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Quantifying public health benefits of environmental strategy of $PM_{2.5}$ air quality management in Beijing–Tianjin–Hebei region, China

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ABSTRACT

In 2013, China issued "Air Pollution Prevention and Control Action Plan (Action Plan)" to improve air quality. To assess the benefits of this program in Beijing-Tianjin-Hebei (BTH) region, where the density of population and emissions vary greatly, we simulated the air quality benefit based on BenMAP to satisfy the Action Plan. In this study, we estimate $PM_{2.5}$ concentration using Voronoi spatial interpolation method on a grid with a spatial resolution of 1×1 km^2. Combined with the exposure-response function between $PM_{2.5}$ concentration and health endpoints, health effects of $PM_{2.5}$ exposure are analyzed. The economic loss is assessed by using the willingness to pay (WTP) method and human capital (HC) method. When the $PM_{2.5}$ concentration falls by 25% in BTH and reached 60 μg/m^3 in Beijing, the avoiding deaths will be in the range of 3175 to 14051 based on different functions each year. Of the estimated mortality attributable to all causes, 3117 annual deaths were due to lung cancer, 1924 – 6318 annual deaths were due to cardiovascular, and 343 – 1697 annual deaths were due to respiratory. Based on WTP, the estimated monetary values for the avoided cases of all cause mortality, cardiovascular mortality, respiratory mortality and lung cancer ranged from 1110 to 29632, 673 to 13325, 120 to 3579, 1091 to 6574 million yuan, respectively. Based on HC, the corresponding values for the avoided cases of these four mortalities were 267 to 1178, 161 to 529, 29 to 143 and 261 million yuan, respectively.

Introduction

It is noted that the air pollution situation in China is serious, especially the high $PM_{2.5}$ and PM_{10} concentrations in the ambient air of a number of regions. Beijing–Tianjin–Hebei (BTH) is one of the most air polluted regions in China. In 2014, the annual average $PM_{2.5}$ concentration was 93 μg/m^3 in BTH, about 6.2 times higher than the China's Class I standard (15 μg/m^3) and 2.7 times higher than the China's Class II standard (35 μg/m^3). Urban air pollution is recognized as a serious problem since it is not only imposing a severe threat to the public health but also affecting the economic burden.

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Hence, it is necessary to develop an effective air quality management strategy to address the challenging air pollution problem. The Chinese government has sought to balance environmental and public health concerns against the economic growth. In recent years, China has implemented a number of air quality control measures that are expected to lead to a future reduction in fine particle concentrations and an ensuing positive impact on public health. For example, the "Air Pollution Prevention and Control Action Plan (hereinafter referred to as Action Plan)" issued in September 2013 was one of these measures. According to this Plan, in force till the year of 2017, the PM_{10} concentrations in a number of cities should be reduced more than 10% compared to those of 2012, and the numbers of good air quality days (Air Quality Index, AQI < 100) would increase annually (State Council of China, 2013). Specifically, $PM_{2.5}$ levels in Beijing–Tianjin–Hebei, Yangtze River Delta and Pearl River Delta will be cut by 25%, 20% and 15%, respectively, and the annual $PM_{2.5}$ concentration in Beijing will be kept around 60 $\mu g/m^3$ in 2017. To achieve these goals, the supporting assessment methods and the implementation details for the Action Plan were issued in 2014.

$PM_{2.5}$ may seriously affect human health because it is able to penetrate deeply into the lung with its small size, and the various chemicals that absorbed on its surface (Rd and Dockery, 2006). A large number of time-series studies of mortality have been published in the past 20 years, but only a few cohort studies have been reported. Epidemiological cohort studies, both in Europe (Cesaroni et al., 2013) and in North America (Turner et al., 2011), have estimated the long-term health risk of being exposed to air pollution. The study in North America showed that long-term exposure to $PM_{2.5}$ was associated with an increase in non-accidental mortality (hazard ratio (HR) = 1.04 (95% CI: 1.03, 1.05) per 10 $\mu g/m^3$ $PM_{2.5}$). Ischemic heart diseases (HR = 1.10 (95% CI: 1.06, 1.13) per 10 $\mu g/m^3$ $PM_{2.5}$) was found to have the strongest association with the $PM_{2.5}$ concentration, followed by cardiovascular diseases and lung cancer. The study in Europe examined the association between mean long-term ambient $PM_{2.5}$ concentrations and lung cancer mortality in a 26-year prospective study among a large cohort of non-smokers. Each 10 mg/m^3 increase in $PM_{2.5}$ concentration was associated with a 15%–27% increase in lung cancer mortality. The Harvard Six Cities study reported a 14% increase in long-term all cause mortality for every 10 $\mu g/m^3$ increase in fine particle concentration (Lepeule et al., 2012). Recent European cohort study (Raaschou-Nielsen et al., 2013) has reported an increase of long-term mortality even at fine particle levels below the ambient air quality standards. In China, several time-series studies and cross-sectional mortality studies were conducted in cities including Shanghai, Beijing, Tianjin, Xi'an, Wuhan, Taiyuan and Anshan (Kan et al., 2007; Guo et al., 2009, 2010; Huang et al., 2012; Wong et al., 2008; Zhang et al., 2008; Chen et al., 2010). Results of these studies were in accordance with those reported from the developed countries.

Quantifying the benefits of air quality programs is an important step in evaluating the efficacy of regulations, comparing alternative strategies, and communicating to the public the importance of these efforts. The U.S. EPA's BenMAP is a windows-based computer program that uses Geographic Information System (GIS)-based data to estimate the health impacts and monetary value when populations experience changes in air quality (US EPA, 2015). Because BenMAP does not model air quality changes, data must be input into BenMAP as modeling data or generated from air pollution monitoring data. Models such as Community Multiscale Air Quality (CMAQ) were used to simulate air pollutant exposure concentrations in several studies (Ding et al., 2016; Wang et al., 2015; Voorhees et al., 2014; Fann et al., 2012; Chae and Park, 2011; Boldo et al., 2014; Sonawane et al., 2012). In this study, we attempted to simulate the air quality surface based on monitoring data. There are some international public released papers using BenMAP-CE to address the health benefit due to air quality improvement in China.

This study took Chinese health impact functions, applied monitored air quality data, and estimated the numbers of avoided cases of mortality and economic benefit for BTH, assuming the Action Plan was completed. The findings of this study can provide scientific basis for implementation of air pollution control strategies.

1. Materials and methods

1.1. Study area

The region of BTH is located in northern China, and includes two municipalities (Beijing, Tianjin) and one province (Hebei). Hebei Province includes Chengde, Qinhuangdao, Tangshan, Langfang, Zhangjiakou, Baoding, Cangzhou, Shijiazhuang, Handan, Hengshui, Xingtai, and is located at the east of the Taihang Mountains and at the north of the Yellow River. The BTH region has a monsoon climate of medium latitudes, which has dry and windy spring, hot and rainy summer and dry-cold winter. It covered 2.3% of the Chinese territory, while generated about 10.4% of the total national GDP in the year of 2014. It also accounts for an approximately 8.1% of the total population and 11.7% of the total motor vehicle numbers in China. The major industries in Hebei are iron, steel, coke and cement. In addition, BTH is also one of the regions with the worst air pollution in the world.

1.2. Data collection

The $PM_{2.5}$ concentration data were collected from the air pollution monitoring network operated by China National Environmental Monitoring Centre (CNEMC) in 2014. The measurement method used for air quality assessment complies with those recommended in China National Ambient Air Quality Standard (No. GB3095-2012). The quality assurance (QA) and quality control (QC) procedures are implemented at CNEMC according to relevant Chinese rules and regulations. There were 90 $PM_{2.5}$ monitoring sites in study area (Fig. 1), including 12 sites in Beijing, 28 sites in Tianjin and 50 sites in Hebei Province. The population data with 1 km resolution were obtained from the Center for International Earth Science Information Network (Columbia University et al., 2005). Fig. 1 shows the spatial distribution of the population. The baseline mortality of BTH was obtained from China Statistical Yearbook and China Health Yearbook. The health endpoints included all cause death, cardiovascular death, respiratory death and lung cancer death.

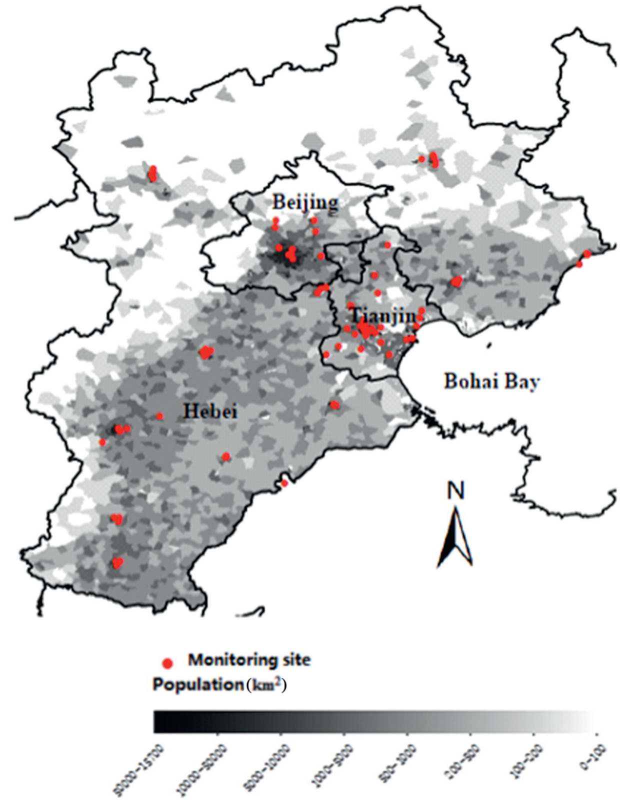

Fig. 1 – Population density and monitoring sites in study area.

1.3. *Health impact and economic benefit assessments*

Fig. 2 showed the main steps of health impact and economic valuation assessments due to the decrease of $PM_{2.5}$ concentration in BTH, assuming the Action Plan was completed.

In 2012, $PM_{2.5}$ monitored data could be obtained in Beijing and Tianjin, however, the data only in one city (Shijiazhuang) was available in Hebei Province. To obtain the baseline scenario in other cities in Heibei Province, the conversion below was done. Firstly, we obtained the $PM_{2.5}$ monitoring data for the years of 2012 and 2014 in Shijiazhuang. The city-wide annual averages of these two years were calculated and the ratio of the two averages was determined. Secondly, the baseline $PM_{2.5}$ concentrations in other cities in Hebei Province were calculated by using the $PM_{2.5}$ concentrations in 2014 multiply by the determined ratio. Thirdly, the baseline $PM_{2.5}$ exposure level with a spatial resolution of 1 km × 1 km (325,174 cells) was interpolated using calculated $PM_{2.5}$ concentration data in Hebei Province and $PM_{2.5}$ monitored data (2012) in Beijing, Tianjin and Shijiazhuang by Voronoi neighborhood averaging. We designed a projected scenario to simulate air pollution distribution in 2017 in a case where Action Plan was performed successfully. Using BenMap-CE v.1.1, air pollution changes in each cell were calculated decreasing 25% (first control) and reducing to the level of 60 $\mu g/m^3$ in the cells of Beijing after the first control.

We estimated attributable death using health impact functions based on studies of fine particles in China (Cao et al., 2011; Huang et al., 2012; Kan et al., 2007; Wong et al., 2008). The concentration-response function relates the fine particle concentration to the mortality. In these cases, the values of the regression coefficients (β) and their standard errors were introduced into the BenMAP software. We calculated the mortality impacts of a reduction in $PM_{2.5}$ concentration for all causes death, cardiovascular death, respiratory death and lung cancer death. The causes of death were coded according to the International Classification of Diseases, Revision 10 (ICD 10), and classified into deaths due to all causes (A00–R99), cardiovascular diseases (I00–I99), respiratory diseases (J00–J98), and lung cancer (C34).

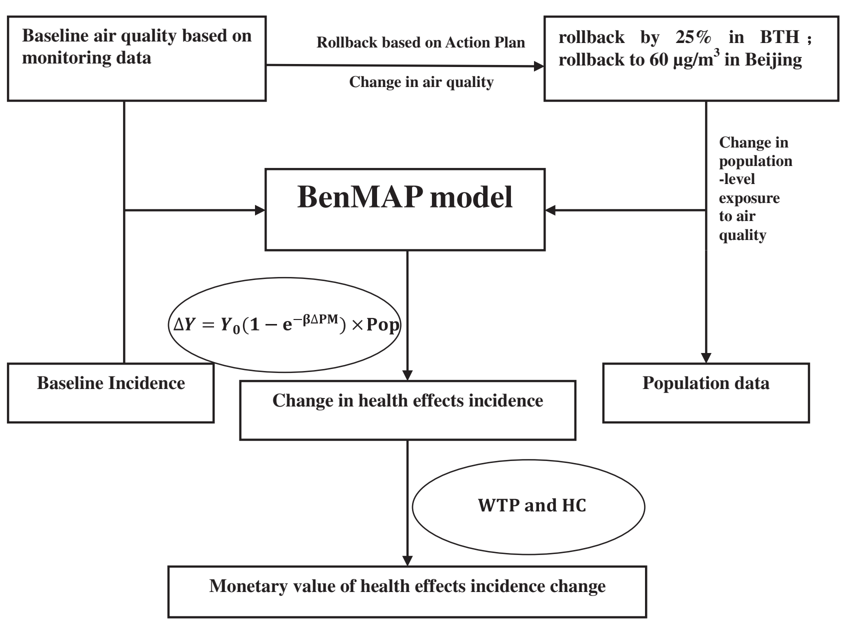

Fig. 2 – Flowchart of health impact and economic benefit assessments.

Assuming that the entire population was exposed to $PM_{2.5}$ air pollution, attributable deaths were calculated on a grid cell-by-cell basis in BTH. The following equations were used to calculate the change in the mortality rate based on the difference in fine particle concentrations between the two simulations (US EPA, 2015):

$$\Delta Y = Y_0\left(1 - e^{-\beta\Delta PM}\right) \times Pop \quad (1)$$

$$\beta = \frac{\ln(RR)}{\Delta PM} \quad (2)$$

$$\beta_{min} = \beta - (1.96 \times \sigma_\beta) \quad (3)$$

$$\beta_{max} = \beta + (1.96 \times \sigma_\beta) \quad (4)$$

where, ΔY (person) is the change in the health or environmental effect, Y_0 is the baseline incidence rate of the health effect (the incidence rate before the change in PM), β is the coefficient of PM and derived from the relative risk (RR) associated with a change in exposure as expressed in concentration–response function, ΔPM ($\mu g/m^3$) is the air quality change, and Pop (person) is the exposed population. β_{min} is the minimum value of β, and β_{max} is the maximum value of β. σ_β (the standard error of β) is calculated as the average of the standard errors implied by the reported lower and upper bounds of the RR.

The BenMAP software calculated a distribution of Monte Carlo estimates in each grid cell of the number of attributable deaths associated with changes in fine particles between the two scenarios considered. For each health endpoint, BenMAP chose values randomly from the probability distribution for each C–R coefficient and then calculated an incidence rate based on the chosen values. It repeated this process 5000 times to generate a distribution of estimated incidence rates. For each grid cell, we selected the median, and the 2.5th and 97.5th percentiles of this distribution to provide a range of uncertainty for the results of health impact assessment. Regional figures of deaths attributable to $PM_{2.5}$ concentration reduction were obtained by adding up all the cell estimates.

Economic valuation functions (for valuing reductions in mortality risk) used in this study were obtained from China-specific valuation studies (Wang and Mullahy, 2006; Zhang, 2002; Hammitt and Zhou, 2006; Deng, 2006), in which willingness to pay (WTP) and human capital (HC) methods were used. The US dollar was converted to Chinese CNY based on Purchasing Power Parity adjusted exchange rates. If there were several estimated costs of different years in one study, we chose the most recent one. The estimated costs of different years were adjusted using Consumer Price Index (CPI) numbers, and the currency year was 2010.

2. Results

2.1. Simulated $PM_{2.5}$ exposure level

As shown in Fig. 3, the monitored average of $PM_{2.5}$ daily (24 hr) mean concentrations in 2014 were 84 $\mu g/m^3$ (range 5–392 $\mu g/m^3$), 86 $\mu g/m^3$ (range 12–383 $\mu g/m^3$), and 94 $\mu g/m^3$ (range 15–341 $\mu g/m^3$) in Beijing, Tianjin, and Hebei Province, respectively. There were 101 days achieved the Class I standard (<35 $\mu g/m^3$) and 106 days satisfied the Class II standard (36–75 $\mu g/m^3$) in Beijing. The corresponding days that satisfied the Class I and II standards were 58 and 137 days in Tianjin, and 39 and 140 days in Hebei Province. The concentrations in winter were the highest for all these three places (98, 106, and 136 $\mu g/m^3$ for Beijing, Tianjin and Hebei), followed by the concentrations in autumn (90, 88, and 93 $\mu g/m^3$) and spring (80, 88, and 81 $\mu g/m^3$), the lowest concentrations were achieved in summer (68, 63, and 64 $\mu g/m^3$).

The regional average concentration of $PM_{2.5}$ in the reference scenario (2012) was 83.99 $\mu g/m^3$ with a standard deviation of 26.38 $\mu g/m^3$. The highest and lowest predicted concentrations were 141.53 and 31.58 $\mu g/m^3$, respectively (Fig. 4). The average population density (population per km^2) was 290 in BTH, and the highest value was 156,565 that appeared in Beijing (Fig. 1).

2.2. Avoided mortality assuming to complete the Action Plan

Table 1 summarizes the mortality findings in terms of the total annual number of attributable deaths (2.5th–97.5th percentiles) in BTH. These benefits were unevenly distributed throughout BTH, due to the wide variation in underlying population health. Based on cohort study (Cao et al., 2011), the avoided impacts on all cause mortality, cardiovascular mortality, respiratory mortality and lung cancer mortality of a year exposure to the

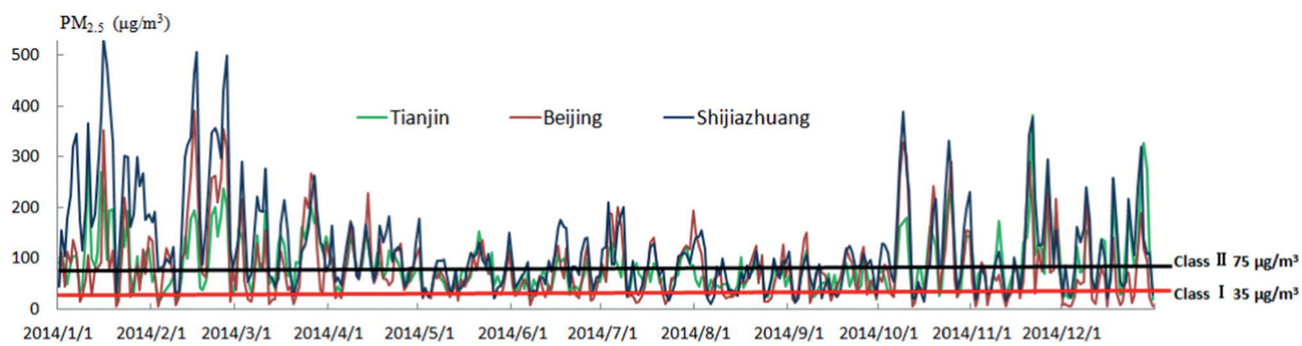

Fig. 3 – $PM_{2.5}$ daily mean concentrations in Beijing, Tianjin and Hebei Province, China, 2014.

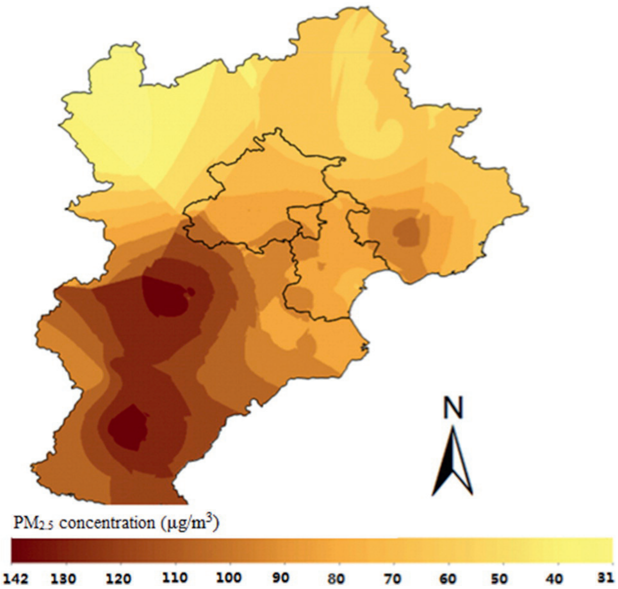

Fig. 4 – Baseline $PM_{2.5}$ concentration in BTH region, China, 2014.

annual mean $PM_{2.5}$ concentration were estimated to be 14,051, 6318, 1561 and 3117 cases per year in BTH, respectively. The avoided deaths for all cause, cardiovascular disease, respiratory disease and lung cancer were 2849, 1327, 259 and 631 per year, respectively, in Beijing. The corresponding avoided deaths are 1457, 907, 131 and 326 per year, respectively, in Tianjin; and are 9746, 4084, 1171 and 2161 per year, respectively, in Hebei. Based on time-series studies (Huang et al., 2012; Kan et al., 2007; Wong et al., 2008), the avoided impacts on all cause mortality, cardiovascular mortality and respiratory mortality of a year exposure to the annual mean $PM_{2.5}$ concentration were estimated to range from 3175 to 5697, from 1924 to 2911 and from 343 to 1697 cases per year, respectively. The avoided deaths for all cause, cardiovascular disease and respiratory disease were 644–1156, 405–612 and 57–282 per year, respectively, in Beijing. The corresponding avoided deaths were 328–590, 276–417 and 29–142 per year, respectively, in Tianjin; and were 2202–3952, 1244–1882 and 258–1274 per year, respectively, in Hebei. The health benefits based on cohort study are greater than those based on time-series studies in all cause and cardiovascular mortalities.

2.3. *Economic benefits assuming to complete the Action Plan*

Table 2 summarizes the estimated values of health effects in BTH. Based on WTP, the estimated monetary values for the avoided cases of all cause mortality, cardiovascular mortality, respiratory mortality and lung cancer ranged from 1110 to 29,632, 673 to 13,325, 120 to 3579, and 1091 to 6574 million CNY, respectively. Based on HC, the corresponding values for the avoided cases of these four mortalities were 267 to 1178, 161 to 529, 29 to 143 and 261 million CNY, respectively. Based on WTP, the estimated values of avoided deaths for all cause were 225–6007 million CNY (accounting for 0.01%–0.3% of 2012 GDP of Beijing), 115–3073 million CNY (accounting for 0.01%–0.2% of 2012 GDP of Tianjin) and 770–20,552 million CNY (accounting for 0.03%–0.8% of 2012 GDP of Hebei), for Beijing, Tianjin and Hebei, respectively. Based on HC, the corresponding estimated values of avoided deaths for all cause were 54–239, 28–122, 185–817 million CNY in Beijing, Tianjin, and Hebei, respectively.

Fig. 5 shows the economic benefits under projected scenario for different cities. The raw data in Fig. 5 were based on the average of the WTP values in all cities of BTH. The economic value due to the decrease of $PM_{2.5}$ concentration, assuming the Action Plan was completed, varies in different cities. The values in Beijing and Shijiazhuang were the highest, followed by Baoding and Handan, the values in Zhangjiakou and Chengde were the lowest.

Table 1 – Estimated avoided mortality of health effects in BTH using monitoring data *.

Health endpoint	Avoided mortality (person)												Reference
	Beijing			Tianjin			Hebei			BTH			
	2.5th	50th	97.5th	2.5th	50th	97.5th	2.5th	50th	97.5th	2.5th	50th	97.5th	
All cause	−482	2849	6104	−246	1457	3129	−1648	9746	20,890	−2375	14,051	30,123	Cao et al. (2011)
	226	644	1061	115	328	541	771	2202	3628	1112	3175	5230	Huang et al. (2012)
	354	1156	1951	181	590	996	1212	3952	6674	1747	5697	9622	Kan et al. (2007), Wong et al. (2008)
Cardiovascular	−225	1327	2844	−153	907	1949	−690	4084	8753	1068	6318	13,546	Cao et al. (2011)
	120	405	688	82	276	469	369	1244	2114	571	1924	3271	Huang et al. (2012)
	0	612	1218	0	417	832	0	1882	3746	−1	2911	5796	Kan et al. (2007), Wong et al. (2008)
Respiratory	−616	259	1082	−306	131	548	−2781	1171	4900	−3703	1561	6530	Cao et al. (2011)
	−62	57	175	−31	29	88	−282	258	792	−375	343	1055	Huang et al. (2012)
	52	282	508	26	142	256	234	1274	2297	311	1697	3061	Kan et al. (2007) Wong et al. (2008)
Lung cancer	−49	631	1261	−25	326	656	−168	2161	4328	−242	3117	6245	Cao et al. (2011)

BTH: Beijing–Tianjin–Hebei.

* The $PM_{2.5}$ concentration was decreased by 25% in BTH, and the $PM_{2.5}$ concentration was decreased to 60 μg/m³.

Table 2 – Estimated values of health effects in BTH using monitoring data.

Health endpoint	Monitoring annual mean, BTH rollback by 25% and Beijing rollback to 60 μg/m³									
	WTP, value (×10⁶ CNY, 2010)					HC, value (×10⁶ CNY, 2010)				
	Beijing	Tianjin	Hebei	BTH	Source	Beijing	Tianjin	Hebei	BTH	Source
All cause	997, 6007	510, 3073	3409, 20,552	4916, 29632	Wang and Mullahy (2006), Zhang (2002)	239	122	817	1178	Deng (2006)
	225, 1358	115, 693	770, 4645	1110, 6696	Hammitt and Zhou (2006), Zhang (2002)	54	28	185	267	Deng (2006)
	404, 2437	206, 1243	1382, 8333	1992, 12013	Wang and Mullahy (2006), Zhang (2002)	97	49	331	477	Deng (2006)
	464, 2799	317, 1914	1428, 8612	2209, 13325	Wang and Mullahy (2006), Zhang (2002)	111	76	342	529	Deng (2006)
Cardiovascular	142, 853	96, 582	435, 2623	673, 4058	Hammitt and Zhou (2006), Zhang (2002)	34	23	104	161	Deng (2006)
	214, 1290	146, 880	658, 3965	1018, 6135	Hammitt and Zhou (2006), Zhang (2002)	51	35	158	244	Deng (2006)
	91, 546	46, 276	410, 2470	547, 3292	Wang and Mullahy (2006), Zhang (2002)	22	11	98	131	Deng (2006)
Respiratory	20, 120	10, 60	90, 543	120, 723	Wang and Mullahy (2006), Zhang (2002)	5	2	22	29	Deng (2006)
	99, 594	49, 298	446, 2687	594, 3579	Wang and Mullahy (2006), Zhang (2002)	24	12	107	143	Deng (2006)
Lung cancer	221, 1330	114, 687	756, 4557	1091, 6574	Hammitt and Zhou (2006), Zhang (2002)	53	27	181	261	Deng (2006)

WTP: willingness to pay; HC: human capital.

3. Discussion

Combining monitoring data of $PM_{2.5}$, population data, health outcome data, and published concentration–response functions for $PM_{2.5}$, we estimated the region-wide and public health benefits. Upon full implementation of Action Plan, air quality improvements in BTH are expected to avoid almost 8000 deaths for all cause each year. These benefits are expected to reduce the region's overall $PM_{2.5}$ burden. The benefits of this program were found to be uneven across BTH, with the greatest health benefit occurring in high population density area of Beijing. The attributable deaths for all causes, cardiovascular, and respiratory based on time-series study were 17%–32%, 24%–41% and 17%–48% of the results based on cohort study, respectively. The health benefits based on cohort study are greater than those based on time-series studies in all cause and cardiovascular mortalities. Based on cohort study, the attributable deaths for cardiovascular, respiratory and lung cancer accounted for 45%, 11% and 22%, respectively. Based on time-series study, the attributable deaths for cardiovascular and respiratory accounted for 51%–59% and 11%–30%, respectively. The economical value of health using HC is about 4%–25% less than the value when we used the method of WTP. The human capital approach provides an incomplete assessment of the health benefits because it is limited to measuring productivity gains resulting only from the increased availability of work time.

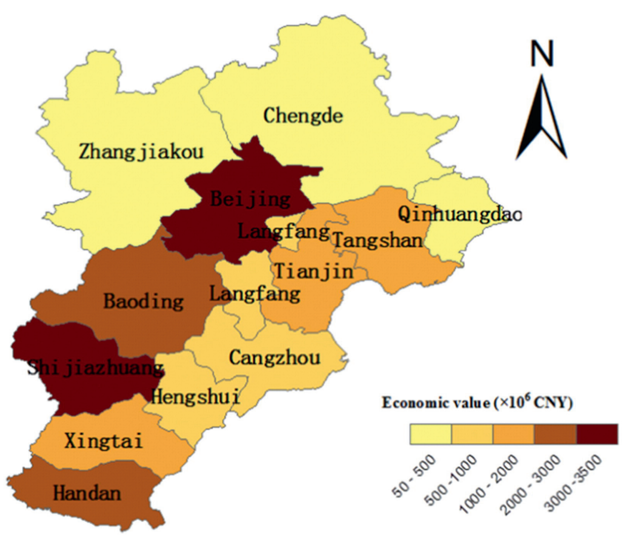

Fig. 5 – Economic benefits under projected scenario for different cities.

Based on the assessment of this study, we suggest to adopt more efficient air quality control and emergency response measures to reduce the health effect of being exposed to $PM_{2.5}$. Our study showed that the avoided deaths for all cause and economic values due to the decrease of $PM_{2.5}$ concentration in Beijing and Shijiazhuang were similar, assuming the Action Plan was completed. The population in Beijing (20.69 million) is about two times higher than that of Shijiazhuang (10.16 million), and the GDP of Beijing (1787.9 billion) is about four times higher than that of Shijiazhuang (450.02 billion). However, the $PM_{2.5}$ annual average concentration of Beijing was 1.5 times lower than that in Shijiazhuang. According to the most recent source apportionment of $PM_{2.5}$, vehicle emission and the coal combustion account for the most in Beijing (http://www.bj.xinhuanet.com/bjyw/2014-04/17/c_1110289403.htm) and Shijiazhuang (http://www.he.xinhuanet.com/news/2014-08/29/c_1112288346.htm), respectively, thus we should control the automobile volume, coal consumption and transform energy structure in subsequent years.

The estimates reported here are still subject to a variety of limitations. In previous works, Model3/CMAQ has been used to simulate air pollutants exposure concentrations (Voorhees et al., 2014; Fann et al., 2012; Chae and Park, 2011; Boldo et al., 2014; Sonawane et al., 2012). In China, it is very difficult to obtain the high-resolution $PM_{2.5}$ emission inventory, because detailed activity data with high-resolution are not publicly available. Most of the emission inventories were either developed using a top-down approach or resolved with low resolutions (*e.g.*, provincial-level or prefectural-level), which resulted in significant uncertainties in emission factors selection as well as the data temporal and spatial allocation. Most of the $PM_{2.5}$ emission inventory was not validated. It affects the accuracy of air quality simulation. In this study, we simulated the air quality surface based on monitoring data. The health impact analysis includes a variety of uncertainties and assumptions inherent in local-scale air quality benefit analyses. Some of these uncertainties have been reduced through the use of local baseline health data and well characterized risks of air pollution exposures. Since there is limited cohort study (only one is available) in China, our study relied on the results of time-series studies. We only quantified $PM_{2.5}$ associated deaths for cardiovascular, respiratory and lung cancer end points which do not account for additional benefits that are expected to come from other avoided end points. Furthermore, only mortality was assessed in this study, while morbidity was not considered.

4. Conclusions

In this study, the numbers of avoided cases of mortality and economic benefits due to the decrease of $PM_{2.5}$ concentration in BTH were estimated, assuming the Action Plan was completed. The avoided impacts on all cause mortality of a year exposure to the annual mean $PM_{2.5}$ concentration were estimated to be 14,051 and 3175, respectively, by using the results of cohort study and time-series studies. Based on WTP, the estimated values of avoided deaths for all cause in Beijing, Tianjin and Hebei accounted for 0.01%–0.3% of 2012 GDP of Beijing, 0.01%–0.2% of 2012 GDP of Tianjin and 0.03%–0.8% of 2012 GDP of Hebei, respectively. The economic benefits of Beijing and Shijiazhuang were the highest, followed by Baoding and Handan, the values in Zhangjiakou and Chengde were the lowest.

With the rapid economic development, $PM_{2.5}$ pollution in China has become a severe problem. Health and environmental benefit – cost analyses can aid in making strategic decisions needed to implement policies such as Action Plan. This study demonstrates a method, which can identify the impacts of air quality plans, for estimating health benefits that can be applied in BTH and other areas in China. In order to further improve the air quality and public health benefits, comprehensive control policies such as control of $PM_{2.5}$ emission from different sources should be implemented.

Acknowledgments

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REFERENCES

Boldo, E., Linares, C., Aragonés, N., Lumbreras, J., Borge, R., de la Paz, D., et al., 2014. Air quality modeling and mortality impact of fine particles reduction policies in Spain. Environ. Res. 128 (1), 15–26.

Cao, J., Yang, C., Li, J., Chen, R., Chen, B., Gu, D., et al., 2011. Association between long-term exposure to outdoor air pollution and mortality in China: a cohort study. J. Hazard. Mater. 186 (2), 1594–1600.

Cesaroni, G., Badaloni, C., Gariazzo, C., Stafoggia, M., Sozzi, R., Davoli, M., et al., 2013. Long-term exposure to urban air pollution and mortality in a cohort of more than a million adults in Rome. Environ. Health Perspect. 121 (3), 324–331.

Chae, Y., Park, J., 2011. Quantifying costs and benefits of integrated environmental strategies of air quality management and greenhouse gas reduction in the Seoul Metropolitan Area. Energ Policy 39 (9), 5296–5308.

Chen, R., Panm, G., Kan, H., Tan, J., Song, W., Wu, Z., 2010. Ambient air pollution and daily mortality in Anshan, China: a time-stratified case-crossover analysis. Sci. Total Environ. 408 (24), 6086–6091.

Columbia University, Center for International Earth Science Information Network (CIESIN), United Nations Food and Agriculture Programme (FAO), Centro Internacional de Agricultura Tropical (CIAT), 2005. Gridded Population of theWorld: Future Estimates (GPWFE). Socioeconomic Data and Applications Center (SEDAC), Columbia University, Palisades, NY ((cited 2012 Oct). Available from http://sedac.ciesin.columbia.edu/gpw).

Deng, X., 2006. Economic costs of motor vehicle emissions in China: a case study. Transp. Res. D TR 11 (3), 216–226.

Ding, D., Zhu, Y., Jang, C., Lin, C., Wang, S., Fu, J., et al., 2016. Evaluation of health benefit using BenMAP-CE with an integrated scheme of model and monitor data during Guangzhou Asian Games. J. Environ. Sci. 42 (4), 9–18.

Fann, N., Baker, K., Fulcher, C., 2012. Characterizing the $PM_{2.5}$-related health benefits of emission reductions for 17 industrial, area and mobile emission sectors across the U.S. Environ. Int. 49 (49), 141–151.

Guo, Y., Jia, Y., Pan, X., Liu, L., Wichmann, H.E., 2009. The association between fine particulate air pollution and hospital emergency room visits for cardiovascular diseases in Beijing, China. Sci. Total Environ. 407 (17), 4826–4830.

Guo, Y., Barnett, A.G., Zhang, Y., Tong, S., Yu, W., Pan, X., 2010. The short-term effect of air pollution on cardiovascular mortality in Tianjin, China: comparison of time series and case cross over analyses. Sci. Total Environ. 409 (2), 300–306.

Hammitt, J.K., Zhou, Y., 2006. The economic value of air-pollution-related health risks in China: a contingent valuation study. Environ. Resour. Econ. 33 (3), 399–423.

Huang, W., Cao, J., Tao, Y., Dai, L., Lu, S., Hou, B., et al., 2012. Seasonal variation of chemical species associated with short-term mortality effects of $PM_{2.5}$ in Xi'an, a central city in China. Am. J. Epidemiol. 175 (6), 556–566.

Kan, H., London, S.J., Chen, G., Zhang, Y., 2007. Differentiating the effects of fine and coarse particles on daily mortality in Shanghai, China. Environ. Int. 33 (3), 376–384.

Lepeule, J., Laden, F., Dockery, D., Schwartz, J., 2012. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. Environ. Health Perspect. 120 (7), 965–970.

Raaschou-Nielsen, O., Andersen, Z.J., Beelen, R., Samoli, E., Stafoggia, M., Weinmayr, G., et al., 2013. Air pollution and lung cancer incidence in 17 European cohorts: prospective analyses from the European Study of Cohorts for Air Pollution Effects (ESCAPE). Lancet Oncol. 14 (9), 813–822.

Rd, P.C., Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. J. Air Waste Manage. Assoc. 56 (6), 709–742.

Sonawane, N.V., Patil, R.S., Sethi, V., 2012. Health benefit modelling and optimization of vehicular pollution control strategies. Atmos. Environ. 60 (60), 193–201.

State Council of China, 2013. Air pollution prevention and control action plan. http://www.cleanairchina.org/product/6349.html.

Turner, M.C., Krewski, D., PopeIII, C.A., Chen, Y., Gapstur, S.M., Thun, M.J., 2011. Long-term ambient fine particulate matter air pollution and lung cancer in a large cohort of never-smokers. Am. J. Respir. Crit. Care Med. 184 (12), 1374–1381.

US EPA, 2015. BenMAP User's manual. Available at: http://www2.epa.gov/benmap/manual-and-appendices-benmap-ce.

Voorhees, A.S., Wang, J.D., Wang, C.C., Zhao, B., Wang, S.X., Kan, H.D., 2014. 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.

Wang, H., Mullahy, J., 2006. Willingness to pay for reducing fatal risk by improving air quality: a contingent valuation study in Chongqing, China. Sci. Total Environ. 367 (1), 50–57.

Wang, J.D., Wang, S.X., Voorhees, A.S., Zhao, B., Jang, C., Jiang, J.K., et al., 2015. Assessment of short-term $PM_{2.5}$-related mortality due to different emission sources in the Yangtze River Delta, China. Atmos. Environ. 123 (B), 440–448.

Wong, C.M., Vichit-Vadakan, N., Kan, H.D., Qian, Z.M., 2008. Public health and air pollution in Asia (PAPA): a multicity study of short-term effects of air pollution on mortality. Environ. Health Perspect. 116 (9), 1195–1202.

Zhang, X., 2002. Valuing mortality risk reductions using the contingent valuation methods: evidence from a survey of Beijing residents in 1999. Presented at the Second World Congress of Environmental Economists. Centre for Environment and Development, Chinese Academy of Social Sciences, Beijing.

Zhang, Y.P., Li, J.F., Zhang, Z.Q., 2008. Exposure–response relationship between particulate pollution level and hospital outpatient visits in Taiyuan. J. Environ. Health 25 (6), 479–482.