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Original Research

Death Effects Assessment of $PM_{2.5}$ Pollution in China

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Abstract

The provinces of China have suffered from severe $PM_{2.5}$ pollution in recent years, presenting a significant threat to human health. Identifying associations between mortality rate and $PM_{2.5}$ level is extremely useful for a range of purposes, such as the development of preventive measures, increasing health awareness, and establishing disaster warning systems. Based on remote sensing data, station monitoring data, and statistical data, this paper uses the exposure response function, regression analysis, and kriging to evaluate the number of deaths in China's 31 provinces caused by $PM_{2.5}$ pollution in 2015. Variations in the number of deaths and mortality rates in China under different $PM_{2.5}$ concentration control standards have been simulated by a range of countries and organizations helping to develop optimal control standards for each province individually according to actual $PM_{2.5}$ concentration. These results show that:

1) $PM_{2.5}$ pollution has an important effect on the mortality rate in China. The rate caused by $PM_{2.5}$ pollution in 2015 accounted for 1.75‰, or approximately 2.62 million people and 31.14% of all deaths in China.
2) Strict control standards for $PM_{2.5}$ concentration can bring significant health benefits, with projections that if $PM_{2.5}$ concentration in China's provinces were controlled to the level set by China, the EU, Japan, USA, and Australia, the number of deaths caused by $PM_{2.5}$ pollution would be reduced by approximately 0.95, 1.52, 2.02, 2.26, and 2.49 million people, respectively, or 36.24%, 58.08%, 79.91%, 86.47%, and 95.20% compared with baseline year data.
3) Choosing appropriate control targets for limiting $PM_{2.5}$ concentrations in different provinces in China is an effective way to obtain optimal health benefits. Beijing, Tianjin, Hebei, Shandong, and Henan should adopt a 35 μg/m^3 standard with a 25 μg/m^3 standard appropriate for Shanxi, Liaoning, Jilin, Shanghai, Jiangsu, Zhejiang, Anhui, Hubei, Hunan, Chongqing, Shanxi, and Xinjiang; 13 provinces, including Inner Mongolia, Heilongjiang, Fujian, Jiangxi, Guangdong, Guangxi, Sichuan, Guizhou, Yunnan, Tibet, Gansu, Qinghai, and Ningxia, should adopt the 15 μg/m^3 standard; and Hainan should consider choosing a 12 μg/m^3 standard.

Keywords: $PM_{2.5}$ pollution, number of deaths, mortality rate, exposure response function

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Introduction

The 2015 Global Burden of Disease (GBD) study established that 4.2 million deaths were caused by $PM_{2.5}$ pollution, accounting for 7.6% of total deaths and making $PM_{2.5}$ pollution the fifth most common cause of death for people of all ages worldwide [1]. With the rapid development of Chinese industry in recent decades, $PM_{2.5}$ pollution in China has become an increasingly serious environmental problem [2]. In 2013, according to data released by the China Environment Monitoring Station, none of China's 74 cities that monitored $PM_{2.5}$ concentration met the air quality standard (10-20 μg/m³) as recommended by the World Health Organization (WHO 2005). Marginal improvements can be seen, as in 2014, when one city out of 190 monitored reached the standard, while in 2015 11 cities out of 367 monitored satisfied WHO standards. $PM_{2.5}$ pollution episodes in China occur with high frequency, causing a heavy depth of damage with large-scale coverage and evaluating the impact of $PM_{2.5}$ pollution on human health has becomes an increasing focus of research in China and worldwide.

Many studies in recent years have assessed associations between mortality rate and $PM_{2.5}$ pollution, establishing a close association [3-4]. Based on data from 22,905 subjects between 1982 and 2000 in Los Angeles, Jerrett et al. [5] found that mortality rate increased by 1.17% for each 10 μg/m³ increase in $PM_{2.5}$ concentration, while Beelen et al. [6] used meta-analysis to evaluate 367,251 participants in Europe, finding that each 5 μg/m³increase in $PM_{2.5}$ concentration increased mortality rate by 1.07%. Further studies by Puett et al. [7], Turner et al. [8], and Hoek et al. [9] concluded that increased $PM_{2.5}$ concentrations result in higher mortality rates due to cardiovascular, respiratory, and lung cancer causes based on epidemiological analysis. Critically, Dan et al. [10] studied mortality effects associated with $PM_{2.5}$, O_3, and NO_2 over a 16-year period in Canada, finding that the rise in mortality rate was also affected by other factors associated with and in addition to $PM_{2.5}$ pollution. $PM_{2.5}$ monitoring stations in China have recently become common, although monitored data for $PM_{2.5}$ concentrations are not available prior to 2013. In comparison with global research themes, Chinese scholars have mainly focused on exploring temporal and spatial variations of $PM_{2.5}$ concentrations [11-13], identifying the chemical or physical components of $PM_{2.5}$ material [14-15], understanding the socio-economic causes for $PM_{2.5}$ pollution [16-17], identifying potential point source or the air flow trajectories of $PM_{2.5}$ material [18-19], and other physical characteristics and patterns. With less attention on the associations of $PM_{2.5}$ pollution with public health [20], by monitoring atmospheric concentrations of suspended particulate matter, life expectancy and socio-economic data from 90 cities located on both sides of the Huai River, Chen et al. [21] found that the average life expectancy in northern China was shortened by five years due to air pollution, while Liu et al. [22] established that in 2013 the number of adults who died of $PM_{2.5}$ pollution reached 1.37 million based on ground-level monitoring data. Fang et al. [23] analyzed morality rates in 74 Chinese cities under five different $PM_{2.5}$ concentration control standards as formulated by China's Air Pollution Prevention and Control (APPC 2013) regulations and the World Health Organization standards (WHO 2005; although the more stringent the control standards for $PM_{2.5}$ concentration, the greater the health benefits). Recently, research by Liu et al. [24] on the short-term mortality effects of $PM_{2.5}$ pollution found that in areas where the average daily $PM_{2.5}$ concentrations were more than 75 μg/m³, mortality rate increased by 0.33% with each 10 μg/m³increase in $PM_{2.5}$ concentration.

Despite global efforts to understand the complex associations that exist between mortality rate and $PM_{2.5}$ pollution, the role of $PM_{2.5}$ pollution in global deaths remains only partly understood, with complex dynamics and uncertainty on a regional and global level. Therefore, a better understanding of $PM_{2.5}$ pollution-associated mortality rates has become an important and challenging scientific focus, with a need to improve various aspects, including:

1) Data sources, as the distribution of $PM_{2.5}$ concentration shows strong temporal and spatial dynamics, with long-term historical data required to establish associations with mortality rates. Unfortunately, Chinese governmental monitoring of $PM_{2.5}$ concentrations only started in some major cities in 2012, resulting in a lack of a long-term datasets for $PM_{2.5}$ concentrations and a lack of uniformity in the spatial spread of monitoring stations, which significantly influences the accuracy of comparisons and evaluations.
2) In terms of research methods used, exposure response function and meta-analysis have been commonly used by Chinese scholars. However, when applying meta-analysis method to determine exposure response coefficients between the number of deaths and $PM_{2.5}$ pollution levels, most scholars had to rely on empirical literature on associations of $PM_{2.5}$ pollution on mortality rates in Europe and North America to overcome the shortcomings of Chinese literature in this area, which may result in an underestimation of evaluation results.
3) In terms of the control standard selected, most countries and organizations worldwide have adopted a unified control standard for $PM_{2.5}$ concentration, not accounting for regional diversity due to meteorological factors, topographic conditions, and degree of $PM_{2.5}$ pollution, which directly affects the amount of deaths and the ability to achieve observable health benefits. Based on a combination of remote sensing data, station monitoring data, and statistical data, this study applies regression analysis to assess the exposure response coefficient between the average number of deaths and $PM_{2.5}$ concentrations in China's 31 provinces (excluding Hong Kong, Macao, and

Taiwan) from 1998 to 2014. The exposure response coefficient was then applied to the evaluation model of exposure response function to estimate the number of deaths in China caused by $PM_{2.5}$ pollution in 2015. On the basis of these findings, we simulated the variations in the number of deaths and mortality rates under different $PM_{2.5}$ concentration control standards, as formulated by different countries and organizations worldwide, allowing for selection of the optimal $PM_{2.5}$ control standards for each province and providing valid reference data for the development of effective prevention strategies, as well as enhancing awareness of the health risks associated with $PM_{2.5}$ pollution.

Material and Methods

Data Sources

China's 31 provinces were used as the study area, with data collected on $PM_{2.5}$ concentration and population mortality data. Specifically, $PM_{2.5}$ concentration from 1998 to 2014 were derived by the Socioeconomic Data and Applications Center at Columbia University based on satellite monitoring data collected using the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multiangle Imaging Spectroradiometer (MISR) instruments [25], providing data on $PM_{2.5}$ concentrations at 35% relative humidity and at spatial resolution of 0.1°*0.1°. Data on $PM_{2.5}$ concentration in 2015 came from the China Environmental Monitoring Center, while data on the number of deaths from 1998 to 2015 was collected from statistical yearbooks officially published by the National Bureau of Statics of the People's Republic of China (www.stats.gov.cn). ArcGIS10.2 software was used to establish average $PM_{2.5}$ concentrations over the 17-year period, as the available data for $PM_{2.5}$ concentrations between 1998 and 2014 is the average of each of three consecutive years. Data on $PM_{2.5}$ concentrations in 2015 were ultimately obtained from 358 cities in China (Fig. 1a), with the elimination of 1,436 monitoring stations and 367 cities based on compliance with the three following conditions:

1) The stations whose daily monitoring hours have more than 6 hours of missing data are eliminated.
2) The stations whose monthly monitoring days have more than 8 days of missing data are eliminated.
3) Cities that have more than 50% shortage of monitoring stations are eliminated.

Finally, we utilized the kriging method to map the spatial distribution of $PM_{2.5}$ concentration in China (Fig. 1b), forming the basis of calculated $PM_{2.5}$ concentration across China's provinces in 2015 using the zonal statistics tool. In addition, considering that there existed errors between remote sensing data and station monitoring data, we used the formula of relative error to evaluate the data errors based on available remote sensing data and station monitoring data from 2013 to 2014, and found that the average relative error was 9.61% within the error range of 10%. In a sense, the data selected in the paper basically meets the research requirement.

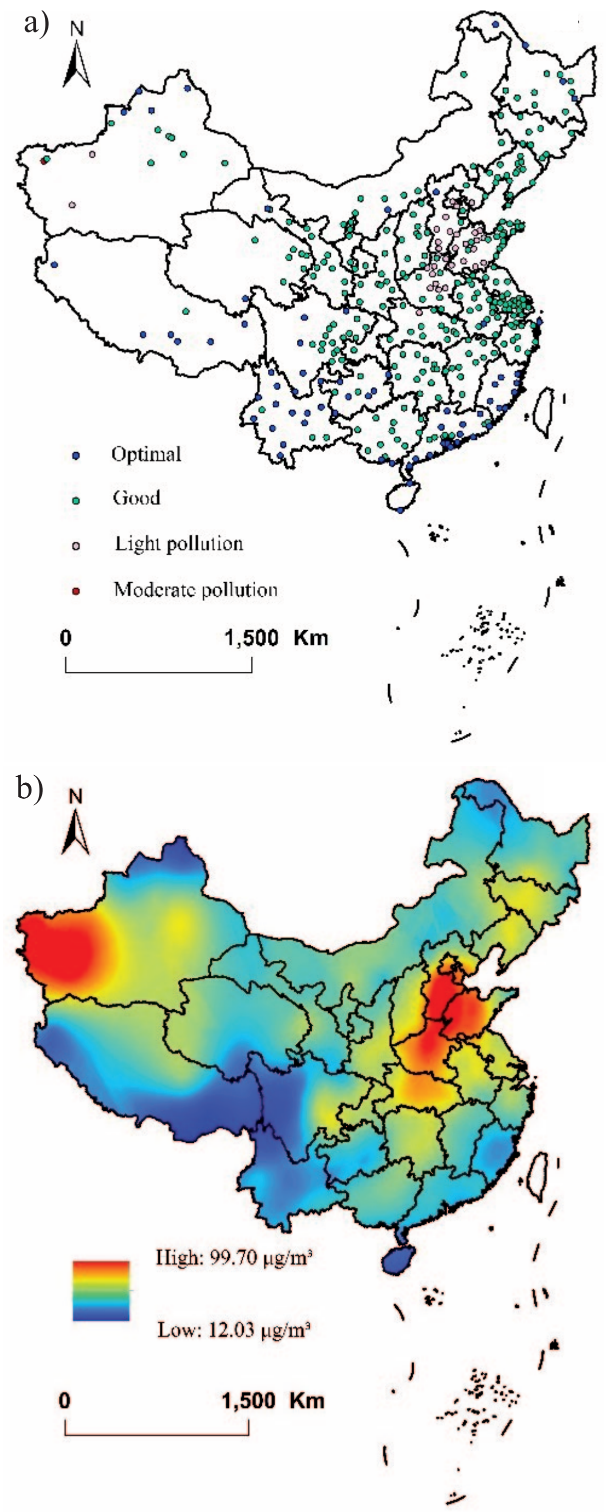

Fig. 1. Spatial distribution of $PM_{2.5}$ monitoring cities and associated $PM_{2.5}$ concentrations in China. Chinese environmental air quality standard as: optimal: 0-35 μg/m³; good: 35-70 μg/m³; light pollution 75-115 μg/m³; moderate pollution: 115-150 μg/m³; heavy pollution: 150-250 μg/m³; serious pollution: 250-500 μg/m³.

Methods

Evaluation Model of the Exposure Response Function

Evaluation models of exposure response function is used to assess the association of mortality rate and $PM_{2.5}$ pollution, with the formula as follows [22-23, 26]:

$$I = I_0 * e^{\beta(C,C_0)} \quad (1)$$

$$\Delta I = I - I_0 = I * \left[1 - \frac{1}{e^{\beta(C,C_0)}}\right] \quad (2)$$

…where I is the number of deaths associated with actual $PM_{2.5}$ concentration C, I_0 is the number of deaths associated with baseline $PM_{2.5}$ concentrations C_0, β represents the exposure response coefficient, and ΔI refers to avoided deaths when $PM_{2.5}$ concentration reduce from C to C_0. Usually, C_0 is regarded as a threshold concentration, where no $PM_{2.5}$ pollution-associated deaths occur [27], and according to the global burden of disease study, this threshold concentration is usually between 5.8 μg/m³ and 8.8 μg/m³. Based on these previous research results, the threshold concentrations selected for this study were set at 5.8 μg/m³ [22-23].

To combat $PM_{2.5}$ pollution, different countries and regional organizations have adopted their own control standards of $PM_{2.5}$ concentration. We simulated the potential changes in number of deaths due to $PM_{2.5}$ pollution in China under different $PM_{2.5}$ concentration control standards issued by different countries and regional organizations worldwide (Table 1).

Regression Analysis

According to the evaluation model of the exposure response function, the exposure response coefficient was established. Findings show that average $PM_{2.5}$ concentrations and number of deaths in China's 31 provinces between 1998 and 2014 presents a non-linear relationship as shown by mapping scatter diagrams. The regression analysis model used to establish the exposure response coefficient utilized the following regression equation [28]:

$$Log(Y) = a * X + b \quad (3)$$

…where Y refers to the average number of deaths between 1998 and 2014, X represents average $PM_{2.5}$ concentrations between 1998 and 2014, a is the regression coefficient, and b is a constant term.

Kriging

The kriging method allows linear, unbiased, and optimized estimation of region variables at non-sampled points based on the numerical values of existing regional variables and the structural characteristics of variation functions. Kriging is based on the following formula [29]:

$$Z_v^*(x) = \sum_{i=1}^{n} \lambda_i Z\,(x_i) \quad (4)$$

…where i represents the sample point, n is the number of sample points in study area, $Z(x_i)$ refers to measured values for i sample point, λ_i is regarded as the weight coefficient, and $Z_v^*(x)$ is the kriging estimated value for the measured value of $Z(x_i)$.

Results

Exposure Response Coefficient Established by Regression Analysis

The average number of deaths and $PM_{2.5}$ concentrations between 1998 and 2014 were included in Formula (3) to calculate the exposure response coefficient, establishing regression coefficient of 0.0068, with an R^2 of 0.206, and the F statistic value of 7.532. The F threshold established with a 95% confidence level was found to be 4.180 – significantly lower than the F statistic value, showing effective application of the regression equation. From this data, we established that the number of deaths increase by 6.8% with each 10 μg/m³ increase in $PM_{2.5}$ concentration.

Number of Deaths and Morality Caused by $PM_{2.5}$ Pollution in China

Based on data from China's 31 provinces for average $PM_{2.5}$ concentration and the average number of deaths in 2015, Formula (3) established that there were 2.62 million deaths attributable to $PM_{2.5}$ pollution, accounting for 31.14% of the total deaths in China. Fig. 2a) reflects the spatial distribution of the deaths caused by $PM_{2.5}$ pollution,

Table 1. Control standards of $PM_{2.5}$ concentrations for different countries and regional organization.

Country or organization	Control standard	Release time	Character of standard
China	35 μg/m³	2012	Mandatory
European Union	25 μg/m³	2010	Mandatory
Japan	15 μg/m³	2009	Mandatory
America	12 μg/m³	2012	Mandatory
Australia	8 μg/m³	2003	voluntary

showing that provinces with more than 200,000 $PM_{2.5}$-associated deaths were Shandong and Henan; provinces with between 100,000 and 200,000 $PM_{2.5}$-associated deaths included Jiangsu, Hebei, Hunan, Hubei, Anhui, and Sichuan; provinces with between 50,000 and 100,000 $PM_{2.5}$-associated deaths were Heilongjiang, Liaoning, Shanxi, Shaanxi, Zhejiang, Jiangxi, Guangdong, Guangxi, Chongqing, and Guizhou; Jilin, Yunnan, Beijing, Tianjin, Fujian, Xinjiang, Gansu, Shanghai, and Inner Mongolia had between 10,000 and 50,000 $PM_{2.5}$-associated deaths; and provinces with less than 10,000 $PM_{2.5}$-associated deaths were Qinghai, Ningxia, Hainan, and Tibet. Due to significant differences in population characteristics and dynamics across China's 31 provinces, as well as variations in other factors such as degree of pollution, economic development, industrial structure, medical conditions, and population structure, a notable bias existed when using absolute death numbers to analyze the effects of $PM_{2.5}$ pollution on human health. Therefore, it was necessary to introduce relative mortality rates to measure the effects of $PM_{2.5}$ pollution, showing that China's whole population mortality rate caused by $PM_{2.5}$ pollution in 2015 was 1.91‰, accounting for more than a quarter of the overall mortality rate of 7.11‰, showing $PM_{2.5}$ pollution to be a serious threat to human health. Mortality rate caused by $PM_{2.5}$ pollution was highest in Henan Province at 3.20‰, while the lowest level of mortality rate was observed in Hainan Province, with only 0.60‰, showing more than a five-fold difference between mortality levels in Henan and Hainan and therefore the level of variation across China.

Fig. 2b) reflects the spatial distribution in mortality rates caused by $PM_{2.5}$ pollution across China, where provinces with mortality rates of more than 2.50‰ were Henan, Shandong, Tianjin, and Jiangsu; provinces with mortality rates between 2.00‰ and 2.50‰ were Hebei, Liaoning, Hubei, Chongqing, Beijing, and Hunan; provinces with mortality rates between 1.50‰ to 2.00‰ were Anhui, Shanxi, Shaanxi, Heilongjiang, Jilin, Xinjiang, Jiangxi, and Shanghai; provinces with mortality rates between 1.00‰ to 1.50‰ were Zhejiang, Fujian, Guangxi, Sichuan, Guizhou, Gansu, Qinghai, and Ningxia; and mortality rates in the remaining provinces were below 1.0‰. It is noteworthy that in general the provinces with the highest number of $PM_{2.5}$ pollution-associated deaths were mainly concentrated in the north China plain and the middle and lower plain regions of the Yangtze River.

Simulated Changes in the Number of Deaths Across China under Different Control Standards

Overall Changes of the Number of Deaths and Mortality

The number of deaths across China in 2015 were regarded as the benchmark, with Formulas (1) and (2) used to simulate the overall change in number of deaths under different control standards for $PM_{2.5}$ concentrations, as published by different countries and regional organizations worldwide. As previously started, the overall number of deaths caused by $PM_{2.5}$ pollution in China in 2015 was established to be 2.62 million people, or 1.91‰ of total mortality rate. As shown in Table. 2, China's control standard for $PM_{2.5}$ concentration result in relatively small health benefits, but is realistically attainable for many provinces. If actual $PM_{2.5}$

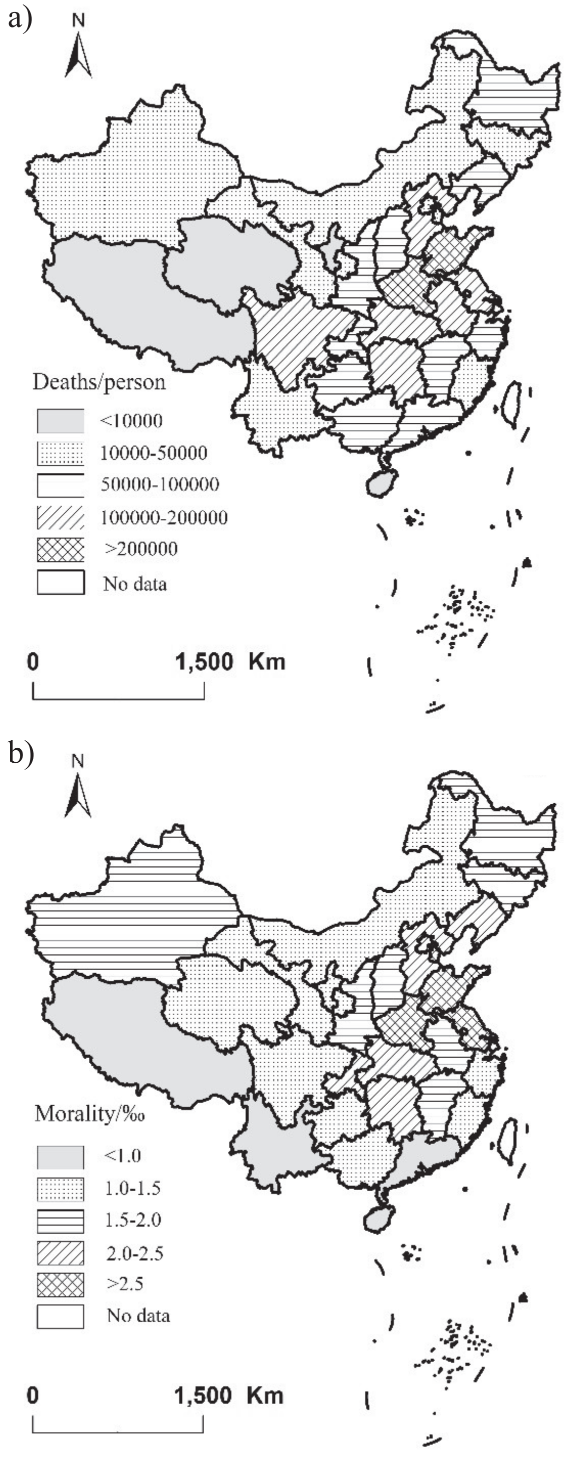

Fig. 2. Spatial distribution of the number of deaths caused by $PM_{2.5}$ pollution across China in 2015.

Table 2. Overall changes in number of deaths and mortality rates under different standards for $PM_{2.5}$.

Control standard	Deaths/person	Morality rates/‰
Benchmark	2,619,400	1.91
China	1,670,200	1.22
European Union	1,098,100	0.80
Japan	526,200	0.38
America	354,500	0.26
Australia	125,800	0.09

concentrations were controlled to China's standard, the mortality rate would decrease 0.69‰, or 949,200 deaths could be avoided, resulting in a 36.24% reduction compared with the benchmark year. The EU's control standard for $PM_{2.5}$ concentration is more stringent than China's standard, following which it would be reduced to 1.67 million, relating to a decline of 58.08%. Japan's control standard is even more strict than both China's and EU standards, which would further reduce mortality rate to as low as 0.38‰, effectively avoiding 2.02 million deaths. The control standard established in the USA for $PM_{2.5}$ concentration is close to the control standard recommended by WHO, which could further reduce mortality rate to below 0.38‰ and avoid 2.26 million deaths. Finally, Australia's $PM_{2.5}$ concentration control standard is the strictest of all compared standards and while being the most difficult to achieve, it would allow 2.49 million deaths to be avoided, reducing mortality to about 22-fold lower than in the benchmark year.

Changes in the Number of Deaths and Mortality in Provinces

Fig. 3a) presents changes in the number of deaths in China's provinces under varying control standards for $PM_{2.5}$ concentrations as formulated by different countries or organizations. If actual $PM_{2.5}$ concentrations could be controlled to the level prescribed by China's standard, the five provinces that would have the most significant number of deaths avoided Shandong, Henan, Jiangsu, Hubei, and Anhui, saving 179,600, 170,600, 88,700, 64,700, and 64,700 lives, respectively. Surprisingly, the number of deaths in Fujian, Guangdong, Sichuan, Yunnan, and Tibet showed an increasing trend, meaning that actual $PM_{2.5}$ concentrations of these provinces was lower than China's standard and suggesting that these provinces should adopt more stringent control standards for $PM_{2.5}$ to avoid deaths due to $PM_{2.5}$ pollution. Only Hainan showed that the number of deaths would increase if the EU's control standard is adopted, suggesting that Hainan province may adopt a stricter standard than the EU in order to avoid a further increase in mortality rate. The control standards applied in the USA and Japan, and by WHO are similar, and can be used as a target for future

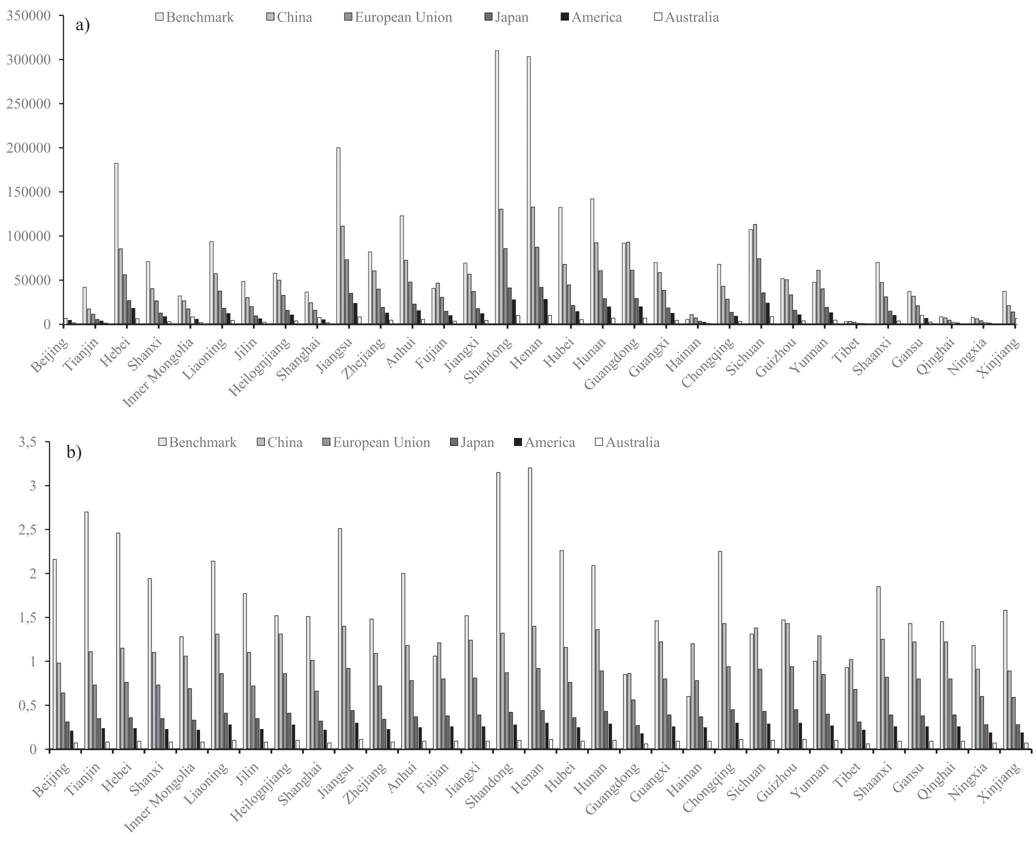

Fig. 3. Changes of number of deaths and mortality rates in provinces.

reference. Most significantly, the health benefits gained by adopting Australia's control standard are significant, but it is an unobtainable target for most of China's provinces at present. Fig. 3b) reflects the changes in mortality rates in provinces under different control standards for $PM_{2.5}$, as established by different countries or organizations, showing that five provinces at present have declining mortality rates: Shandong, Henan, Tianjin, Hebei, and Beijing, with decreases in mortality rate by 1.83, 1.80, 1.59, 1.31, and 1.18‰, respectively. If the EU's control standard was met, morality rates in all provinces would present a downward trend except for Hainan, while if actual $PM_{2.5}$ concentration was reduced to meet the control standards of Japan, USA, or Australia, morality rates caused by $PM_{2.5}$ pollution would be significantly reduced, creating great health benefits.

Selecting Optimal Control Standards for $PM_{2.5}$ Concentrations for Different Provinces

Table 2 and Fig. 3 present the simulated changes in the number of deaths and mortality rates observed under different control standards for $PM_{2.5}$ concentrations. It is worth noting that some limitations of this analysis were that a unified control standard for $PM_{2.5}$ concentration was applied for all provinces, ignoring the regional differences in actual $PM_{2.5}$ concentrations. Theoretically, each province should select the appropriate control standard for $PM_{2.5}$ concentration according to the actual level of $PM_{2.5}$ pollution present. This study established the optimal control standard for $PM_{2.5}$ concentration for each province in China based on the following two principles:

1) Degree of difficulty in managing $PM_{2.5}$ pollution. For provinces with serious $PM_{2.5}$ pollution levels, their difficulties in managing $PM_{2.5}$ pollution will gradually increase during the process of controlling $PM_{2.5}$ concentration, finally resulting in provinces with low initial $PM_{2.5}$ concentrations aiming for stricter control standards than provinces with high initial $PM_{2.5}$ concentrations.
2) Health benefits gained by managing $PM_{2.5}$ pollution. Generally, provinces with high $PM_{2.5}$ concentrations and large populations are the most affected areas for deaths caused by $PM_{2.5}$ pollution. Consideration of these two core principles allows for optimal control standards of $PM_{2.5}$ concentrations to be selected for China's different provinces, which would not only decrease $PM_{2.5}$ concentration, but also reduce the number of deaths, allowing China to obtain large health benefits in the shortest period possible. To facilitate calculations, we regarded a 50% reduction in the number of deaths caused by adopting an initial new control standard (from high to low) for $PM_{2.5}$ concentration as the optimal control standard as compared with the baseline year, with results provided (Table 3).

Table 3 shows that Beijing, Tianjin, Hebei, Shandong, and Henan should apply the current Chinese control standard as a control target for $PM_{2.5}$ concentration, which can bring health benefits for 497,400 people. 12 provinces, including Shanxi, Liaoning, Jilin, Shanghai, Jiangsu, Zhejiang, Anhui, Hubei, Hunan, Chongqing, Shaanxi, and Xinjiang, should apply the EU control standard, avoiding 665,100 deaths associated with $PM_{2.5}$ pollution. Japan's control standard is appropriate for 13 provinces, consisting of Inner Mongolia, Heilongjiang, Fujian, Jiangxi, Guangdong, Guangxi, Sichuan, Guizhou, Yunnan, Tibet, Gansu, Qinghai, and Ningxia, and avoiding 434,700 deaths. Finally, Hainan should consider using the USA's control standard, avoiding 3,200 deaths. If actual $PM_{2.5}$ concentrations in all provinces were controlled to the level outlined above, approximately 1.60 million deaths in China could be avoided as compared with the baseline year, reducing mortality by 61.10%.

Discussion

This study evaluates the number of deaths and mortality rates caused by $PM_{2.5}$ pollution in China in 2015, with simulated changes in the number of deaths and mortality rates under different control standards for $PM_{2.5}$ concentrations. Simulation was performed using regression analysis and exposure response function, with the appropriate control standard applied according to the actual $PM_{2.5}$ concentration, which is an important addition to the analysis of the impact of $PM_{2.5}$ pollution,

Table 3. Optimal control standards selected for different provinces in China.

Control standard	Province	Health benefit/Person
China	Beijing, Tianjin, Hebei, Shandong, Henan	497,400
European Union	Shanxi, Liaoning, Jilin, Shanghai, Jiangsu, Zhejiang, Anhui, Hubei, Hunan, Chongqing, Shaanxi, Xinjiang	665,100
Japan	Inner Mongolia, Heilongjiang, Fujian, Jiangxi, Guangdong, Guangxi, Sichuan, Guizhou, Yunnan, Tibet, Gansu, Qinghai, Ningxia	434,700
America	Hainan	3,200
Australia	No	0
Total	No	1,600,400

helping formulate prevention policies, conduct disaster monitoring, or warning systems for different provinces. Difficulties exist in finding accurate results on the number of deaths and mortality rates caused by $PM_{2.5}$ pollution. First, the data format of $PM_{2.5}$ concentration from 1998 to 2014 is in grid style, while data for $PM_{2.5}$ concentration in 2015 is measured data obtained from national monitoring stations, with notable variation in both datasets. Grid-style data is also susceptible to influence by factors such as cloud coverage, rainfall, and wind speed, resulting in grid-style data being slightly lower than measured data from monitoring stations.

Uncertainty exists regarding establishing exposure response coefficients based on grid-style data for $PM_{2.5}$ concentrations between 1998 and 2014, which underestimate the actual number of deaths caused by $PM_{2.5}$ pollution. Secondly, the nature of deaths affects the assessment of $PM_{2.5}$ pollution in China on a provincial scale, which should have the premise of homogeneity of existence. However, the differences in $PM_{2.5}$ pollution levels in cities, between cities, and countryside regions, and between counties within provinces are significant and can be attributed to such factors as climate, terrain conditions, energy structure, degree of $PM_{2.5}$ pollution, level of economic development, medical conditions, and population structure, leading to uncertainties in the evaluation of results on the micro-scale. Thirdly, control standards from developed economies worldwide were selected, allowing for simulation of changes in the number of deaths and mortality rates in China under different $PM_{2.5}$ concentration control standards, although notable gaps exist between $PM_{2.5}$ concentrations in developed economies and within China. In addition, this study did not account for the difficulty in managing $PM_{2.5}$ pollution, according to the level of regional development, resident health awareness, government management ability, and the influence of population migration and fertility, which would result in the selection of optimal control standards for $PM_{2.5}$.

Conclusions

This study uses an evaluation model of exposure response function, regression analysis, and kriging to estimate the number of deaths in China's 31 provinces caused by $PM_{2.5}$ pollution in 2015 based on a combination of remote sensing data, station monitoring data, and statistical data. On this basis, we simulated the number of deaths avoidable in each province under varying control standards for $PM_{2.5}$ concentrations, which can in turn be used to establish optimal control standards for $PM_{2.5}$ concentrations for each province. The main conclusions of this study are as follows:

(1) Human health in China is seriously affected by $PM_{2.5}$ pollution. It is estimated that approximately 2.62 million deaths in China were associated with $PM_{2.5}$ pollution in 2015, which accounted for 31.14% of all deaths. The mortality rate related by $PM_{2.5}$ pollution in 2015 was 1.75‰, accounting for about a quarter of the overall mortality rate.

(2) Applying strict control standards for $PM_{2.5}$ concentrations can bring major health benefits. If all provinces in China successfully met the national control standards of China, the EU, Japan, USA, and Australia, the number of deaths in China due to $PM_{2.5}$ pollution would be reduced by 0.95, 1.52, 2.02, 2.26, and 2.49 million deaths, having the drop of 36.24%, 58.08%, 79.91%, 86.47%, and 95.20% compared with baseline year data, respectively.

(3) Selecting appropriate control standards for $PM_{2.5}$ concentrations for each province in China according to local conditions is an effective way to obtain optimal benefits. Beijing, Tianjin, Hebei, Shandong, and Henan should apply China's standard; Shanxi, Liaoning, Jilin, Shanghai, Jiangsu, Zhejiang, Anhui, Hubei, Hunan, Chongqing, Shanxi, and Xinjiang should consider applying the EU's standard; Inner Mongolia, Heilongjiang, Fujian, Jiangxi, Guangdong, Guangxi, Sichuan, Guizhou, Yunnan, Tibet, Gansu, Qinghai, and Ningxia should apply Japan's standard; Hainan should consider applying the USA standard.

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