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# Economic evaluation of health losses from air pollution in Beijing, China

Xiaoli Zhao<sup>1</sup> · Xueying Yu<sup>2</sup> · Ying Wang<sup>3</sup> · Chunyang Fan<sup>3</sup>

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**Abstract** Aggravated air pollution in Beijing, China has caused serious health concern. This paper comprehensively evaluates the health losses from illness and premature death caused by air pollution in monetary terms. We use the concentration of PM<sub>10</sub> as an indicator of the pollution since it constitutes the primary pollutant in Beijing. By our estimation, air pollution in Beijing caused a health loss equivalent to 583.02 million or 0.03 % of its GDP. Most of the losses took the form of depreciation in human capital that resulted from premature death. The losses from premature deaths were most salient for people of either old or young ages, with the former group suffering from the highest mortality rates and the latter group the highest per capital losses of human capitals from premature death. Policies that target on PM<sub>10</sub> emission reduction, urban vegetation expansion, and protection of vulnerable groups are all proposed as possible solutions to air pollution risks in Beijing.

**Keywords** Air pollution · Health damage · Corrected human capital method

## Introduction

As Chinese people enjoyed an economic miracle during the past 30 years, they also unfortunately witnessed some by-products of the miracle, such as energy resource deprivation, serious air pollution, other kinds of environmental degradation, as well as the resultant increase in health risks and mortality rates. In 2001, about one third of China's air quality monitored cities failed to attain the lowest level of National Ambient Air Quality Standard (NAAQS).<sup>1</sup> Annual mean concentrations of major pollutants, including sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), and particulate matter smaller than 10 μm (PM<sub>10</sub>)<sup>2</sup> in those cities, all exceeded the poorest standards in the NAAQS. Another one third of Chinese cities controlled their air quality within the range defined by grade III, but exceeded grade II. Only one third of cities kept their PM<sub>10</sub> and NO<sub>2</sub> pollution level below the nationally recognized standard, which is 40 μg/m<sup>3</sup>. Although China has made impressive progress in air quality management in the past decade (2001–2009),<sup>3</sup> its air condition would still be considered hazardous compared with that in the developed world (Fig. 1), and its pollution concentrations are far above the

Responsible editor: Philippe Garrigues

✉ Xueying Yu  
 xueying@buaa.edu.cn

<sup>1</sup> School of Business Administration, China University of Petroleum–Beijing, Beijing, China

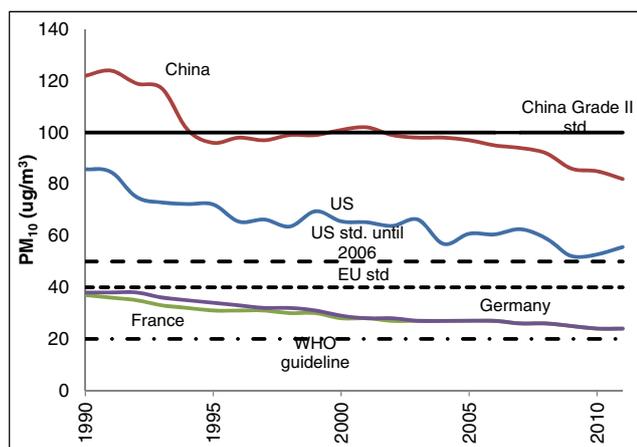
<sup>2</sup> School of Economics and Management, Beihang University, 37 Xueyuan Road, Beijing 100191, China

<sup>3</sup> School of Economics and Management, North China Electric Power University, Beijing, China

<sup>1</sup> The National Ambient Air Quality Standard specifies three levels of compliance (NAAQS I–III). Grade I indicates that annual mean concentrations of NO<sub>2</sub> and PM<sub>10</sub> are lower than 40 μg/m<sup>3</sup> and that of SO<sub>2</sub> is lower than 20 μg/m<sup>3</sup>; grade II in the range of 40–70 μg/m<sup>3</sup> for PM<sub>10</sub> and 20–60 μg/m<sup>3</sup> for SO<sub>2</sub>; and annual mean concentrations of SO<sub>2</sub>, NO<sub>2</sub>, and PM<sub>10</sub> exceeding 60, 40, and 70 μg/m<sup>3</sup>, respectively, reflect air quality worse than the grade III standard (see GB 3095-2012).

<sup>2</sup> By definition PM10 consists of particular matters with diameters less than 10 micrometer, definitely including those less than 2.5 micrometer, which are PM2.5.

<sup>3</sup> According to a recent survey of air quality in China by the World Bank, almost 80 % cities were in grade I or II, and only a few left above grade III (China Ministry of Environmental Protection and World Bank 2012).



**Fig. 1** Comparison of annual average  $PM_{10}$  concentration trend of China, USA, France, and Germany (1990–2011). Data source: The World Bank World Development Indicators (WDI) Database

levels that are considered safe by the US, the European countries, and the World Health Organization (WHO) committee.

Air pollution definitely leads to health risks. It is estimated by the World Health Organization (WHO) that about 7 million people around the world die of air pollution related diseases each year, which accounts for 12.5 % of the total deaths (Kuehn 2014). The report from WHO (2013) addressed that air pollution is most closely associated with two families of symptoms, i.e., respiratory and cardiovascular illness, which could lead to premature death. Given the well-known aggravated air pollution in China, its health damage would be more serious compared to other parts of the world. According to a rough estimation by Reuters' staff, air pollution caused 350,000 to 500,000 premature deaths in China each year (Reuters Staff 2014).

The health impacts of air pollution have drawn attention from pathologists and have been widely investigated since the 1950s. These studies confirm the correlation between severe air pollution and increased risk of respiratory symptoms and death,<sup>4</sup> and also indicate that such impacts may vary among human groups from different regions, of different races, and at different ages. For example, a long-run investigation (May 1996–December 2010) showed that for an interquartile range increase in  $NO_2$  concentration, the morbidity rate of respiratory diseases increased by 2.43 % in São Paulo, Brazil (Bravo et al. 2016). As to  $SO_2$ , the same increase in pollutant concentration would raise the morbidity rate of respiratory diseases by 1.6 % in Switzerland, and the hospitalization rate by 0.8–2.2 % in Brisbane, Australia, with adults relatively less affected and juveniles more affected (Holland et al. 2005; Samakovlis et al. 2005). Such impact was more precisely measured in the European Commission's ExternE Project, which applied a dose-response

<sup>4</sup> By comparing the health impacts of air pollution in coal-combustion and non-coal-combustion regions, Jin and his colleagues (2002) conclude that an adult is 1.7 times more likely to incur respiratory diseases in regions severely polluted by  $PM_{10}$ ,  $NO_2$ , and  $SO_2$  than a counterpart in a relatively clean area, and the chance is 2.23 times higher for juveniles.

model to estimate the health impact of major air pollutants, with the potential influence from weather condition, sunshine level, and seasonal variation all controlled. The Commission reported that 0.06 % of people exposed to  $PM_{10}$  pollution would die from related diseases if its concentration increased by  $1 \mu\text{g}/\text{m}^3$ .

The health impacts of these air pollutants, including  $NO_2$ ,  $SO_2$ , and  $PM_{10}$ , have also been evaluated in some parts of China. For example,  $NO_2$  pollution in Shanghai, China has raised the morbidity rate of respiratory diseases by 1.50 %, and for every additional  $10 \mu\text{g}/\text{m}^3$  increase in  $PM_{10}$  concentration, the city's mortality rate increased by 0.84 % (Chen et al. 2002; Li et al. 2004). As an effort to fight against air pollution, the city of Chengde in Hebei province adopted an integrated heating system in 1997, which successfully reduced local  $SO_2$  concentration from 3.86 to  $0.264 \mu\text{g}/\text{m}^3$ . Along with the improvement, mortality rate of respiratory diseases decreased from 8.1 to 2.3 % (Zhang et al. 2000). A  $10 \mu\text{g}/\text{m}^3$  increase in  $PM_{10}$  concentration in Beijing, China was associated with an increase of 0.33 % in daily ischemic heart disease (IHD) mortality (Xu et al. 2014). It is also found that the impact of  $PM_{10}$  is more salient in summer than in other seasons. Males and older people are more sensitive to  $PM_{10}$  pollution (Xu et al. 2014).

Yang and Pan (2008) evaluated the impacts of individual pollutants in Beijing and concluded that for every additional  $10 \mu\text{g}/\text{m}^3$  increase in the concentration of  $SO_2$ ,  $NO_2$ , and  $PM_{10}$ , the death risks of cardiovascular and cerebrovascular diseases would increase by 0.40, 1.30, and 0.40 %, respectively. Zhang et al. (1999) comprehensively evaluated the impacts of all the three pollutants on human health. They found that the morbidity rate of respiratory diseases among juveniles was four times as high in heavily polluted zones in Tianjin compared to that in air-clean zones.

Health impact of air pollution has been separately related to individual pollutants in some existing studies; these pollutants, i.e.,  $SO_2$ ,  $NO_2$ , and  $PM_{10}$ , however, are correlated, and their impacts are in fact overlapped (Künzli et al. 2000). A summation of the health impacts of individual pollutants would overestimate losses from air pollution. Hence, we evaluate air pollution in this study with  $PM_{10}$  since both  $SO_2$  and  $NO_2$  are important precursors of  $PM_{10}$  and their impacts are part of that of  $PM_{10}$  (Pope and Dockery 2006). Moreover, in the study year of 2012,  $PM_{10}$  constituted the primary pollutant<sup>5</sup> on 337 days of the 366 days in that year.

<sup>5</sup> The concept of "primary pollutant" is derived from the definition of Air Pollution Index (API, GB3095-96). It was a comprehensive air quality standard used in China between 1996 and 2012 (Air Quality Index, AQI, replaced API in 2013). The index gauges pollution condition by comprehensively considering pollution caused by the three major pollutants,  $PM_{10}$ ,  $NO_2$ , and  $SO_2$ , and measures air pollution with the concentration of the worst pollutant, which is also called primary pollutant, on each day. In this way, API can better reflect air condition improvement than other indicators, such as average pollution level or the best level. The primary pollutant may vary day to day, but the score is kept consistently.

After the health impacts have been sufficiently assessed in pathological studies, more attention now is directed to economic valuation of these impacts. It is estimated that, each year, 1.2–2.0 % of the newly generated wealth around the world is lost due to health deterioration from air pollution (WHO 2006). The costs consist of two parts: (1) increase in protection cost and medical expenditure spent on treating air-pollution-related diseases, and (2) human capital depreciation, i.e., the decline and incapacity of labor force caused by physical condition deterioration, fatigue, diseases, and death. As a pioneer scholar in this field, Ostro (1983) delicately analyzed the US Health Interview Survey and found that a 10 % decrease in ambient levels of total suspended particular (TSP) was related to a 4.4 % decrease in average working loss days and 3.1 % in restricted activity days. The statistically significant and quantitatively important effect was later confirmed by Hausman et al. (1984). In China, the effect is also monetized. It is estimated that health loss caused by PM<sub>10</sub> pollution accounts for 0.53 % of the gross domestic production (GDP) in Beijing (Cao and Han 2014; Zhang et al. 2007a, b) and 1.03 % in Shanghai (Kan and Chen 2004).<sup>6</sup>

While those aforementioned studies provided a useful perspective in detecting air pollution's health impact in an era characterized by pollution, the studies concerning China still have some shortages. In the works with focus on a Chinese city, many studies used dose-response coefficients cited from other studies (the mostly cited work includes Xu et al. 2014 and Aunan and Pan 2004) in assessing air pollution's health impact and the associated economics losses; meanwhile, the most fundamental work of estimating the dose-response coefficients with field data is quite limited. Even among empirical studies that did make first-hand estimation of the dose-response coefficients, research attention was mostly restricted to the association between air pollution and mortality, leaving the investigation of air-pollution-induced morbidity quite sparse. This is because data of mortality was relatively easy to access, but data necessary for evaluating disease-specific morbidity are hardly available in China. According to a 2004 survey (Aunan and Pan 2004), only three studies, one for Beijing and two for Hong Kong, used outpatient visit data to estimate simple association between air pollution and hospital admission among Chinese populations, and they became the primary citing sources in following studies. However, those studies are quite old and may not be able to properly reflect the impact of current air pollution. For example, the study focusing on Beijing was published far back to 1995, over 20 years ago (Xu et al. 2014).

Our primary contribution lies in the most updated empirical estimation about how air pollution is associated with *both* death and illness among Chinese people, with supporting morbidity data collected from three local hospitals in Beijing in the year 2012. Possible human symptoms associated with air pollution

consist of circulation system diseases, respiratory system diseases, and immune function deterioration (An et al. 2006; Dong et al. 2007). Since immune disadvantage may cause circulation diseases, and the impact of air pollution on them may overlap, we do not separately consider the health impact channeled through immune function deterioration in this study.

The second contribution is that we separate the impacts among subgroups defined by among populations with varied age, residence location, and etiology, with the potential influence from dietary habit and weather condition all controlled.

The evaluation of economic losses caused by diseases and premature death due to air pollution in Beijing constitutes our third contribution. It is estimated in the study that the city of Beijing lost 583.02 million in 2102 due to air pollution. Of the losses, 18.3 % was spent to treat cardiovascular diseases that resulted from air pollution and 12.6 % to treat respiratory diseases. The other 69.1 % of the loss resulted from depreciation of human capital due to premature death. As confirmed by most previous studies, people of old age are more vulnerable to air pollution than their younger counterparts since they are most likely to be infected with cardiovascular diseases and respiratory diseases. The rules are especially true for groups older than 35. People under this age are less likely to be affected by air pollution, except for infants less than 5 years old, who are another major group of victims of Beijing's air pollution.

The remainder of this paper is organized as follows: “Air pollution in Beijing” section introduces current air pollution conditions in Beijing. “Methodology and data” section builds a dose-response model and an economic loss assessment model to evaluate the pathological and economic impact of air pollution in Beijing. “Results and discussion” section discusses the results and “Concluding remarks” section concludes by offering policy suggestions.

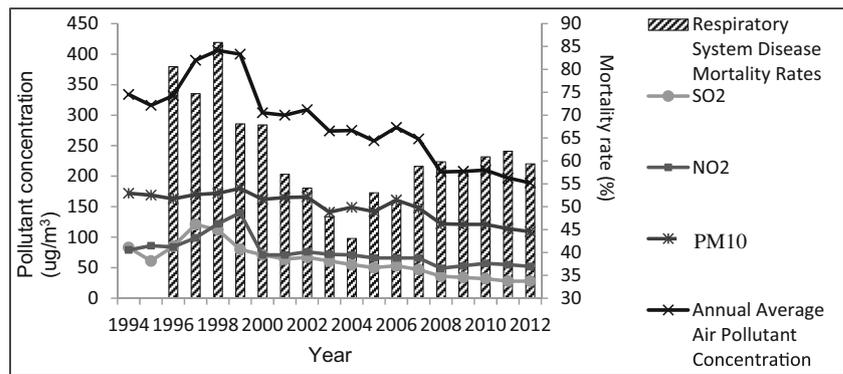
## Air pollution in Beijing

As indicated in the foregoing discussion, when discussing air pollution in Beijing, SO<sub>2</sub>, NO<sub>2</sub>, and PM<sub>10</sub> are the three most referenced pollutants.<sup>7</sup> Figure 2 shows air pollution level in Beijing, as well as the respiratory disease mortality rates during 1994 to 2012. The whole period can be roughly divided into three stages. The first one, from 1994 to 1998, observed an increasing trend of air pollutant concentration along with an ascending mortality rate, which peaked in 1998. The

<sup>6</sup> Since the record of PM<sub>2.5</sub> concentration was not available before 2009 in China, the cited studies all focus on inhalable particulate matter (PM<sub>10</sub>).

<sup>7</sup> This is especially true before the year 2012, when China employed the air pollution index (API) to evaluate its air pollution condition. API consists of only the three pollutants: SO<sub>2</sub>, NO<sub>2</sub>, and PM<sub>10</sub>. In later 2012, however, the API system was replaced with the air quality index (AQI) system which considers a broader range of pollutants. Since the study evaluated the health impact of air pollution for the whole year of 2012, we specifically focus on pollutants covered by API, which are SO<sub>2</sub>, NO<sub>2</sub>, and PM<sub>10</sub>.

**Fig. 2** Air pollutant concentration and respiratory disease mortality rate in Beijing (1994–2012). Data source: 1994–2012 Beijing environment bulletin, 1995–2012 Beijing statistical yearbook



second stage started from 1998 and lasted until 2008. It was characterized by intensive pollution control policies and air condition improvement. During this period, the concentrations of the three major pollutants all declined by 50 %. The remarkable improvement in Beijing’s air quality over this period may be attributed to the 160 air pollution control measures adopted by the Beijing municipal government, which aimed for greeting the 2008 summer Olympic Games. To impress the world as an excellent host of the 29th summer Olympic Games, the municipal government of Beijing also cleansed 16,000 small coal-fired boilers, removed more than 140 polluters, shut down all intensively polluting factories, and even cut off half of the traffic flow with an odd-even number-plate restriction measure in the year 2008. These practices inevitably led to human health benefits. Figure 2 also shows that the mortality rate of respiratory diseases plummeted in 2004, which reached 0.43 ‰. This is because SARS broke out in 2003 and many vulnerable people died of it. In order to control this epidemic disease, industrial production, business activities, and transportation volume were all vastly reduced. As a result of both air pollution mitigation and burst death of respiratory disease vulnerable people in 2003, the mortality rate of respiratory diseases plummeted in 2004. Air pollution concentration after 2008 was kept quite stable, and so was the mortality rate. This is the third stage.

**PM<sub>10</sub>**

In addition to the individual air pollutant concentration standard (Table 1), China also employed the comprehensive air pollution index (API) to evaluate its air quality. The index gauges pollution condition by comprehensively including the three major pollutants and measures air pollution with the concentration of the worst pollutant (which is also called primary pollutant) on each day. In this way, API can better reflect air condition improvement than other indicators, such as average pollution level or the best level. The primary pollutant may vary day to day, but the score is kept consistently.

API in Beijing had been kept decreasing from 1994 to 2012, with three sharp declines in 2000, 2003, and 2008

(Fig. 3). This trend was at least correlated with, if not driven by, Beijing’s air pollution control policies (Table 2). Also, financial investment contributed to this improvement. From 1994 to 2004, the Beijing municipal government had been consistently raising its investment in environmental protection, which peaked twice, respectively, in 1999 and 2004. They may explain pollution mitigation in the following years.

While air pollution in Beijing, as indicated by both the pollutant concentration (Fig. 2) and API index (Fig. 3), had been kept relatively improved during the past decade, it should be noted that the city’s annual mean concentration of NO<sub>2</sub> and PM<sub>10</sub> were still 52 and 109 μg/m<sup>3</sup>, well above the WHO standard of 40 and 20 μg/m<sup>3</sup>, respectively, for the two pollutants and also above the grade I standard in NAAQS of 40 μg/m<sup>3</sup> for both pollutants. The severe air pollution in China, especially in Beijing, causes human health damage.

**Methodology and data**

Economic losses that resulted from air-pollution-related illness consist of two parts: (1) medical costs, i.e., excessive protection cost and medical expenditure resulted from diseases caused by air pollution, and (2) loss of premature death, i.e., the decline and incapacity of labor force caused by premature death. The two parts are estimated separately and then added up together for a general estimation.

**Medical costs** It is assumed that medical costs spent on each patient with air-pollution-related diseases, mainly cardiovascular diseases and diseases, are constant across all age groups, which are denoted by  $C_{car}$  and  $C_{res}$  respectively. Thus, the total air-pollution-related medical and protection costs imposed on a whole society ( $C_{med}$ ) equals individual costs multiplied by the numbers of patients who are affected by cardiovascular diseases and respiratory diseases, i.e.,  $Z_{car}$  and  $Z_{res}$

$$C_{med} = C_{car} \times Z_{car} + C_{res} \times Z_{res} \tag{1}$$

The data we used to evaluate  $C_{car}$  and  $C_{res}$  are collected from *Beijing Short Compile for Health Statistics* in 2012.

Both  $Z_{car}$  and  $Z_{res}$  are assumed to relate with air pollutant concentration, and the relationships are estimated with a dose-response model developed by the U.S. Environmental Protection Agency (EPA):

$$\ln[E(Z_{ij})] = \alpha + \beta_j s(X_i) + DOW + H + s(time, df = 7) + s(temperature, df = 6) + s(humidity, df = 6) + s(price, df = 6) \tag{2}$$

where  $Z_{ij}$  is the amount of people going to see a doctor (PSD) on the  $i$ th day in the  $j$ th sample hospital due to either cardiovascular or respiratory diseases.  $\beta_j$  represents the correlation between air pollutant concentration and the PSD in the district where the  $j$ th sample hospital locates.  $X_{ij}$  is air pollutant concentration on the  $i$ th day at the location of the  $j$ th sample hospital.  $DOW$  is a dummy variable indicating whether the  $i$ th day is a working day or not.  $DOW=1$  represents working days and  $DOW=0$  represents non-working days. This variable is included because the pattern of hospital visits may vary under the two conditions. For a similar reason, we also include in the model the dummy variable of  $H$ , with  $H=1$  indicating heating period and  $H=0$  indicating non-heating period.  $s$  is the denotation of cubic spline function. The model explicitly considers the spline functions of air pollution, time, temperature, humidity, and price levels of meat and eggs<sup>8</sup> since these factors are all assumed to be non-linearly related to the incident of cardiovascular and respiratory diseases (Dusseldorp et al. 1995; Kwiterovich 1997; Chen et al. 2012).

The EPA dose-response model is open in terms of selection of pollution index. In this study, we use the concentration of  $PM_{10}$  as the indicator of air pollution concentration ( $X_{ij}$ ) on each day<sup>9</sup>. We refer to the grade I standard in NAAQS when setting up the thresholds<sup>10</sup> in this study:  $40 \mu\text{g}/\text{m}^3$  for  $PM_{10}$ .

This model is estimated with disease-specific PSD data (Jan 1st–Dec 31st 2012) collected from three local<sup>11</sup> hospitals respectively located in the districts of Shijingshan, Fengtai,

<sup>8</sup> Consumption of meat and eggs is an indicator of residential dietary pattern, which has potential influence on morbidity rate. We assume that supply of meat and eggs in the study period was stable and that price level was positively related to the demand as well as total assumption. Thus, the price index of meat and eggs could be used as an indicator of residential dietary habit.

<sup>9</sup> The study focuses the impact of  $PM_{10}$ , without explicit discussion about that of  $PM_{2.5}$ , which is stemmed from the following reason:  $PM_{10}$  is referred as the inhalable particles with diameters less than  $10 \mu\text{m}$ . It harms the human respiratory system and causes illness. The difference between  $PM_{10}$  and  $PM_{2.5}$  is that the particles with a diameter of  $10 \mu\text{m}$  deposit generally at upper respiratory tracts, while the particles with diameters less than  $2.5 \mu\text{m}$  can enter into deeper place of respiratory tracts.

<sup>10</sup> Thresholds refer to a pollutant concentration, below which we believe air pollution would not harm human health. It is a key factor in almost all evaluations of the health impact of air pollution.

<sup>11</sup> By “local,” we mean hospitals that mainly serve local residents. As the national capital, there are also many national hospitals located in Beijing, which serve both patients from and outside Beijing. These national hospitals are deliberately excluded from our sample.

and Daxing of Beijing. The three districts locate in the central and southern parts of Beijing, as shown in Fig. 4. The reason we use the *local hospital* visiting data is that such data can help eliminate potential sample contamination arising from non-local visits on our estimation of Beijing residents’ health conditions. Since air pollution in the central and southern parts of Beijing is a little more severe than that in the north, this would make simulation from our study slightly exaggerating the health impacts of air pollution in Beijing (Fig. 5).

Air pollution data in the three districts were collected from the air quality monitoring stations in each area, one in Shijingshan, two in Fengtai, and two in Daxing. For the districts with more than one monitoring station, air pollutant concentration is equaled with the average of readings from each station. For the city of Beijing as a whole, air pollutant concentration is average among all pollution monitoring stations. All air quality monitoring stations involved in this study are run by the government, thus all the readings of pollutant concentration used are official data. Meteorology data, including temperature, air humidity, and rainfall in Beijing, were collected from Beijing Meteorological Bureau. The data of PSD associated with each disease in Beijing is collected from 2012 *Beijing Health Statistics Yearbook*, and the food price data is collected from Beijing Xinfadi Agricultural E-Trading Center.

Based on Eq. (2), for each sample hospital, we estimate its  $\beta_j$  and derive the dose-response coefficient  $b_j$  following Eq. (3), which measures the percentage increase in PSD associated with  $10 \mu\text{g}/\text{m}^3$  increase in air pollutant concentration.

$$b_j = \frac{\ln \beta_j}{\Delta D} \tag{3}$$

$\Delta D$  is the gap between annual average air pollutant concentration and its threshold. For a further step,  $b_j$  is averaged among the three sample hospitals to eliminate potential bias that resulted from hospital scale and instability of daily PSD. With the correlation between air pollution and disease-specific PSD, we further estimate the number of people whose health is affected by air pollution in the target city, Beijing, with Eq. (4):

$$Z_{res/car} = \Delta Z = Z_p - Z_c = Z_p \left[ 1 - \frac{1}{(1 + \bar{b})^{\Delta D}} \right] \tag{4}$$

where  $Z_p$  is the overall PSD amount for the cardiovascular diseases and respiratory diseases,  $Z_c$  is the PSD amount without pollution,<sup>12</sup>  $\Delta Z$  is the excessive PSD attributed to air pollution, and  $\bar{b}$  is the weighted average of  $b_j$ <sup>13</sup>.

<sup>12</sup> We define pollution in this study with concentration of a pollutant higher than its threshold.

<sup>13</sup> The weight is identified by the proportion of the PSD for the cardiovascular disease or respiratory disease in a specific hospital to the total PSD for the two kinds of diseases in the three hospitals.

**Table 1** The comparison of air quality standard between China and WHO(2005)

Pollutant	Standards	Pollutant concentration limit( $\mu\text{g}/\text{m}^3$ )		
		1-h mean	24-h mean	Annual mean
SO <sub>2</sub>	China 1st	150	50	20
	China 2nd	500	150	60
	WHO		125	
PM <sub>10</sub>	China 1st		50	40
	China 2nd		150	70
	WHO		50	20
NO <sub>2</sub>	China 1st	200	80	40
	China 2nd	200	80	40
	WHO	200		40

Data source: *China Environmental & Air Quality Standard* (GB 3095-2012), WHO air quality guidelines (2005 update)

**Loss in premature death**

Similar to the estimation of pollution-illness relationship, the daily number of disease-specific premature death is estimated with the EPA’s dose-response model:

$$\ln[E(P_{ik})] = \alpha + \beta_k s(X_i) + DOW + H + s(\text{time}, df = 7) + s(\text{temperature}, df = 6) + s(\text{humidity}, df = 6) + s(\text{price}, df = 6) \tag{5}$$

where  $P_{ik}$  represents the number of premature death on the  $i$ th day caused by the  $k$ th kind of diseases ( $k=1$  means respiratory diseases and  $k=2$  means cardiovascular diseases), and  $\beta_k$  represents the correlation between the number of premature death caused by disease  $k$ .

Disease-specific death toll for each day is necessary to estimate  $\beta_k$  in Eq. (5). However, such data are neither

available from the city of Beijing as a whole nor from the sample hospitals. As an alternative, we use data collected from Hong Kong in 2012 to estimate age-specific  $\beta_k$ . Those data include air pollutant concentration data collected from Hong Kong Environmental Protection Bureau, humidity data from Hong Kong observatory, food price data from Hong Kong Census and Statistics Department, and daily death toll from the Center for Health Protection. Thus, the premature death dose-response coefficient we used in this study is derived from the Hong Kong population. Although it may not perfectly resemble the dose-response relationship among Beijing residents, we think they are currently the best available substitution for two reasons. First, it has been shown in various pathological studies that the dose-response relationships are quite similar among groups with similar races (HEI 2003; Dong and Zhi 2010; Daniel and Petrolia 2011). Second, weights of most chemical components of PM<sub>10</sub> in the air (with similar degree of pollution) collected from Beijing and Hong Kong are not statistically different from each other (see Table 3). Thus, substituting Beijing’s air pollution dose-response coefficients with those of Hong Kong would at least provide us a reasonable estimation of the impact of air pollution on premature death in Beijing.

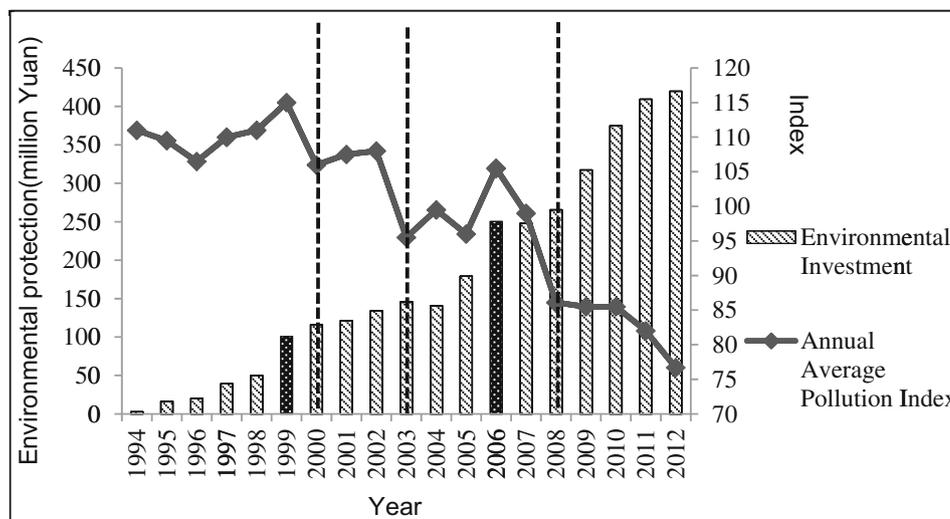
Once we obtain the estimation for  $\beta_k$ , we can calculate the dose-response coefficient  $b_k$  (the percentage increase in premature death caused by 10  $\mu\text{g}/\text{m}^3$  increase in air pollutant) with Eq. (6).

$$b_k = \frac{\ln \beta_k}{\Delta D} \tag{6}$$

where  $\Delta D$  is the gap between annual average concentration of PM<sub>10</sub> and its threshold.

The number of disease-specific daily premature death resulted from air pollution in Beijing is estimated with the dose-

**Fig. 3** Annual average API and environmental investment in Beijing (1994–2012). Data source: *Beijing Statistical Yearbook*, Beijing environmental protection bureau



response model, and a whole year's premature death is estimated by totally summing the number of death on each day and in each district, as shown in Eq. (7):

$$P_k = \sum_{i=1}^{365} \sum_{n=1}^{17} P_{kin} = \sum_{i=1}^{365} \sum_{n=1}^{17} P_n \times \Delta D_{in} \times b_k \quad (7)$$

where  $P_k$  is number of premature death caused by air pollution and channeled through disease  $k$  (cardiovascular disease and respiratory disease, respectively) in Beijing in the study year. We calculate it by summing the number of disease-specific death on each day ( $i$ ) and in each district ( $n$ ) that are attributable to air pollution, which is  $P_{kin}$ .  $P_{kin}$  is estimated by multiplying  $P_n$ , the total number of premature death in district  $n$ , with  $\Delta D_{in}$  (the district-specific gap between daily mean of air pollution concentration and its threshold) and the dose-response coefficient  $b_k$ . To estimate the economic loss caused by premature death, we need to calculate the number of premature deaths for various age strata to explore the economic loss with Eq. (8):

$$P_{km} = \lambda_{km} P_k \quad (8)$$

where  $P_{km}$  is the number of premature deaths associated with illness  $k$  in the  $n$ th age strata;  $\lambda_{km}$  is the proportion of the number of the premature death associated with illness  $k$  for the  $m$ th age stage to the total premature death associated with this disease. The total number of premature deaths caused by air pollution is partitioned into 16 age strata (with five ages as one group) in this study, as shown in Table 4.

The loss varies along with the age at which a patient dies according to the human capital method. It would be reasonable to assume that the younger the patient dies, the greater the loss of human capital in premature death. Specifically, the per capita loss in premature death cost is calculated with a revised human capital method, which takes the loss mainly as the decrease in human capital gain resulted from life expectancy reduction.

$$c_t^{\text{death}} = \sum_{i=1}^{80-t} \frac{gdp(1+g)^i}{(1+r)^i} \quad (9)$$

Equation (9) describes how to calculate the premature death loss for an individual at age  $t$ , which is denoted as  $c_t^{\text{death}}$ . In this calculation, we take 80 years, the average lifespan for Beijing residents in 2012, as life expectancy.<sup>14</sup> Any death that occurs before that would be considered as premature death, and the resultant losses in potential human capital gains from all following years till 80 are first converted to their present values in 2012 and then added up together as estimation for the per capita premature death loss. Human capital gains in each year are estimated with the per capita GDP of that year, which is assumed to increase at a rate of  $g$ . Per capita GDP in 2012 is  $gdp$  and the discount rate is  $r$ .

<sup>14</sup> According to the Chinese National Statistical Report (2013), life expectancy in Beijing is 80.18. We take the integer part in our calculation.

**Table 2** Air pollution regulations implemented in Beijing, 2000–2008

Year	Regulation title
2000	Air Pollution Prevention Law
	Implementation Measures of Beijing for the Air Pollution Prevention Law
	Power Plant SO <sub>2</sub> Emission Standards
	Diesel Vehicle Free Accelerating Smoke Emission Standards
2003	Discharge Levy Standard Management Approach
	Environmental Impact Assessment Law
	Cleaner Production Promotion Law
	Collection and Usage Management Approach of Beijing Municipal Sewage Charge
2008	Inform on Enhancing the Management of SO <sub>2</sub> Emissions from Coal-Fired Furnaces
	Inform on Monitoring Beijing Entry Crossroads and Vehicles Exhaust Emission
	Inform on Optimizing the Declaration Management of New Cars Emissions

The annual average per capita GDP increase rate is estimated with the average increasing rate from 2001 to 2011, with the growth data collected from the *Beijing Statistical Yearbook*. The annual average discount rate data in Beijing is collected from *World Economic Outlook Databases* (IMF 2012).

The total economic loss in premature death is calculated with Eq. (10).

$$TC^{\text{death}} = \sum_{k=1}^2 \sum_{m=1}^{13} P_{km} c_t^{\text{death}} \quad (10)$$

where  $TC^{\text{death}}$  is the total economic loss caused by the premature death of all individuals because of cardiovascular diseases and respiratory diseases.  $P_{km}$  is the number of premature deaths associated with illness  $k$  in the  $m$ th age strata.  $c_t^{\text{death}}$  is the premature death loss for an individual at age  $t$ , which is denoted in Eq. (9).

## Results and discussion

In 2012, PM<sub>10</sub> was the major pollutant in Beijing. On 337 days of the 366 days in 2012, it constituted the primary pollutant for API calculation. Its annual average concentration was far above the NAAQS grade I standard (40 μg/m<sup>3</sup>) in all districts of Beijing (Table 5).

Air pollution does lead to significant health impact. Its impact on morbidity rate of cardiovascular diseases and respiratory diseases may be inferred from Table 6. The positive correlation



**Fig. 4** The map of Beijing

coefficients in the table indicate that, as the concentration of the pollutant increases, the morbidity of the both diseases will increase, with the incidence of respiratory diseases more sensitive to air pollution. To a further step, the dose-response coefficient for each disease in each sample hospital is estimated with the dose-response model and shown in Table 7.

According to the estimation (Table 7), PSD amount of respiratory diseases increases by 0.71, 0.96, and 0.60 %, respectively, for every additional  $10 \mu\text{g}/\text{m}^3$  increase in the concentration of air pollutant. We derive the city's dose-response coefficient by averaging the correlations for both kinds of diseases among the three sample hospitals, with the annual PSD amount for each kind as the average weight. Taking the city as a whole, the dose-response coefficient is 0.42 % for cardiovascular diseases and 0.72 %

for respiratory diseases. In other words, for every additional  $10 \mu\text{g}/\text{m}^3$  increase in  $\text{PM}_{10}$  concentration, the PSD amount of cardiovascular diseases will increase by 0.42 % and that of respiratory diseases will increase by 0.72 % in Beijing.

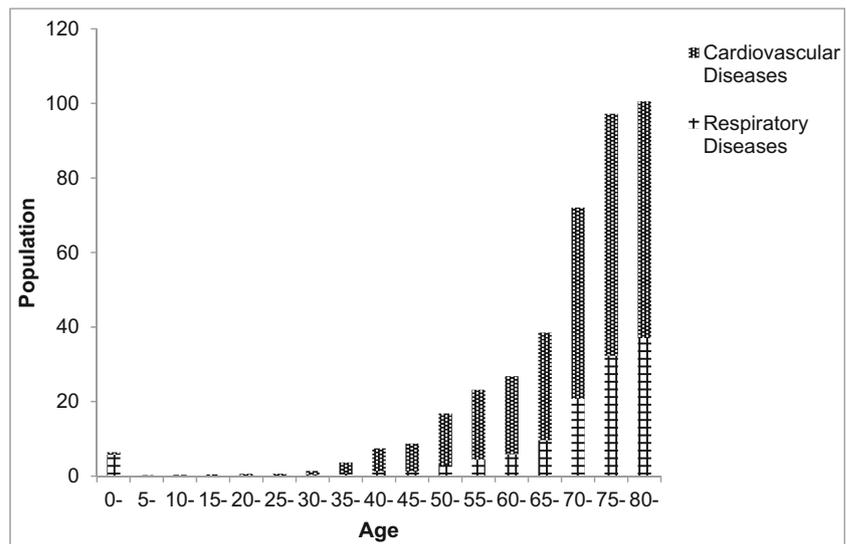
Plugging our estimation of the dose-response coefficients into Eq. (3), we estimated that the PSD associated with cardiovascular diseases caused by air pollution was 278,000 and that of respiratory diseases was 190,700 in Beijing in 2012. Multiplying the two numbers with the per capital medical cost, we conclude that in the year 2012, air pollution in Beijing resulted in an economic loss of 106.8632 million due to an aggravated risk of cardiovascular diseases and 73.3051 million of cardiovascular diseases.

Similarly, the impact on mortality rate of cardiovascular diseases and respiratory diseases due to air pollution may be inferred from Table 6.

It is indicated in Table 6 that for every additional  $10 \mu\text{g}/\text{m}^3$  increase in annual average concentration of  $\text{PM}_{10}$ , the mortality rate of cardiovascular diseases rises by 0.2 % and that of respiratory diseases rises by 0.48 %.

Next, the rates of premature death, respectively channeled through cardiovascular diseases and respiratory diseases, are calculated for each district in Beijing (Table 8). Overall, air pollution in Beijing, as indicated by  $\text{PM}_{10}$  concentration, leads to an economic loss of 402.8535 million in 2012. Also, the health threats diverge markedly among people of different ages. Generally speaking, the probability of air pollution induced death increases with age. Among the cohorts of 5 to 35 years old, very few people would die from air pollution. Beyond 35, noticeably

**Fig. 5** The amount of premature deaths caused by air pollution by diseases



more people are subject to premature death from air pollution. The mortality rate starts to moderately increase since the age of 35, and the increase is accelerated beyond the age of 65. For people older than 65, the risk of death from air pollution is substantially raised. It is estimated for the year 2012 that less than ten adults under age 35 would die of air pollution in Beijing, whereas about 200 adults older than 75 would be killed by the pollution. Finally, it should be noted that the cohort of children under 5 years old is an exception from the increasing trend of death risk with age. They are even more susceptible to air-pollution-induced death compared to juveniles (Table 9).

The health impacts of air pollution among age cohorts are further evaluated in terms of economic losses. It is shown in Fig. 6 that the loss is relatively higher among old age groups, although reduction in human capital for each individual death in these groups is low. Obviously, the size effect (the amounts of premature death in old groups) outweighs the price effect (the economic cost for individual death). Taking premature death channeled through cardiovascular diseases as an example, the death resulted in a loss of about half million among the group with age 0–4, which increased to 6.2 million among people above 70 years old. Compared to that, premature death that resulted from respiratory diseases is generally less harmful for old people. If evaluated in monetary terms, it would only cause an economic loss of 2.7 million in that cohort. However, respiratory diseases would sound terrifying for 0–4-year-old children since deaths caused by respiratory diseases are more than five times higher than those caused by cardiovascular diseases.

According to our estimation, 32.1 % of respiratory-disease-induced depreciation in human capital could be attributed to young child death, which accounted to 3.9 million. The cost is so high because (1) newborns' immunity systems are weak and they are more likely to die if infected by air pollution, and (2) individual death in the youngest cohort results in the highest loss since they potentially have the most future incomes.

Finally, we evaluate the loss of premature death from each district of Beijing. As shown in Fig. 7, the three districts with the highest risks of death from air pollution are Chaoyang, Haidian, and Fengtai, with 20.5, 16.9, and 11.3 % of air-pollution-induced premature deaths located in each district.

Population size is the primary reason for regional differences in air-pollution-induced premature death and economic losses. The districts that suffered the most from such death are those with the largest populations, including Chaoyang (population of 3.745 million), Haidian (population of 3.484 million), and Fengtai (population of 2.214 million). In addition, regional emissions are also responsible for regional variation of premature death due

**Table 3** A comparison of PM<sub>10</sub>'s chemical composition in Beijing and Hong Kong

Beijing		Hong Kong	
Item	Percentage	Lower boundary	Higher boundary
Source: Zhang et al. 2007a, b		Source: Ho et al. 2003	
OC	6.4–12.4 %	4.11 %	25.52 %
EC	2.3–5.6 %	1.01 %	12.01 %
Source: Sun et al. 2006			
Ca	4.53 %	0.00 %	8.07 %
Fe	1.64 %	0.00 %	2.58 %
Al	3.81 %	0.04 %	2.29 %
Ti	0.23 %	0.00 %	70.53 %
Mg <sup>2+</sup>	0.98 %	0.10 %	2.62 %
Mn	0.08 %*	1.65 %	96.29 %
Cr	4.19 %	0.89 %	19.18 %
Ni	0.04 %*	3.05 %	27.47 %
V	8.18 %	1.63 %	14.08 %
As	0.01 %*	1.01 %	20.57 %
Zn	0.16 %	0.00 %	2.01 %
Pb	0.08 %*	39.55 %	100.00 %
Cu	0.03 %*	11.09 %	100.00 %
Na <sup>+</sup>	0.68 %	1.21 %	22.44 %
Cl <sup>-</sup>	1.00 %	0.34 %	29.39 %
K <sup>+</sup>	0.58 %	0.63 %	4.06 %
NH <sub>4</sub> <sup>+</sup>	1.68 %	0.90 %	8.57 %
SO <sub>4</sub> <sup>2-</sup>	3.71 %	3.80 %	41.91 %
NO <sub>3</sub> <sup>-</sup>	1.48 %	2.47 %	14.38 %

Data presented in the table are either direct citations or calculations based on the research results from the three field studies cited in the table. Sample air of Beijing was collected in 2004 and that of Hong Kong was collected in the winter season of 2001 (November 2000 to February 2001). We would assume that air pollution composition in each city would not change a lot over this period. All studies employed rigorous procedures in evaluating PM<sub>10</sub>'s chemical composition, and all have been published in well-recognized journals (see the reference list). In addition to the common chemical symbols, the abbreviation of OC refers to organic carbon and EC for elemental carbon. While the weights of most chemical components of Beijing's PM<sub>10</sub> lie in the confidence intervals of that in Hong Kong, which means those chemical components do not differ significantly as a composition in polluted air of Beijing and Hong Kong, those highlighted with \* do involve such significance, and all highlighted components are hazardous. However, for these hazardous chemicals, their concentration was lower in Beijing, which is quite out of our expectation. Further research efforts would be needed to explain such counter-expectation phenomenon. If it is assumed that those hazardous chemical components in air would impose greater risks on human health, the substitution of Beijing's dose-response coefficient with that of Hong Kong may exaggerate our estimation about the loss from pollution-induced death

to air pollution. As Kenneth et al. (1993) and Tolley et al. (1994) analyzed, vehicle exhaust is one of the major

**Table 4** Mortality rates of cardiovascular and respiratory diseases across age cohorts, 2012 (unit = 1/100,000)

Age groups	0–	5–	10–	15–	20–	25–	30–	35–
CD	7.35	0.85	1.70	2.37	3.38	4.44	8.30	17.33
RD	34.95	1.13	0.66	0.61	0.99	0.79	1.55	2.72
Age groups	40–	45–	50–	55–	60–	65–	70–	75–80
CD	35.71	58.23	99.28	160.18	262.79	487.59	1020.39	1954.55
RD	4.27	5.58	12.10	20.85	41.07	90.29	228.31	538.04

Data source: calculated by the authors based on *China Health Statistical Synopsis 2012*

CD cardiovascular diseases, RD respiratory diseases

**Table 5** Annual mean pollutant concentration ( $\mu\text{g}/\text{m}^3$ ) and population (10,000) of districts in Beijing

District	PM <sub>10</sub>	Population	District	PM <sub>10</sub>	Population
Dongcheng	113	90.8	Changping	97	183
Xicheng	111	128.7	Shunyi	98	95.3
Yizhuang	126	33	Pinggu	98	42
Haidian	114	348.4	Miyun	85	47.4
Chaoyang	114	374.5	Huairou	87	37.7
Shijingshan	124	63.9	Yanqing	82	31.7
Fengtai	113	221.4	Annual average	114	
Tongzhou	119	125	Maximum	138	
Daxing	124	147	Minimum	97	
Fangshan	122	98.6	NAAQS grade I	40	
Mentougou	109	29.8			

Data source: 2012 Beijing environment bulletin

**Table 6** Correlation between air pollution and the morbidity rates of respiratory and cardiovascular diseases in sample districts

	Fengtai	Shijingshan	Daxing
Respiratory disease	0.642	0.638	0.710
Cardiovascular disease	0.385	0.384	0.639

**Table 7** Morbidity dose-response coefficients of respiratory and cardiovascular diseases

District	Disease	Dose-response coefficient	Weight
Fengtai	RD	0.0071	0.2161
	CD	0.0056	0.1810
Shijingshan	RD	0.0096	0.2774
	CD	0.0031	0.3098
Daxing	RD	0.0060	0.5066
	CD	0.0043	0.5092

**Table 8** Mortality dose-response coefficients of respiratory and cardiovascular diseases

Air pollutant	Disease	City average dose-response coefficient
PM <sub>10</sub>	RD	0.004823154
	CD	0.001957569

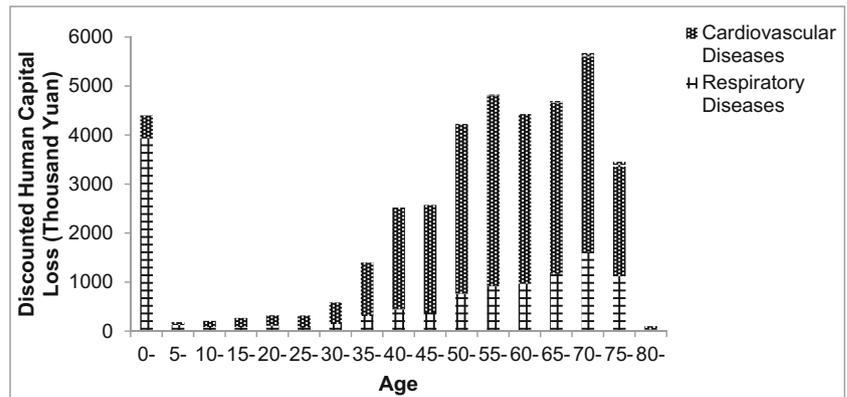
sources of urban emissions. Thus, the costs of air pollution, either in the form of a higher mortality rate or as the associated economic loss, should concentrate around areas with high volume of traffic. In the city of Beijing, two regions are most susceptible to traffic jams: one covers the eastern parts of the 2nd and 3rd Ring Road, both of which are located in Chaoyang District, and the other covers the western part of the 2nd Ring Road, which is located at the intersection of Haidian and Xicheng districts (Public Security Traffic Management Bureau, Beijing Municipal Government). Chaoyang and Haidian are the two districts that suffered most economic losses from air pollution, as estimated in our study.

Another major source of urban emission is industry. Pollution concentration tends to be upheaved in regions

**Table 9** Mortality rates of respiratory and cardiovascular diseases by air pollutant

District	PM <sub>10</sub>		District	PM <sub>10</sub>	
	CD	RD		CD	RD
Dongcheng	1.31 %	3.53 %	Fangshan	1.48 %	3.96 %
Xicheng	1.28 %	3.43 %	Mentougou	1.24 %	3.33 %
Yizhuang	1.55 %	4.16 %	Changping	1.03 %	2.75 %
Haidian	1.33 %	3.58 %	Shunyi	1.04 %	2.80 %
Chaoyang	1.33 %	3.58 %	Pinggu	1.04 %	2.80 %
Shijing Shan	1.51 %	2.02 %	Miyun	0.81 %	2.17 %
Fengtai	1.31 %	3.53 %	Huairou	0.85 %	2.27 %
Tongzhou	1.42 %	3.82 %	Yanqing	0.76 %	2.03 %
Daxing	1.51 %	4.06 %	Average	1.28 %	3.34 %

**Fig. 6** Economic losses from premature death across age cohorts and by diseases



with extensive industrial activities, such as Chaoyang, Haidian, Fengtai, Tongzhou, and Xicheng. The five districts together produced 38 % of total industrial added value of Beijing, and they also paid the most losses from air pollution (Fig. 8).

Finally, lack of vegetation coverage may aggravate adverse health impact of air pollution. As shown in Fig. 9, vegetation coverage in the five districts that incurred the most economic loss from air-pollution-induced premature death are all below the city's average level, i.e., 46.2 %.

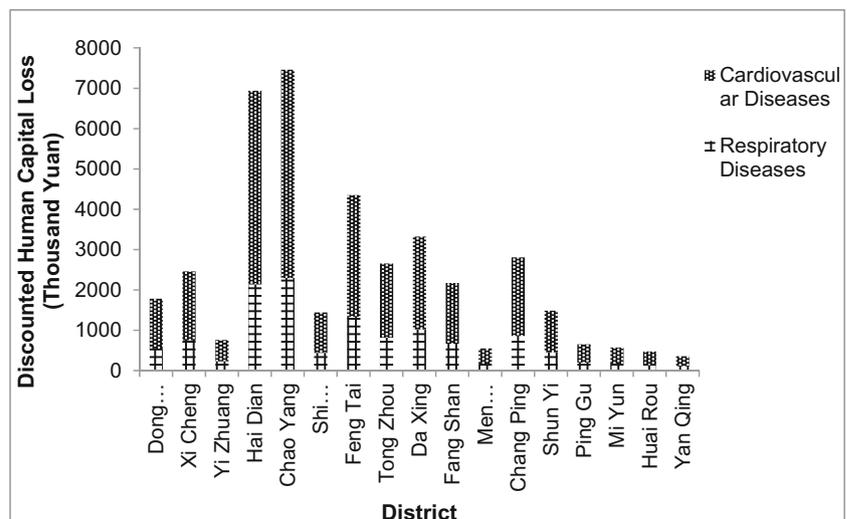
**Concluding remarks**

We provide the most updated estimation of how air pollution influences human health in Beijing with field data collected in three local hospitals in 2012. We also estimate the resultant economic losses. According to our estimation, 278,000 patients with cardiovascular diseases and 190,700 patients with respiratory diseases were victims of the city's air pollution. Among them, 346 people

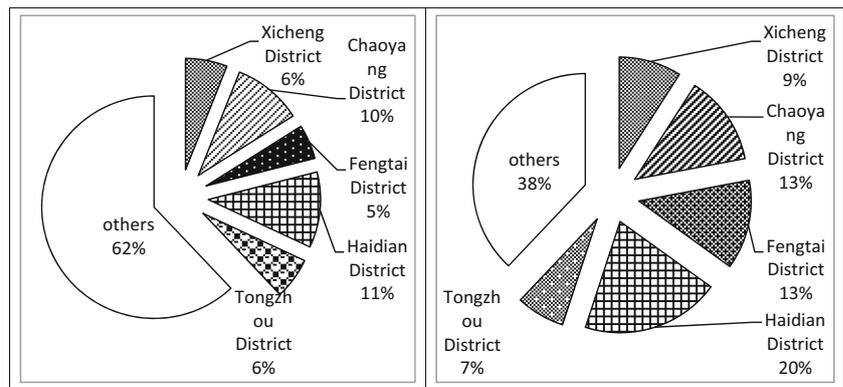
died of cardiovascular diseases and 204 died of respiratory diseases, respectively accounting for 1.27 and 1.64 % of the total deaths from the two kinds of diseases. Considering both the medical costs spent on disease treatment and depreciation of human capital from premature death, the economic losses that resulted from air pollution in Beijing is 583.0218 million, accounting for 0.03 % of the city's GDP in 2012. The total is composed of four parts: (1) medical cost of 106.8632 million spent on cardiovascular disease treatment, (2) medical cost of 73.3051 million spent on respiratory disease treatment, (3) human capital depreciation of 284.5620 million due to premature death that resulted from cardiovascular diseases, and (4) human capital depreciation of 118.2915 million due to premature death that resulted from respiratory diseases.

Our estimation should be used with caution. On the one hand, we select sample hospitals from more polluted districts in Beijing, and when estimating the mortality rate of premature death from air pollution, we substitute the dose-response coefficient calculated based on the data from Hong Kong,

**Fig. 7** Economic losses from premature death by diseases and districts



**Fig. 8** Distributions of industrial production (*left plot*) and construction (*right plot*) in districts of Beijing, 2012. Data source: *Beijing Statistical Yearbook 2012*



where polluted air contains a higher percentage of hazardous chemical components. Both facts may exaggerate the loss from air pollution in our study. However, on the other hand, we do not include the potential loss from infrastructure and building accelerated aging, damaging the city image, reduced investment opportunity, tourism slipping (tourist arrivals, especially inbound tourists, have decreased from 2009), and people’s negative emotion that stemmed from air pollution, all of which would make this study a conservative one.

Air pollution’s health impacts are significantly varied along the dimensions of age and region in Beijing. Facing air pollution, people of old age and children generally suffer more than the other groups. Senior people over 70 years old and children under 5 years old are the major victims of Beijing’s air pollution. As to regional difference, health conditions of people living Chaoyang, Haidian, Fengtai, Tongzhou, and Daxing are more likely to be adversely affected by air pollution, with the first three districts facing the highest risks of death from air pollution.

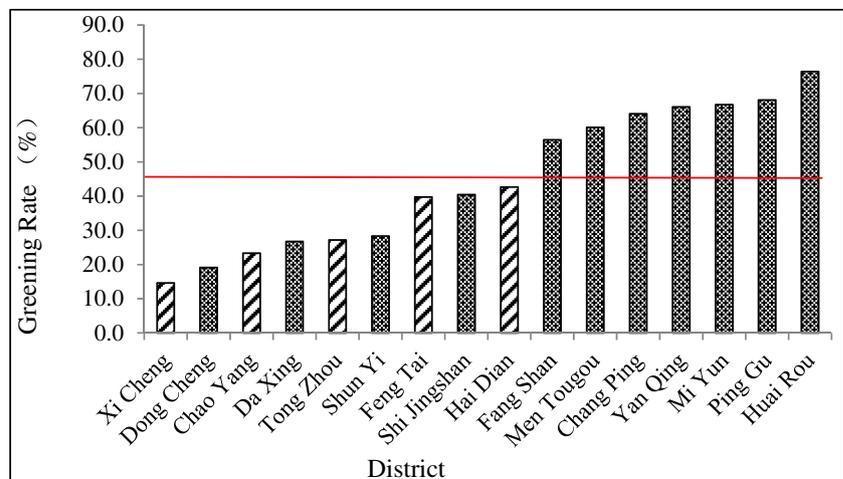
In order to mitigate the negative impacts on human health of air pollution in Beijing, the following policy interventions are possibly effective. First, as the most fatal pollutant in Beijing, emission of PM<sub>10</sub> (of course including PM<sub>2.5</sub>) should be strictly controlled, possibly in ways

including but not limited to shifting Beijing’s industrial structure towards a highly technical and environmental friendly one, curbing private vehicle ownership growth, promoting the development of electric vehicles, reducing traffic jam with improved traffic management system, and cleaning power generation. Second, steps should be taken to green the city, especially the most industrialized parts of Chaoyang, Haidian, and Fengtai, through afforestation. Third, special protective measures should be applied to the elderly and children, as they are most vulnerable air pollution harms.

The main contribution of the paper is to empirically investigate the impact of air pollution on people’s health and accordingly economic loss in Beijing, China. Due to the availability of data, our results may be biased because we only used data collected from three sample hospitals, and we have to use the correlation between the number of premature deaths caused by diseases and air pollutants in Hong Kong to roughly estimate that in Beijing.

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**Fig. 9** Average vegetation coverage of Beijing and its districts, 2012. The red line indicates average coverage in Beijing. Data source: *Beijing Statistical Yearbook 2012*



## References

- An AP, Ke LF, Dong HQ (2006) The effect of atmosphere environment upon human health. *J Environ Occup Med* 3(22):78–81 (in Chinese)
- Aunan K, Pan X (2004) Exposure-response functions for health effects of ambient air pollution applicable for China: a meta-analysis. *Science of the Total Environ* 2004(3):3–16
- Bravo MA, Son J, de Freitas CU, Gouveia N, Bell ML (2016) Air pollution and mortality in São Paulo, Brazil: Effects of multiple pollutants and analysis of susceptible populations. *J Expo Sci Environ Epidemiol*, 26(2):150–61
- Cao, C. H., Han, L. Y., 2014. Evaluation of health costs by PM<sub>10</sub> pollution in Beijing. Working paper. Available at [http://sem.buaa.edu.cn/Teacher/Templet/NewTemplet\\_PL.aspx?tid=84&scolid=11](http://sem.buaa.edu.cn/Teacher/Templet/NewTemplet_PL.aspx?tid=84&scolid=11) (in Chinese)
- Chen BH, Hong CJ, Zhu HG et al (2002) Quantitative evaluation of the impact of air sulfur dioxide on human health in the urban districts of Shanghai. *J Environ Health* 11(1):56–59 (in Chinese)
- Chen R, Kan H, Chen B et al (2012) Association of particulate air pollution with daily mortality: the China Air Pollution and Health Effects Study. *Am J Epidemiol* 175:1173–1181
- Daniel R, Petrolia TK (2011) Preventing land loss in coastal Louisiana: estimates of WTP and WTA. *J Environ Manag* 92(3):859–865
- Dong XW, Zhi RZ (2010) Valuing recreational benefits of environmental amenity based on contingent valuation method: a case study of Jiuzhai Gou. *Conf Environ Sci Inf Appl Technol* 2:91–94
- Dong SZ, Zhang ZY, Cai CK et al (2007) Effects of air pollution on pulmonary function of children in industrial area. *J Environ Health* 15(2):71–73 (in Chinese)
- Dusseldorp A, Kruize H, Brunekreef B et al (1995) Association of PM<sub>10</sub> and airborne iron with respiratory health of adults living near a steel factory. *Am J Respir Crit Care Med* 152:1032–1039
- Hausman A, Ostro B, Wise DA (1984) Air pollution and lost work. *NBER*. 31, 1263
- HEI Accountability Working Group (2003) Assessing health impact of air quality regulations: concepts and methods for accountability research. HEI communication
- Ho KF, Lee SC, Chan CK, Yu JC, Chow JC, Yao XH (2003) Characterization of chemical species in PM<sub>2.5</sub> and PM<sub>10</sub> aerosols in Hong Kong. *Atmos Environ* 37:31–39
- Holland M, Watkiss P, Pye S, Oliveira AD, Regemorter DV (2005) Cost-benefit analysis of policy option scenarios for the Clean Air for Europe Programme. AEA Technology Environment
- International Monetary Fund (2012) World Economic Outlook Database-April 2012 Edition. Available at <http://www.imf.org/external/pubs/ft/weo/2012/01/weodata/index.aspx>
- Kan HD, Chen BH (2004) Particular air pollution in urban areas of Shanghai, China: health-based economic assessment. *Sci Total Environ* 322(1):71–79
- Kuehn BM (2014) WHO: more than 7 million air pollution deaths each year. *J Am Med Assoc* 311(15):1486
- Künzli N, Kaiser R, Medina S, Studnicka M, Chanel O, Filliger P, Herry M, Horak F Jr, Puybonnieux-Textier V, Quénel P, Schneider J, Seethaler R, Vergnaud J-C, Sommer H (2000) Public-health impact of outdoor and traffic-related air pollution: a European assessment. *Lancet* 356:795–801
- Kwiterovich P (1997) The effect of dietary fat, antioxidants, and pro-oxidants on blood lipids, lipoproteins, and atherosclerosis. *Am Diet Assoc* 97:31–41
- Li J, Guttikunda SK, Carmichael GR et al (2004) Quantifying the human health benefits of curbing air pollution in Shanghai. *J Environ Manag* 70(1):49–62
- Ostro BD (1983) The effects of air pollution on work loss and morbidity. *J Environ Econ Manag* 10(4):371–382
- Pope CA III, Dockery DW (2006) Health effects of fine particulate air pollution: lines that connect. *J Air Waste Manag Assoc* 56:709–742
- Reuters Staff BEIJING (2014) China sets targets for curbing air pollution, Reuters Health Medical News. January 9
- Samakovlis E, Huhtala A, Bellander T, Svartengren M (2005) Valuing health effects of air pollution focus on concentration-response functions. *J Urban Econ* 58(2):230–249
- Sun Y, Zhuang G, Tang A, Wang Y, An Z (2006) Chemical characteristics of PM<sub>2.5</sub> and PM<sub>10</sub> in haze-fog episodes in Beijing. *Environ Sci Technol* 40:3148–3155
- WHO (2006) Air Quality Guidelines, Global Update 2005, particulate matter, ozone, nitrogen dioxide and sulphur dioxide. WHO Regional Publications, WHO Regional Office for Europe, Copenhagen
- WHO (2013) Review of Evidence on Health Aspects of Air Pollution - REVIHAAP Project. WHO Regional Publications, WHO Regional Office for Europe, Copenhagen
- Xu MM, Guo YM, Zhang YJ, Westerdahl D et al (2014) Spatiotemporal analysis of particulate air pollution and ischemic heart disease mortality in Beijing, China. *Environ Heal* 13(1):1–12
- Yang MJ, Pan XC (2008) Time-series analysis of air pollution and cardiovascular mortality in Beijing, China. *J Environ Health* 25(4): 294–297
- Zhang LY, Liu FZ, Jin L (1999) The study on the effects of air pollution on the children's health in an industrial area in Tianjin. *J Environ Health* 16(2):93 (in Chinese)
- Zhang XM, Pei XK, Wang JH (2000) Epidemiological study on air pollution. *J Environ Health* 17(1):9
- Zhang M, Song Y, Cai X (2007a) A health-based assessment of particulate air pollution in urban areas of Beijing in 2000–2004. *Sci Total Environ* 376(1–3):100–108
- Zhang R, Cao J, Lee S, Shen Z, Ho K (2007b) Carbonaceous aerosols in PM<sub>10</sub> and pollution gases in winter in Beijing. *J Environ Sci* 19: 564–571