LETTER

Addressing the source contribution of PM$_{2.5}$ on mortality: an evaluation study of its impacts on excess mortality in China

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Abstract

We estimated PM$_{2.5}$ concentrations using satellite data and population mortality values for cause-specific diseases and employed the integrated exposure–response model to obtain the associations between exposure and response. PM$_{2.5}$ source apportionment data were then used to evaluate the excess mortality attributable to PM$_{2.5}$ from different emission sources. In 2013, 1.07 million excess deaths were attributed to PM$_{2.5}$ exposure in China. The potentially avoidable excess deaths would be 279,000, 459,000, 731,000 and 898,000 if the PM$_{2.5}$ concentrations were reduced to meet WHO interim target (IT)-1 (35 $\mu$g m$^{-3}$, also the Chinese standard), IT-2 (25 $\mu$g m$^{-3}$), IT-3 (15 $\mu$g m$^{-3}$) and the air quality guidelines (10 $\mu$g m$^{-3}$), respectively, compared with concentrations experienced in 2013. There were 249,000 (95% CI: 115–337), 228,000 (95% CI: 105–309), 203,000 (95% CI: 94–274), 197,000 (95% CI: 91–266), and 193,000 (95% CI: 88–262) excess deaths attributed to PM$_{2.5}$ from coal burning, vehicle emissions, industry-related emissions, dust and other sources in 2013, respectively. Coal burning was the main source of atmospheric PM$_{2.5}$; it contributed the most to excess mortalities and the health effects were likely to have been conservatively estimated. Considerable health benefits could be achieved if more stringent ambient PM$_{2.5}$ standards were achieved in China.

Introduction

In recent years, with the rapid development of its national economy, China has become the world’s largest coal producer and consumer for industrial needs, heating and power production. As energy requirements have grown, China has experienced a range of related serious air pollution problems. The World Health Organization (WHO) has estimated that air pollution is responsible for 6.7% of all deaths and 7.6% of disability adjusted life years globally [1]. Among all the air pollutants, PM$_{2.5}$ emitted from coal production and utilization processes are associated with more serious adverse health effects than the other air pollutants, specifically respiratory and cardiovascular health problems [2–4]. Several PM$_{2.5}$ constituents, originating from different sources, may have acute effects on human health [5].

Many studies of the source apportionment of PM$_{2.5}$ have been carried out around the world in recent years. The WHO conducted a review of sources of ambient particulate matter around the world and indicated that, globally, 25% of urban ambient PM$_{2.5}$ is contributed by traffic, 15% by industrial activities, 20% by domestic fuel burning, 22% from unspecified sources of human origin, and 18% from natural dust and salt [6]. The PM$_{2.5}$ source apportionment research in China has focused on these main sources. There are five autonomous regions, four municipalities, two
special administrative regions, as well as 23 provinces, which are the highest-level administrative divisions in China, with differing climates, geographical environments and economic forms, which causes a discrepancy in the pollutant source composition. The development of relevant policies and regulations in different regions requires accurate determination and quantification of PM$_{2.5}$ sources. It is important to identify the source-specific health effects of PM$_{2.5}$, which would be helpful for people in order to take precautions to effectively avoid the harm of air pollution.

Satellite-derived PM$_{2.5}$ obtained by aerosol optical depth (AOD) data is a good approach for PM$_{2.5}$ exposure estimation and has advanced rapidly in recent years. Using available national level ground PM$_{2.5}$ measurements, the spatiotemporal PM$_{2.5}$ gap left by ground monitors could be filled by AOD-driven models. Several recent studies have used AOD-estimated PM$_{2.5}$ concentrations as their exposure alternatives. However, the estimated PM$_{2.5}$ concentration surface was at relatively lower spatial resolution [7, 8]. High-resolution satellite-derived data is needed to improve the accuracy of the evaluation.

The integrated exposure–response (IER) model was first demonstrated by Pope et al [9] to combine data regarding the associations of cardiovascular mortality with PM$_{2.5}$ exposures. This method was also adapted for the development of PM$_{2.5}$ exposure-cause-specific mortality functions in the 2010 Global Burden of Disease (GBD) project [10]. The advantage of this model is its ability to integrate updated exposure–response relationships worldwide, and it has been used in many recent studies [8, 11–13].

Studies of excess mortality have been conducted in China. However, they have been limited by the relatively small amount of air monitoring data available for PM$_{2.5}$ in China. In this study, we will access a larger data set using more precise satellite-derived PM$_{2.5}$ data, adopting an advanced exposure–response model and adding new knowledge about the source contributions of adverse health outcomes. The health impacts evaluated include cause-specific excess mortality, ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), and lung cancer (LC) attributable to PM$_{2.5}$ exposure from different sources. We have also compared our study result with a previous study in China. These findings provide new evidence for air pollution control.

### Gridded population data

Detailed 1 km × 1 km population data across China were obtained from the Institute of Geographic Sciences and the Natural Resources Research, Chinese Academy of Sciences, using the sixth China population census from 2010, and was projected for 2013 based on the provincial population in the China Statistical Yearbook. We calculated the population of adults older than 25 years according to the provincial population age structure of the 2010 Population Census. Then we rescaled the data with a 0.1° × 0.1° resolution in accordance with the PM$_{2.5}$ concentration data. The details of the disease-specific mortality rates are summarized in table 1 of the supplementary data (table S1) available at stacks.iop.org/ERL/12/104016/mmedia.

### Provincial PM$_{2.5}$ source apportionment data

We obtained the PM$_{2.5}$ source apportionment data from the websites of the Ministry of Environmental Protection for 15 provinces and direct-controlled municipalities. The primary sources included in the inventory were coal burning, vehicle emissions, industry-related emissions and dust. Studies on source apportionment were mainly conducted in provincial capitals, and we used the data to represent the mean levels for each province. The nationwide source apportionment level was obtained by averaging the data from all 15 regions.

### Exposure–response relationship assessment

We calculated relative risk (RR) in different concentrations of PM$_{2.5}$ based on the integrated exposure–response model, which was used in GBD 2010. The equations employed were:

\[
\begin{align*}
\text{For } z < z_{cf}, & \quad RRIER(z) = 1 \\
\text{For } z \geq z_{cf}, & \quad RRIER(z) = 1 + \alpha \left[1 - \exp(-\gamma (z - z_{cf})^\delta)\right]
\end{align*}
\]

where $z$ is the exposure to PM$_{2.5}$ concentrations ($\mu g m^{-3}$); $z_{cf}$ is the counterfactual concentration below which no adverse health effect is observed; $\alpha$, $\gamma$ and $\delta$ are unknown parameters that can be estimated by nonlinear regression methods. One thousand sets of parameters were provided by Burnett [10]. The central
(50%), lower (2.5%) and upper (97.5%) values of the results of the 1000 sets of parameters were used as the mean, lower and upper CI.

Excess mortality rate and excess mortality calculation

The selected health outcomes were classified by the International Classification of Diseases, 10th revision (ICD-10), including ischemic heart disease (ICD-10, I20-25), stroke (ICD-10, I60-69), chronic obstructive pulmonary disease (ICD-10, J40-44), and lung cancer (ICD-10, C33-34). The relationship between PM pollution and RR was used to estimate the excess mortality in China for causes of premature mortality in adults (≥25 years).

We calculated the excess mortality rate attributable to PM$_{2.5}$ pollution by grid level based on the following:

\[
\Delta \text{Mort} = ((\text{RR} - 1) \times \text{RR}) \times \gamma_0 \times \text{Pop} \tag{2}
\]

where $\Delta \text{Mort}$ is the excess mortality attributable to PM$_{2.5}$ exposure in a grid level; $\gamma_0$ is the baseline mortality rate of a specific health outcome and Pop is the size of the exposed population; RR is the grid level relative risk. Unless indicated, the excess mortality mentioned in this paper refers to the estimated excess mortality attributable to ambient PM$_{2.5}$.

Excess mortality under different scenarios

The WHO air quality guidelines are designed to offer guidance for reducing the health impacts of air pollution, and these guidelines have set 10 $\mu$g m$^{-3}$ as the annual standard worldwide and include three interim targets (ITs) of 35, 25 and 15 $\mu$g m$^{-3}$ as IT-1, IT-2, and IT-3, respectively [15]. We regarded the year 2013 as a baseline scenario and established four other PM$_{2.5}$ scenarios to assess the avoidable excess mortality resulting from the attainment of the WHO guidelines as WHO IT-1, IT-2, IT-3, and the air quality guidelines (AQG) scenario. The concentration of 35 $\mu$g m$^{-3}$ is also the Chinese ambient air quality standard that was established in 2016 as the Chinese standard scenario. We developed these four scenarios to calculate the excess mortality and potentially avoidable excess mortality after reducing ambient PM$_{2.5}$ concentrations.

Excess mortality from different sources

To analyze the health burden by source contribution, we primarily assumed that PM$_{2.5}$ from different sources had similar compositions and toxicities and the same health effects. Excess mortality from different PM$_{2.5}$ sources were then estimated by the contribution proportion of each source in different provincial divisions, and equation (2). Through this step we could estimate the overall excess mortality and compare the mortality attributed to PM$_{2.5}$ from different sources in each province. Given that the relative toxicities of various sources of PM$_{2.5}$ could be different, we conducted a sensitivity analysis on the basis of some recent findings considering the different toxicity and health effects of PM$_{2.5}$ from various sources.

Results

PM$_{2.5}$ exposure assessment

The nationwide population-weighted PM$_{2.5}$ exposure level was 71.62 $\mu$g m$^{-3}$ in 2013. Figure 1 shows the distribution of annual PM$_{2.5}$ concentrations in 2013. The highest PM$_{2.5}$ concentrations were in Eastern and Central China, including the Beijing–Tianjin–Hebei area, the Yangtze River Delta, the Pearl River Delta and the Sichuan Basin. We also found 99.99% of the whole population was living in areas where the PM$_{2.5}$ concentration exceeded 10 $\mu$g m$^{-3}$ (AQG) (table S2).

Excess mortality attributed to PM$_{2.5}$ exposure

Figure 2 shows the disease-specific mortalities attributable to PM$_{2.5}$ exposure across China, and detailed results are presented in table S3. The regions with the highest excess mortality for all four diseases were located in the eastern and central parts of China, which is in accordance with the distribution of the annual PM$_{2.5}$ concentrations. In 2013, 1,066,000 (95% CI: 493–1,442) excess deaths from the four diseases were due to PM$_{2.5}$ exposure in China. The top five ranking provinces were Shandong, Henan, Guangdong, Jiangsu and Hebei. Strokes were the greatest cause, with 568,800 excess deaths, followed by IHD with 262,000, COPD with 133,000, and LC with 103,000, with the contributions of 53.3%, 24.5%, 12.5% and 9.6%. The spatial distribution of the excess mortality for IHD, stroke, LC and COPD in mainland China are shown in figures 3–6. Four areas with relatively high PM$_{2.5}$ concentrations included the Beijing–Tianjin–Hebei region, the Yangtze River Delta, the Pearl River Delta, and the Sichuan Basin, which were magnified in the figures. Figures S1–S4 show the spatial distribution of the excess mortality rate (1/1000 000) for COPD, LC, stroke and IHD in mainland China in 2013. For cardiovascular disease mortalities (IHD, stroke) and LC, the excess mortalities from different health outcomes attributable to PM$_{2.5}$ in different scenarios in China (thousand).

|                  | 2013 Scenario | WHO IT-1 | WHO IT-2 | WHO IT-3 | WHO AQG |
|------------------|---------------|----------|----------|----------|----------|
|                  | (PM$_{2.5}$) | (PM$_{2.5}$) | (PM$_{2.5}$) | (PM$_{2.5}$) | (PM$_{2.5}$) |
| COPD             | 133 (69,189) | 86 (37,134) | 67 (26,109) | 40 (13,73) | 20 (5,44) |
| IHD              | 262 (183,408) | 205 (142,305) | 176 (122,244) | 130 (85,176) | 87 (33,140) |
| Stroke           | 569 (204,706) | 431 (144,590) | 315 (117,513) | 137 (70,209) | 47 (5,127) |
| LC               | 103 (37,140) | 65 (17,99) | 49 ( 11,79) | 29 (5,51) | 14 (1,29) |
| Total            | 1066 (493,1442) | 787 (339,1127) | 607 (276,944) | 335 (173,508) | 168 (45,340) |
| Avoidable deaths | — | 279 | 459 | 731 | 898 |
mortality rates in the Beijing–Tianjin–Hebei area and the Yangtze River Delta were relatively higher than that in the Pearl River Delta and the Sichuan Basin. However, for COPD, the excess mortality rate in the Sichuan Basin was the highest among the four areas.

Potentially avoidable mortality in different scenarios

Table 1 shows the potential health benefits of controlling PM$_{2.5}$ emissions in different scenarios. The number of potentially avoidable mortalities in these scenarios decreased with the declining PM$_{2.5}$ concentration. In the WHO AQG scenario, the total excess mortality was the lowest of the three scenarios with 168,000 deaths, to which IHD contributed the most, followed by strokes. A comparison of the excess deaths from the four diseases in different scenarios are presented in figure 7, which shows the avoidable excess mortality was 279,000, 459,000, 731,000 and 898,000 in the WHO IT-1, IT-2, IT-3 and AQG scenarios compared with that in 2013.

Excess mortality attributed to PM$_{2.5}$ from different sources

Figure 8 shows the proportion of different PM$_{2.5}$ sources in different regions. Coal burning contributed 36% PM$_{2.5}$ in Heilongjiang, which was the highest of all the provinces, and vehicle emissions were the main PM$_{2.5}$ source in Beijing with the proportion of 31%. The highest proportion of industry-related emission and dust were in Hubei and Qinghai, respectively.
Figure 2. Spatial distribution of excess mortalities caused by PM$_{2.5}$.

Table 2. Excess mortality (95% CI) attributed to PM$_{2.5}$ from different sources in China in 2013 (thousand).

| Regions       | Coal burning | Vehicle emissions | Industry-related emissions | Dust | Other sources | Total   |
|---------------|--------------|-------------------|---------------------------|------|---------------|---------|
| China         | 249(115,337) | 228(105,309)     | 203(94,274)               | 197(91,266) | 193(88,262) | 1066(492,1442) |
| Shandong      | 25(12,33)    | 14(7,18)          | 17(8,22)                  | 22(11,29)    | 15(7,20)   | 92(45,122)    |
| Henan         | 15(7,19)     | 15(7,19)          | 15(7,19)                  | 15(7,19)     | 15(7,19)   | 74(35,99)     |
| Guangdong     | 16(7,22)     | 16(7,23)          | 9(4,12)                   | 8(4,11)       | 27(12,38)  | 76(34,105)    |
| Jiangsu       | 20(10,27)    | 18(9,24)          | 14(7,19)                  | 10(5,14)      | 11(5,15)   | 74(35,99)     |
| Hebei         | 19(9,25)     | 10(5,13)          | 17(8,22)                  | 15(7,20)      | 6(3,8)     | 66(33,87)     |
| Sichuan       | 14(7,19)     | 14(7,19)          | 12(5,16)                  | 12(6,16)      | 11(5,14)   | 63(29,83)     |
| Hunan         | 7(3,9)       | 14(6,18)          | 11(5,15)                  | 8(4,11)       | 15(7,21)   | 55(25,73)     |
| Anhui         | 12(6,15)     | 11(5,15)          | 10(5,13)                  | 10(5,13)      | 9(4,12)    | 50(24,67)     |
| Hubei         | 10(5,13)     | 13(6,18)          | 16(8,21)                  | 4(2,6)        | 6(3,8)     | 49(23,66)     |
| Zhejiang      | 9(4,12)      | 13(6,18)          | 11(5,15)                  | 10(4,13)      | 5(2,7)     | 48(22,66)     |
| Liaoning      | 9(4,12)      | 8(4,11)           | 7(3,10)                   | 7(3,10)       | 6(3,9)     | 37(17,52)     |
| Jiangxi       | 7(3,10)      | 7(3,10)           | 6(3,8)                    | 6(3,8)        | 6(3,8)     | 32(15,44)     |
| Guangxi       | 7(3,10)      | 7(3,9)            | 6(3,8)                    | 6(3,9)        | 6(2,7)     | 32(14,43)     |
| Heilongjiang  | 11(5,15)     | 5(2,7)            | 2(1,2)                    | 1(1,2)        | 12(5,17)   | 29(13,41)     |
| Shanxi        | 9(4,13)      | 5(2,6)            | 3(2,5)                    | 9(4,12)       | 2(1,3)     | 28(13,38)     |
| Shaanxi       | 7(3,9)       | 6(3,8)            | 5(2,7)                    | 6(3,7)        | 5(2,6)     | 28(13,38)     |
| Fujian        | 6(3,8)       | 5(2,8)            | 5(2,7)                    | 5(2,7)        | 4(2,6)     | 25(11,36)     |
| Yunnan        | 6(2,8)       | 5(2,8)            | 5(2,7)                    | 5(2,7)        | 4(2,6)     | 25(10,35)     |
| Shanghai      | 3(2,4)       | 7(3,9)            | 7(3,9)                    | 3(2,4)        | 4(2,5)     | 24(11,32)     |
| Chongqing     | 2(2,7)       | 5(2,6)            | 4(2,6)                    | 4(2,6)        | 4(2,5)     | 22(10,30)     |
| Guizhou       | 3(2,7)       | 5(2,6)            | 4(2,6)                    | 4(2,6)        | 4(2,5)     | 22(9,30)      |
| Beijing       | 3(2,6)       | 6(3,9)            | 4(2,5)                    | 3(1,4)        | 3(1,4)     | 21(10,27)     |
| Jilin         | 3(2,6)       | 4(2,6)            | 4(2,5)                    | 4(2,6)        | 3(2,5)     | 20(9,28)      |
| Gansu         | 4(3,8)       | 3(1,4)            | 1(0,1)                    | 1(0,1)        | 1(0,1)     | 17(7,23)      |
| Xinjiang      | 3(2,5)       | 3(1,4)            | 3(1,4)                    | 3(1,4)        | 3(1,4)     | 15(6,20)      |
| Tianjin       | 4(2,5)       | 3(1,4)            | 3(1,4)                    | 4(2,6)        | 10(1,1)    | 15(7,19)      |
| Inner Mongolia| 3(1,5)       | 3(1,4)            | 3(1,4)                    | 3(1,4)        | 2(1,4)     | 14(6,20)      |
| Hainan        | 1(1,2)       | 1(1,1)            | 1(0,1)                    | 1(0,1)        | 1(0,1)     | 5(2,7)        |
| Ningxia       | 1(0,1)       | 1(0,1)            | 1(0,1)                    | 1(0,1)        | 1(0,1)     | 4(2,5)        |
| Qinghai       | 1(0,1)       | 1(0,1)            | 1(0,1)                    | 1(0,1)        | 1(0,1)     | 4(2,5)        |
| Tibet         | 0(0,0)       | 0(0,0)            | 0(0,0)                    | 0(0,0)        | 0(0,0)     | 1(1,2)        |

* The average levels of China were used to represent the PM$_{2.5}$ source apportionment status of provinces without announced data.

with corresponding contributions of 32% and 35%. For the mean level in China, the proportion of coal burning, vehicle emissions, industry-related emissions, dust and other sources were 23%, 22%, 19%, 20%, and 17%, respectively. Excess mortality at the provincial level from different PM$_{2.5}$ sources is presented in table 2, of which particles from different sources are treated as having equal toxicity. There were 249 000 (95% CI: 115–337), 228 000 (95% CI: 105–309), 203 000 (95% CI: 94–274), 197 000 (95% CI: 91–266), and 193 000 (95% CI: 88–262) excess deaths attributed to PM$_{2.5}$ from coal burning, vehicle emissions, industry-related emissions, dust and other sources, respectively, in China in 2013.

Sensitivity analysis
The evidence for different toxicities of PM$_{2.5}$ from various sources is far from conclusive, so we calculated
Discussion

In this study, we used the updated IER model to estimate the excess mortality attributable to PM$_{2.5}$ exposure, from satellite-based PM$_{2.5}$ concentration data using high resolution imaging in China. We addressed an important gap in past health burden analyses of Chinese air pollution by source contribution, which may inform and guide policy makers.

Although the newly constructed PM$_{2.5}$ monitoring stations in China provided sufficient ground level PM$_{2.5}$ measurement, there are still large gaps in PM$_{2.5}$ data for high-quality predictions. Satellite-retrieved AOD data was used to estimate ground-level PM$_{2.5}$ in this study. A two-stage model was developed to calibrate relationships between these factors that combined a linear mixed-effects model and the generalized additive model to refine predictions. The results showed that the model’s predictions for seasonal level observations were accurate compared with historical observations made by Ma et al ($R^2 = 0.79$) [14]. The
Table 3. Excess mortality (95% CI) attributed to unequally toxic PM$_{2.5}$ from different sources in China in 2013 (thousand).

| Estimated excess mortality | Based research information |
|----------------------------|---------------------------|
|                            | Total | References | Study period | Study area | study population | Disease category |
|                            |       |            |              |            |                  |                  |
| Coal burning               |       |            |              |            |                  |                  |
| All-cause                  | 347(160,470) | [11]        | 2010         | China      | adults ≥ 30       | COPD, IHD, CEV, LC |
| All-cause                  | 812(375,1098) | [33]        | 1979–1988    | 6 US cities | all ages          | IHD, pneumonia, COPD |
| All-cause                  | 202(93,274) | [35]        | 2003–2007    | Barcelona, Spain | all ages | all-cause (minus accidents and homicides) |
| All-cause                  | 53(37,83) | [32]        | 2000–2005    | 100 US metropolitan areas | adults ≥ 30 | IHD |
| Vehicle emissions          |       |            |              |            |                  |                  |
| Industry-related emissions |       |            |              |            |                  |                  |
| Dust                       | 57(26,77) | [35]        | 2003–2007    | Barcelona, Spain | all ages | Cardiovascular disease |
| Other sources              | 54(25,74) | [34]        | 2003–2007    | Seoul, Korea | all ages | Respiratory disease |
| All-cause                  | 126(59,169) | [33]        | 2003–2007    | Barcelona, Spain | all ages | Cardiovascular disease |
| Respiratory disease        | 133(69,189) | [34]        | 2003–2007    | Seoul, Korea | all ages | Respiratory disease |
Figure 4. Spatial distribution of the stroke excess mortality for mainland China (a), the Beijing–Tianjin–Hebei region (b), the Yangtze River Delta (c), the Pearl River Delta (d), and the Sichuan Basin (e) in 2013.

average PM$_{2.5}$ population exposure level in 2013 was 71.62 $\mu$g m$^{-3}$, which was similar to the average annual mean PM$_{2.5}$ concentration of 72 $\mu$g m$^{-3}$ announced by the Ministry of Environmental Protection of China in 2014.

Table S4 compares our estimates of excess mortalities caused by PM$_{2.5}$ with other studies in China. We used satellite-derived AOD data to measure ground level PM$_{2.5}$ concentration at a 0.1° × 0.1° resolution. Former studies have employed a coarser resolution of 1.1° × 1.1° latitude × longitude (110 km × 110 km) [11], 2° × 2.5° latitude × longitude [8]. Spatially resolved data may be more suitable for environmental health research [16]. The prior GBD 2010 study also employed 0.1° × 0.1° resolution data. However, it used ground-level monitoring of PM$_{10}$ data to obtain PM$_{2.5}$ data in China. In contrast, the satellite based AOD model developed in this study generated PM$_{2.5}$ predictions which increased the accuracy. Further improvements in exposure accuracy could be achieved if land use and emission information were available, but this is not possible in China at this time. Improved estimates could also be achieved if finer scale or less noisy satellite-based data were available [14, 17]. Lelieveld et al assessed the contribution of PM$_{2.5}$ and O$_3$ on a global scale and found that the excess mortality in China was 1.36 million in 2010 [11]. Rohde and Muller [13] found 1.6 million excess mortalities in China in 2014. Our results were also lower than the results of the 2010 GBD study (1.23 million) [18] and the 1.37...
Figure 5. Spatial distribution of the LC excess mortality for mainland China (a), the Beijing–Tianjin–Hebei region (b), the Yangtze River Delta (c), the Pearl River Delta (d), and the Sichuan Basin (e) in 2013.

million reported by Liu et al [12], but higher than the 2013 HEI report (0.91 million) [19]. Considering the population in the original IER model building were adults and special exposure–response characteristics in teenagers and children, we used the population group of older than 25 in our analysis, which may contribute to our lower estimates. This comparison confirmed that air pollution, especially PM$_{2.5}$, is a large threat to public health.

The exposure–response curve between PM$_{2.5}$ and the health endpoints is one important factor that affects the mortality estimates. There are no long term studies that have established this relationship for China. We adopted the IER function to model the health risks across a wide range of PM$_{2.5}$ mass concentrations [8,10]. This method involves assembling evidence from health effects research on exposure to different combustion-related sources of PM$_{2.5}$ and requires assumptions in selecting studies with different types of exposure to describe ambient PM$_{2.5}$ [20]. Many studies [21–23] used a linear model to deduce the health risks, which usually result in overestimates because the relationship between PM$_{2.5}$ exposure and excess mortality RR is not necessarily a linear function [9, 24].

We estimated the potentially avoidable mortality by converting PM$_{2.5}$ from present concentrations to the WHO AQG and three ITs. The number of potentially avoidable mortalities in these scenarios would obviously decrease with the declining PM$_{2.5}$
concentrations if these guidelines were achieved. However, the mortality benefits did not increase proportionally because of the nonlinear relationships between \( \text{PM}_{2.5} \) and the health outcomes. The assumption of unchanged cause-specific mortality rates in different scenarios was counterfactual. In past decades, mortality from non-communicable diseases has obviously increased with demographic and economic changes, such as aging, urbanization, and increases in income [25, 26]. Socioeconomic status (SES) is an important source of health disparities [27]. Our results might underestimate the mortality benefits from \( \text{PM}_{2.5} \) concentration reduction without considering the demographic and socioeconomic transitions [28].

The estimates from our study indicate that in 2013 the population-weighted mean concentration of \( \text{PM}_{2.5} \) for China was 71.62 \( \mu \text{g m}^{-3} \), with more than 99.99% of the population living in areas exceeding the WHO AQG of 10 \( \mu \text{g m}^{-3} \), which was higher than the findings of the 2013 GBD study, indicating that 87% of the world’s population lived in areas exceeding the AQG annual average in 2013 [29]. We found that coal burning is a main source of atmospheric \( \text{PM}_{2.5} \), contributing approximately 23% of the overall \( \text{PM}_{2.5} \) concentration or nearly 249 000 (95% CI: 115–337) excess mortalities. A study by the Health Effects Institute shows that coal combustion is the single largest source of air pollution-related health impact, contributing to 366 000 excess deaths in China.
in 2013 [19]. The Goddard Earth Observing System chemical transport model was used in the HEI report which found that coal-burning was responsible for 40% of population-weighted PM$_{2.5}$ in China. The report estimated excess mortality of 916 000 in 2013. Considering the complex geography and social economics of China, the systematic and integrated methods for PM$_{2.5}$ source apportionment used in our study are perhaps more suitable for the evaluation in China. With the increase in car ownership on top of the large numbers of trucks and buses in recent years in China, vehicle emissions have also become an increasingly important pollutant source that cannot be ignored, contributing 228 000 excess mortalities.

Some studies suggest that PM$_{2.5}$ derived from gas- and diesel-fueled vehicles, meat cooking, and high-sulfur fuel combustion were associated with cardiovascular, pulmonary and IHD mortality [30, 31]. One study in the USA indicated that the coal combustion PM$_{2.5}$ had an IHD HR of 1.05 (95% CI: 1.02–1.08) per $\mu$g m$^{-3}$ and 1.01 (95% CI: 1–1.02) per $\mu$g m$^{-3}$ PM$_{2.5}$ mass, but PM$_{2.5}$ from both windblown soil and biomass combustion was not associated with IHD mortality [32]. Another study in the USA showed that a 10 $\mu$g m$^{-3}$ increase in PM$_{2.5}$ from mobile and coal combustion sources accounted for a 3.4% (95% CI: 1.7%–5.2%) and 1.1% (95% CI: 0.3%–2.0%) increase in daily mortality, respectively [33]. Research regarding the health effects of source-specific PM$_{2.5}$ have been included in numerous cohort studies in America and Europe, but this is not well developed in China. We used the available source apportionment of PM$_{2.5}$ for our analysis with a counterfactual assumption that the toxicities of PM$_{2.5}$ from different sources were equal.
The health impacts from different PM$_{2.5}$ sources did not vary too much in this study, but it still indicated that coal burning was the main source of atmospheric PM$_{2.5}$, which contributed most to excess mortalities, followed by vehicle emissions. Industry-related emissions and windblown dust contributed to far fewer deaths which is consistent with other international studies. There is a possibility that the health impacts of PM$_{2.5}$ from coal burning in China are greatly underestimated, considering the relatively higher toxicity of this source. Others like windblown soil and biomass combustion could be overestimated. Coal is the main source of energy in China, and controlling coal combustion might lead to far more health benefits than estimated in this study. Further studies should focus on refining the role of specific common PM sources in China.

The initial working assumption of our study was that the toxicity of PM from different sources was the same, from which we could estimate the overall excess mortality and compare the mortality attributed to PM$_{2.5}$ from different sources in each province. For the moment, we could not get accurate parameters or weights to evaluate the differences in health effects of PM$_{2.5}$ from different sources in China. We then performed sensitivity analyses, where we used the existing study results on the different toxicity and health effects of PM$_{2.5}$ and composition of energy generation technologies. However, the economic development, transportation and composition of energy generation technologies are quite different in each country, thus the PM$_{2.5}$ sources are different and estimated mortality ranges could be large. Overall, we find that future analyses need to consider the varying toxicities of particulate matter in China, which will require improved source and toxicity information.

There are limitations to our study. First, we assumed that PM$_{2.5}$ from different sources had the same composition and toxicity. Considering the existing research level and available information, we could not accurately analyze the composition-specific health effects and human toxicity of PM$_{2.5}$ on a national scale. Second, we used the PM$_{2.5}$ source apportionment data of provincial capitals to represent the mean levels for each province and calculated the nationwide source apportionment level by averaging the data from all 15 regions. But the source apportionment studies were mainly conducted in the capital cities of each province and were not available in all the provinces and municipalities of China. Finally, associations between air pollutants exposure and mortality are often modified by age, SES and gender. However, information on these factors could not be fully captured in this study because the current mortality data that we used are insufficient to provide such details to support the calculation. We studied the total population without considering age-, sex- or SES-specific mortality.

Conclusions

There were significant associations between the estimated PM$_{2.5}$ and the IHD, stroke, COPD, and lung cancer mortality in China in 2013. Coal burning is the primary source of atmospheric PM$_{2.5}$, and it contributes the greatest number of excess mortalities compared with other sources. It is likely that the estimates regarding health effects were conservatively estimated because coal combustion PM$_{2.5}$ has a greater health impact per unit than the average PM$_{2.5}$ mass. Controlling these sources would lead to a decrease in exposed population, and substantial health benefits could be achieved if more stringent ambient PM$_{2.5}$ standards or guidelines were achieved in China.

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