. Inform.* **2019**, *21*, 1–9. [[CrossRef](#)]
4. Ameen, R.F.M.; Mourshed, M. Urban environmental challenges in developing countries—A stakeholder perspective. *Habitat Int.* **2017**, *64*, 1–10. [[CrossRef](#)]
5. City, B.L.; Assessment, E. Urbanization and health. *Bull. World Health Organ.* **2010**, *88*, 245–246.

6. WHO. Air Pollution. Available online: https://www.who.int/health-topics/air-pollution#tab=tab_1 (accessed on 10 November 2020).
7. Pope, C.A.; Dockery, D.W. Health effects of fine particulate air pollution: Lines that connect. *J. Air Waste Manag.* **2006**, *56*, 709–742. [[CrossRef](#)]
8. Lin, H.; Liu, T.; Xiao, J.; Zeng, W.; Li, X.; Guo, L.; Zhang, Y.; Xu, Y.; Tao, J.; Xian, H.; et al. Mortality burden of ambient fine particulate air pollution in six Chinese cities: Results from the Pearl River Delta study. *Environ. Int.* **2016**, *96*, 91–97. [[CrossRef](#)]
9. Ho, H.C.; Wong, M.S.; Yang, L.; Shi, W.; Yang, J.; Bilal, M.; Chan, T.C. Spatiotemporal influence of temperature, air quality, and urban environment on cause-specific mortality during hazy days. *Environ. Int.* **2018**, *112*, 10–22. [[CrossRef](#)]
10. Pope III, C.A.; Burnett, R.T.; Thun, M.J.; Calle, E.E.; Krewski, D.; Ito, K.; Thurston, G.D. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA* **2002**, *287*, 1132–1141. [[CrossRef](#)]
11. Guo, Y.; Jia, Y.; Pan, X.; Liu, L.; Wichmann, H.E. The association between fine particulate air pollution and hospital emergency room visits for cardiovascular diseases in Beijing, China. *Sci. Total Environ.* **2009**, *407*, 4826–4830. [[CrossRef](#)]
12. Chen, H.; Burnett, R.T.; Kwong, J.C.; Villeneuve, P.J.; Goldberg, M.S.; Brook, R.D.; van Donkelaar, A.; Jerrett, M.; Martin, R.V.; Kopp, A.; et al. Spatial Association Between Ambient Fine Particulate Matter and Incident Hypertension. *Circulation* **2014**, *129*, 562–569. [[CrossRef](#)]
13. Guan, W.-J.; Zheng, X.-Y.; Chung, K.F.; Zhong, N.-S. Impact of air pollution on the burden of chronic respiratory diseases in China: Time for urgent action. *Lancet* **2016**, *388*, 1939–1951. [[CrossRef](#)]
14. Huang, F.; Pan, B.; Wu, J.; Chen, E.; Chen, L. Relationship between exposure to PM_{2.5} and lung cancer incidence and mortality: A meta-analysis. *Oncotarget* **2017**, *8*, 43322–43331. [[CrossRef](#)] [[PubMed](#)]
15. Li, R.; Zhou, R.; Zhang, J. Function of PM_{2.5} in the pathogenesis of lung cancer and chronic airway inflammatory diseases. *Oncol. Lett.* **2018**, *15*, 7506–7514. [[CrossRef](#)] [[PubMed](#)]
16. Cohen, A.J.; Brauer, M.; Burnett, R.; Anderson, H.R.; Frostad, J.; Estep, K.; Balakrishnan, K.; Brunekreef, B.; Dandona, L.; Dandona, R.; et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. *Lancet* **2017**, *389*, 1907–1918. [[CrossRef](#)]
17. Ministry of Ecological Environment of the People’s Republic of China. Available online: <http://www.mee.gov.cn/> (accessed on 10 November 2020).
18. Apte, J.S.; Marshall, J.D.; Cohen, A.J.; Brauer, M. Addressing global mortality from ambient PM_{2.5}. *Environ. Sci. Technol.* **2015**, *49*, 8057–8066. [[CrossRef](#)]
19. Zhang, Q.; He, K.; Hou, H. Policy: Cleaning China’s air. *Nature* **2012**, *484*, 161–162. [[CrossRef](#)]
20. SCPRC. Air Pollution Prevention and Control Action Plan. 2013. Available online: http://www.gov.cn/zhengce/content/2013-09/13/content_4561.htm (accessed on 10 November 2020).
21. Zhang, Q.; Zheng, Y.; Tong, D.; Shao, M.; Wang, S.; Zhang, Y.; Xu, X.; Wang, J.; He, H.; Liu, W.; et al. Drivers of improved PM_{2.5} air quality in China from 2013 to 2017. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 24463–24469. [[CrossRef](#)]
22. Xu, Y.; Xue, W.; Lei, Y.; Huang, Q.; Zhao, Y.; Cheng, S.; Ren, Z.; Wang, J. Spatiotemporal variation in the impact of meteorological conditions on PM_{2.5} pollution in China from 2000 to 2017. *Atmos. Environ.* **2020**, *223*, 117215. [[CrossRef](#)]
23. Zhong, Q.; Tao, S.; Ma, J.; Liu, J.; Shen, H.; Shen, G.; Guan, D.; Yun, X.; Meng, W.; Yu, X.; et al. PM_{2.5} reductions in Chinese cities from 2013 to 2019 remain significant despite the inflating effects of meteorological conditions. *One Earth* **2021**, *4*, 448–458. [[CrossRef](#)]
24. Duan, N. Models for human exposure to air pollution. *Environ. Int.* **1982**, *8*, 305–309. [[CrossRef](#)]
25. Ott, W.R. Total human exposure. *Environ. Sci. Technol.* **1985**, *19*, 880–886. [[CrossRef](#)]
26. Zou, B.; Li, S.; Lin, Y.; Wang, B.; Cao, S.; Zhao, X.; Peng, F.; Qin, N.; Guo, Q.; Feng, H.; et al. Efforts in reducing air pollution exposure risk in China: State versus individuals. *Environ. Int.* **2020**, *137*, 105504. [[CrossRef](#)] [[PubMed](#)]
27. Lu, X.; Lin, C.; Li, Y.; Yao, T.; Fung, J.C.; Lau, A.K. Assessment of health burden caused by particulate matter in southern China using high-resolution satellite observation. *Environ. Int.* **2017**, *98*, 160–170. [[CrossRef](#)]
28. Wu, J.; Zhu, J.; Li, W.; Xu, D.; Liu, J. Estimation of the PM_{2.5} health effects in China during 2000–2011. *Environ. Sci. Pollut. Control. Ser.* **2017**, *24*, 10695–10707. [[CrossRef](#)]
29. Song, C.; He, J.; Wu, L.; Jin, T.; Chen, X.; Li, R.; Ren, P.; Zhang, L.; Mao, H. Health burden attributable to ambient PM_{2.5} in China. *Environ. Pollut.* **2017**, *223*, 575–586. [[CrossRef](#)]
30. Wang, Q.; Wang, J.; He, M.Z.; Kinney, P.L.; Li, T. A county-level estimate of PM_{2.5}-related chronic mortality risk in China based on multi-model exposure data. *Environ. Int.* **2018**, *110*, 105–112. [[CrossRef](#)] [[PubMed](#)]
31. Guan, Y.; Kang, L.; Wang, Y.; Zhang, N.; Ju, M. Health loss attributed to PM_{2.5} pollution in China’s cities: Economic impact, annual change and reduction potential. *J. Clean. Prod.* **2019**, *217*, 284–294. [[CrossRef](#)]
32. Feng, L.; Ye, B.; Feng, H.; Ren, F.; Huang, S.; Zhang, X.; Zhang, Y.; Du, Q.; Ma, L. Spatiotemporal Changes in Fine Particulate Matter Pollution and the Associated Mortality Burden in China between 2015 and 2016. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1321. [[CrossRef](#)]
33. Wang, Q.; Wang, J.; Zhou, J.; Ban, J.; Li, T. Estimation of PM_{2.5}-associated disease burden in China in 2020 and 2030 using population and air quality scenarios: A modelling study. *Lancet Planet. Health* **2019**, *3*, E71–E80. [[CrossRef](#)]
34. Li, Y.; Liao, Q.; Zhao, X.; Tao, Y.; Bai, Y.; Peng, L. Premature mortality attributable to PM_{2.5} pollution in China during 2008–2016: Underlying causes and responses to emission reductions. *Chemosphere* **2021**, *263*, 127925. [[CrossRef](#)]

35. Maji, K.J. Substantial changes in PM_{2.5} pollution and corresponding premature deaths across China during 2015–2019: A model prospective. *Sci. Total Environ.* **2020**, *729*, 138838. [[CrossRef](#)]
36. Mao, H.N.; Ahn, Y.Y.; Bhaduri, B.; Thakur, G. Improving land use inference by factorizing mobile phone call activity matrix. *J. Land Use Sci.* **2017**, *12*, 138–153. [[CrossRef](#)]
37. Wu, W.; Yang, X.; Yao, M.; Wu, G.; Xu, J.; Zhao, X.; Zhang, J. Assessment of mortality burden and economic loss attributed to long-term PM_{2.5} exposure in the Beijing-Tianjin-Hebei area. *Chin. J. Epidemiol.* **2020**, *41*, 1471–1476.
38. Burnett, R.T.; Pope III, C.A.; Ezzati, M.; Olives, C.; Lim, S.S.; Mehta, S.; Shin, H.H.; Singh, G.; Hubbell, B.; Brauer, M.; et al. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Perspect.* **2014**, *122*, 397–403. [[CrossRef](#)]
39. Maji, K.J.; Ye, W.F.; Arora, M.; Nagendra, S.M.S. PM_{2.5}-related health and economic loss assessment for 338 Chinese cities. *Environ. Int.* **2018**, *121*, 392–403. [[CrossRef](#)] [[PubMed](#)]
40. Pope, C.A.; Cohen, A.J.; Burnett, R.T. Cardiovascular disease and fine particulate matter. *Circ. Res.* **2018**, *122*, 1645–1647. [[CrossRef](#)] [[PubMed](#)]
41. Burnett, R.; Chen, H.; Szyszkowicz, M.; Fann, N.; Hubbell, B.; Pope, C.A.; Apte, J.S.; Brauer, M.; Cohen, A.; Weichenthal, S.; et al. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 9592–9597. [[CrossRef](#)] [[PubMed](#)]
42. Hammer, M.S.; van Donkelaar, A.; Li, C.; Lyapustin, A.; Sayer, A.M.; Hsu, N.C.; Levy, R.C.; Garay, M.J.; Kalashnikova, O.V.; Kahn, R.A.; et al. Global Estimates and Long-Term Trends of Fine Particulate Matter Concentrations (1998–2018). *Environ. Sci. Technol.* **2020**, *54*, 7879–7890. [[CrossRef](#)] [[PubMed](#)]
43. Dobson, J.; Bright, E.; Coleman, P.; Durfee, R.; Worley, B. A global population database for estimating populations at risk. *Photogramm. Eng. Remote Sens.* **2000**, *66*, 849–857.
44. Chen, Y.; Guo, F.; Wang, J.; Cai, W.; Wang, C.; Wang, K. Provincial and gridded population projection for China under shared socioeconomic pathways from 2010 to 2100. *Sci. Data* **2020**, *7*, 83. [[CrossRef](#)]
45. GBD Database. Available online: <http://ghdx.healthdata.org/gbd-results-tool> (accessed on 10 November 2020).
46. Zhou, M.; Wang, H.; Zhu, J.; Chen, W.; Wang, L.; Liu, S.; Li, Y.; Wang, L.; Liu, Y.; Yin, P.; et al. Cause-specific mortality for 240 causes in China during 1990–2013: A systematic subnational analysis for the Global Burden of Disease Study 2013. *Lancet* **2016**, *387*, 251–272. [[CrossRef](#)]
47. RESDC. Available online: <http://www.resdc.cn> (accessed on 10 November 2020).
48. Zhao, H. Progress of formulating “13th Five-year Plan” for national environmental protection. *Environ. Prot.* **2014**, *42*, 28–32.
49. Samir, K.C.; Lutz, W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Chang.* **2017**, *42*, 181–192.
50. Korhonen, A.; Lehtomaki, H.; Lehtomaki, H.; Karvosenoja, N.; Karvosenoja, N.; Kupiainen, K.; Sofiev, M.; Palamarchuk, Y.; Kukkonen, J.; Kangas, L.; et al. Influence of spatial resolution on population PM_{2.5} exposure and health impacts. *Air Qual. Atmos. Health* **2019**, *12*, 705–718. [[CrossRef](#)]
51. SCPRC. Healthy China 2030. 2016. Available online: http://www.gov.cn/zhengce/2016-10/25/content_5124174.htm (accessed on 10 November 2020).
52. Ma, Z.; Hu, X.; Sayer, A.M.; Levy, R.; Levy, R.; Xue, Y.; Tong, S.; Bi, J.; Huang, L.; Liu, Y. Satellite-based spatiotemporal trends in PM_{2.5} concentrations: China, 2004–2013. *Environ. Health Perspect.* **2016**, *124*, 184–192. [[CrossRef](#)]
53. Xie, G.; Wang, M.; Pan, J.; Zhu, Y. Spatio-temporal variations and trends of MODIS C6.1 Dark Target and Deep Blue merged aerosol optical depth over China during 2000–2017. *Atmos. Environ.* **2019**, *214*, 116846. [[CrossRef](#)]
54. Ding, S.; He, J.; Liu, D.; Zhang, R.; Yu, S. The spatially heterogeneous response of aerosol properties to anthropogenic activities and meteorology changes in China during 1980–2018 based on the singular value decomposition method. *Sci. Total Environ.* **2020**, *724*, 138135. [[CrossRef](#)]
55. Li, Y.; Song, Y.; Kaskaoutis, D.G.; Zan, J.; Orozbaev, R.; Tan, L.; Chen, X. Aeolian dust dynamics in the Fergana Valley, Central Asia, since ~30 ka inferred from loess deposits. *Geosci. Front.* **2021**, *12*, 101180. [[CrossRef](#)]
56. Qin, H.; Liao, T.F. The association between rural-urban migration flows and urban air quality in China. *Reg. Environ. Chang.* **2016**, *16*, 1375–1387. [[CrossRef](#)]
57. Lin, B.; Zhu, J. Changes in urban air quality during urbanization in China. *J. Clean. Prod.* **2018**, *188*, 312–321. [[CrossRef](#)]
58. Liddle, B.; Lung, S. Age-structure, urbanization, and climate change in developed countries: Revisiting STIRPAT for disaggregated population and consumption-related environmental impacts. *Popul. Environ.* **2010**, *31*, 317–343. [[CrossRef](#)]
59. Sadorsky, P. The effect of urbanization on CO₂ emissions in emerging economies. *Energy Econ.* **2018**, *41*, 147–153. [[CrossRef](#)]
60. Yue, H.; He, C.; Huang, Q.; Yin, D.; Bryan, B.A. Stronger policy required to substantially reduce deaths from PM_{2.5} pollution in China. *Nat. Commun.* **2020**, *11*, 1462. [[CrossRef](#)]
61. Hu, J.; Huang, L.; Chen, M.; Liao, H.; Zhang, H.; Wang, S.; Ying, Q. Premature mortality attributable to particulate matter in China: Source contributions and responses to reductions. *Environ. Sci. Technol.* **2017**, *51*, 9950–9959. [[CrossRef](#)]
62. Li, T.; Guo, Y.; Liu, Y.; Wang, J.; Wang, Q.; Sun, Z.; He, M.Z.; Shi, X. Estimating mortality burden attributable to short-term PM_{2.5} exposure: A national observational study in China. *Environ. Int.* **2019**, *125*, 245–251. [[CrossRef](#)] [[PubMed](#)]
63. Diao, B.; Ding, L.; Zhang, Q.; Na, J.; Cheng, J. Impact of Urbanization on PM_{2.5}-Related Health and Economic Loss in China 338 Cities. *Int. J. Environ. Res. Public Health* **2020**, *17*, 990. [[CrossRef](#)]

64. Xue, T.; Zhu, T.; Zheng, Y.; Liu, J.; Li, X.; Zhang, Q. Change in the number of PM_{2.5}-attributed deaths in China from 2000 to 2010: Comparison between estimations from census-based epidemiology and pre-established exposure-response functions. *Environ. Int.* **2019**, *129*, 430–437. [[CrossRef](#)] [[PubMed](#)]
65. Lelieveld, J.; Evans, J.S.; Fnais, M.; Giannadaki, D.; Pozzer, A. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* **2015**, *525*, 367–371. [[CrossRef](#)] [[PubMed](#)]
66. Yang, Y.; Ruan, Z.; Wang, X.; Yang, Y.; Mason, T.G.; Lin, H.; Tian, L. Short-term and long-term exposures to fine particulate matter constituents and health: A systematic review and meta-analysis. *Environ. Pollut.* **2019**, *247*, 874–882. [[CrossRef](#)] [[PubMed](#)]