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RESEARCH ARTICLE

Health damage assessment of particulate matter pollution in Jing-Jin-Ji region of China

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Abstract
Jing-Jin-Ji is the largest and most dynamic economic region in northern China, and its air pollution has attracted much public attention. Scientific evaluation of health losses caused by air pollution can provide decision-making basis for formulation and improvement of pollution reduction policies in the Jing-Jin-Ji region. This paper estimated the adverse effects of particulate matter pollution on health in the Jing-Jin-Ji region in 2016 by using logarithmic linear exposure-response function, and monetized the health effects by adjusting human capital method and disease cost method. The results show non-ignorable health hazards and economic impacts caused by atmospheric particulate pollution. The economic losses relevant to health hazards by PM2.5 in the Jing-Jin-Ji region are 122.40 billion yuan, and those relevant to PM10 are 118.34 billion yuan, accounting for 1.62% and 1.56% of the region's GDP, respectively. Similar evaluations previously conducted in other countries yielded figures within the same order of magnitude. Considering the difference in economic losses per unit among disease types, the economic losses caused by air pollution in the Jing-Jin-Ji region mainly come from premature deaths. Infants and elderly people are the main victims of particulate matter. Affected by population, pollutant concentration, industrial structure, and other factors, the economic losses of particulate matter pollution in Beijing, Tianjin, Shijiazhuang, Tangshan, and Baoding are large. In order to reduce health hazards and economic impacts caused by particulate matter pollution, this paper put forward to guide the urban population diversion, reduce the outgoing frequency of susceptible groups such as infants and the elderly in haze weather, adopt high-efficiency particulate matter air purifier indoors, and develop public transportation to reduce motor vehicle exhaust emissions. In Tianjin and Hebei, promoting cleaner production in industries such as steel and cement and reducing coal use in the power industry are also suggested.

Keywords Health damage · Economic losses · Particulate matter pollution · Exposure-response function · Jing-Jin-Ji region

Introduction

With the rapid development of China's economy, the rapid progress of industrialization and urbanization, it is obvious for the overall deterioration of air quality in Chinese cities and regions. Extreme air pollution incidents occur frequently, especially in urban economic belts such as the Jing-Jin-Ji region, the Pearl River region, the Yangtze River region, and the Guanzhong region (Wang et al. 2014). Jing-Jin-Ji is the largest and most dynamic economic region in northern China. Under

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China's New Normal, the severe ecological environment has become an important constraint to promote the coordinated development of Jing-Jin-Ji region. For a long time, Jing-Jin-Ji region has been seriously affected by air pollution, and fog and haze weather showed a sustained high incidence (Wang et al. 2017). According to the "Ecology Bulletin of China's Environmental Situation in 2017" issued by the Ministry of Ecology and Environment of China, six of the ten cities with poor air quality in the 74 key monitoring cities are located in the Jing-Jin-Ji region. The proportion of fine days of 13 cities in Jing-Jin-Ji region ranged from 38.9 to 79.7%, with an average of 56.0%. Five of those cities had fine days less than 50%.

The increasing pollution not only causes serious problems but also could threaten to end human life on our planet (Li and Zhang 2018). Among the known air pollutants, particulate matter is considered as the most harmful and representative pollutant to human health, and is the main component of haze pollution. A large number of epidemiological studies have confirmed that particulate matter (PM) pollution is closely related to mortality and morbidity of many diseases, and is most significantly related to adverse health effects (Pope 2000). With the rapid development of urban motor vehicles and industry, the air pollution in Jing-Jin-Ji region has changed from the traditional coal-smoke pollution to the more complex composite air pollution of coal-smoke and motor vehicle exhaust. Particulate matter has become the primary pollutant in Jing-Jin-Ji region. The number of days with PM2.5 and PM10 as the primary pollutants accounted for 59.2% of the total pollution days (Ministry of ecological environment of China 2018). Therefore, it is necessary to pay attention to the health impact of the particulate matter pollution and evaluate the economic losses.

The impact of environmental pollution on public health has attracted the attention of scholars at home and abroad for a long time. Current research mainly focuses on three aspects: first, the relationship between air pollution and health exposure response; second, the research on the health impact of air pollution; and third, the monetization of air pollution, that is, the determination of economic losses caused by premature deaths or illness of the affected population.

Over the past 30 years, many foreign studies have reported the exposure-response relationship between atmospheric pollution and human health (Yu et al. 2007). Dockery et al. (1993) analyzed the relationship between long-term exposure to atmospheric pollution and mortality in six American cities. The American Cancer Society conducted a cohort study to assess the relationship between long-term exposure to fine particulate air pollution and all-cause mortality, lung cancer mortality, and cardiopulmonary mortality (Pope et al. 2002). The Public Health and Air Pollution in Asia (PAPA) project assessed the effects of short-term exposure to air pollution on daily mortality in Bangkok, Thailand, and in three cities in China: Hong Kong, Shanghai, and Wuhan (Wong et al. 2008). Since the 1990s, Chinese researchers have also begun exploring the relationship between exposure-response to atmospheric pollution and health outcomes by using case-control methods. Aunan and Pan (2004) proposed exposure-response functions for health effects of PM10 and SO_2 pollution in China. Kan et al. (2007), Qian et al. (2007), and Xu et al. (2014) examined the associations of daily cause-specific mortality with daily mean concentrations of particulate matter in Shanghai, Wuhan, and Beijing. In addition, a number of studies have reported the relationship between air pollution and tumor mortality, adverse respiratory effects, outpatient and emergency visits, immune system effects, and adverse reproductive outcomes (Li et al. 2016a, b; Burnett et al. 2014; Xie et al. 2009).

The key to quantitatively analyze and evaluate the health risk of air pollution is to determine the number of premature deaths caused by air pollution and the number of hospitalizations and morbidity, that is, the amount of hazards. Although the health effects caused by air pollution cannot be attributed to certain kinds of air pollutants, some scholars still focus on analyzing the impact of air pollution on human health. Khaniabadi et al. (2018) estimated the mortality and morbidity due to PM10 and SO_2 in Iran. Chen et al. (2018) discussed the relationship between daily variation in air pollution and student illnesses and absences from more than 3000 schools in Guangzhou, China. Brønnum-Hansen et al. (2018) estimated the health benefits of reduced exposure to vehicle emissions at the residence among the citizens of Copenhagen Municipality, Denmark. A generalized additive model (GAM) was used by Ma et al. (2017) to investigate the short-term effects of air pollutants (PM10, SO_2, and NO_2) on daily cardiovascular admissions from March 1st to May 31st during 2007 to 2011 in Lanzhou, China. Fang et al. (2016) analyzed the impact of PM2.5 on deaths in 74 cities in China. Similar studies are also known as Chen et al. (2013), Pope et al. (1995), Bergin et al. (2005), Ostro et al. (1996), Xu et al. (2014), Wong et al. (2002), and Son and Bell (2013).

Air pollution not only endangers health, but also causes economic losses. As to what extent to the changes in the air pollution content will affect the economy through people's physical health, they are mainly manifested in two aspects: first, the decline of people's health, fatigue, disease and death, which leads to the decline or losses of people's ability to work, resulting in a decline in income, that is, the depreciation of human capital; second, the increase of diseases related to environmental changes leads to the increase of medical and prevention costs (Zhao et al. 2014). For example, Quah and Boon (2003) and Zhu et al. (2013) estimated the health costs of air pollution in Singapore and China, respectively, believing that air pollution has a direct and serious impact on public health. Guo and Chen (2018) applied the generalized addictive model (GAM) to analyze the association between ambient air pollutants and asthma patients with economic cost assessment in Shanghai. Hedley et al. (2008) estimated the cost of childhood asthma attributable to residential NRP exposure, O_3 and NO_2 levels in Los Angeles County. Ridker (1967) used the human capital method to calculate the economic losses of different diseases caused by air pollution in the United States in 1958. Zmirou et al. (1999), Patankar and Trivedi (2011), and Zhang et al. (2008) adopted the economic burden of disease to assess the medical costs resulting from exposure to particulate air pollution in three metropolitan areas of France, Mumbai, and 111 cities in China, respectively. Istamto et al. (2014) conducted a multinational study in the framework of a large European project and estimated the economic value of traffic-related air pollution and noise damage using the willingness to pay method. Li et al. (2016a) assessed the public health and economic losses caused by air pollution in 74 Chinese cities on the basis of revising the data of Ho and Jorgenson (2007). Guo and Hammitt (2009) estimated the economic value of mortality risk in China using the compensating-wage-differential method.

After analyzing, the existing literature has the following deficiencies: (1) Most of the studies are carried out in a certain country or region. The Jing-Jin-Ji region in China is densely populated and has serious air pollution problems. With the implementation of air pollution control policies, SO_2, NO_2, and other pollutants basically meet the national secondary standards, but particulate matter (PM) pollution has not been effectively solved, and the assessment of its health effects is obviously inadequate. (2) Because of the late development of the actual measurement of pollutants in China, a lot of literature use conversion coefficient to convert one pollutant into another, which brings great uncertainty to the analysis. (3) In the quantitative assessment of the economic losses of health risk, the methods commonly used in the world are willingness to pay method, human capital method, compensation wage method, disease cost method, and adjustment according to existing research results. The willingness to pay method is to evaluate the value through the risk willingness survey. If the questionnaire is designed differently, there is a big gap between the answers and the results are very controversial (Cao and Han 2015). The traditional human capital method is pre-measurement method with ethical and moral defects (Zhao et al. 2014). Compensation wage method is seldom applied in China. Under the condition of fully competitive labor market, every job seeker has a clear understanding of the risk of injury and death of work, and the choice of work and salary. The actual situation of the research object is not considered when adjusting results according to the previous literature, and the error is large.

In view of this, this paper used the newly available data, and based on the exposure-response coefficient, the adjusted human capital method and the disease cost method were adopted to study the health effects and economic losses of air particulate matter pollution of Jing-Jin-Ji region in 2016.

Materials and methods

On the basis of the main problems (air pollution factors, health outcomes, health outcomes exposure-response relationship) what determines the health effects caused by particulate matter pollution, the exposure-response relationship between pollutants and human health impacts was established. The monitoring data of urban environmental quality in Jing-Jin-Ji region were used. The number of premature deaths, the number of hospitalized patients with respiratory and circulatory diseases, the incidence of bronchitis and asthma, and the number of outpatient visits caused by atmospheric particulate matter pollution of Jing-Jin-Ji region in 2016 were obtained, and the health and economic losses caused by atmospheric pollution were estimated.

Health impact mechanism of air pollution and the determination of pollution factors

Air pollution is a major public health problem, especially the impact of particulate matter on health attracts more attention. The health effects of particulate matter are closely related to the composition of particulate matter. In the process of air suspension, particulate matter in the air suspension process will further absorb the organic and metal chemical components, bacteria, viruses, fungi, and other microbial components in the air, thus damaging the respiratory defense function and causing blood rheology alteration, acute vascular dysfunction, plaque instability, cardiac dysrhythmias, and atherosclerosis development. Particulates larger than 10 μm are not easy to enter the respiratory tract. Particulates smaller than 2.5 μm are easy to stay in the terminal bronchioles and alveoli, and some components can penetrate the alveoli into the blood, which has a greater impact on health. Therefore, PM2.5 and PM10 are selected as the indicators of air pollutants in this paper. They are also the primary air pollutants in Jing-Jin-Ji region.

Threshold of pollution factors

The threshold of pollution refers to the minimum concentration of pollutants that may cause adverse health effects. Whether there is a threshold for atmospheric pollutants is a key issue in health impact assessment. In the

1980s, the Air Quality Guideline (AQG) promulgated by the World Health Organization (WHO) recognized the existence of a threshold for health hazards and suggested the benchmark recommended in the guidelines as a threshold (Shah et al. 1997). A large number of epidemiological studies have also shown that when some air pollution reaches a certain concentration, the corresponding incidence and mortality of the population will change. Current studies suggest that PM2.5, the main component of haze, can enter the human body, which is very harmful to the body and has no threshold for health effects. Therefore, in this study, the zero concentration was used for PM2.5, and the World Health Organization (WHO) atmospheric quality guidance value of 15 μg/m^3 is selected as PM10 reference concentration.

Selection of health outcomes

The impact of particulate matter on human health is very complex. Damages to human health caused by particulate matter mainly include the rise of mortality, morbidity, emergency rate, outpatient rate and hospitalization rate, and the decline of human immune function. The following principles should be followed in selecting the outcome of health effects of air pollution: (1) Give full consideration to the availability of data and give priority to disease endpoints that can be provided by China's health statistics, i.e., health and disease data that can be statistically analyzed according to the International Classification of Diseases (ICD10), including data on population mortality, hospital admissions, and outpatient and emergency visits by health institutions. (2) Choose the health hazard outcomes of exposure-response relationship with atmospheric pollutants known in previous literature. (3) Choose health hazard outcomes that can be compared with similar studies.

According to the above basic principles, respiratory and circulatory diseases with strong correlation with atmospheric pollution are selected as the outcomes of health hazards in this study, including mortality, morbidity, the number of hospitalizations, and absence of work due to disease and other measurable indicators. The number of days off in the outpatient and emergency service is not considered due to the difficulty of obtaining data.

Health effects of air pollution

Human health is often affected by many factors, when the concentration of pollutants exceeds a certain value, it will become a cause of respiratory diseases and cardiovascular diseases. At present, most of the epidemiological studies on air pollution are based on proportional hazards model of Poisson regression. Under this model, the health effect value of a certain air pollutant concentration is:

$$E = E_0 \times \exp[\beta \times (C - C_0)]. \tag{1}$$

Therefore, the change of health risk attributable to air pollution is:

$$\Delta E = E - E_0 = E_0 \times \{\exp[\beta \times (C - C_0)] - 1\} \\ = E \times \{1 - 1/\exp[\beta \times (C - C_0)]\}. \tag{2}$$

Therefore, as long as the parameters of E, β, C, and C_0 are obtained and combined with the exposure population P, the change of health effects attributable to the change of atmospheric pollutant concentration can be calculated.

$$I = P \times \Delta E = P \times E \times \{1 - 1/\exp[\beta \times (C - C_0)]\} \tag{3}$$

Among them, β is the exposure-response coefficient, i.e., the percentage of change in the health effect value caused by the increase of unit concentration of pollutants. ΔE represents the health effect caused by pollutants, E is the actual health effect value (such as mortality, outpatient rate, incidence), C is the actual concentration of pollutants, and C_0 is the critical concentration of pollutants (reference concentration).

When determining the parameters of exposure-response relationship between air pollution and health terminal, most studies abroad have been carried out under the condition of low concentration of air pollution. The exposure-response coefficients cannot be directly applied to China with high pollution concentration. In this paper, the exposure-response relationship coefficients of various health terminals in Jing-Jin-Ji region are determined by using Chinese research results and foreign research results as supplements (Table 1).

Health economic losses

The physical quantity and economic losses of health hazards caused by air pollution consist of two parts: (1) premature deaths and loss of deaths caused by air pollution; (2) the increase of hospitalization, morbidity, and days off work of patients with respiratory and cardiovascular diseases caused by air pollution and their economic losses. The cost of hospitalization and sickness due to air pollution is estimated by the disease cost method, and income losses due to premature deaths are estimated by the revised human capital method. The sum of the two parts is the health cost caused by air pollution.

Table 1 Parameters of exposure-response between air pollutants and health terminals

Influence classification	Health terminals	Exposure-response coefficients	Source
PM2.5			
Death	Cardiovascular	0.53 (0.15,0.90)	Xie et al. (2009)
	Respiratory	1.43 (0.85,2.01)	Xie et al. (2009)
	Lung cancer	5.56 (3.02,8.11)	Fang (2014)
Hospitalization	Cardiovascular	0.68 (0.43,0.93)	Liu et al. (2010)
	Respiratory	1.09 (0,2.21)	Liu et al. (2010)
Morbidity	Acute bronchitis	7.90 (2.70,13.00)	Liu et al. (2010)
	Asthma—the whole crowd	2.10 (1.45,2.74)	Xie et al. (2009)
Outpatient	Internal medicine	0.49 (0.27,0.70)	Liu et al. (2010)
	Pediatric	0.56 (0.20,0.90)	Liu et al. (2010)
PM10			
Death	Cardiovascular	0.40 (0.31,0.49)	Xie et al. (2009)
	Respiratory	0.65 (0.35,0.95)	Xie et al. (2009)
	Lung cancer	8.55 (4.65,12.48)	Our study[a]
Hospitalization	Cardiovascular	0.66 (0.36,0.95)	Liu et al. (2010)
	Respiratory	1.24 (0.84,1.62)	Liu et al. (2010)
Morbidity	Acute bronchitis	5.50 (1.89,9.11)	Liu et al. (2010)
	Asthma—the whole crowd	1.90 (1.45,2.35)	Xie et al. (2009)
Outpatient	Internal medicine	0.34 (0.19,0.49)	Liu et al. (2010)
	Pediatric	0.39 (0.14,0.64)	Liu et al. (2010)

Exposure-response coefficient is the percentage (%) and 95% confidence interval of mortality change per 10 μg/m^3 increase in pollutant concentration

[a] Conversion as PM2.5/PM10 ≈ 0.65 (Cao et al. 2011)

Economic losses of premature deaths caused by air pollution

Economic losses caused by premature deaths refer to the future income loss due to premature deaths of residents. The research steps are as follows:

First, calculate the number of premature deaths among residents of different ages caused by air pollutants.

$$p_{\chi\delta n} = \lambda_{\delta n} \times P_{\chi\delta} \tag{4}$$

Among them, $p_{\chi\delta n}$ is the number of deaths of the δ-*th* disease in the n-th age group caused by the χ-th pollutant, $\lambda_{\delta n}$ is the death rate of the δ disease in the n-th age group (under 1 year, 1–4 years old, then every 5 years for an interval, up to 85 years old, a total of 19 age groups). $P_{\chi\delta}$ is the total number of premature deaths of the δ-th disease caused by the χ-th pollutant.

Second, calculate the number of years in which an individual dies earlier than his life expectancy.

$$t_i = s_i - k_i \tag{5}$$

Among them, t is the number of premature *deaths; s* is the life expectancy; k is the age of death; and i is the different regions.

Third, discount the future income loss caused by premature death of the individual

$$GDP_i = \frac{GDP_0(1+\alpha)^i}{(1+\gamma)^i} \tag{6}$$

Among them, GDP_i is the per capita GDP of each year in the future (the *ith*-year) converted to the base year (2016); GDP_0 is the per capita GDP in the base year; α is the per capita annual GDP growth rate (calculated according to the average of 6.3% in the past 3 years). γ is the discount rate (which is 4.7% of the current medium- and long-term loan interest rate).

Fourth, sum up the losses of the future years

$$c = \sum_{i=1}^{t} GDP_i \tag{7}$$

Among them, c is the sum of economic losses caused by premature death for individuals.

Fifth, calculate the sum of economic losses of all premature deaths caused by pollution.

$$C_T = \sum_{\delta=1}^{3} \sum_{n=1}^{19} p_{\chi\delta n} c \tag{8}$$

Table 2 Health effects of air pollution in Jing-Jin-Ji region (thousand person)

	Classification	Diseases	Beijing	Tianjin	Hebei	Jing-Jin-Ji region
PM 2.5	Death	Cardiovascular	9.65 (3.12, 14.49)	6.64 (2.13, 10.03)	32.16 (10.34, 48.48)	51.62 (16.84, 76.93)
		Respiratory	9.71 (6.92, 11.53)	6.77 (47.87, 8.09)	32.644 (23.150, 38.97)	51.11 (36.79, 60.34)
		Lung cancer	10.21 (9.24, 10.37)	7.312 (6.544, 7.446)	35.01 (31.44, 35.62)	53.13 (48.10, 54.12)
	Hospitalization	Cardiovascular	27.34 (18.82, 34.44)	18.85 (12.924, 23.840)	91.24 (62.623, 115.253)	145.75 (100.887, 182.729)
		Respiratory	90.70 (0, 132.43)	62.93 (0, 93.125)	304.05 (0, 448.213)	479.95 (0, 691.977)
	Morbidity	Acute bronchitis	150.32 (129.70, 150.79)	107.95 (91.603, 108.397)	516.38 (440.332, 518.364)	784.51 (675.761, 1308.055)
		Asthma	211.07 (175.72, 232.82)	148.26 (122.52, 164.49)	713.80 (591.13, 790.62)	1103.78 (925.08, 2003.46)
	Outpatient	Internal medicine	3107.02 (1848.00, 4134.51)	2135.96 (1265.62, 2852.08)	10,346.65 (6137.27, 13,802.18)	16,633.39 (9945.84, 22,034.39)
		Pediatric clinic	1164.44 (471.27, 1671.63)	801.44 (322.35, 1156.69)	3880.93 (1563.70, 5592.73)	6224.09 (2540.97, 8874.66)
	Total		4780.45 (2662.80,6393.00)	3296.11 (1828.48,4424.19)	17,450.77 (9798.98,23,160.49)	25,527.33 (14,290.26,33,977.68)
PM 10	Death	Cardiovascular	7.97 (6.38, 9.45)	6.44 (5.19, 7.61)	36.10 (29.27, 42.30)	56.34 (43.60, 62.86)
		Respiratory	5.89 (3.53, 7.77)	4.71 (2.87, 6.12)	25.86 (16.12, 32.92)	38.36 (24.00, 48.77)
		Lung cancer	10.38 (10.11, 10.39)	7.46 (7.26, 7.47)	35.69 (34.74, 35.73)	54.41 (52.97, 54.48)
	Hospitalization	Cardiovascular	27.82 (16.90, 36.24)	22.21 (13.69, 28.56)	121.93 (76.97, 153.61)	180.89 (114.57, 227.56)
		Respiratory	101.64 (78.68, 117.81)	79.16 (62.30, 90.51)	418.23 (337.58, 468.65)	619.48 (500.28, 695.06)
	Morbidity	Acute bronchitis	148.59 (115.46, 150.66)	107.57 (87.96, 108.38)	516.99 (449.91, 518.39)	784.78 (668.32, 790.07)
		Asthma	206.79 (180.93, 225.09)	157.48 (139.82, 169.35)	805.18 (730.20, 851.49)	1196.13 (1082.17, 1269.12)
	Outpatient	Internal medicine	2378.24 (1405.04, 3245.57)	1928.99 (1148.76, 2612.49)	10,859.70 (6551.23, 14,528.85)	16,170.10 (9780.14, 21,590.11)
		Pediatric clinic	899.59 (354.30, 1349.64)	727.77 (354.30, 1078.50)	4080.20 (1663.91, 5928.99)	6070.98 (2486.50, 8797.56)
	Total		3786.91 (2171.34, 5152.62)	3041.80 (1758.31, 4108.99)	18,340.13 (10,822.89, 24,273.97)	25,168.83 (14,752.54, 33,535.58)

Note: Hebei is calculated from the average concentration of pollutants in 11 regions, while the Jing-Jin-Ji region is sum of 13 regions

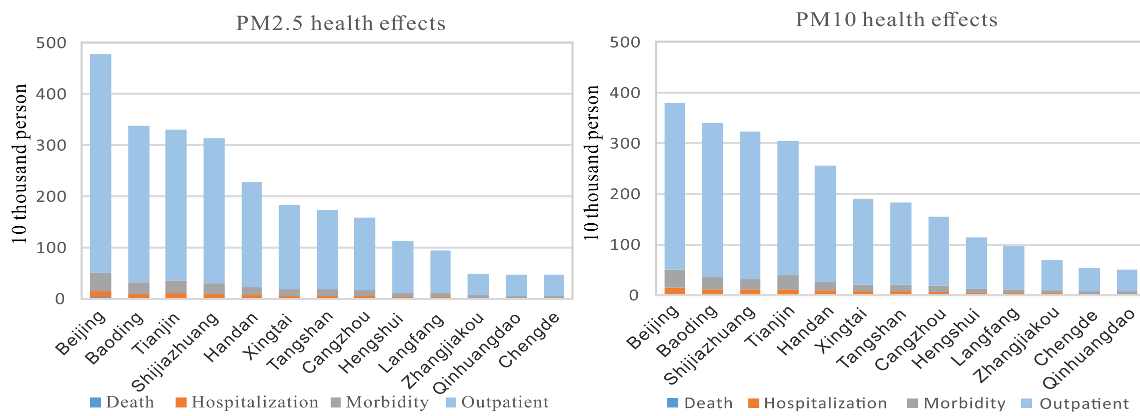

Fig. 1 Health effect of particulate matter pollution in Jing-Jin-Ji region (measured by mean value)

C_T is the sum of the economic losses from all individuals who died prematurely due to pollution; δ is the cause of premature deaths due to environmental pollution, which mainly refers to lung cancer, cardiovascular diseases and respiratory diseases in this article. n is the age group of individuals who die prematurely under environmental pollution.

Economic losses of hospitalization and disease caused by air pollution

The economic losses of disease caused by air pollution from hospitalization, morbidity, and work rest are shown in the following formula:

$$C_i = \left(C_{pi} + GDP_p \times T_i\right) \times \Delta I_i \quad (9)$$

where, C_i refers to the total cost of diseases caused by air pollutants to health terminal i; C_{pi} is the disease cost per case of health terminal i, $GDPp$ is the daily average per capita GDP of Jing-Jin-Ji region (yuan/person day), and T_i is the health effect change of health terminal i caused by air pollution.

Data sources and descriptions

The health costs of air pollution are not only related to the concentration of air pollution, but also related to the social and economic development of the whole city, such as population size, economic development level, hospitalization, and outpatient expenses. The concentration data of PM2.5 and PM10 are obtained from the Ministry of Ecology and Environment of the People's Republic of China. In this paper, the permanent residents in Beijing, Tianjin, and Hebei cities at the end of 2016 are taken as the exposed population. Population, per capita GDP, GDP, and other economic data are derived from Beijing, Tianjin, and Hebei statistical yearbooks. Data such as per capita medical expenses of outpatients and inpatients, hospital expenses for different diseases, average hospitalization days, life expectancy in each region, and age-related disease mortality of residents are derived from the 2017 China Health and Family Planning Statistical Yearbook. The number of people in different age groups is from China's sixth census.

Results and discussion

Health damage assessment

Data on baseline mortality, morbidity, and hospitalization rates, as well as population exposure at different ages, were brought into the "exposure-response" relationship model, and the estimated results of deaths, hospitalizations, and sick populations in various regions were shown in Table 2.

It can be seen from the assessment results that the health damage caused by particulate matter pollution in Hebei Province is higher than that in Beijing and Tianjin. The number of health damage caused by PM2.5 in Beijing, Tianjin, and Hebei reached 4.78 million, 3.30 million, and 17.45 million, and the number of health damage caused by PM10 reached 3.79 million, 3.04 million, and 18.34 million. To a certain extent, even without considering the interaction between different regions, the control of local pollutants can also bring good health benefits.

Affected by PM2.5, there are about 155.86 thousand premature deaths in Jing-Jin-Ji region, while PM10 results in 149.11 thousand premature deaths. PM2.5 also results in 145.75 thousand hospitalizations for cardiovascular diseases, 479.95 thousand hospitalizations for respiratory diseases, 784.51 thousand acute bronchitis, and 1103.78 thousand asthma cases, and an increase of 16,633.39 thousand and 6224.09 thousand for medical and pediatric outpatient visits. In contrast, PM10 pollution has a greater non-fatal health effect, resulting in 800.37 thousand hospitalizations, 784.78 thousand episodes of acute bronchitis, 1196.13 thousand asthma attacks, and 22,241.08 thousand outpatient visits. This is mainly due to the higher average concentration of pollutants in PM10 in Jing-Jin-Ji region in 2016.

Table 3 Economic effect assessment of air pollution in Jing-Jin-Ji region (million yuan)

	Classification	Diseases	Beijing	Tianjin	Hebei	Jing-Jin-Ji region
PM 2.5	Death	Cardiovascular	12,643 (4086,18,983)	7869 (2526,11,884)	11,393 (3730,16,991)	31,905 (10,342,47,858)
		Respiratory	10,396 (7415,12,349)	6544 (4630,7826)	9052 (6539,10,660)	25,992 (18,584,30,836)
		Lung cancer	20,599 (18,640,20,907)	13,342 (11,940,13,585)	17,919 (16,240,18,266)	51,859 (46,820,52,758)
	Hospita lization	Cardiovascular	348 (240, 344)	239 (164, 238)	1084 (753, 1245)	1671 (1156,1827)
		Respiratory	741 (0, 1324)	510 (0, 931)	2127 (0, 4664)	3378 (0, 6920)
	Morbidity	Acute bronchitis	174 (150, 175)	108 (92, 108)	275 (235, 278)	557 (477, 561)
		Asthma	244 (203, 270)	148 (123, 164)	384 (323, 422)	777 (649, 856)
	Outpatient	Internal medicine	1400 (833, 1863)	635 (376, 847)	2524 (1514, 3335)	4559 (2723, 6045)
		Pediatric clinic	525 (212, 753)	238 (96, 344)	944 (387, 1340)	1707 (695, 2437)
Total			47,071 (31,780,56,969)	29,631 (19,946,35,928)	45,701 (29,721,57,200)	122,404 (81,446,150,097)
PM 10	Death	Cardiovascular	10,440 (8362,12,378)	7637 (6146,9015)	13,086 (10,660,15,276)	31,163 (25,168,36,669)
		Respiratory	6312 (3786,8319)	4552 (2771,5919)	9503 (6045,11,901)	20,368 (12,602,26,139)
		Lung cancer	20,935 (20,380, 20,963)	13,616 (13,255,13,634)	18,592 (18,099,18,617)	53,143 (51,734,53,213)
	Hospita lization	Cardiovascular	354 (215, 462)	281 (173, 361)	1426 (915, 1775)	2062 (1304, 2597)
		Respiratory	831 (643, 963)	641 (504, 733)	2865 (2345, 3180)	4337 (3493, 4876)
	Morbidity	Acute bronchitis	172 (134, 174)	108 (88, 108)	277 (242, 278)	556 (463, 561)
		Asthma	239 (209, 261)	157 (140, 169)	432 (395, 455)	829 (744, 885)
	Outpatient	Internal medicine	1072 (633, 1463)	573 (341, 776)	2629 (1601, 3486)	4274 (2576, 5725)
		Pediatric clinic	405 (160, 608)	216 (86, 320)	985 (408, 1411)	1606 (654, 2340)
Total			40,760 (34,522, 45,590)	27,782 (23,505, 31,037)	49,795 (40,711, 56,380)	118,337 (98,738, 133,007)

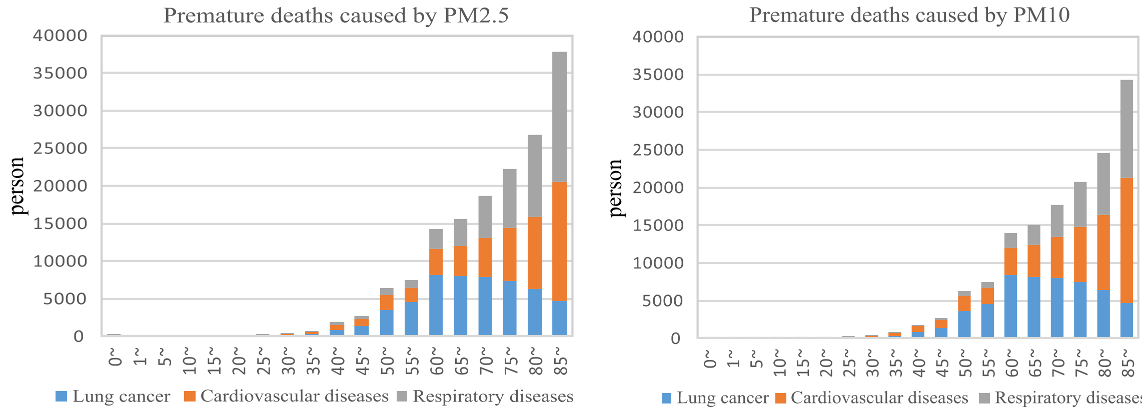

Fig. 2 Death of different ages and pathogenies in Jing-Jin-Ji region (measured by mean value)

As can be seen from Fig. 1, the health effects of particulate matter pollution in Beijing are far greater than that of other cities in the Jing-Jin-Ji region. The health damages in Baoding, Shijiazhuang, and Tianjin are great, while Zhangjiakou, Chengde, and Qinhuangdao have smaller health damages. This is consistent with the findings of Huang and Zhang (2013). This is because Beijing, Tianjin, and other megacities or large cities have higher pollutant concentration, relatively dense population and more people exposed to pollution, so they are also greatly affected by air pollution.

In terms of health types, the number of outpatients caused by air particulate matter pollution in the Jing-Jin-Ji region increased the most, with the impact of PM2.5 and PM10 reaching 22.86 million and 22.24 million, respectively, and the number of deaths was at least, with 155.86 thousand deaths and 149.11 thousand deaths, respectively. Overall, the number of hospitalized patients with respiratory diseases is greater than that with cardiovascular diseases, the prevalence of asthma is higher than that with acute bronchitis, and the number of medical outpatients is increasing more than that of pediatric outpatients.

Healthy economic evaluation

The economic effects of air pollution in Jing-Jin-Ji region are shown in Table 3.

From the perspective of administrative divisions, the health and economic losses caused by air pollution in Beijing, Tianjin, and Hebei are very large (Table 3). The health economic damages caused by PM2.5 are 47.07 billion yuan (31.78 billion yuan–56.97 billion yuan), 29.63 billion yuan (19.95 billion yuan–35.93 billion yuan), and 45.70 billion yuan (29.72 billion yuan–57.20 billion yuan), respectively. They accounted for 1.83% (1.23–2.21%), 1.66% (1.11–2.01%), and 1.43% (0.93–1.78%) of the GDP, respectively. This is slightly lower than the evaluation results of Chen (2018) and Xie et al. (2016), and higher than that of Liu et al. (2010). The health economic damages caused by PM10 are 40.76 billion yuan (34.52 billion yuan–44.59 billion yuan), 22.78 billion yuan (23.51 billion yuan–31.04 billion yuan), and 49.80 billion yuan (40.71 billion yuan–56.38 billion yuan), accounting for 1.59% (1.34–1.78%), 1.55% (1.31–1.74%), and 1.55% (1.27–1.76%) of GDP, respectively. This is similar to the evaluation results of 74 cities in China by Li et al. (2016a), but slightly lower than that of Yu et al. (2007).

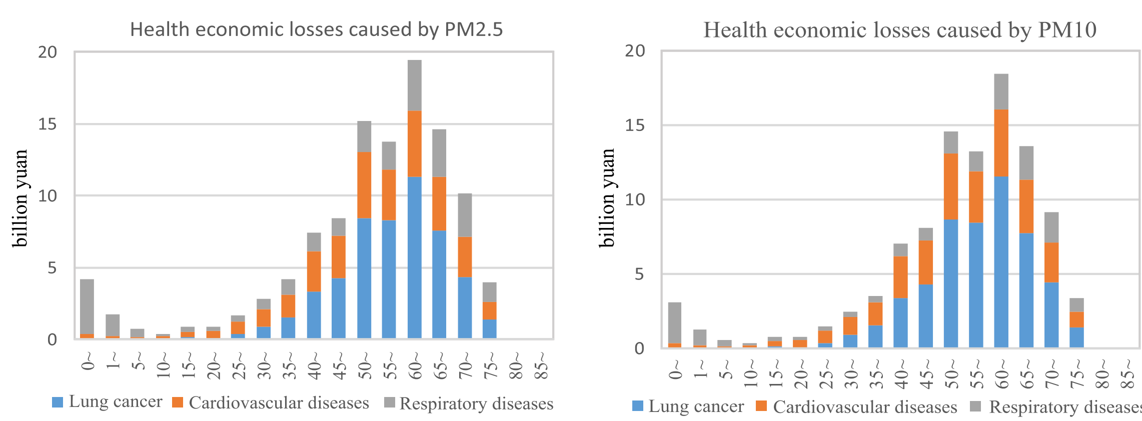

Fig. 3 Economic losses of different ages and pathogenies from premature deaths in Jing-Jin-Ji region (measured by mean value)

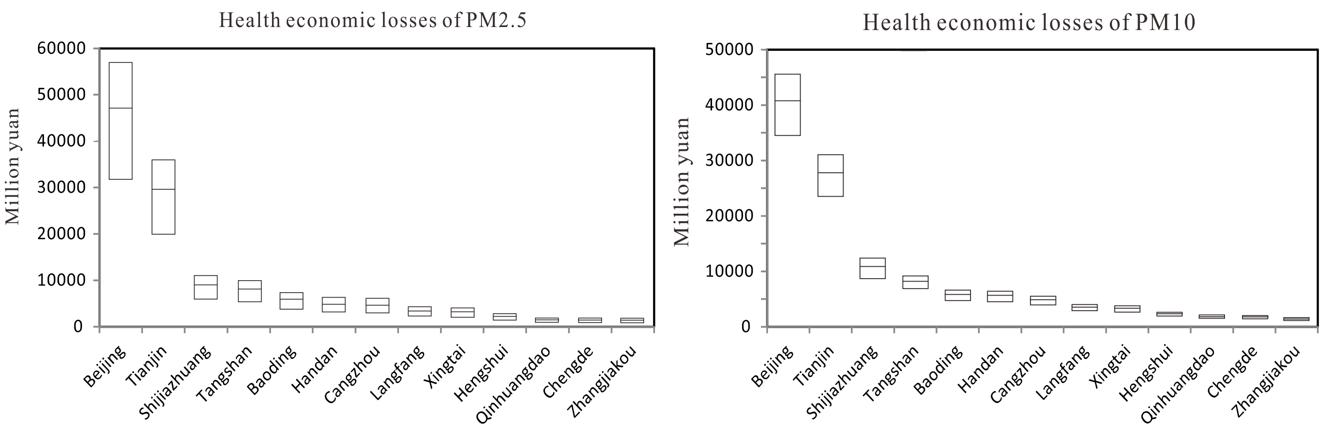

Fig. 4 Health economic losses of particulate matter pollution in Jing-Jin-Ji region

The difference in estimation results reflects the degree of pollution, economic development level, and exposed population in different regions to a certain extent, and this is also related to the selection and estimation of pollutants and the choice of health terminals.

As mentioned above, the number of deaths caused by atmospheric particulate matter pollution is smaller than that caused by hospitalization, disease, and outpatient service, but the economic losses caused by premature deaths caused by PM2.5 and PM10, respectively account for 90.4% and 86.1% of the total losses, and the health economic losses caused by premature deaths are higher than other types. This is consistent with the conclusions on indoor air pollution in France proposed by Boulanger et al. (2017). Premature deaths and the costs of the quality of life loss in France accounted for approximately 90% of the total cost. Formulas (4) ~(8) can be used to calculate the number of premature deaths caused by particulate matter pollution in Jing-Jin-Ji region in 2016 (Fig. 2). It can be seen that the number of premature deaths caused by particulate matter pollution increases with the age of residents. When the residents are in the age range of 5 to 35 years old, the number of premature deaths caused by particulate matter pollution is very small, and from the age of 35, the number of premature deaths gradually rises. At the age of 55, the number of premature deaths caused by particulate matter pollution rises rapidly. It is worth noting that the mortality of cardiovascular and respiratory diseases caused by atmospheric particulate matter is relatively high in the age group of 0–5 years and over 45 years, that is, infants and the elderly are the main victims of particulate matter pollution.

The economic losses of health by age and cause in Jing-Jin-Ji region are shown in Fig. 3. The economic losses of premature deaths caused by particulate matter are increasing. The healthy economic losses of premature deaths due to lung cancer and cardiovascular disease increases with the age of the death population in the 0–60 age group. The economic losses due to premature deaths of respiratory diseases gradually decreased between 0 and 10 years old, and increased gradually between 10 and 60 years old. The economic losses of premature deaths caused by PM2.5 and PM10 between 0 and 5 years old amounted to 5.97 billion yuan and 4.22 billion yuan respectively, accounting for 22.7% of all respiratory diseases. This is due to the fact that infants and young children have poor self-immunity and are prone to premature deaths after being polluted by air. Furthermore, the premature deaths of infants and young children leads to more life loss than other age groups, so the potential economy losses are greater.

Figure 3 also shows that all three diseases gradually declined after 60. This is mainly because according to the principle of adjusting the human capital method, the life losses caused by premature deaths of the elderly is lower than that of infants and young adults. When a child and an elderly person die from air pollution, the economic losses of the child is greater than that of the elderly, which results in that although particulate matter causes more deaths among the elderly, the economic losses are less than that of the former. The economic losses after the age of 80 is 0, because the life expectancy of the region is not above 80 years.

From the perspective of various areas in Jing-Jin-Ji region, the top five areas caused by particulate matter pollution are Beijing, Tianjin, Shijiazhuang, Tangshan, and Baoding, while Zhangjiakou, Chengde, and Qinhuangdao are the three regions with the lowest health economic losses. The health economic losses of Beijing, Tianjin, Baoding, and Qinhuangdao are greatly affected by PM2.5, while those of other areas are greatly affected by PM10. The average economic losses caused by PM2.5 and PM10 amounted to 122.40 billion yuan and 118.34 billion yuan (Fig. 4). This makes the particulate matter pollution in these areas relatively large, and potential economic losses are ranked in the top five, higher than in other regions.

The causes of regional differences in health damage and economic losses are not only influenced by uncertainties such as research methods, but also closely related to factors such as regional population, pollutant emissions, and industrial structure. The more the population, the greater the exposure to pollutants, and the more the health pollution losses caused by residents. According to Fang et al. (2017), the resuspended dust (17.5–35.0%), vehicle exhaust (14.9–23.6%), and secondary particulates (20.4–28.8%) are the major source categories of ambient particulate matter. Therefore, in places with a high degree of urbanization development, serious road dust, and heavy vehicle exhaust emissions, a large number of particulate pollutants are often produced. The particulate pollutants are also positively correlated with indoor inhalable bacteria and fungi, which may lead to some common diseases, such as respiratory symptoms, allergies, and asthma, and seriously endanger human health (Liu et al. 2017). The impact of regional industrial structure should not be ignored. Industry and construction are easy to cause air pollution. According to statistics, Beijing, Tianjin, Shijiazhuang, Tangshan, and Baoding accounted for 72% of the total industrial output in Jing-Jin-Ji region, and 75% of the total construction output, making particulate matter pollution in these areas is relatively large, and the potential economic losses are ranked in the top five, higher than other areas.

Conclusion and policy implications

Conclusion

Taking 2016 as the base year, the health effects and economic losses of particulate pollutants in Jing-Jin-Ji region were evaluated. The following conclusions are obtained.

(1) Two kinds of particulate matter pollution caused the largest increase in outpatient numbers and the least number of deaths. Compared to PM2.5, the non-fatal health effects caused by PM10 pollution are greater. More attention should be paid to the fatal health hazard of PM2.5.
(2) The average health and economic losses caused by PM2.5 and PM10 amount to 122.40 billion yuan and 118.34 billion yuan, respectively, accounting for 1.62% and 1.56% of the region's GDP. The results of the evaluation are slightly lower than those of previous studies. The economic losses caused by air pollution in Jing-Jin-Ji region are not as serious as expected. The economic losses from premature deaths caused by PM2.5 and PM10 account for 90.4% and 86.1% of the total losses, respectively. Health effects are mainly due to economic losses caused by premature deaths.
(3) Deaths from cardiovascular diseases and respiratory diseases caused by particulate matter pollution are relatively high in the ages of 0–5 years and 45 years old. In the healthy economic losses of respiratory diseases, the loss of premature deaths from respiratory diseases are relatively high in the age of 0–5 years old. Infants and elderly people are the main victims of particulate matter pollution. In respiratory diseases, infants and young children are more vulnerable groups.
(4) The health and economic losses caused by particulate matter pollution in Beijing, Tianjin, Shijiazhuang, Tangshan, and Baoding are higher than those in other areas. It can be seen that the economic losses caused by particulate matter pollution are more serious in large cities with large population density and heavy industrial cities.

Policy implications

The health costs caused by air pollution are the losses of society and families. Relevant studies have shown that man-made environmental pollution is the intrinsic internal cause of air pollution, but when the emission source is relatively stable, adverse meteorological conditions, as external causes, are often the decisive factors for the formation of air pollution (Peng 2013). At present, the government has taken many measures to control air pollution. In order to achieve long-term control effect, people can participate in improving some policies and measures to achieve continuous improvement of air quality. Based on the above research conclusions, the following policy implications are obtained:

(1) Excessive population exposure to polluted air, as an important factor, may cause health costs. In order to reduce the economic losses, overpopulation in central urban areas should be controlled by guiding urban population diversion through the development of characteristic industries in suburban areas.
(2) The air pollution levels and population characteristics of different cities in the Jing-Jin-Ji region are quite different, and the health benefits brought by air pollution control are also very different. This paper shows that the elderly and children are disadvantaged groups in resisting the damage caused by pollutants, which is the main factor causing economic losses of premature deaths. In the case that it is difficult to effectively reduce air pollution emissions in the short term, health protection for the elderly and children should be strengthened. Respiratory tracts of the elderly and children are relatively more sensitive to climate change, so it is necessary to keep warm in winter and spring, and minimize outdoor travel in haze days. The use of high-efficiency particulate matter air purifiers in indoors can effectively reduce indoor PM 10 and PM 2.5 exposure.
(3) Healthy economic losses are higher in Beijing, Tianjin, Shijiazhuang, Tangshan, and Baoding, and the concentrations of pollutants in these areas are usually higher. Vehicle exhaust emissions and high proportion of

industrial and construction industries are important factors leading to particulate matter pollution in these areas. The emission reduction policies in Jing-Jin-Ji region can be oriented according to functional positioning and pollutant emission characteristics of each region. Beijing should rely on the development of new energy automobile industry, introduce and develop new energy busses, actively develop urban rapid transit system, and reduce the exhaust emissions of motor vehicles on the ground. Heavy industrial cities in Tianjin and Hebei should complete cleaner production audits in iron and steel, cement, and other industries to improve energy efficiency, and conduct coal removal and clean substitution in the power industry to control coal consumption. Qinhuangdao, Chengde, Zhangjiakou, and other places that are less damaged by particulate matter pollution can improve the service system and develop tourism, making it a leisure and old-age base for Beijing and Tianjin.

Limitations

In this study, health impacts and economic losses of air pollution in the Jing-Jin-Ji region were analyzed, in the hope of providing reference for the formulation of air pollution control policies based on health effects. In the research, the Chinese research results can be adopted as far as possible, which can effectively reduce the error caused by the particularity of international research. At the same time, health effects of a number of diseases were evaluated, including not only respiratory diseases and cardiovascular diseases in the hospital and clinic, but also the incidence of acute bronchitis and asthma. The analysis method, process and results were clarified and the rigor of the evaluation was reflected; however, there is still a lack of cohort studies on the health damage of air pollution in China, and the results of health damage assessment under different methods are quite different and controversial. Furthermore, due to the late start of research on the health effects of pollutants in China and the limitations of the original data and basic research, there are still some uncertainties in this study, mainly as follows: (1) The threshold selection still needs to be further explored, the existence or the value of the threshold will cause the difference of evaluation results. (2) There is a lack of systematic statistics on the incidence of various diseases in China. Regional differences in population health status and the accuracy of statistical data may have an impact on the evaluation results, bringing uncertainty to the evaluation results, and the uncertainty trend is difficult to judge. (3) The occurrence of diseases is complex and influenced by many factors. At present, the impact mechanism of air pollution on health is not completely clear. The causes of health outcomes and the extent of air pollution's influence on health outcomes still need to be further studied. (4) The time length of the data used in this paper is limited, and the methods adopted mainly refer to the existing research methods. The scientificity of the methods needs to be further tested, so there may be some errors caused by assumptions.

This paper mainly used the results of epidemiological studies in China, and estimated the mean, upper and lower bounds of the calculated results, which controlled the uncertainties in a relatively reliable range. The results of the calculation mainly serve for policy improvement or the introduction of preventive policies, while not necessarily accurately determine the reasons for the health outcomes and the influences of air pollution on health.

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