



Including intangible costs into the cost-of-illness approach: a method refinement illustrated based on the PM_{2.5} economic burden in China

Bangzhu Zhu^{1,2} · Runzhi Pang² · Julien Chevallier^{3,4}  · Yi-Ming Wei⁵ · Dinh-Tri Vo^{3,6}

Received: 12 December 2017 / Accepted: 23 October 2018 / Published online: 30 October 2018
© Springer-Verlag GmbH Germany, part of Springer Nature 2018

Abstract

The concentrations of particulate matter with aerodynamic diameters less than 2.5 μm (PM_{2.5}) and 10 μm (PM₁₀) is a widespread concern and has been demonstrated for 103 countries. During the past few years, the exposure–response function (ERf) has been widely used to estimate the health effects of air pollution. However, past studies are either based on the cost-of-illness or the willingness-to-pay approach, and therefore, either do not cover intangible costs or costs due to the absence of work. To address this limitation, a hybrid health effect and economic loss model is developed in this study. This novel approach is applied to a sample of environmental and cost data in China. First, the ERf is used to link PM_{2.5} concentrations to health endpoints of chronic mortality, acute mortality, respiratory hospital admission, cardiovascular hospital admission, outpatient visits—internal medicine, outpatient visits—pediatrics, asthma attack, acute bronchitis, and chronic bronchitis. Second, the health effect of PM_{2.5} is monetized into the economic loss. The mean economic loss due to PM_{2.5} was much heavier in the North than the South of China. Furthermore, the empirical results from 76 cities in China show that the health effects and economic losses were over 4.98 million cases and 382.30 billion-yuan in 2014 and decreased dramatically compared with those in 2013.

Keywords PM_{2.5} · Exposure–response function · Cost-of-illness method · Willingness-to-pay method · Health effects · Economic losses

JEL Classification Q5

✉ Bangzhu Zhu
wpzbz@126.com

✉ Julien Chevallier
julien.chevallier@ipag.fr

¹ Business School, Nanjing University of Information Science and Technology, Nanjing 210044, China

² Industrial and Economic Research Institute, Jinan University, Guangzhou 510632, China

³ IPAG Business School, IPAG Lab, 184 Boulevard Saint-Germain, 75006 Paris, France

⁴ Université Paris 8, LED, 2 rue de la Liberté, 93526 Saint-Denis, France

⁵ Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China

⁶ University of Economics Ho Chi Minh City, 59C Nguyen Dinh Chieu Dist. 3, Ho Chi Minh City, Vietnam

Introduction

Air pollution has a great effect on human health and has become a widespread concern [2]. The World Health Organization (WHO) announced that the concentrations of particulate matter with aerodynamic diameters less than 2.5 μm (PM_{2.5}) and 10 μm (PM₁₀) in more than 2400 cities distributed throughout 103 countries were higher than the ambient air quality standard in 2016 [48], which indicates that global PM_{2.5} pollution is very serious and has become a widespread concern.

During the past few years, the exposure–response function (ERf) has been widely used to estimate the health effects of air pollution. It refers to the relationship between the concentration of contaminants and the incidence of premature death or illness in exposed populations. In this article, it indicates more specifically the percentage change in the incidence rate of premature death or disease caused by per 1 μg/m³ fluctuation of PM_{2.5} in the concentration

level. A large number of studies have used it to measure the relationships between air pollution exposure and human health in developed countries. For example, some studies conducted in America [7, 32], Austria, France, and Switzerland [20], Europe [26], Italy [6] and 14 WHO member states [5] all concluded that great health effects could be attributed to $PM_{2.5}$, PM_{10} , and other air pollutants.

Past studies were either based on the cost-of-illness (COI) or the willingness-to-pay (WTP) approach. They ignored intangible costs, as well as costs due to the absence of work. To address this limitation, this study develops a hybrid health effect and economic loss model. Based on the previous literature [14, 17, 23, 31, 40], this article combines the exposure–response function with the economic burden of disease analysis to estimate the health effect and economic loss respectively due to $PM_{2.5}$ in China. These two approaches were usually used in the medical and epidemiology field separately, while rarely used to evaluate the costs caused by environmental pollution. Therefore, the hybrid health effect and economic loss model will provide a theoretical reference for cost analysis of environmental pollution.

To demonstrate the empirical relevance of the new method, we implement it on a sample of Chinese cities. The purpose of this illustrative example is to show that the hybrid model proposed can be applied in various contexts worldwide, including Europe. China is the second largest economy in term of GDP. Only 16 of 161 cities in China met the updated air quality standard in 2014 [34]. Hence it appears urgent to estimate the health effect and economic loss of air pollutions including $PM_{2.5}$ to design and implement the targeted abatement measures in this country. Recently the health effect of air pollutions has also been estimated by the ERf method in China [9, 17, 22, 52]. Several characteristics can be found from these studies. First, most of them focused on developed cities or regions, including Dalian [43], Shanghai [40], Taiyuan [38], Hongkong [37], Nanjing [21], the Yangtze River Delta [42], the Pearl River Delta [22], 75 major cities in China [9] and 32 large cities in China [53]. However, pollution characteristics, economic development level and geographical population distribution are different from cities to cities. More empirical results are necessary to measure the negative impacts of air pollution in China. Second, existing studies focused on estimating the health effects of PM_{10} , SO_2 , and NO_2 [35, 53], few on $PM_{2.5}$. During recent years, air pollution in urban areas in China has transformed from coal-smog pollution into a mixture of coal-smog and automobile pollution. $PM_{2.5}$ has become one of the heavy fog and haze pollutions in China. Third, they only focused on the health endpoints of all-cause, cardiopulmonary, respiratory mortality and hospital admissions [12], few on else health endpoints. However, air pollution has numerous health endpoints; more health endpoints should be taken into

account to make the health effect estimation more accurate and comprehensive.

This study aims to propose a hybrid health effect and economic loss model. Besides this theoretical contribution, we include an example of application on a sample of 76 Chinese cities that can be relevant in the European setting as well. The central methodological contribution consists in using the ERf to link $PM_{2.5}$ concentrations to nine health endpoints, including chronic mortality, acute mortality, respiratory hospital admission, cardiovascular hospital admission, outpatient visits—internal medicine, outpatient visits—pediatrics, asthma attack, acute bronchitis, and chronic bronchitis. Owing to the new method, more health endpoints are introduced into the estimation. Namely, the health effect of $PM_{2.5}$ is monetized into the economic loss through the economic burden of disease analysis, willingness to pay (WTP) and cost of illness (COI) methods [46, 47]. Furthermore, scenario analysis is conducted to capture the uncertainties of the estimations of health effect and economic loss of $PM_{2.5}$.

With respect to the illustration based on a sample of 76 cities in China, the results show that the health effect and economic loss were over 4.98 million cases and 382.30 billion yuan (RMB), accounting for 2.16% of total urban population and 1.33% of total GDP of these cities in 2014, which decreased dramatically compared with those in 2013. More importantly, the health effects in 2014 accounted for 14.34% of GDP growth of the 76 cities at the constant prices of 2013. Furthermore, in the baseline scenario, the mean health effect of $PM_{2.5}$ in the North was 13,366 cases higher than that of the South with the same $PM_{2.5}$ concentration and total urban population.

It is worth noting that, although the object of this article is Chinese residents, the method of environmental pollution costs analysis is appropriate for various countries including emerging countries as well as European countries. In previous studies, the WTP and COI method were usually used in the medical and epidemiology field, while rarely used to evaluate the economic losses caused by environmental pollution. Therefore, we combine the two methods and the exposure–response function to measure the health effects and the economic losses due to $PM_{2.5}$ respectively, which can provide a theoretical reference for cost analysis of environmental pollution in various countries. Meantime, the article will enable global readers, including European readers, to deeply understand China, and take effective measures to avoid greater health costs due to $PM_{2.5}$ when they invest or work in China.

The remainder of the article is structured as follows. “[Hybrid health effect and economic loss model for \$PM_{2.5}\$](#) ” details the new methodology. “[Illustration of the new model based on Chinese data](#)” explains the data set of Chinese cities used for illustrative proposes. “[Empirical results achieved by](#)

the hybrid model in the context of Chinese cities” contains the results and sensitivity tests. “Conclusion” concludes.

Hybrid health effect and economic loss model for PM_{2.5}

The exposure–response function (ERf)

In this study, the ERf is used to estimate the health effect of PM_{2.5} by linking the PM_{2.5} concentrations to nine health endpoints, classified by the ICD-10 code. Not everyone exposed to PM_{2.5} pollution would suffer health effects. The human health is often affected by many factors, a threshold value that is the lowest concentration of PM_{2.5} below which no harmful health effects can be observed is introduced to identify the health effects due to PM_{2.5}. Only when the PM_{2.5} concentration exceeds the threshold value, PM_{2.5} can become a cause of respiratory diseases and cardiovascular diseases and so on. The exposure–response coefficient measures the percentage change of the incidence rate of health endpoints due to PM_{2.5} in populations exposed PM_{2.5} concentrations above the threshold value when compared with that of populations under the threshold of PM_{2.5} concentration. Following Refs. [9, 22, 40, 52], the exposure–response function is expressed as:

$$I_0 = \frac{I}{\exp(\beta \times (C - C_0))},$$

where I_0 is the incidence rate of mortality or morbidity of health endpoints at the threshold of PM_{2.5} concentration. β is the exposure–response coefficient, C is the actual PM_{2.5} concentration, C_0 is the threshold of PM_{2.5} concentration, and I is the normal incidence rate of health endpoints at the actual PM_{2.5} concentration.

Concerning zero health effects below the threshold of PM_{2.5} concentration, the incidence rate of mortality or morbidity due to PM_{2.5} is the difference between I and I_0 (ΔI):

$$\Delta I = I - I_0 = I \cdot \left(1 - \frac{1}{\exp(\beta \cdot (C - C_0))}\right).$$

Therefore, the health effects associated with PM_{2.5} can be calculated through the difference between actual baseline incidence rate of health endpoints and the incidence rate under the threshold level, which is specifically defined as the product of ΔI and the exposed population:

$$E = P \cdot \Delta I,$$

in which P is the exposed population.

The economic burden of disease analysis

In this study, the economic burden of disease analysis is applied to monetize the health effects of PM_{2.5}. The

economic burden due to PM_{2.5} includes tangible and intangible costs. The former includes the direct costs of treatment and hospitalization related to PM_{2.5}, as well as the reduction in the income and wealth created by absence from work or premature death due to illness. The latter refers to the pains and other spiritual losses of diseases due to PM_{2.5} [31, 46].

The WTP and COI are the prevailing methods for valuing the economic burden due to PM_{2.5} [9, 22, 40, 52]. The WTP measures what a person would pay to reduce the risk of illness or death through a questionnaire survey. It can not only capture the intangible costs including the value of spiritual suffering that people are unwilling to bear and the value of leisure time lost due to illness or premature death. It also reflects the tangible costs of medical treatment people expected. However, it is hard to operate a comprehensive large sample survey due to the wide geographical area of China.

Moreover, due to different health insurances and economic incomes, it is really difficult to obtain reliable and correct results from a questionnaire survey. The COI method assesses the economic losses caused by environmental pollution on human health and labor productivity. It can not only estimate the medical costs of illness treatment including outpatient costs, hospital costs, and drug costs but also measure the lost earnings due to absences from work because hospitalization or premature death leads to reduced working hours and illness leads to lower work productivity [19].

Nonetheless, it ignores the indirect costs such as spiritual utility losses, resulting in an underestimation of costs [36, 46, 49]. On the one hand, the WTP method can comprehensively reflect the tangible costs and intangible costs of diseases or death, but it is quite difficult to collect the data in practice. On the other hand, the COI method can only reflect the tangible medical expenditure and failed to take the intangible spiritual utility losses into account. Hence, the COI can be theoretically regarded as a lower bound to WTP in cases where WTP estimates are not available [46].

In our opinion, previous literature exhibits two shortcomings. (i) Past studies are solely based on the cost-of-illness (COI), or the willingness-to-pay (WTP) approaches to evaluate the economic losses due to PM_{2.5}. (ii) Previous works tend to ignore intangible costs, as well as costs due to the absence of work. To address these methodological design flaws, in this study we propose a new hybrid health effect and economic loss model. Given the availability of data, we integrated WTP and COI methods to take full use of their advantages and capture tangible and intangible costs.

Valuing mortality risks

Economic losses of mortality risks are typically assessed using the WTP method. Essentially, how to accurately value the WTP for mortality risk reduction is difficult due to commonly

accepted market price. In this study, the “value of a statistical life” (VSL), advocated in previous studies [10, 31, 44], is introduced into valuing the mortality risks. VSL is the sum of what a society is willing to pay to reduce the premature death risk of one of the members of society caused by pollution based on the WTP method. It is usually estimated using a questionnaire survey to ask people directly what they are willing to pay for a reduction in risk of dying from air pollution.

The VSLs vary with cities and social–economic factors such as age, job and income [1, 8, 13, 14, 41, 51]. Therefore, this study introduces the benefits transfer approach to adjust the VSLs:

$$VSL_{it} = VSL_{base} \times (I_{it}/I_{base})^e,$$

in which VSL_{it} and VSL_{base} are the VSL of the city i year t and the VSL of the base city, respectively. I_{it} and I_{base} are the urban per capita disposable income of the city i year t and the base city, respectively. e is the income elasticity coefficient.

Valuing morbidity risks

In this study, the COI method is used to value the morbidity risks from direct and indirect costs. Direct costs include treatment, medication and hospitalization expenses, and the indirect costs include the lost earnings due to absence from work [31, 33, 46]. The total cost of health endpoint i is defined as:

$$C_i = (C_{pi} + GDP_p \times T_i) \times E_i,$$

in which, C_{pi} is the direct cost of a unit case of illness i , per capita medical expenses of health endpoint i . The indirect

cost of health endpoint i is estimated by the product of GDP_p and T_i . GDP_p is a daily average of per capita GDP. T_i is the treatment and hospitalization days. E_i is the cases associated with health endpoint i .

The proposed hybrid health effect and economic loss model for PM_{2.5}

Inspired by the previous studies [14, 17, 23], this study proposes a hybrid health effect and economic loss model to estimate the health effect and economic loss of PM_{2.5} via two steps: estimating health effects and valuing economic losses, as shown in Fig. 1.

Step 1 Inspired by the previous epidemiological studies [14, 17, 31, 36] and ensuring data availability, this study chose nine health endpoints closely related to PM_{2.5} as discussed before for health effect estimations. Because urban populations are likely to be the primary group exposed to PM_{2.5} [15, 45], we chose only the urban residents as the main exposed population. Furthermore, the ERF is used to linking the PM_{2.5} concentrations to the nine health endpoints, to obtain the health effect estimations of PM_{2.5}.

Step 2 The economic burden of disease analysis is used to monetize the health effects of PM_{2.5}. In this study, the VSLs are used to value the mortality risk. The COI method is used to value the morbidity risks. All the estimations are summed as the final economic losses due to PM_{2.5}.

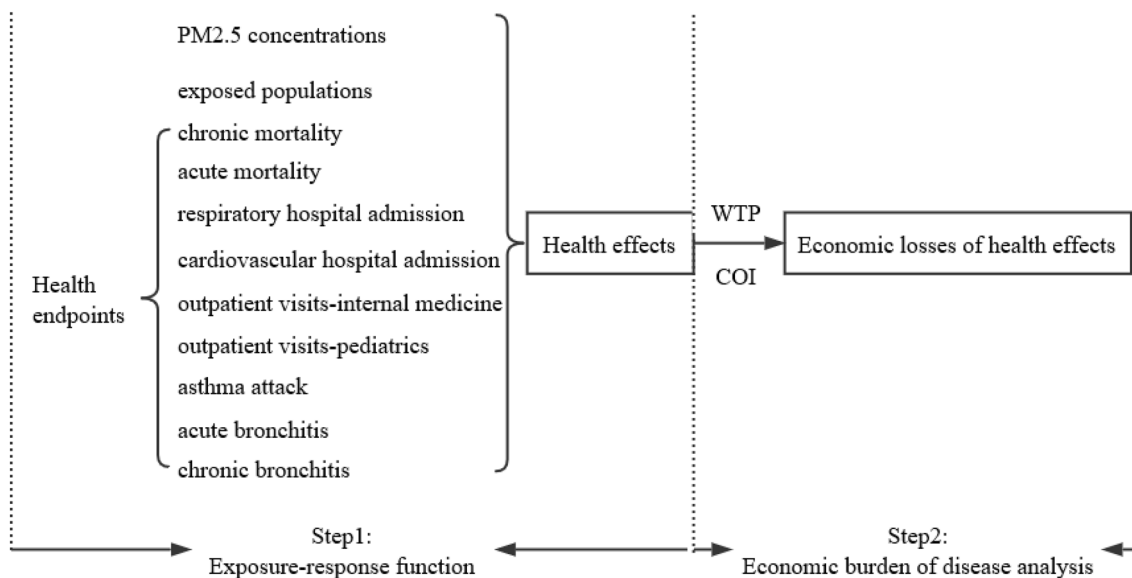


Fig. 1 The hybrid health effect and economic loss model for PM_{2.5}

Illustration of the new model based on Chinese data

In this section, we detail the dataset of Chinese cities used to show the soundness of the new proposed approach. It is interesting to note that this application can be carried out in various context, such as to investigate the European experience on that matter.

- $PM_{2.5}$ concentrations (C): We obtain the actual annual $PM_{2.5}$ concentrations of 76 cities from the China Statistical Yearbooks on Environment (2014, 2015) [30], and Environmental Quality Bulletin published on urban environmental protection agency website of each city.
- The threshold of $PM_{2.5}$ concentrations (C_0): The $PM_{2.5}$ concentrations in China are much higher than that of developed countries, so this study selects the Chinese second grade standard ($35 \mu\text{g}/\text{m}^3$) in the China Ambient Air Quality Standard (GB3905-2012) as the threshold concentration of $PM_{2.5}$, rather than the air quality standards of WHO.
- Exposure–response coefficient (β): Inspired by the previous studies [14, 17, 50], we determine the mean exposure–response coefficients of nine health endpoints and their 95% confidence intervals, presented in Table 1.
- The normal incidence rate (I): The normal incidence rate of chronic mortality, acute mortality, respiratory hospital admission, cardiovascular hospital admission, and chronic bronchitis are obtained from the China Health Statistical Yearbook (2014, 2015) [29]. The percentage of outpatient visits—internal medicine and pediatrics cases to the total urban populations in Chinese cities is reported as the normal incidence of outpatient visits—internal medicine and pediatrics, as also shown in Table 1. For lack of data of acute bronchitis and asthma attack, their incidence rates are obtained from Huang et al. [14].

- Value of a statistical life (VSL) and income elasticity coefficient (e): Follow Xie [49]; we use the VSL of Beijing (1.68 million RMB) as the VSL_{base} in our study. To adjust the VSLs to other cities, we use the benefits transfer approach, regarding per capita disposable income compared with Beijing. Inspired by Hammitt and Zhou [11] and Mu and Zhang [25], the elastic income coefficient (e) is set to be 1 in this study.
- The unit cost of health endpoints: The per capita medical expenses (C_{pi}) and average days spent in the hospital (T_i) of illness i are obtained from the China Health Statistical Yearbook (2015, 2016). Referring to Kan and Chen [17], the costs of outpatient visits, asthma attack and acute bronchitis in 2013 and 2014 are adjusted by the per capita disposable income for various cities using the benefits transfer approach. For chronic bronchitis, we use findings of Viscusi et al. [39] and multiply the VSL by 0.32 to obtain the cost of a case of chronic bronchitis.
- Exposed population and GDP: The urban population and per capita GDP are obtained from the China City Statistical Yearbook (2014, 2015) [28]. The urban per capita disposable incomes are obtained from the Statistical Communique of China on China Economic and Social Development (2014, 2015) [27]. All the data are adjusted to the constant prices of 2013.

Empirical results achieved by the hybrid model in the context of Chinese cities

Health effects of $PM_{2.5}$

Results in Table 2 show that, in total, 5.67 million cases of deaths and diseases were related to $PM_{2.5}$ in 2013, accounting for 2.63% of the total urban population. In details, there were 0.19 million cases of premature deaths, 0.23 million cases of hospital admissions, 2.80 million cases of outpatient visits, 0.16 million cases of an asthma attack, 0.12 million cases of chronic bronchitis, and 2.16 million cases of acute

Table 1 Exposure–response coefficients and normal incidences of health endpoints

Health endpoints	Exposure–response coefficients (lower limit, mean, upper limit)	Incidence rate (%)	
		2013	2014
Chronic mortality	(0.00076, 0.00296, 0.00504)	7.16	7.16
Acute mortality	(0.00019, 0.00040, 0.00062)	7.16	7.16
Respiratory hospital admission	(0.00000, 0.00109, 0.00221)	11.5	11.5
Cardiovascular hospital admission	(0.00043, 0.00068, 0.00093)	21.9	21.9
Outpatient visits—internal medicine	(0.00027, 0.00049, 0.00070)	442.07	476.07
Outpatient visits—pediatrics	(0.00020, 0.00056, 0.00090)	191.36	205.1
Asthma attack	(0.00145, 0.00210, 0.00274)	9.4	9.4
Chronic bronchitis	(0.00366, 0.01009, 0.01559)	1.8	1.8
Acute bronchitis	(0.00270, 0.00790, 0.01300)	38	38

Table 2 Health effects and economic losses of PM_{2.5} in 2013 (top) and 2014 (bottom)

Health endpoints	Health effects (cases)	Percentages of total health effects (%)	Economic losses (ten thousand yuan)	Percentages of total economic losses (%)
2013				
Chronic mortality	171,996	3.03	31,022,673	72.06
Acute mortality	24,820	0.44	4,466,661	10.37
Respiratory hospital admission	106,696	1.88	77,948	0.18
Cardiovascular hospital admission	128,116	2.26	159,383	0.37
Outpatient visits—internal medicine	1,872,795	32.98	52,068	0.12
Outpatient visits—pediatrics	924,801	16.28	25,713	0.06
Asthma attack	163,723	2.88	1625	0.00
Chronic bronchitis	124,391	2.19	7,216,888	16.76
Acute bronchitis	2,161,872	38.07	30,493	0.07
Total	5,679,211	100.00	43,053,452	100.00
2014				
Chronic mortality	147,350	2.96	27,516,387	71.98
Acute mortality	21,011	0.42	3,915,153	10.24
Respiratory hospital admission	89,200	1.79	64,821	0.17
Cardiovascular hospital admission	106,888	2.15	132,773	0.35
Outpatient visits—internal medicine	1,681,050	33.75	48,413	0.13
Outpatient visits—pediatrics	826,469	16.59	23,803	0.06
Asthma attack	137,553	2.76	1414	0.00
Chronic bronchitis	108,158	2.17	6,499,836	17.00
Acute bronchitis	1,863,578	37.41	27,227	0.07
Total	4,981,258	100.00	38,229,828	100.00

bronchitis. The health effects were over 4.98 million cases due to PM_{2.5} in 2014, accounting for 2.16% of the total urban population of the 76 cities, which was smaller than that of 2013.

Economic losses of health effects

Economic losses of health effects due to PM_{2.5} are also reported in Table 2. A loss of 430.53 (382.30) billion RMB was associated with PM_{2.5}, accounting for 1.67% (1.33%) of total GDP of the sample in 2013 (2014). More importantly, the economic losses in 2014 accounted for 14.34% of GDP growth of these cities at the constant price of 2013. PM_{2.5} had a great influence on the health of urban residents.

A comparative analysis between 2013 and 2014

This study finds two common characteristics through estimations. Firstly, the ranks of economic losses corresponding to health endpoints were unchanged, i.e., chronic mortality, and chronic bronchitis contributed most to the total economic loss of PM_{2.5}. From the perspective of WTP, premature death can make the loss of labor income that residents may earn in future work, and chronic bronchitis needs greater treatment costs and spiritual utility loss. Therefore, residents

are willing to pay more to reduce the risk of death or chronic bronchitis.

Second, besides PM_{2.5} concentrations, urban populations, and economic levels were also important factors of health effects. The larger populations and the more developed economy, the higher health effects of PM_{2.5}. For example, Beijing and Wuhan had similar PM_{2.5} concentrations in 2014 (86 and 82 µg/m³). However, the health effect of Beijing (430,384 cases) was much higher than that of Wuhan (163,669 cases), because Beijing had larger urban populations and a more advanced economy.

However, a difference between 2013 and 2014 is also evident. The health effect and economic loss of PM_{2.5} in 2014 were much lower than those of 2013. The reason may be that on the one hand, China has taken a series of policies to improve her air quality. On the other hand, with the economic development, medical equipment, technology, and insurance system are further improved, to the decline in mortality due to PM_{2.5}.

A uncertainty analysis of health effects and economic losses due to PM_{2.5}

Kroop et al. [18] and Nam et al. [26] argue that the exposure–response coefficients vary with pollution levels and

places, so the estimations of health effects and economic losses due to $PM_{2.5}$ could be biased. To obtain robust estimations, we conduct an uncertainty analysis. Regarding uncertainty analysis in economic evaluation, Briggs et al. [3] reviewed the different types of sensitivity analysis and their strengths and weaknesses, respectively, and pointed out that sensitivity analysis is similar with the extreme-conditions test. Therefore, we define the means of exposure–response coefficients as the normal scenario, with the lower limits and upper limits of exposure–response coefficients as the lower limit scenario and upper limit scenario, respectively, which can be regarded as an extreme-conditions test. Inspired by Huang and Zhang [14], Kan and Chen [16] and Xie et al. [50], we determine the mean exposure–response coefficients of nine health endpoints and their 95% confidence intervals, as listed in Table 1. The detailed results of uncertainty analysis are reported in Table 3. It is obvious that $PM_{2.5}$ had great health effects and economic losses, even if in the lower limit scenario.

In the lower limit scenario, the health effects and economic losses due to $PM_{2.5}$ were respectively 2.35 million cases and 129.91 billion RMB in 2013, which fell by 58.55% and 69.83%, respectively, compared with those in the normal scenario. The health effects and economic losses due to $PM_{2.5}$ were respectively 2.14 million cases and 116.17 billion RMB in 2014, which fell by 56.86% and 69.61%, respectively compared with those in the normal scenario.

Meantime, the estimations in 2014 were much smaller than those in 2013, which was consistent with the normal scenario.

In the upper limit scenario, the health effects and economic losses due to $PM_{2.5}$ were respectively 7.82 million cases and 639.04 billion RMB in 2013, which rose by 37.81% and 48.43%, respectively compared with those in the normal scenario. The health effects and economic losses due to $PM_{2.5}$ were respectively 7.26 million cases and 583.39 billion RMB in 2014, which rose by 45.82% and 52.60%, respectively compared with those in the normal scenario. Meantime, the estimations in 2014 were much smaller than those in 2013, which was also consistent with the normal scenario.

Robustness checks: a comparative analysis between the South and North of China

To further explore the research question, we divided the 76 cities into the South and North by the line formed by the Huai River and Qinling Mountain range: 44 cities in the South and 32 cities the North. In 2013, the highest/lowest concentration of $PM_{2.5}$ in the North was in Xingtai/Zhangjiakou with $160 \mu\text{g}/\text{m}^3$ and $40 \mu\text{g}/\text{m}^3$, respectively. These two cities kept their rankings in 2014 but with the ratio of $131 \mu\text{g}/\text{m}^3$ and $35 \mu\text{g}/\text{m}^3$. For cities in the South, the highest concentration in 2013/2014 was Chengdu and Taizhou with

Table 3 The uncertainty analysis of health effects and economic losses due to $PM_{2.5}$ in 2013 (top) and 2014 (bottom)

Health endpoints	Health effects (cases)	Economic losses (ten thousand yuan)
2013		
Chronic mortality	(43,700, 259,596)	(7,970,526, 47,550,404)
Acute mortality	(11,093, 35,783)	(2,021,978, 6,525,584)
Respiratory hospital admission	(0, 196,463)	(0, 145,304)
Cardiovascular hospital admission	(76,295, 162,825)	(78,277, 167,064)
Outpatient visits—internal medicine	(971,176, 2,489,082)	(27,348, 70,126)
Outpatient visits—pediatrics	(311,990, 1,377,950)	(8785, 38,830)
Asthma attack	(107,478, 196,387)	(1080, 1977)
Chronic bronchitis	(49,064, 158,448)	(2,872,143, 9,362,363)
Acute bronchitis	(783,121, 2,949,937)	(11,151, 42,366)
Total	(2,353,917, 7,826,471)	(12,991,288, 63,904,018)
2014		
Chronic mortality	(38,240, 232,046)	(7,098,931, 43,222,699)
Acute mortality	(9677, 31,288)	(1,795,615, 5,807,854)
Respiratory hospital admission	(0, 173,212)	(0, 125,707)
Cardiovascular hospital admission	(66,642, 142,605)	(82,688, 176,950)
Outpatient visits—internal medicine	(912,767, 2,344,785)	(26,165, 67,240)
Outpatient visits—pediatrics	(291,724, 1,293,282)	(8362, 37,093)
Asthma attack	(94,389, 173,608)	(966, 1778)
Chronic bronchitis	(43,570, 147,713)	(2,594,391, 8,860,094)
Acute bronchitis	(692,148, 2,725,104)	(10,027, 39,744)
Total	(2,149,157, 7,263,643)	(11,617,144, 58,339,159)

96 $\mu\text{g}/\text{m}^3$ and 107 $\mu\text{g}/\text{m}^3$ accordingly. The lowest ratio in 2013/2014 was at Fuzhou, Xiamen, and Fuzhou, Shenzhen, Zhuhai with 36 $\mu\text{g}/\text{m}^3$ and 34 $\mu\text{g}/\text{m}^3$ subsequently.

In 2013, the mean of $\text{PM}_{2.5}$ in the South was 62 $\mu\text{g}/\text{m}^3$, related to 2,626,111 cases of health effects, 211.91 billion RMB of economic losses, and the per capita loss of 80,700 RMB. It can be found that $\text{PM}_{2.5}$ of the North is more serious than that of the South when the average of $\text{PM}_{2.5}$ in the North were 1.42 times, 1.16 times, 1.03 times, 0.89 times of those of the South, respectively. First, the Huai River and Qinling Mountain line is divided by differences of climate and terrain. For the South, its rich rainfall can take away the $\text{PM}_{2.5}$ [36]. Besides this, the main terrain of hills and basins makes it easy to form local convections to diffuse $\text{PM}_{2.5}$ better. For the North, however, dry climate, poor vegetation coverage, and loosen soil surface can form the higher $\text{PM}_{2.5}$ concentrations. Second, there is a significant difference in energy structures between the two regions. The South generally produces electricity with water, while the North mainly adopts thermal power with coal. Last but not least, due to rich mineral resources in the North, more heavy industries, instead of tertiary industries, are developed for economic growth. When we consider the gross cases, the health effects and economic losses due to $\text{PM}_{2.5}$ of the North were more serious. Regarding the individual case, per capita economic loss in the North due to $\text{PM}_{2.5}$ was much lower, because residents in the South were willing to pay more for reducing the risk of dying from $\text{PM}_{2.5}$ with higher per capita disposable income level. Furthermore, the coefficient of variation (CV) in the North is higher than that of the South (35% compared with 25%). Therefore, the $\text{PM}_{2.5}$ in the North is more dispersed, as shown in Fig. 2.

In 2014, the mean of $\text{PM}_{2.5}$ in the South was 56 $\mu\text{g}/\text{m}^3$, related to 2,218,380 cases of health effect, 186.97 billion RMB of economic loss, and 84,200 RMB of per capita loss. While the mean of $\text{PM}_{2.5}$ in the North was 77 $\mu\text{g}/\text{m}^3$, related to 2,762,878 cases of health effect, 195.33 billion RMB of economic loss and 70,700 RMB of per capita loss. Compared with 2013, the health effect and economic loss in the North dropped by 12.50%, 9.51%, and 11.36%, respectively at the constant prices of 2013. At the same time, the health effects and economic losses in the South dropped by 9.68%, 15.53%, and 12.47%, respectively at the constant prices of 2013. The main reason for a big drop of $\text{PM}_{2.5}$ in the North could lie in coal-fired boiler modification and old motor vehicle abolishment [24].

Regarding the individual case, per capita, economic loss in the North due to $\text{PM}_{2.5}$ was much lower than that of the South, which was consistent with 2013. Per capita economic loss rose by 4.3% in the South, while fell by 1.3% in the North. Explanations could be that the growth rate of economic losses due to $\text{PM}_{2.5}$ was greater than that of health effects in the South because of rapidly increasing

income levels. Also, the growth rate of health effects due to $\text{PM}_{2.5}$ was greater than that of economic losses in the North because of the rapid rise of $\text{PM}_{2.5}$ concentrations. The CV of $\text{PM}_{2.5}$ decreased in the North while rose in the South, so the $\text{PM}_{2.5}$ tended to be centralized in the North while scattered in the South.

To compare the health effects of $\text{PM}_{2.5}$ in the North and South, we conduct a regression analysis with the health effect as the dependent variable, $\text{PM}_{2.5}$ concentration, the exposed population and a dummy variable (the Northern cities: 1; and the Southern cities: 0) as the independent variables. With pooled data, we introduce the OLS to estimate the regression analysis. All the variance inflation factors (VIFs) of independent variables are less than 1.5. Thus, there is no serious multicollinearity between them.

$$E = 1158.595C + 24153.810P + 13366.256D - 86422.874,$$

where, E and C are the health effect and $\text{PM}_{2.5}$ concentration, respectively. P is the exposed population of 76 cities. D is the dummy variable. The regression equation is significant at the level of 1%. Therefore, it can be concluded that the mean health effect of $\text{PM}_{2.5}$ in the North was 13,366 cases higher than that of the South when their $\text{PM}_{2.5}$ concentrations and urban population are same.

To compare the health effects due to $\text{PM}_{2.5}$ between the North and South in 2013 and 2014, we implement another regression analysis, and the results obtained are reported in Table 4. D was not significant in 2013 while significant in 2014 at the level of 5%. It seemed that the diversity of health effects due to $\text{PM}_{2.5}$ between the North and South had become larger.

The Kruskal–Wallis test is also used to test the differences in $\text{PM}_{2.5}$ concentrations between the North and South, and the results obtained are presented in Table 4. It implied that there was significant heterogeneity of $\text{PM}_{2.5}$ concentrations between the North and South at the level of 1%.

Conclusion

This study proposes a new hybrid health effect and economic loss model to estimate the health effects and economic losses of $\text{PM}_{2.5}$. This new methodology is illustrated based on a sample of 76 cities in China in 2013 and 2014. Against this background, the results obtained show that in the normal scenario, a substantial social–economic burden was related to $\text{PM}_{2.5}$. In 2013, more than 5.67 million cases of health effects and 430.53 billion RMB of economic losses were associated with $\text{PM}_{2.5}$. In 2014, the health effects and economic losses due to $\text{PM}_{2.5}$ were over 4.98 million cases and 382.30 billion RMB, which decreased substantially compared with those of 2013. More importantly, the economic loss in 2014 accounted for 14.34% of GDP growth of the 76

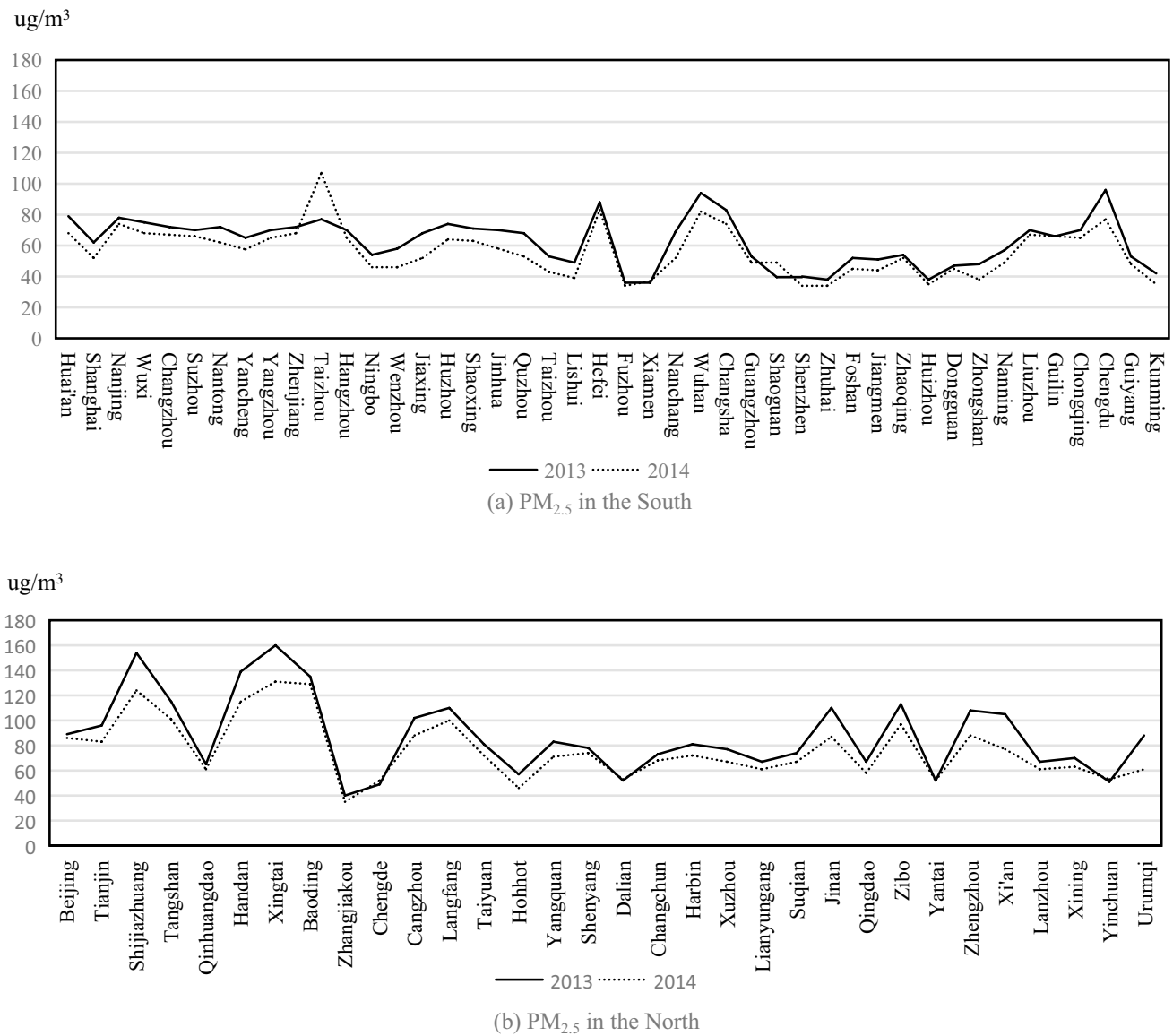


Fig. 2 The PM_{2.5} concentrations in the North and South of China

Table 4 OLS regression analysis (top) and Kruskal–Wallis test results (bottom)

Independent variables	Whole	2013	2014
OLS			
<i>C</i>	1158.595***	1139.448***	1142.811***
<i>P</i>	24153.810***	25870.053***	22664.344***
<i>D</i>	13366.256**	10809.139	16722.419**
Years	Chi square	<i>df</i>	Sig.
Kruskal–Wallis test			
2013	13.927	1	0.000
2014	14.888	1	0.000

*** and ** are significant at the levels of 1% and 5%, respectively

cities at the constant price of 2013. A comparison between the South and North showed that PM_{2.5} pollution was much heavier in the North than the South.

The empirical application contained in this article aims at showing the accuracy achieved by the new hybrid model. Its implementation in Europe is left for further research, although the policy implications of our work can already be appealing to policymakers in the European context. Although China has taken much effort to reduce PM_{2.5} pollution, more effective countermeasures are needed. On the one hand, the data disclosure of PM_{2.5} should be reinforced to get a more sound and comprehensive assessment of its health effect and economic loss. On the other hand, urban residents should strengthen environmental protection consciousness and take the environmental-friendly ways to commute. Especially, to reduce the heavy PM_{2.5} pollution in the North, more abatement and control measures are needed. First, massive afforestation can be helpful. Second, it is necessary to reduce coal utilization rate, implement stricter emissions standards, and promote the development of clean energy. Last but not least, industrial structure adjustment for heavy industry is also important, such as promoting the development of financial services and high technology enterprises [4].

Acknowledgements Our heartfelt thanks should also be given to the National Natural Science Foundation of China (NSFC) (71473180, 71201010, 71303174, 71303076, and 71673083), National Philosophy and Social Science Foundation of China (14AZD068, 15ZDA054, 16ZZD049), Guangdong Young Zhujiang Scholar (Yue Jiaoshi [2016]95), Natural Science Foundation for Distinguished Young Talents of Guangdong (2014A030306031), Soft Science Foundation of Guangdong (2014A070703062), Social Science Foundation of Guangdong (GD14XYJ21), Distinguished Young Teachers of Guangdong ([2014]145), High-level Personnel Project of Guangdong ([2013]246), Guangdong key base of humanities and social science—Enterprise Development Research Institute, Institute of Resource, Environment and Sustainable Development Research, and Guangzhou key base of humanities and social science—Centre for Low Carbon Economic Research for funding supports. Dinh-Tri Vo recognizes financial support from University of Economics Ho Chi Minh city, Vietnam.

Compliance with ethical standards

Conflict of interest There are no conflicts of interest on behalf of all authors, neither ethics violation coming from the funding sources that have been acknowledged (main academic).

References

- Alberini, A., Cropper, M., Fu, T.T., Krupnick, A., Liu, J.T., Shaw, D., et al.: Valuing health effects of air pollution in developing countries: the case of Taiwan. *J. Environ. Econ. Manag.* **34**(2), 107–126 (1997)
- BP Group World Energy Statistics Yearbook, 2016. https://www.bp.com/zh_cn/china/reports-and-publications/_bp_2017_-_html (2017). Accessed 16 Dec 2016
- Briggs, A., Sculpher, M., Buxton, M.: Uncertainty in the economic evaluation of health care technologies: the role of sensitivity analysis. *Health Econ.* **3**:95–104 (1994)
- Clean Air Alliance of China. 12th Five-year plan on prevention and control of air pollution in key regions. <http://en.cleanairchina.org/product/6285.html> (2012)
- Cohen, A.J., Ross, A.H.B., Pandey, K.D., Krzyzanowski, M., Kunzli, N., Gutschmidt, K., et al.: The global burden of disease due to outdoor air pollution. *J. Toxicol. Environ. Health* **68**(13–14), 1301–1307 (2005)
- Carugno, M., Consonni, D., Randi, G., Catelan, D., Grisotto, L., Bertazzi, P.A., et al.: Air pollution exposure, cause-specific deaths, and hospitalizations in a highly polluted Italian region. *Environ. Res.* **147**, 415–424 (2016)
- Dockery, D.W., Rd, P.C., Xu, X., et al.: An association between air pollution and mortality in six U.S. cities. *N. Engl. J. Med.* **329**(24), 1753–1759 (1993)
- Evans, M.F., Poulos, C., Smith, V.K.: Who counts in evaluating the effects of air pollution policies on households? Non-market valuation in the presence of dependencies. *J. Environ. Econ. Manag.* **62**(1), 65–79 (2011)
- Guo, Y., Zeng, H., Zheng, R., Li, S., Barnett, A.G., Zhang, S., et al., 2016. The association between lung cancer incidence and ambient air pollution in China: a spatiotemporal analysis. *Environ. Res.* **144**(Pt A), 60–65
- Gao, T., Guo, X.L.I., Mei, X.U., Wang, X.Y., Liang, F.C., Zeng, Q., et al.: Health economic loss evaluation of ambient PM_{2.5} pollution based on willingness to pay. *J. Environ. Health* **8**, 697–700 (2015)
- Hammitt, J., Zhou, Y.: The economic value of air-pollution-related health risks in china: a contingent valuation study. *Environ. Resour. Econ.* **33**, 399–423 (2006)
- He, G., Fan, M., Zhou, M.: The effect of air pollution on mortality in China: evidence from the 2008 Beijing Olympic Games. *J. Environ. Econ. Manag.* **79**, 18–39 (2016)
- Hoffmann, S., Qin, P., Krupnick, A., et al.: The willingness to pay for mortality risk reductions in Mongolia. *Resour. Energy Econ.* **34**, 493–513 (2012)
- Huang, D.S., Zhang, S.Q.: Health benefit evaluation for PM_{2.5} pollution control in the Beijing–Tianjin–Hebei region of China. *China Environ. Sci.* **33**(1), 166–174 (2013)
- Hao, Y., Liu, Y.M.: The influential factors of urban PM_{2.5} concentrations in China: a spatial econometric analysis. *J. Clean. Prod.* **112**, 1443–1453 (2015)
- Kan, H., Chen, B.: Analysis of exposure–response relationships of air particulate matter and adverse health outcomes in China. *J. Environ. Health* **19**(06), 422–424 (2002)
- Kan, H., Chen, B.: Particulate air pollution in urban areas of Shanghai, China: a health-based economic assessment. *Sci. Total Environ.* **322**(1–3), 71–79 (2004)
- Koop, G., Tole, L.: Measuring the health effects of air pollution: to what extent can we really say that people are dying from bad air? *J. Environ. Econ. Manag.* **47**, 30–54 (2004)
- Krupnick, A., Cropper, M.: The social costs of chronic heart and lung disease. In: Elgar, E. (ed.) *Valuing Environmental Benefits, Selected Essays of Maureen Cropper*. Edward Elgar, Cheltenham (2000)
- Kunzli, N., Kaiser, R., Medina, S., et al.: Public-health impact of outdoor and traffic-related air pollution: a European assessment. *Lancet.* **356**(9232), 795–801 (2000)
- Lu, F., Zhou, L., Xu, Y., Zheng, T., Guo, Y., Wellenius, G.A., et al.: Short-term effects of air pollution on daily mortality and years of life lost in Nanjing, China. *Sci. Total Environ.* **536**, 123–129 (2015)

22. Lu, X., Teng, Y., Fung, J.C.H., Lin, C.: Estimation of health and economic costs of air pollution over the Pearl River Delta region in China. *Sci. Total Environ.* **566–567**, 134–143 (2016)
23. Li, W., Xie, Y., Chen, J.: *Methods and Applications of Strategic Environmental Assessment in Health Risk Assessment of Residents in Exposure to Ambient Air Pollution*. Science Press, Beijing (2016)
24. Ministry of Environmental Protection. Air pollution prevention and control action plan. <http://www.cleanairechina.org/product/6349.html> (2013). Accessed 16 Dec 2016
25. Mu, Q., Zhang, S.: Assessment of historical change of economic losses and health effects due to PM_{2.5} heavy pollution in 2001–2013 in China. *Peking Univ. (Nat. Sci. Ed.)* **51**(4), 694–706 (2015)
26. Nam, K.M., Selin, N.E., Reilly, J.M., Paltsev, S.: Measuring welfare loss caused by air pollution in Europe: a CEG analysis. *Energy Policy* **38**(9), 5059–5071 (2010)
27. National Bureau of Statistics of China. Statistical communique of China on the national economic and social development. <http://www.tjcn.org/tjgb/>. Accessed 16 Dec 2016
28. National Bureau of Statistics of the People's Republic of China, 2014–2015. China city statistical yearbook. <http://www.stats.gov.cn/tjsj/ndsj/>. Accessed 16 Dec 2016
29. National Health and Family Planning Commission of China. Health Statistical Yearbook, 2013. <http://www.nhfpc.gov.cn/zwgkzt/tjnj/list.shtml>. Accessed 16 Dec 2016
30. National Bureau of Statistics, State Environmental Protection Administration. China statistical yearbook on environment, 2014–2015
31. Pan, X., Li, G., Gao, T.: *Dangerous Breath: Study on the Health Damages and Economic Losses of PM_{2.5}*. China Environmental Science Press, Beijing (2012)
32. Pope, C.A., Burnett, R.T., Thun, M.J., et al.: Lung cancer, cardio-pulmonary mortality, and long-term exposure to fine particulate air pollution. *J. Am. Med. Assoc.* **287**(9), 1132–1141 (2002)
33. Rui, W., Dai, H., Yong, G., Yang, X., Masui, T., Liu, Z., et al.: Economic impacts from PM_{2.5} pollution-related health effects: a case study in Shanghai. *Environ. Sci. Technol.* **51**(9), 5035–5042 (2017)
34. State Environmental Protection Administration of China. Report on the state of the environment in China. <http://www.zhb.gov.cn/hjzl/zghjzkgb/lnzghjzkgb/> (2014). Accessed 16 Dec 2016
35. Sueyoshi, T., Yuan, Y.: China's regional sustainability and diversified resource allocation: DEA environmental assessment on economic development and air pollution. *Energy Econ.* **49**, 239–256 (2015)
36. Sun, J., Zhong, Y.: Economic analysis of the factors influencing PM_{2.5} in China's Metropolises: an empirical Study based on city-level panel data. *Ecol. Econ.* **31**(3), 62–65 (2015)
37. Tam, W.W.S., Wong, T.W., Wong, A.H.S.: Association between air pollution and daily mortality and hospital admission due to ischaemic heart diseases in Hong Kong. *Atmos. Environ.* **120**, 360–368 (2015)
38. Tang, D., Wang, C., Nie, J., Chen, R., Qiao, N., Kan, H., et al.: Health benefits of improving air quality in Taiyuan, China. *Environ. Int.* **73C**(4), 235–242 (2014)
39. Viscusi, W.K., Magat, W.A., Huber, J.: Pricing environmental health risks: survey assessments of risk-risk and risk-dollar trade-offs for chronic bronchitis. *J. Environ. Econ. Manag.* **21**(1), 32–51 (1991)
40. Voorhees, A.S., Wang, J., Wang, C., Zhao, B., Wang, S., Kan, H.: Public health benefits of reducing air pollution in Shanghai: a proof-of-concept methodology with application to BenMap. *Sci. Total Environ.* **485–486**(1), 396–405 (2014)
41. Wang, H., Mullahy, J.: Willingness to pay for reducing fatal risk by improving air quality: a contingent valuation study in Chongqing, China. *Sci. Total Environ.* **367**, 50–57 (2006)
42. Wang, J., Wang, S., Voorhees, A., et al.: Assessment of short-term PM_{2.5}-related mortality due to different emission sources in the Yangtze River Delta, China. *Atmos. Environ.* **123**, 440–448 (2015)
43. Wang, P., Mu, H.: Economic assessment on health loss of particulate air pollution in Dalian of China. In: *Bioinformatics and Biomedical Engineering (iCBBE), 2010 4th International Conference on IEEE*. pp. 1–4 (2010)
44. Wei, W.X., Luo, Q.H.: An empirical analysis of residents' willingness to pay and their behaviors in PM_{2.5} governance in the Beijing–Tianjin–Hebei region. *Stat. Res.* **34**(3), 55–64 (2017)
45. Wang, S., Zhou, C., Wang, Z., Feng, K., Hubacek, K.: The characteristics and drivers of fine particulate matter (PM_{2.5}) distribution in China. *J. Clean. Prod.* **142**, 1800–1809 (2017)
46. World Bank. *Cost of Pollution in China: Economic Estimates of Physical Damages*. The World Bank, Washington, DC (2007)
47. World Health Organization. *Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease*. WHO Document Production Services, Geneva (2016)
48. World Health Organization. WHO's Urban Ambient Air Pollution database. http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/ (2016). Accessed 16 Dec 2016
49. Xie, X.: *The value of health: assessment of environmental benefits and control strategy of urban air pollution*, Doctoral Dissertation, Peking University (2011)
50. Xie, P., Liu, X.Y., Liu, Z.R., Tian-Tian, L.I., Bai, Y.H.: Exposure-response functions for health effects of ambient particulate matter pollution applicable to China. *China Environ. Sci.* **29**(10), 1034–1040 (2009)
51. Zhang, X.: *Valuing Mortality Risk Reductions Using the Contingent Valuation Methods: Evidence from A Survey of Beijing Residents in 1999*. Centre for Environment and Development, Chinese Academy of Social Sciences, Beijing (2002)
52. Zhang, M., Song, Y., Cai, X., et al.: Economic assessment of the health effects related to particulate matter pollution in 111 Chinese cities by using the economic burden of disease analysis. *J. Environ. Manag.* **88**, 947–954 (2008)
53. Zhou, M., He, G., Liu, Y., Yin, P., Li, Y., Kan, H., et al.: The associations between ambient air pollution and adult respiratory mortality in 32 major Chinese cities, 2006–2010. *Environ. Res.* **137**, 278–286 (2015)