Assessment of Black Carbon Exposure Level And Health Economic Loss In China

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Abstract

Based on GIS (Geographic Information System) software, applied the black carbon (BC)and fine particulate matter ($PM_{2.5}$)concentration ratio method, this paper analyzed and calculated the national BC concentration distribution from 2015 to 2017, and evaluated the national human exposure of BC. The results show that from 2015 to 2017, 2/3 of the national land and nearly half of the population were exposed to the concentration range of 1-3 ug/m^3, and the area and population exposed to the concentration below 2 ug/m^3 increased year by year, while the area and population exposed to the concentration above 9 ug/m^3 decreased year by year. The estimated results of economic loss show that 77.3% of the targeted districts or counties claimed a loss per square kilometer of 50 million RMB or less From the perspective of annual changes, districts and counties in Beijing-Tianjin-Hebei and Hunan with annual losses between 50 and 500 million RMB show an increasing trend. Meanwhile, the BC ratio (the proportion of black carbon economic loss to GDP) of Beijing-Tianjin-Hebei and Hunan also shows an increasing trend year by year.

Introduction

Black carbon (BC) is the pyrolysis product of incomplete combustion of carbonaceous materials (mainly oil, coal, charcoal, trees, firewood, plastic waste, animal manure, etc.). Human actions are the main causes of BC in the atmosphere (Bond et al. 2013;Kuhlbusch 1998). With the rise in the urbanization rate, the total BC emissions of various sectors were estimated to have increased from 1083.47 in 2002 to 2550.83 Gg in 2012. They were then reduced to 2478.63 Gg in 2017 (Deng et al. 2021).

More and more epidemiological and toxicological evidences show 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 $PM_{2.5}$ and 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 black carbon can affect 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 black carbon and $PM_{2.5}$ had a significant impact on the number of children with asthma hospitalized, and black carbon had a slightly higher impact on the number of children with asthma hospitalized than $PM_{2.5}$(Jing et al. 2011). Wilker et al. conducted a study on black carbon 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 black carbon environment and atherosclerosis (Wilker et al. 2013). The relative risk (RR) of BC exposure on mortality showed the highest in winter and the lowest in summer, and compared with all-cause and cardiovascular mortality, respiratory mortality caused by the BC showed the highest risk(Zhao et al. 2021). Jacobson et al conducted a group study on 234 Brazilian school children aged 6 to 15 years. The results showed that PM_{10} and BC could both reduce the peak expiratory flow (PEF) of children, and had a stronger impact on children aged 6 to 8 years (Jacobson et al. 2014). Zhao et al studied metabolic syndrome patients in Beijing from February to July 2012, and found that high levels of black carbon exposure were significantly associated with adverse cardiovascular reactions(Zhao et al. 2014).

BC not only has adverse effects on human health, but also is the second most important factor affecting global warming after carbon dioxide (Jacobson 2001). BC occupies a large proportion in 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 found that the concentrations of $PM_{2.5}$ and BC in the suburbs of Beijing showed obvious diurnal variations(Jing et al. 2011).Tao Jun and other studies found that the concentration of black carbon in Guangzhou was positively correlated with the concentration of $PM_{2.5}$, with a correlation coefficient of 0.707(Tao et al. 2008).Sun et al 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 between BC concentration and $PM_{2.5}$ and PM_{10} at the level of 0.01. The correlation coefficients were 0.657 and 0.638, respectively (Sun et al. 2016). Qiu et al found that the concentration of black carbon in Guiyang City was positively correlated with PM concentration in the atmosphere, with a correlation coefficient of 0.84 (Qiu et al. 2011). Du et al found that the correlation coefficient between BC and $PM_{2.5}$ in Yulin in autumn and winter of 2011 was 0.92. From the above studies, $PM_{2.5}$ and BC concentrations are positively correlated, and the correlation coefficients are different at different stations, but the correlation coefficients are higher (Du et al. 2014) .

In this study, using GIS software, 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/GDP data. The findings of the study provide a scientific basis for the formulation of air pollution control measures from the perspective of protecting the health of residents.

Data And Method

2.1. Data

2.1.1. Black carbon data, $PM_{2.5}$ data and meteorological data

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 black carbon aerosol observer AE-31 of Machie Science Corporation of the United States. BC observations have been carried out at 54 stations in China up to 2017, providing basic data for the study of black carbon aerosols on a large scale. The hourly data of 47 stations with continuous black carbon observations from 2015 to 2017 were collected and the annual average BC concentration data of 47 stations were calculated.

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 2013 to 2017, covering 31 provinces, municipalities, and autonomous regions evenly (http://www.mee.gov.cn/). By averaging the collected hourly data, we can get the annual average $PM_{2.5}$ data of 1498 stations in China from 2015 to 2017.In addition, daily meteorological observation data from 2013 to 2016, including air pressure, temperature, humidity, wind speed and precipitation data are collected for calculation of exposure-response relationship.

2.1.2. Disease Data

Daily mortality data from January 1, 2006, 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 from total non-accidental death (A00–R99).

2.1.3. GDP data, population data and total mortality data

In this paper, the GDP data, GDP per capita data, population data and total mortality data of 2372 districts and counties in the country from 2015 to 2017 are used in the calculation of human health economic losses, all of which come from statistical yearbooks published year by year by provinces and cities (http://www.stats.gov.cn/tjsj/ndsj/). As can be seen from Fig. 1, China's population density is high in the southeast and low in the northwest. For example, the central and west part of China, inner Mongolia and the eastern part of northeast China have a much lower population density, with 100 person/km^2 or less. In contrast, the eastern part of southwest China, north China, the Huang-Huai Rivers Basin, eastern China, and the coastal areas of southern China are densely populated, with a density exceeding 500 person/km^2.

2.2. Method

2.2.1. GAM model and exposure response relationship

In this study, a semi parametric generalized additive model (GAM) is used (Hastie et al. 1990). The specific model is as follows:

$$Log[E(Y_k)] = \alpha + DOW + \beta \times X_k + s(time,df)+s(Z_k,df) \quad (1)$$

Among them, $E(Y_k)$ is the expected values of deaths on day k; β is the regression coefficient, known as the exposure response relationship coefficient; X_k is the concentration of pollutants;S (smoothing spline function) is a nonparametric spline smoothing function, excluding long trend effect, seasonality, calendar effect, temperature, relative humidity, air pressure, wind speed, daily precipitation, df is the degree of freedom. Considering the "day of the week effect" of the number of residents admitted to hospital in a week, the virtual function Dow; *time* is the calendar time to remove the temporal trend from the data; Z_k is temperature, relative humidity, air pressure, wind speed, daily precipitation. The model is used to fit the daily number of deaths with the daily average concentration of BC, and the exposure response coefficient β is obtained, thus the exposure response relationship between black carbon and the daily number of deaths established.

2.2.2. Calculation of excess deaths

Because the occurrence of disease or death is a small probability event relative to the population and conforms to the Poisson's law in statistics, the exposure-response relationship function can be summarized by Formula 2 (Hou et al. 2016;Zhang et al. 2007):

$$N = P \times (E - E_0) = P \times E \times (1 - 1/\exp[\beta \times (C - C_0)]) \quad (2)$$

In formula (2): N - the case number of illness or excess death incurred by some pollutants (person); P- the exposed population(person); E - the actual morbidity or mortality (%); $E0$- the morbidity or mortality at threshold concentration level (%); β-exposure-response coefficient; C - the ambient concentration of Black carbon (ug/m^3); C_0- is a threshold level at which no health effects are yet assumed. The threshold concentration is selected as 0 in this article.
According to the total mortality data combined with the corresponding exposure-response coefficient β and BC concentration values, the excess deaths of respiratory system and circulatory system associated with BC can be calculated according to formula 2.

2.2.3. 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.

$$HC_{city} = GDP_{city} \cdot \sum_{i=1}^{t} \frac{(1+\alpha)^i}{(1+r)^i} \quad (3)$$

In formula (3), GDP_{city} is the annual per capita GDP, α is the growth rate of per capita GDP, r is the discount rate, and t is the life lost per capita. In this paper, α=10%,r=8%, t =18 is assumed. The per capita GDP data year by year can be obtained from the statistical yearbook of each province.

In addition to 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 value of VSL in China can be estimated by formula 4.

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

In formula (4), $VSL_{c,n}$ is the VSL for country c in year n; VSL_{OECD} is the average base VSL estimate from the sample of WTP studies in Organization for Economic Co-operation and Development (OECD) countries; $Y_{c,n}$ is 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 is assumed, with a range from 1.0 to 1.4 for sensitivity analysis. Due to the wide application of AHC method in China (WB and SEPA 2007), this article mainly uses the AHC method to assess the economic loss of human health related to BC. The results of VSL method are mainly used for discussion.

2.2.4. Ratio method

From 2015 to 2107, the number of $PM_{2.5}$ stations with continuous observation data (1498) in China is much more than that of BC stations (47), and there is a positive correlation between BC and $PM_{2.5}$ concentration. Therefore, the BC concentration is inversely calculated by using the ratio of BC to $PM_{2.5}$ combine with the monitoring concentration of $PM_{2.5}$ in order to obtain a reasonable spatial distribution of BC in the whole country.

Using the annual average value of 880 nm wavelength black carbon (BC) data, the distance between BC site and surrounding $PM_{2.5}$ site is calculated (Fig. 2). The nearest $PM_{2.5}$ site with BC site is found. The ratio of BC to $PM_{2.5}$ concentration of each BC site in 2015–2017 is calculated. The BC concentration of each $PM_{2.5}$ site in 2015–2017 is also deduced according to the Ratio value of the nearest point, and thus the national BC concentration distribution is obtained.

Results

3.1. Characteristics of black carbon concentration and inversely calculated spatial variation characteristics of BC concentration

3.1.1. Annual variation characteristics of BC concentration

The annual average BC concentration data of 23 stations with continuous BC observation data in China from 2006 to 2017 were calculated, and the inter-annual variation characteristics of BC were analyzed as well (Fig. 3). As can be seen, the annual average concentration of BC in China has been fluctuating and declining year by year since 2006. It dropped from 5.64 ug/m^3 in 2006 to 2.64 ug/m^3 in 2017, a drop of more than 50%.

3.1.2. The spatial variation of BC concentration based on ratio method

The BC concentration of more stations in the whole country was estimated by the Ratio Method, and the spatial distribution of BC concentration from 2015 to 2017 was calculated based on GIS platform. Figure 4 is an average BC concentration interpolated graph of 2015–2017 calculated by the Ratio Method .

As can be seen from Fig. 4, in 2015–2017, the annual average BC concentration in China is higher than 7 ug/m^3 in eastern Sichuan, southern Shaanxi, southern Shanxi, northwest and southeastern Henan, southern Beijing, Tianjin and Hebei, and the south of Northeast China. The low BC concentration is mainly distributed in Northwest China, Southwest China, Inner Mongolia, Northern Jiangxi, and the average exposure concentration is below 2 ug/m^3.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 cloud computing platform. The products cover 10 major atmospheric pollutants, greenhouse gases and more than 700 anthropogenic emission sources. Drawing the MEIC2016 BC emission classification distribution map (Fig. 5), we can see that the BC high-emission areas in China are in the south-central part of Northeast China, the south of North China, the west of Huanghuai, the east of Southwest China, the Yangtze River Delta, and the Pearl River Delta. The graded distribution of the average BC concentration in China from 2015 to 2017 calculated by the ratio method shows that the high value areas are in the eastern part of Southwest China, the western part of Huanghuai River, the central and south part of Hebei Province and the central and southern part of northeast China. The BC concentration distribution is basically consistent with distribution of MEIC black carbon emission.

3.2 Assessment of BC exposure level in China

3.2.1. The general situation of exposure level of BC in China

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

$$PWEL = \Sigma(P_i \times C_i)/\Sigma(P_i) \quad (5)$$

In formula (5), i is the number of analysis areas; P_i is the number of populations in the analysis area; C_i is the concentration of BC in the analysis area.

Using GIS software, this paper analyzes the national BC concentration and population density from 2015 to 2017, and calculates the exposure area of BC in different concentration ranges (Table 1) and population status (Table 2).As can be seen from Table 1, from 2015 to 2017, the area of China exposed to areas that below 2 ug/m^3 increased year by year, while the area exposed between 2–5 ug/m^3 decreased year by year, indicating that more areas of China exposed to lower concentration of BC in recent years. In addition, from 2015 to 2017, 3.02%, 1.15% and 1.22% of the areas exposed to BC above 7 ug/m^3 in China respectively, while the areas exposed to BC between 5–7 ug/m^3 did not change much, all of which were about 4%.It can be seen from the three-year average that the land area exposed to 1–2 ug/m^3 concentration range is the largest, about 43.21%, followed by 32.01% of the land area exposed to 2–3 ug/m^3 concentration range, while the land area exposed to more than 9 ug/m^3 is only 0.32%.

Table 1. Area Ratio of Exposure to Different BC Concentrations in China from 2015 to 2017

BC concentration range	2015	2016	2017	3 years average
BC<1	2.26%	6.00%	14.41%	6.45%
1<BC<2	33.15%	34.59%	43.73%	43.21%
2<BC<3	35.79%	35.26%	24.64%	32.01%
3<BC<4	16.64%	13.64%	8.40%	9.87%
4<BC<5	5.32%	4.87%	2.97%	2.78%
5<BC<6	1.99%	2.93%	2.86%	2.61%
6<BC<7	1.84%	1.56%	1.77%	1.66%
7<BC<8	0.99%	0.55%	0.86%	0.80%
8<BC<9	0.81%	0.34%	0.26%	0.29%
9<BC	1.22%	0.26%	0.11%	0.32%

As can be seen from the exposure of the population, from 2015 to 2017 the ratio of population exposed to BC concentration above 9 ug/m^3 in China decreased year by year from 4.78% in 2015 to 0.74% in 2017. Indicating that the proportion of population exposed to BC concentration in high-value areas decreased year by year. The ratio of population exposed to concentrations below 3 ug/m^3 increased year by year, from 43.45% in 2015 to 61.84% in 2017. Indicating that more and more people in China are exposed to relatively low BC concentration. It can be seen from three years average that the population exposed to 2–3 ug/m^3 concentration range is the largest, accounting for 30.10% of the national population, followed by the population exposed to 1–2 ug/m^3 concentration range, accounting for 19.36% of the national population, 8.35% of the population less than 1 ug/m^3, while the population exposed to 9 ug/m^3 or more accounts for 1.16% of the total population.

Table 2. Population ratios of exposed to different BC concentrations in China from 2015 to 2017

BC concentration range	2015	2016	2017	3 years average
BC<1	4.87%	9.30%	8.44%	8.35%
1<BC<2	17.26%	18.53%	26.31%	19.36%
2<BC<3	21.32%	29.60%	27.09%	30.10%
3<BC<4	23.25%	13.11%	12.91%	16.45%
4<BC<5	12.24%	9.74%	6.31%	5.95%
5<BC<6	5.49%	11.24%	7.52%	8.67%
6<BC<7	4.65%	5.14%	5.30%	6.81%
7<BC<8	3.32%	1.40%	4.05%	2.32%
8<BC<9	2.82%	0.90%	1.32%	0.83%
9<BC	4.78%	1.04%	0.74%	1.16%

3.2.2. Assessment of BC Population Exposure Level in 11 Climate Regions of China

China has a vast territory, special geographical location. The complex topography and various elements of the atmosphere circulation affect climate together. It makes climate types and natural landscape extremely diverse. According to meteorological and geographical zoning map, China is divided into 11 climatic regions (Fig. 6). We can get conclusion that the high value area of BC population weighted concentration in China is in the southwest and North China, by calculating the BC population weighted concentration of each region from 2015 to 2017 (Table 3),. The average concentration of BC population weighted concentration in these two regions is about 4 ug/m^3, followed by the northwest, Northeast and Huanghuai regions, the average concentration of BC population weighted concentration in these three regions is about 3 ug/m^3. The lowest concentration of BC population weighted concentration in Tibet is about 2 ug/m^3. In terms of annual change, BC population weighted concentration in Northeast, South China, Huanghuai, Jianghuai, Northwest and Southwest China decreased year by year. In Inner Mongolia, it increased slightly year by year, but remained a relatively low level.

Table 3. Weighted BC Population Concentrations in 11 Climate Regions of China from 2015 to 2017

11Climate region	2015	2016	2017	3 years average
1Northeast China	3.37	3.11	2.66	3.05
2North China	5.95	4.77	5.46	5.39
3South China	3.00	2.63	2.12	2.58
4HuangHuai area	4.09	3.08	2.76	3.31
5Jianghan area	2.74	2.38	2.47	2.53
6Jianghuai Region	3.38	2.81	2.51	2.90
7Jiangnan area	2.68	2.08	2.25	2.34
8Inner Mongolia	2.05	2.04	2.10	2.06
9Northwest China	3.61	3.24	2.91	3.25
10Tibet area	1.93	2.48	1.25	1.88
11Southwest China	4.38	4.10	3.51	4.00

The difference between the weighted concentration of BC population in each climatic region and the regional spatial average BC concentration, and the ratio of BC concentration to the regional spatial average BC concentration, can reflect the population exposure of BC in this region. Table 4 shows that the ratio of northwest, southwest and south of the Yangtze River is the highest, indicating that more people are exposed to the high concentration of BC in this region, while the ratio of Huanghuai area is the lowest, indicating that more people are exposed to the low concentration of BC in this region. On the basis of the annual change, the ratios of South China, Jianghan and Inner Mongolia are decreasing year by year, which indicates that more and more people in these areas are exposed to low BC concentration. Meanwhile, the ratios of North, Northwest and Southwest are increasing year by year, which indicates that more and more people are exposed to high BC concentration.

Table 4. Comparative analysis of BC population weighted concentration and spatial average concentration in 11 climatic regions of China from 2015 to 2017

11Climate region	2015	2016	2017	3-year average
1Northeast China	-3.49%	-6.08%	-5.82%	-5.07%
2North China	1.66%	4.19%	7.57%	4.34%
3South China	0.93%	-0.03%	-4.64%	-0.98%
4Huang Huai area	-11.19%	-10.18%	-11.41%	-10.94%
5Jianghan area	2.47%	2.04%	0.58%	1.71%
6Jianghuai Region	0.06%	-1.86%	-0.35%	-0.68%
7Jiangnan area	13.36%	13.68%	11.90%	12.98%
8Inner Mongolia	2.27%	2.11%	-3.30%	0.26%
9Northwest China	11.77%	10.97%	17.59%	13.17%
10Tibet area	4.40%	4.84%	0.75%	3.76%
11Southwest China	11.11%	13.21%	15.43%	13.06%

3.3 Black carbon health economic loss assessment in China

3.3.1. Black carbon exposure response relationship

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

Table 5. Exposure-response coefficient and estimated excess risk of excess death in representative city of Beijing (95%CI)

city	lag day	β(95%CI)	ER (%) (95% CI)
Beijing	lag1	0.003 (0.002~0.004)	0.26*** (0.17,0.36)

Footnote 1: *** $p < 0.001$

3.3.2. Economic loss of human exposure to BC in China from 2015 to 2017

One can calculate the number of excess deaths associated with BC in 2,372 districts and counties from 2015 to 2017 (formula 2). One can also calculate the unit economic value of each district and county (formula 3). And finally, the health-related economic loss from BC in 2,372 districts and counties in China can be obtained (Fig. 7A).This figure shows that 77.3% of the targeted districts or counties claimed a loss per square kilometer of 50 million RMB or less, and the regions with higher annual losses are mainly located in Wuhan, Chengdu, Shenyang, Changchun, Xi'an, Hangzhou, and Shanghai, with an annual loss value of more than 200 million RMB.

One can obtain the distribution of China's BC-related health economic loss as a proportion of GDP (BC ratio) by dividing the BC-related health economic losses registered in 2,372 districts and counties by their annual GDPs (Fig. 7B). From 2015 to 2017, the BC ratio of most districts and counties in China was lower than 1‰, mainly located in northwest, southwest and northeast China. Districts and counties with BC ratio greater than 3‰ mainly located in the eastern part of northeast China, the eastern part of Sichuan and parts of Henan and North China. The number of districts and counties with BC ratio lower than 1‰ increases year by year, and the BC ratio of Yunnan, Guangdong, Guangxi, Fujian, Anhui and Zhejiang decreases year by year, while the BC ratio of Beijing-Tianjin-Hebei and Hunan increases year by year (table 6).

As an estimate, from 2015 to 2017, China's BC ratio showed a decreasing trend year by year. The China's BC-related health economic loss in 2017 was the lowest, about 95.956(63.970, 127.941) billion RMB, accounting for 1.16‰ (0.77‰, 1.55‰) of the GDP. The loss cost in 2015 was the highest, 116.795(77.863, 155.726) billion RMB, accounting for 1.70‰ (1.13‰, 2.26‰) of the GDP. In 2016, the loss cost was 98.887(65.925, 131.850) billion RMB, accounting for 1.33‰ (0.89‰, 1.77‰) of the GDP.

Table 6. Distribution of economic losses associated with BC at different levels in China from 2015 to 2017

	2015	2016	2017
<1‰	44.35%	52.87%	57.93%
1‰-2‰	35.62%	30.61%	25.42%
2‰-3‰	11.64%	13.45%	13.95%
3‰-4‰	5.23%	2.53%	2.49%
4‰-5‰	2.19%	0.46%	0.21%
>5‰	0.97%	0.08%	0.00%

3.3.3. Economic loss of human health in 11 major climatic regions of China from 2015 to 2017

By calculating the human health economic loss value and BC ratio of 11 climatic regions in China from 2015 to 2017 (table 7), it can be seen that North China, Jiangnan and Southwest China have the highest annual loss, while Inner Mongolia and Tibet have the lowest annual loss. The BC ratio in North China, Huanghuai, and Southwest China is relatively high, fluctuating between 1‰ and 2‰, while the BC ratio in Inner Mongolia and Tibet area is relatively low, around 0.6‰. The annual loss values of Northeast, South China, Huanghuai, Jianghuai, Northwest and Southwest China decreased year by year, while those of North China, Jianghan and Southwest China increased year by year. The BC ratio decreased year by year in Northeast China, South China, Huanghuai, Jianghuai, Northwest China, Tibet and Southwest China.

Table 7. The changes of human health economic loss value and BC ratio in 11 climatic regions in China from 2015 to 2017

	Total loss (billion RMB)			BC ratio (‰)		
	2015	2016	2017	2015	2016	2017
1Northeast China	91.84	85.15	69.88	1.53	1.46	1.24
2North China	243.11	201.84	238.22	2.12	1.63	1.81
3South China	137.70	128.62	102.10	0.93	0.82	0.69
4Huang Huai area	138.42	100.13	94.02	1.86	1.38	1.26
5Jianghan area	18.70	16.05	16.79	1.13	0.98	1.03
6Jianghuai Region	52.77	42.44	39.19	1.41	1.19	1.04
7Jiangnan area	230.76	178.63	192.65	0.94	0.74	0.84
8Inner Mongolia	8.51	8.21	8.41	0.61	0.61	0.66
9Northwest China	69.05	61.17	57.13	1.18	1.08	0.91
10Tibet area	0.65	0.85	0.45	0.57	0.73	0.38
11Southwest China	176.43	165.78	140.72	1.62	1.49	1.27

Conclusions And Discussions

In this paper, BC concentration in China is calculated by the method of concentration ratio between BC and $PM_{2.5}$ in near stations. Population exposure level of BC in 11 climatic regions in China is assessed by superimposing population data. The results showed that 2/3 of China's land area and nearly half of the population are exposed to 1–3 ug/m^3 concentration range. The area under 2 ug/m^3 concentration increases year by year, while the area under 2–5 ug/m^3 concentration decreases year by year, which indicates that more areas in China are exposed to low concentration of BC in recent years. According to the analysis of 11 climatic regions, the weighted concentration of BC population in Southwest and North China is the highest, while that in Tibet area and Inner Mongolia is the lowest. Overlapping population analysis, the ratio of population exposure concentration to regional concentration in Northwest and Southwest China is the highest, showing an increasing trend year by year, indicating that more and more people are exposed to high concentration of BC in these areas.

By calculating the economic loss value of human health caused by excess deaths associated with BC, the annual loss value of about 77.3% districts and counties in China is less than 50 million RMB. From the perspective of yearly changes, the economic losses in most parts of China are decreasing year by year.

In this paper, the assessment results of BC exposure level are uncertain due to the limitations of data and basic research and other objective factors. Specifically, as follows: (1) Because the data of BC observation stations in China are not available, the national BC concentration is calculated by the method of concentration ratio between BC and $PM_{2.5}$ near stations, and the exposure level is evaluated based on this method, which will result in uncertainty of the analysis results. (2) The distribution of population in China is unbalanced between urban and rural areas, urban and suburban areas. In this paper, the population of most cities in China is assumed to be evenly distributed, which will also lead to the deviation of the evaluation results. (3) In the calculation of national economic losses, the exposure-response relationship selected is crucial, which will cause uncertainty of the results. Moreover, the economic loss estimation only considers the economic loss caused by excess death, which will also result in a small result.

The economic assessment methods employed may also affect the outcome of the calculation. The VSL method is an alternative which is widely used in high-income countries for valuing mortality risks associated with pollution. The value of statistical life (VSL) represents the sum of many individuals' willing to pay (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 RMB) total approximately 1.70‰(1.13‰, 2.26‰) 1.33‰(0.89‰, 1.77‰) and1.16‰(0.77‰, 1.55‰) of 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 RMB), they reach 5.15‰ (4.05‰, 6.69‰) 4.54‰ (3.62‰, 5.79‰) and 4.45‰ (3.62‰, 5.59‰) of GDP. The economic loss that was estimated using the VSL method are higher than that estimated by 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.

Declarations

Author's Contributions Formal analysis, Liang Ke; Methodology, Sun Zhaobin and Zhang Chao; Writing – original draft, Hou Qing; Writing – review & editing, An Xingqin.

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Competing interests The authors declare that they have no conflicts of interest.

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Figures

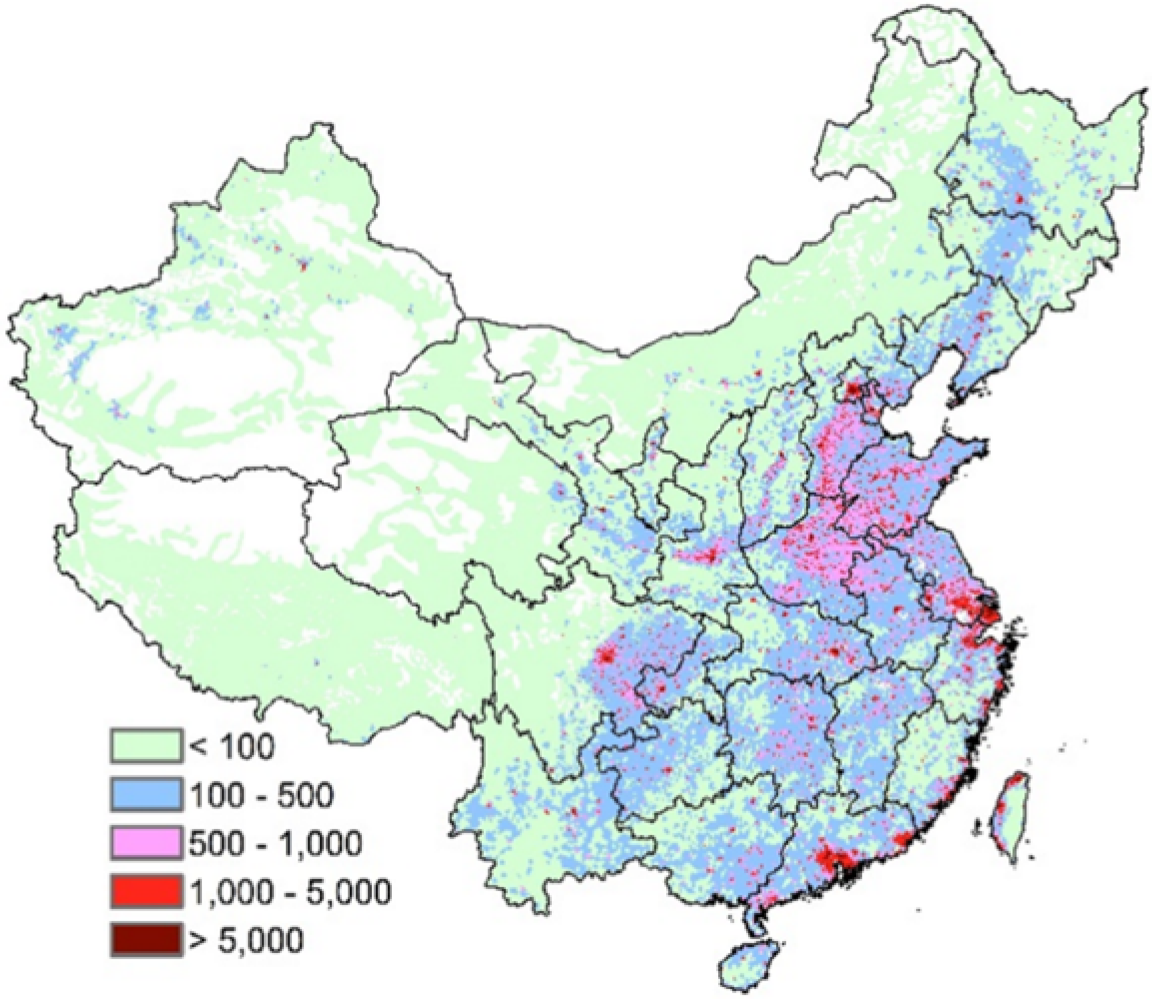

Figure 1

Population density distribution in China in 2015

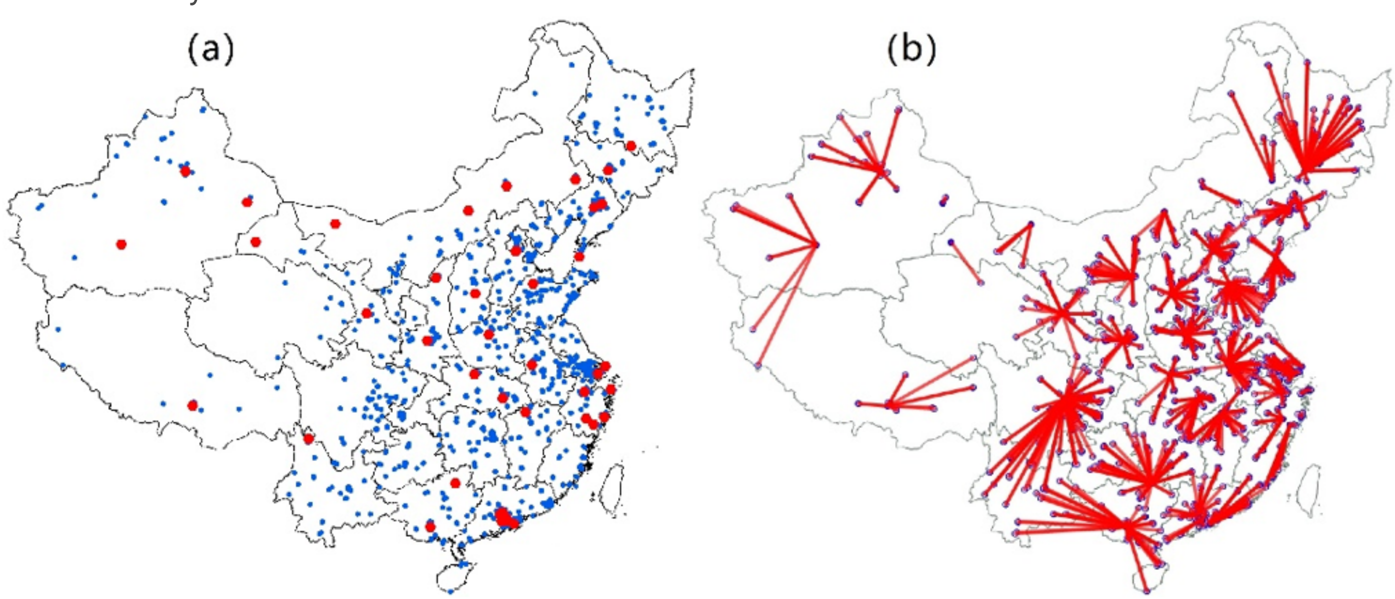

Figure 2

(a) Black carbon (47 stations) (red dots) and PM2.5 (1498 stations) (blue dots) and (b) the Calculating distance between Black carbon site and the adjacent PM2.5 site

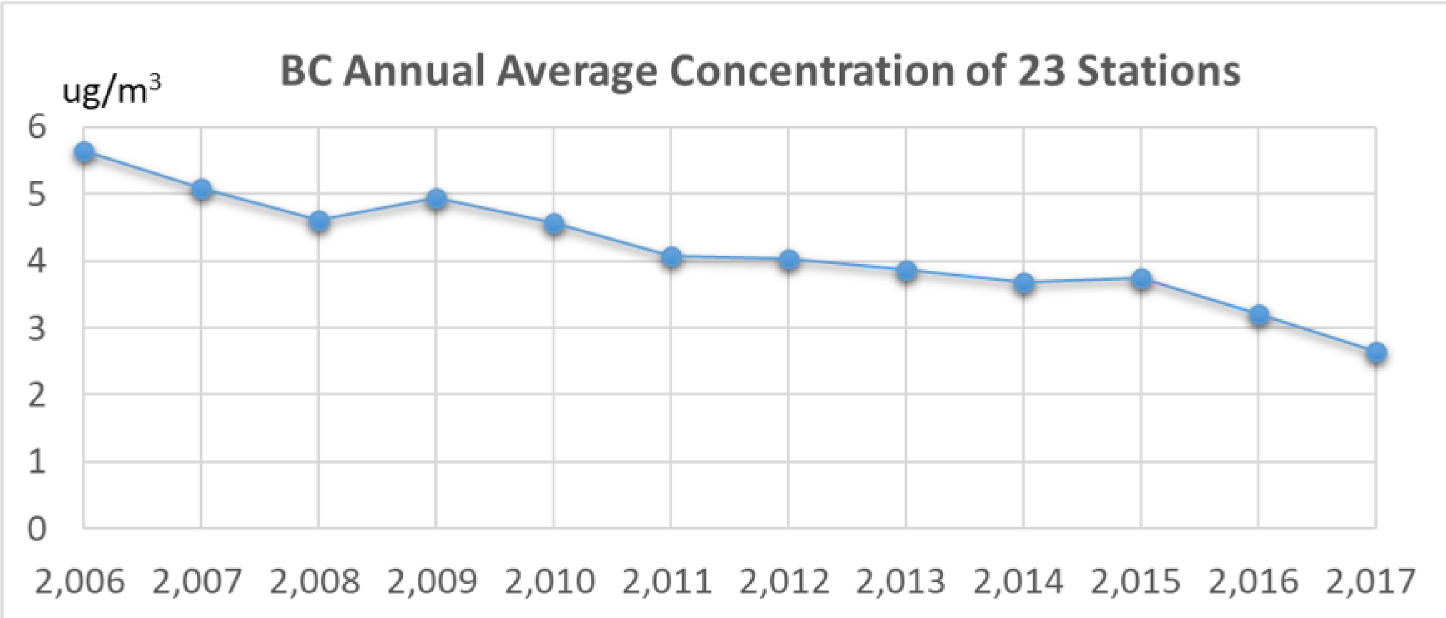

Figure 3

Annual average concentration change chart of 23 BC stations in China from 2006 to 2017

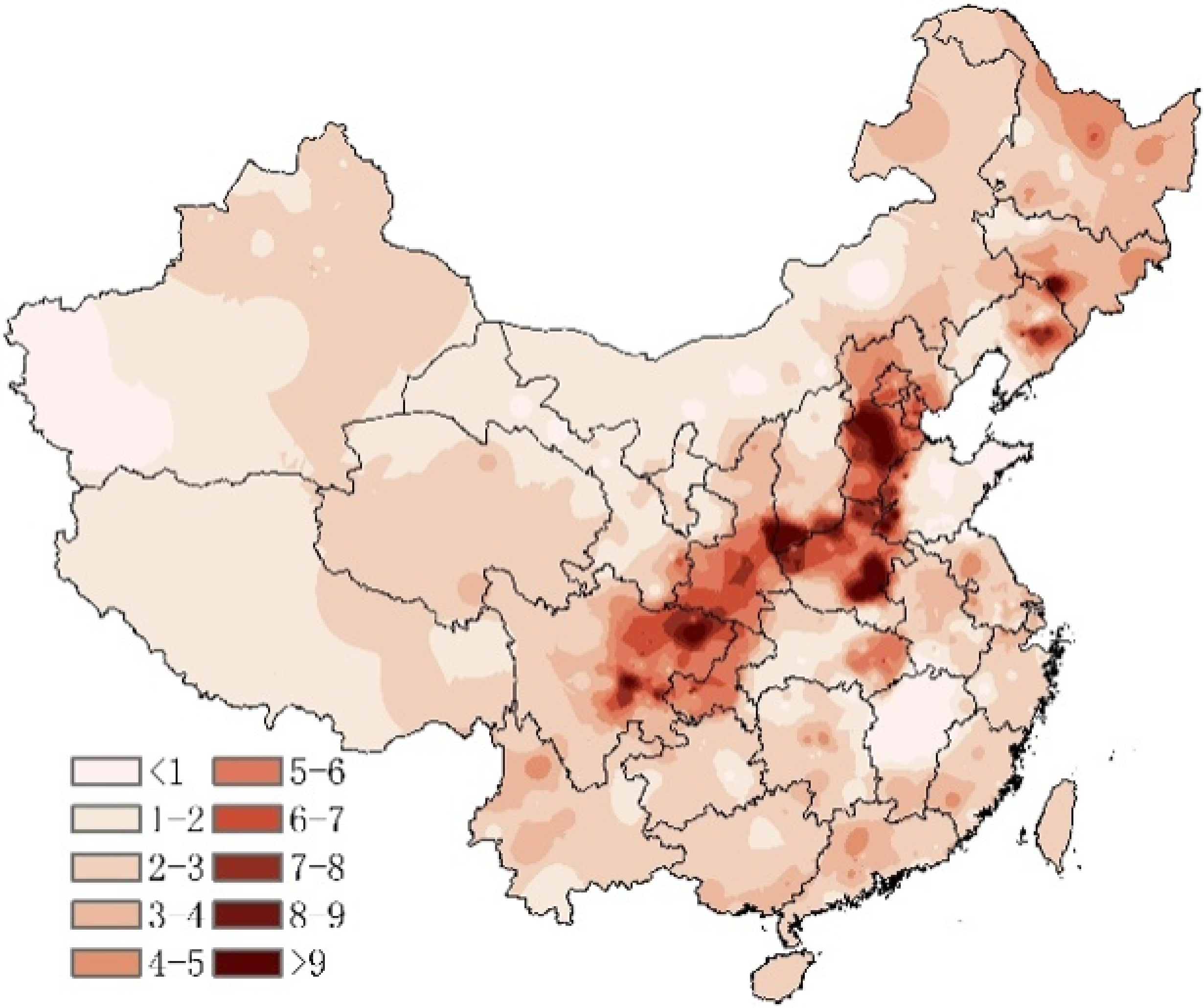

Figure 4

Distribution of Average BC Concentration in 2015-2017 Calculated by Ratio Method (ug/m3)

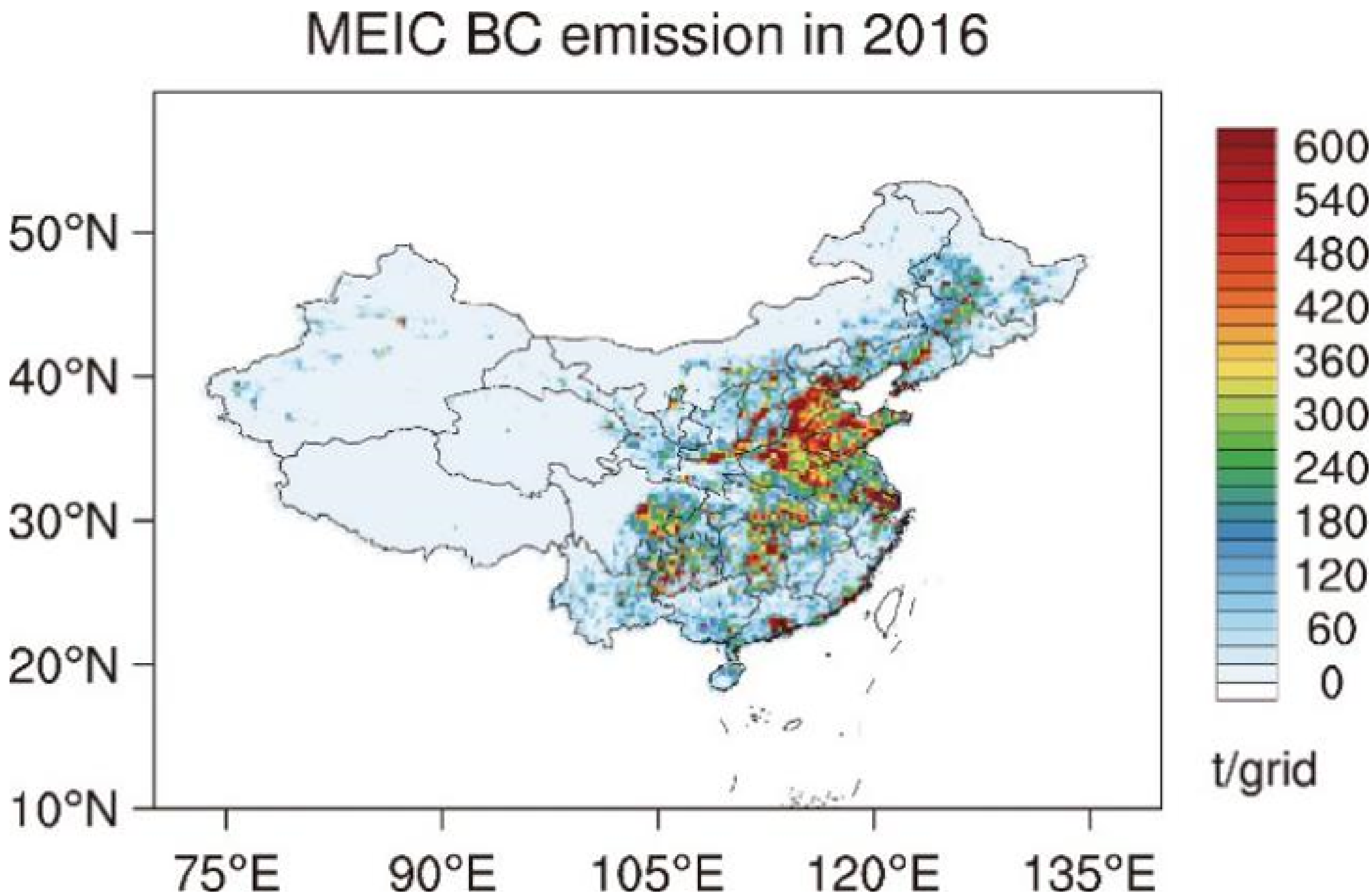

Figure 5

Graded distribution of MEIC BC emission inventories in 2016

Figure 6

Distribution map of 11 climatic regions in China

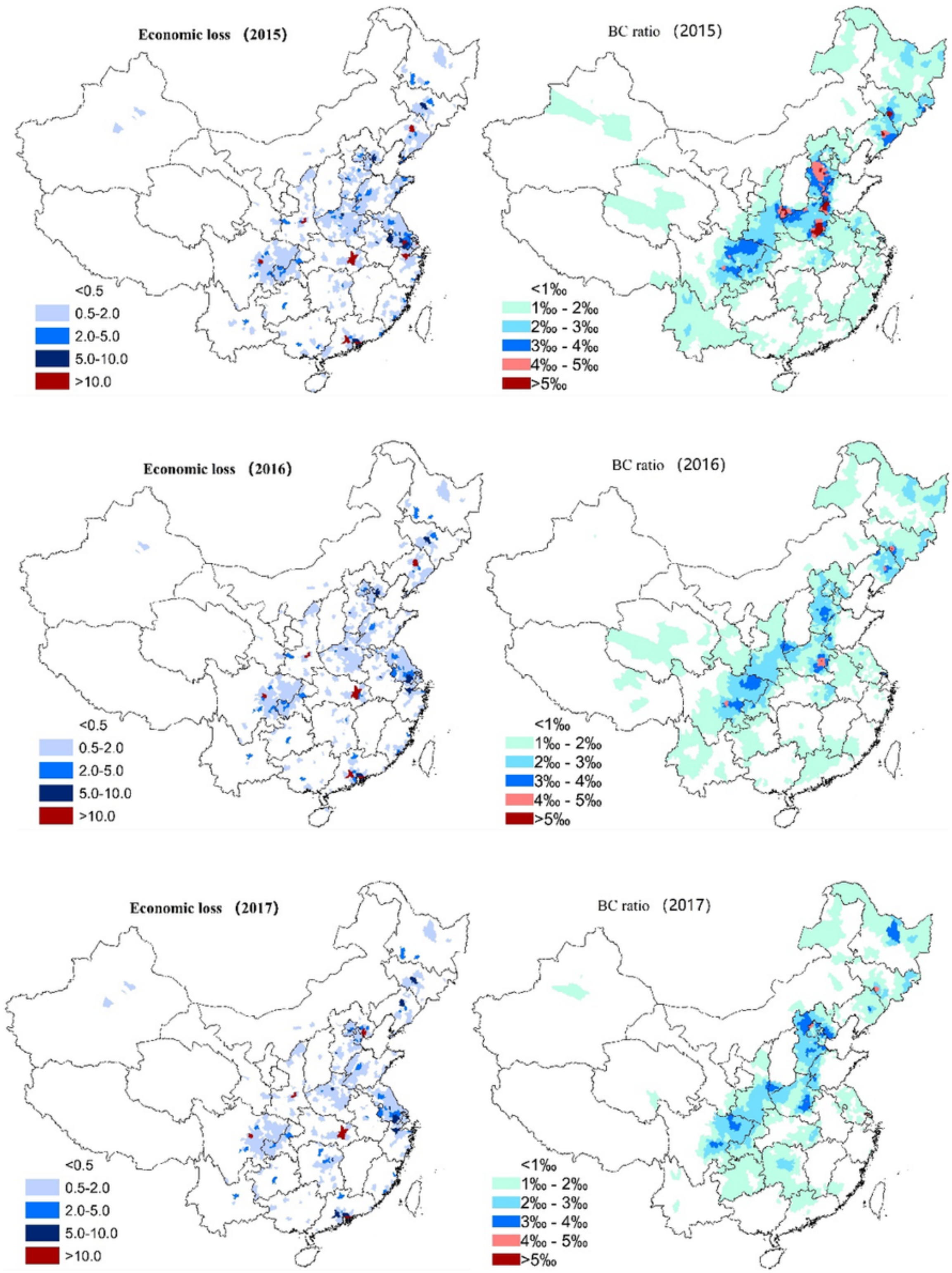

Figure 7

2015-2017 distribution of excess BC death loss value (billion RMB) and BC ratio (%)