Assessment of black carbon exposure level and health economic loss in China

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Abstract

Based on the geographic information system (GIS) software and the application of the black carbon (BC) and fine particulate matter ($\text{PM}_{2.5}$) ratio method, this paper analyzed and calculated the national BC distribution from 2015 to 2017 and evaluated the national human exposure to BC. The results showed that from 2015 to 2017, 2/3 of the national land area and nearly half of the population were exposed to $1–3 \mu\text{g/m}^3$, and the area and population exposed to a concentration less than $2 \mu\text{g/m}^3$ increased yearly, while the area and population exposed to a concentration higher than $9 \mu\text{g/m}^3$ decreased yearly. The estimated economic loss showed that 77.3% of the targeted districts or counties claimed a loss per square kilometer of 50 million Chinese Yuan (CNY) or less from the perspective of annual changes, and districts and counties in Beijing-Tianjin-Hebei and Hunan with annual losses between 50 and 500 million CNY showed an increasing trend. The BC ratio (the proportion of BC economic loss to GDP) of Beijing-Tianjin-Hebei and Hunan also showed an increasing trend yearly.

Keywords
Black carbon (BC); Resident exposure level; Health economic loss; 11 climatic regions

Black carbon (BC) is the pyrolysis product of the incomplete combustion of carbonaceous materials (such as oil, coal, charcoal, trees, firewood, plastic waste, and animal manure). Human activities are a major cause of BC emissions (Bond et al. 2013; Kuhlbusch 1998). With the increase in the urbanization rate, the total BC emissions of various sectors were estimated to have increased from 1083.47 Gg in 2002 to 2550.83 Gg in 2012, after which they decreased to 2478.63 Gg in 2017 (Deng et al. 2021).

Increasing epidemiological and toxicological evidence shows that BC is more closely related to health than particulate matter (Beegum et al. 2009). The adverse health effects of BC on the respiratory system have been shown to be greater than those of fine particulate matter ($\text{PM}_{2.5}$) and respirable particulate matter ($\text{PM}_{10}$) (Peng et al. 2019; Isley et al. 2017; Hua et al. 2014). BC is a valuable additional air quality indicator to evaluate the health risks of ambient particles (Geng et al. 2013). Exposure to BC can affect the human cardiovascular, respiratory, and nervous systems (Cui et al. 2020; Chen et al. 2018; Lin et al. 2019; Ji and Hershey 2012; Zanobetti et al. 2013; Baumgartner et al. 2014; Colicino et al. 2014; Provost et al. 2016). It was pointed out that BC and $\text{PM}_{2.5}$ had a significant impact on the number of children hospitalized with asthma, and BC had a slightly greater impact on the number of children hospitalized with asthma than $\text{PM}_{2.5}$ (Jing et al. 2011). Wilker et al. (2013) conducted a
study on BC exposure and intima-media thickness of the common carotid artery in elderly men in Greater Boston, Massachusetts from 2004 to 2008, and the results confirmed the relationship between long-term exposure to a BC environment and atherosclerosis. The relative risk (RR) of BC exposure for mortality was the highest in the winter and the lowest in the summer, and compared with all-cause and cardiovascular mortality, respiratory mortality caused by BC had the highest risk (Zhao et al. 2021). Jacobson et al. (2014) conducted a group study on 234 Brazilian school children aged 6–15 years. The results showed that both PM$_{10}$ and BC reduced the peak expiratory flow (PEF) of children and had a stronger impact on children aged 6–8 years. Zhao et al. (2014) studied patients with metabolic syndrome in Beijing from February to July 2012 and found that high levels of BC exposure were significantly associated with adverse cardiovascular reactions.

BC occupies a large proportion of both PM$_{2.5}$ and PM$_{10}$ and is one of the important components of atmospheric particulate pollutants (Zhang et al. 2020; Liu et al. 2019). Jing et al. (2011) found that the concentrations of PM$_{2.5}$ and BC in the suburbs of Beijing exhibited obvious diurnal variations. Tao et al. (2008) and studies conducted by other authors found that the concentration of BC in Guangzhou was positively correlated with the concentration of PM$_{2.5}$, with a correlation coefficient of 0.707. Sun et al. (2016) found that the change rate of BC concentration in Chengdu was consistent with that of PM$_{2.5}$ and PM$_{10}$, and there was a significant positive correlation (at the 0.01 level) between the BC concentration and PM$_{2.5}$ and PM$_{10}$; the correlation coefficients were 0.657 and 0.638, respectively. Qiu et al. (2011) found that the concentration of BC in Guiyang City was positively correlated with the particulate matter concentration in the atmosphere, with a correlation coefficient of 0.84. Du et al. (2014) found that the correlation coefficient between BC and PM$_{2.5}$ in Yulin in the autumn and winter in 2011 was 0.92. From the above studies, it can be seen that the PM$_{2.5}$ and BC concentrations are positively correlated and the correlation coefficients are high in the above-mentioned cities.

In this study, using geographic information system (GIS), the authors quantitatively assessed the effects of BC on health in China and 11 major climatic regions from 2015 to 2017 using exposure–response functions that were based on countrywide BC and PM$_{2.5}$ data and high-precision population/gross domestic product (GDP). The findings of this study provide a scientific basis for the formulation of air pollution control measures from the perspective of protecting the health of residents.

Data and methods

Data

BC, PM$_{2.5}$, and meteorological factors

In order to reflect the overall environmental air quality of the country, the China Meteorological Administration began to carry out BC observations at some atmospheric composition stations nationwide in 2004. The instrument used was the BC aerosol observer AE-31, manufactured by the Machine Science Corporation of the United States of America. BC observations were carried out at 54 stations in China until 2017, providing basic data for the study of BC aerosols on a large scale. The hourly data of 47 stations with continuous BC observations from 2015 to 2017 were collected, and the annual average BC concentrations were calculated. In addition, the hourly BC data of Beijing from 2013 to 2016 were collected for calculation of the exposure–response relationship in Beijing.

In this study, the authors analyzed data that were collected by PM$_{2.5}$ monitoring stations from 1498 sites in 367 cities, which were released by the Chinese Ministry of Environmental Protection from 2015 to 2017, with even coverage of 31 provinces, municipalities, and autonomous regions (http://www.mee.gov.cn/). By averaging the collected hourly data, the annual average PM$_{2.5}$ data of 1498 stations in China from 2015 to 2017 can be obtained. In addition, daily meteorological observation data from 2013 to 2016, including air pressure, temperature, humidity, wind speed, and precipitation data, were collected for the calculation of the exposure–response relationship.

Disease data

The daily mortality data for Beijing from January 1, 2013 to December 31, 2016 were provided by the Chinese Center for Disease Control and Prevention. According to the 10th Revision of the International Classification of Disease (ICD-10), causes of deaths were coded and classified into deaths not attributed to non-accidental deaths (A00–R99).

GDP and population

In this paper, the GDP data, the GDP per capita data, population data, and total mortality data of 2372 districts and counties in China from 2015 to 2017 are used for the calculation of human health economic losses, all of which originated from statistical yearbooks published year by year by
provinces and cities (http://www.stats.gov.cn/tjsj/ndsj/). As can be seen in Fig. 1, China’s population density is high in the southeast and low in the northwest. For example, the central and western parts of China, Inner Mongolia, and the eastern part of Northeast China have a much lower population density, with 100 persons/km2 or less. In contrast, the eastern part of southwestern China, northern China, the Huang-Huai River Basin, eastern China, and the coastal areas of southern China are densely populated, with a density exceeding 500 persons/km2.

Methods

GAM model and exposure–response relationship

In this study, a semi-parametric generalized additive model (GAM) (Hastie and Tibshirani, 1990) was used. The specific model is as follows:

$$\log[E(Y_k)] = \alpha + DOW + \beta \times X_k + s(time, df) + s(Z_k, df)$$

(1)

where $E(Y_k)$ is the expected value of deaths on day $k$; $\beta$ is the regression coefficient, known as the exposure–response relationship coefficient; $X_k$ is the concentration of pollutants; $S$ is a nonparametric smoothing spline function, excluding long-term effects, seasonality, calendar effect, temperature, relative humidity, air pressure, wind speed, and daily precipitation, and $df$ is the degree of freedom. $DOW$ is a virtual function that represents the “day of the week effect” of the calendar time to remove the temporal trend from the data; $time$ is the calendar time to remove the daily number of deaths to the daily average concentration of BC, and the exposure response coefficient $\beta$ is obtained; thus, the exposure–response relationship between BC and the daily number of deaths can be established.

Calculation of excess deaths

Because the occurrence of disease or death is a low-probability event relative to the population and conforms to the Poisson’s law in statistics, the exposure–response relationship function can be expressed as follows (Hou et al. 2016; Zhang et al. 2007):

$$N = P \times (E - E_0) = P \times E \times \left(1 - \frac{1}{\exp[\beta \times (C - C_0)]}\right)$$

(2)

where $N$ is the number of cases of illnesses or excess death caused by a pollutant/s (person); $P$ is the exposed population (person); $E$ is the actual morbidity or mortality (%); $E_0$ is the morbidity or mortality at a threshold concentration level (%); $\beta$ is the exposure–response coefficient; $C$ is the ambient concentration of BC ($\mu g/m^3$); $C_0$ is the threshold level at which no health effects are assumed. The threshold concentration was selected as 0 in this article.

According to the total mortality data combined with the corresponding exposure–response coefficient $\beta$ and BC concentration values, the excess deaths attributed to the respiratory system and circulatory system associated with BC can be calculated using Formula 2.

Economic loss assessment method

The adjusted human capital (AHC) approach represents an important departure from the traditional human capital approach, and it can be viewed as a social statement of the value of avoiding premature mortality (WB and SEPA 2007). In this paper, the AHC approach is used to evaluate the economic losses caused by excess deaths associated with BC.

$$HC_{city} = GDP_{city} \times \sum_{i=1}^{t} \frac{(1 + \alpha)^i}{(1 + r)^i}$$

(3)

where $GDP_{city}$ is the annual per capita GDP, $\alpha$ is the growth rate of per capita GDP, $r$ is the discount rate, and $t$ is the life lost per capita. In this paper, $\alpha = 10\%$, $r = 8\%$, and $t = 18$. The per capita GDP data year by year were obtained from the statistical yearbook of each province.

In addition to the AHC method, the value of statistical life (VSL) method has become the standard approach in
high-income countries for valuing mortality risks associated with pollution (WB and IHME 2016). The VSL in China can be estimated as follows:

$$VSL_{c,n} = VSL_{OECD} \cdot \left( \frac{Y_{c,n}}{Y_{OECD}} \right)^e \quad (4)$$

where \(VSL_{c,n}\) is the VSL for country \(c\) in year \(n\); \(VSL_{OECD}\) is the average base VSL estimated from the sample of willingness to pay (WTP) studies conducted in the Organization for Economic Co-operation and Development (OECD) countries; \(Y_{c,n}\) is the GDP per capita for country \(c\) in year \(n\); \(Y_{OECD}\) is the average GDP per capita for the base sample of OECD countries; and \(e\) is the income elasticity of the VSL. For this study, a central value of 1.2 was assumed, with a range from 1.0 to 1.4 for sensitivity analysis. Due to the wide application of the AHC method in China (WB and SEPA 2007), this article mainly used this method to assess the economic loss of human health related to BC. The results of the VSL method are mainly used for discussion.

**Results**

**The spatial variation of the BC concentration based on the ratio method**

The BC concentration of several stations across the whole country was estimated by the ratio method, and the spatial distribution of the BC concentration from 2015 to 2017 was calculated based on the GIS platform. Figure 3 shows an average BC concentration-interpolated graph for 2015–2017 calculated by the ratio method.

As can be seen in Fig. 3, from 2015 to 2017, the annual average BC concentration in China was higher than 7 \(\mu g/m^3\) in eastern Sichuan, southern Shaanxi, southern Shanxi, northwestern and southeastern Henan, southern Beijing, Tianjin and Hebei, and the south of Northeast China. The low BC concentration was mainly distributed in Northwest China, Southwest China, Inner Mongolia, and Northern Jiangxi, and the average exposure concentration was less than 2 \(\mu g/m^3\). The Multi-resolution Emission Inventory for China (MEIC, Source: http://www.meicmodel.org/index.html) is a set of anthropogenic emission inventory models of atmospheric pollutants and greenhouse gases in China based on a cloud computing platform. The products cover 10 major atmospheric pollutants, greenhouse gases, and more than 700 anthropogenic emission sources.

**Assessment of the BC exposure level in China**

**The general situation of the BC exposure level in China**

The spatial distribution characteristics of the population and BC concentration in China differ, so only the BC concentration in China is not sufficient to reflect the exposure level.
of the population. According to the population-weighted atmospheric pollutant calculation (Formula 5), the BC population-weighted exposure concentration in each region was obtained.

$$PWEL = \frac{\sum (P_i \times C_i)}{\sum (P_i)}.$$  

(5)

where $i$ is the number of analysis areas, $P_i$ is the population in the analysis area, and $C_i$ is the concentration of BC in the analysis area.

Using the GIS software, this paper analyzed the national BC concentration and population density from 2015 to 2017 and calculated the exposure area of BC for different concentration ranges (Table 1) and among different population statuses (Table 2). As can be seen in Table 1, from 2015 to 2017, the sections of China exposed to areas with a concentration less than 2 $\mu g/m^3$ increased yearly, while the area exposed to concentrations between 2 and 5 $\mu g/m^3$ decreased yearly, indicating that more areas of China were exposed to lower concentrations of BC in recent years. In addition, from 2015 to 2017, 3.02%, 1.15%, and 1.22% of the areas in China were exposed to BC concentrations higher than 7 $\mu g/m^3$, while the areas exposed to BC concentrations between 5 and 7 $\mu g/m^3$ did not change much, i.e., about 4% of the area. It can be seen from the 3-year average that the land area exposed to the 1–2 $\mu g/m^3$ concentration range was the largest, about 43.21%, followed by 32.01% of the land area exposed to the 2–3 $\mu g/m^3$ concentration range, while the land area exposed to concentrations higher than 9 $\mu g/m^3$ was only 0.32%.

As can be seen from the exposure of the population, from 2015 to 2017, the ratio of the Chinese population exposed to BC concentrations higher than 9 $\mu g/m^3$ decreased year by year from 4.78% in 2015 to 0.74% in 2017, indicating that the proportion of the population exposed to BC concentrations in high-value areas decreased yearly. The ratio of the population exposed to concentrations less than 3 $\mu g/m^3$ increased yearly, from 43.45% in 2015 to 61.84% in 2017, indicating that more and more people in China were exposed to relatively low BC concentrations. It can be seen from the 3-year average that most of the population was exposed to the 2–3 $\mu g/m^3$ concentration range, accounting for 30.10% of the national population;
8.35% of the population was exposed to concentrations less than 1 μg/m$^3$, while 1.16% of the total population was exposed to BC concentrations of at least 9 μg/m$^3$.

**Assessment of the BC population exposure level in the 11 climatic regions of China**

China has a vast territory with a unique geographical location. The complex topography and various elements of the atmospheric circulation jointly affect the climate, making the climate types and natural landscape extremely diverse. According to the meteorological and geographical zoning map, China is divided into 11 climatic regions (Fig. 4). By calculating the population-weighted BC concentration of each region from 2015 to 2017, it can be concluded that the high-value areas of the population-weighted BC concentration in China were in the southwest and North China (Table 3). The average population-weighted BC concentration in these two regions was about 4 μg/m$^3$, followed by the northwest, northeast, and Huanghuai regions; the average population-weighted BC concentration in these three regions was about 3 μg/m$^3$. The lowest population-weighted BC concentration in Tibet was about 2 μg/m$^3$. In terms of annual change, the population-weighted BC concentration in Northeast, South China, Huanghuai, Jianghuai, Northwest, and Southwest China decreased yearly. In Inner Mongolia, it increased slightly year by year but remained at a relatively low level.

| No | Climatic region       | 2015   | 2016   | 2017   | Three-year average |
|----|-----------------------|--------|--------|--------|--------------------|
| 1  | Northeast China       | 3.37   | 3.11   | 2.66   | 3.05               |
| 2  | North China           | 5.95   | 4.77   | 5.46   | 5.39               |
| 3  | South China           | 3.00   | 2.63   | 2.12   | 2.58               |
| 4  | Huang Huai area       | 4.09   | 3.08   | 2.76   | 3.31               |
| 5  | Jianghan area         | 2.74   | 2.38   | 2.47   | 2.53               |
| 6  | Jianghuai Region      | 3.38   | 2.81   | 2.51   | 2.90               |
| 7  | Jiangnan area         | 2.68   | 2.08   | 2.25   | 2.34               |
| 8  | Inner Mongolia        | 2.05   | 2.04   | 2.10   | 2.06               |
| 9  | Northwest China       | 3.61   | 3.24   | 2.91   | 3.25               |
| 10 | Tibet area            | 1.93   | 2.48   | 1.25   | 1.88               |
| 11 | Southwest China       | 4.38   | 4.10   | 3.51   | 4.00               |

The difference between the population-weighted BC concentration in each climatic region and the regional spatial average BC concentration, as well as the ratio of the BC concentration to the regional spatial average BC concentration, can reflect the population exposure to BC in a region. Table 4 shows that the ratio in the northwest, southwest, and south of the Yangtze River was the highest, indicating that more people were exposed to high BC concentration in this region, while the ratio was the lowest in Huanghuai area, indicating that more people were exposed to a low BC concentration in this region. On the basis of the annual change, the ratios of South China, Jianghan, and Inner Mongolia decreased yearly, which indicates that more and more people in these areas were exposed to low BC concentrations. However, the ratios of the North, Northwest, and Southwest increased yearly, which indicates that more and more people were exposed to high BC concentrations.

**BC health economic loss assessment in China**

**BC exposure–response relationship**

The exposure–response relationship coefficient of the representative city of Beijing was calculated by using the GAM model and was used to calculate the economic loss due to BC exposure. The percentage excess risk (ER (%)) is a percentage of the change in death due to a 1 μg/m$^3$ change in the BC concentration. The mortality risks were greatest on the exposure day (lag1) (Table 5).

**Economic loss associated with human exposure to BC in China from 2015 to 2017**

One can calculate the number of excess deaths associated with BC in 2372 districts and counties from 2015 to 2017...
One can also calculate the unit economic value of each district and county (Formula 3). Finally, the health-related economic loss caused by BC in 2372 districts and counties in China can be obtained (Fig. 5). This figure shows that 77.3% of the targeted districts or counties claimed a loss per square kilometer of 50 million CNY or less, and the regions with higher annual losses were mainly located in Wuhan, Chengdu, Shenyang, Changchun, Xi’an, Hangzhou, and Shanghai, with an annual loss value that exceeded 200 million CNY.

As an estimate, from 2015 to 2017, China’s BC ratio showed a decreasing trend yearly. China’s BC-related health economic loss in 2017 was the lowest, about 116.795 (77.863, 155.726) billion CNY, accounting for 1.70‰ (1.13‰, 2.26‰) of the GDP. In 2016, the loss cost was 98.887 (65.925, 131.850) billion CNY, accounting for 1.33‰ (0.89‰, 1.77‰) of the GDP.

**Economic loss of human health in the 11 major climatic regions of China from 2015 to 2017**

Calculation of the human health economic loss value and the BC ratio of the 11 climatic regions in China from 2015 to 2017 (Table 7) showed that North China, Jiangnan, and Southwest China had the highest annual loss, while Inner Mongolia and Tibet had the lowest annual loss. The BC ratio in North China, Huanghui, and Southwest China was relatively high, fluctuating between 1 and 2‰, while the BC ratio in Inner Mongolia and Tibet area was relatively low, around 0.6‰. The annual loss values of Northeast, South China, Huanghui, Jianghuai, Northwest China, Tibet, and Southwest China decreased yearly, while those of North China, Jianghan, and Southwest China increased yearly. The BC ratio decreased yearly in Northeast China, South China, Huanghui, Jianghuai, Northwest China, Tibet, and Southwest China.

**Discussion and conclusions**

In this paper, the BC concentration in China was calculated using the concentration ratio between BC and PM$_{2.5}$ in nearby stations. The population exposure to BC in the 11 climatic regions in China was assessed by superimposing population data. The results showed that 2/3 of China’s land area and nearly half of the population were exposed to BC concentrations of 1–3 μg/m$^3$. The area exposed to BC concentrations less than 2 μg/m$^3$ increased yearly, while the area exposed to BC concentrations less than 2–5 μg/m$^3$ decreased yearly, which indicates that more areas in China were exposed to low concentrations of BC in recent years.
According to the analysis of the 11 climatic regions, the weighted concentration of the BC population in Southwest and North China was the highest, while that in Tibet and Inner Mongolia was the lowest. Through overlapping of the population analysis, the ratio of the population exposure to the regional concentration in Northwest and Southwest China was the highest, showing an increasing trend yearly, indicating that more and more people were exposed to high BC concentrations in these areas.

Calculation of the economic loss value of human health caused by excess deaths associated with BC indicated that the annual loss value of about 77.3% districts and counties in China was less than 50 million CNY. From the perspective of yearly changes, the economic losses in most parts of China decreased yearly.

In this paper, the assessment results of the BC exposure level were uncertain due to the limitations of the data and basic research and other objective factors. Specifically, (1) because BC data were not available from observation stations in China, the national BC concentration was calculated based on the concentration ratio between BC and PM$_{2.5}$ from stations in close proximity, and the exposure...
level was evaluated based on this method, which will result in uncertainty of the analysis results. (2) The distribution of the population in China is unbalanced between urban and rural areas and between urban and suburban areas. In this paper, the population of most cities in China was assumed to be evenly distributed, which will also lead to the deviation of the evaluation results. (3) In this paper, only the β value of Beijing was used to calculate the economic loss value of human health caused by excess deaths associated with BC in China, which will cause uncertainty in the evaluation results. Based on the assumption that the exposure–response coefficients are the same in economically developed areas, the densely populated areas and areas with a low population density may result in higher monetary losses. Moreover, the economic loss estimation only considered the economic loss caused by excess death, which will also result in a small value.

The economic assessment methods employed may also affect the outcome of the calculation. The VSL method is an alternative that is widely used in high-income countries for evaluating mortality risks associated with pollution. The VSL represents the sum of many individuals’ WTP for marginal reductions in their mortality risks (WB and IHME 2016). From 2015 to 2017, the annual health-related economic losses from BC, when monetized using the AHC approach (116.795 (77.863, 155.726), 98.887 (65.925, 131.850), and 95.956 (63.970, 127.941) billion CNY), were approximately 1.70‰ (1.13‰, 2.26‰), 1.33‰ (0.89‰, 1.77‰), and 1.16‰ (0.77‰, 1.55‰) of the GDP; when valued using the VSL method (355.003 (278.926, 461.033), 337.447 (269.677, 431.065), and 368.130 (299.488, 461.938) billion CNY), the values reached 5.15‰ (4.05‰, 6.69‰), 4.54‰ (3.62‰, 5.79‰), and 4.45‰ (3.62‰, 5.59‰) of the GDP. The economic loss that was estimated using the VSL method was higher than that estimated using the AHC method. This is because the VSL method reflects all the losses of individual welfare caused by death or diseases, including the time cost, income loss, and medical expenses, whereas the AHC method only considers the loss of an individual’s contribution to the productivity of society (Huang et al. 2012).

Despite the above-mentioned uncertainties in this article, the evaluation results can still reflect the current spatial distribution of BC in China macroscopically and provide a scientific basis for economic development and environmental protection in China.

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**Data Availability** Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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