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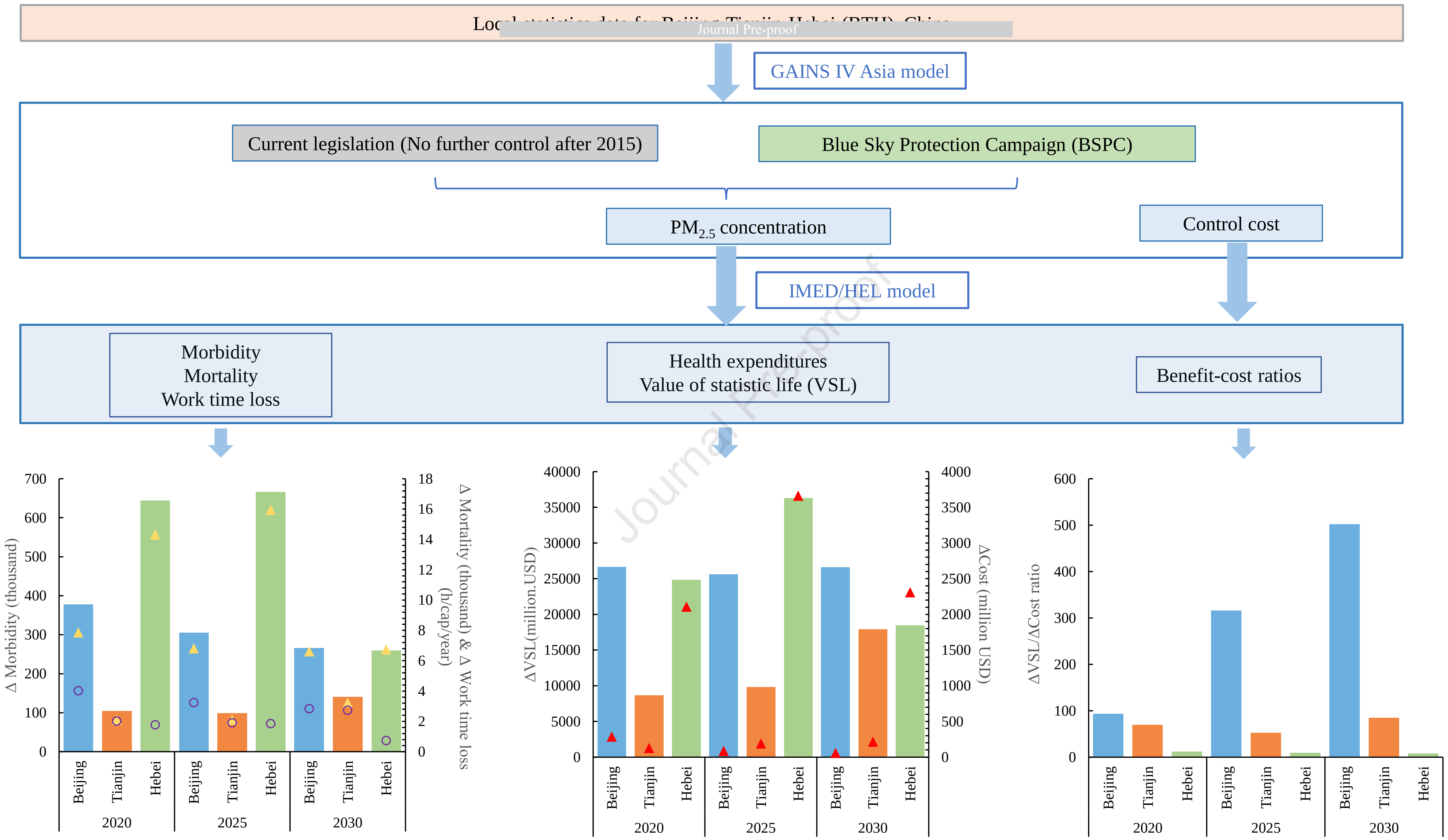

Bars refer to the left Y-axis while triangles and circles refer to the right Y-axis

Health and economic benefits of clean air policies in China: a case study for Beijing-Tianjin-Hebei region

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Abstract

Exposure to $PM_{2.5}$ is associated with many adverse health effects, leading to additional social costs. The Blue Sky Protection Campaign (BSPC) has been implemented in 2018 in the Beijing-Tianjin-Hebei (BTH) area to control air pollution. This study assesses $PM_{2.5}$-related health and economic benefits of the BSPC in the BTH region. Results show that by 2020, $PM_{2.5}$ reduction can avoid 3561 thousand morbidity cases (equivalent to a 24% reduction in the 2020 baseline scenario) and 24 thousand premature deaths (12%) in the BTH region, with the majority benefit in Hebei. By 2030, the avoided morbidity and mortality cases will be 2943 (18%) thousand and 20 (9%) thousand, respectively. $PM_{2.5}$ reductions are highly effective in reducing work time loss, which will decrease the total annual work time by 1.7×10^{8} hours (24%) in the BTH region by 2020. From the economic aspect, the reduced $PM_{2.5}$ concentration will save 30 million USD (25%) health expenditures and avoid 60 billion USD (13%) economic loss by using the value of statistical life (VSL) by 2020. In 2030, the health expenditures and economic loss will also decrease

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significantly, with 17 million USD (18%) and 63 billion USD (10%), respectively, in the BTH region. Besides, the economic benefits far exceed the policy costs of the BSPC, and the Δ benefit/Δ cost ratios of Beijing are significantly higher than those of Hebei. The BSPC in BTH has significant positive health and economic impacts. This study can provide a basis for future $PM_{2.5}$-related health risk studies at an urban level in China.

Keywords:
Blue Sky Protection Campaign, Air quality, Health assessments, Economic effects, Integrated assessment methods.

1 Introduction

With the fast industrialization and urbanization in China, air pollution has become increasingly prominent (Cao et al., 2011; Dong et al., 2015; Hossain et al., 2021; Kuerban et al., 2020). Over 83% of the Chinese population live in areas with annual $PM_{2.5}$ concentrations that exceed the World Health Organization Interim Target-1 (WHO IT-1) of 35 μg/m^3. Air pollution in China leads to serious health concerns (Brauer et al., 2012; Brauer et al., 2016; Liu et al., 2016). Epidemiological evidence has shown that $PM_{2.5}$ exposure is associated with increasing the risks of respiratory, cardiovascular, and cerebrovascular diseases and even premature deaths (Dockery et al., 1993; Pope et al., 2002; Pope et al., 2004). For instance, the premature deaths associated with $PM_{2.5}$ accounted for nearly 7.1% of worldwide deaths in 2010 (Evans et al., 2013). An analysis from Global Burden of Disease suggested that $PM_{2.5}$ pollution had caused 4.09 million mortalities in 2016, in which ischemic heart disease, chronic obstructive pulmonary disease, lower respiratory infections, and lung cancer accounting for 38.51%, 19.23%, 15.97%, and 6.83%, respectively (Roth et al., 2018). $PM_{2.5}$ pollution has been recognized as the prime environmental health risk (Cohen et al., 2005; Lim et al., 2012), predominantly in China and India (Anenberg et al., 2010; Ji et al., 2019; Lelieveld et al., 2015). Based on the provincial $PM_{2.5}$ concentrations and health data, Rong and Wang (2016) suggested that $PM_{2.5}$ pollution in China caused 1,255,400 mortalities in 2010, 42% higher than the level in 2000. Further, mortalities associated with $PM_{2.5}$ pollution would be 2.3 million in China by 2030 (Xie et al., 2019). It suggests that $PM_{2.5}$ pollution in China has been an urgent issue needing been addressed.

The adverse effects of $PM_{2.5}$ pollution on health also lead to economic costs, including additional expenditures and labor productivity reduction. Tian et al. (2018) evaluated the economic impacts of $PM_{2.5}$-related health impacts on China's road transport sector. They found air pollution from transportation led to 442.90 billion Yuan of the value of statistical life (VSL) loss and 2.09 hours/capita of work time loss in 2015. Besides, it would cause 737.15 billion Yuan of statistical life loss and 2.23 hours/capita of work time loss by 2030 (Tian et al., 2018). Xie et al. (2016a) examined the health and economic effects of $PM_{2.5}$ at a provincial level in China, indicating that without any pollution controls, China would experience 2.00% GDP loss and 25.2 billion USD in health expenditures by 2030. Xie et al. (2016b) concluded that controlling $PM_{2.5}$ pollution could avoid 80.4% of health expenditure expenditures, and the benefit is much higher than the policy cost in the BTH region. Beijing, Tianjin, and Hebei would obtain 1.75%, 2.02%, and 1.46% GDP gains. Wu et al. (2017) evaluated the health and economic impacts of $PM_{2.5}$ exposure in Shanghai and suggested that controlling emissions could avoid 82.7% of mortality cases, 1.89% of GDP losses, and 2.63% of welfare losses.

To control $PM_{2.5}$ pollution, China has implemented several air pollutant control plans. The Air Pollution Prevention and Control Action Plan (APPCAP) launched in 2013 aimed to reduce urban PM_{10} levels by 10% and decrease the $PM_{2.5}$ concentrations of the Beijing-Tianjin-Hebei (BTH), the Pearl River Delta (PRD), and the Yangtze River Delta (YRD) by 15%-25% from 2012 to 2017 (Ma et al., 2020). APPCAP made an outstanding achievement and reduced $PM_{2.5}$ concentrations by over 30% in China (Zhang et al., 2018). Huang et al. (2018) assessed the health effects of the APPCAP in 74 cities of China and found 47,240 fewer mortalities and 710,020 fewer years of life lost in 2017 compared with 2013. Lu et al. (2019) conducted a provincial-level evaluation of the health impacts of $PM_{2.5}$ after implementing the APPCAP in China, and found that deaths decreased from 1,078,800 of 2014 to 962,900 of 2017. The health cost benefits were estimated to be the USD 193,800 in 2017. However, the BTH region is still the most over-polluted area in China. In 2017, the annual average $PM_{2.5}$ concentration in BTH was 58-67 μg/m³, much higher than the WHO standard (CNEMC, 2018). In 2018, the Chinese government launched a three-year plan, the Blue Sky Protection Campaign (BSPC), to control air pollution in BTH, YRD, and Fenwei Plain. One of the specific goals is to reduce $PM_{2.5}$ concentration by 18% compared with the 2015 level. As the BTH region is one of the most developed regions and one of the regions suffering from the most severe air pollution in China (Hao et al., 2018; Qi et al., 2017; Yang et al., 2019), it has been identified as a priority area for air pollution control and prioritized an investigation of the policy impacts. Systematic analysis of the BSPC impacts on air quality and air pollutant emissions in the BTH region has been evaluated in our previously published study (Xu et al., 2020). However, the study only focused on the environmental impacts of implementing the BSPC in BTH rather than the health and economic impacts. In addition, most previous studies have concentrated on the health and economic improvement about the APPCAP. Few studies have involved a system evaluation of the health and economic effects due to implementing the BSPC.

The previous studies mainly focused on the one-city level (Wu et al., 2017), individual-sector level (Zhang et al., 2019), or the whole country (Maji et al., 2017). We provide the first comprehensive systematic assessment on the health and economic impacts due to implementing the BSPC in the BTH region to the best of our knowledge. This study aims to solve two key questions. Firstly, this study focuses on evaluating the health and economic effects of BSPC by 2030 in the BTH region. Secondly, this study will analyze the costs and benefits of the BSPC toward 2030 in the BTH region. It contributes to these existing studies in three aspects. (1) Quantifying the health impacts of the BSPC in the BTH region. (2) Evaluating the economic effects containing health expenditures and the VSLs. (3) Exploring the cost-benefits ratios of the clean air policies. This study will make a certain contribution to demonstrate the feasibility and necessity of the BSPC in BTH and provide a reference for policy-makers.

This paper is organized as follows. Section 2 describes the methodology. Section 3 presents the results, including health effects, economic effects, and a cost-benefit analysis. Section 4 presents the discussion, and section 5 summarizes the conclusions.

2 Methodology

2.1 Integrated assessment methods

This study uses an integrated assessment approach by combining the Greenhouse Gas and Air Pollution Interactions and Synergies IV Asia (GAINS IV Asia) model and the Integrated Model of Energy, Environment and Economy for Sustainable Development/Health (IMED/HEL) model to evaluate the health and economic impacts of implementing the BSPC in the BTH region (Fig.1). This approach has been used in our previous studies (Xie et al., 2016a; 2016b; 2018; 2019; 2020). Firstly, we use the GAINS IV Asia model to predict the $PM_{2.5}$ concentration reductions and the control technologies cost due to the implementation of BSPC. The IMED/HEL model evaluates the health and economic effects of $PM_{2.5}$ pollution, including morbidity, mortality, work time loss, medical expenditures, and VSL.

2.1.1 The GAINS IV Asia model

The GAINS IV Asia model is used to evaluate the effects of various control and policies. It takes into account the activity pathways (for example, power and heating plants, industry and transport) and air pollution control measures for different pollutants from different sectors at a five-year interval (Amann et al., 2011) and quantifies emissions and implementing costs. This study integrates and calibrates original parameters into the GAINS IV Asia model. Specifically, parameters such as energy consumption by fuel types and sectors, industrial activities, the utilization rates of air pollution control technology, and other values and assumptions are considered.

According to the policy restrictions, we change the scenario assumptions in the model to assess changes in pollutant emissions, $PM_{2.5}$ concentrations, and emission reduction costs under various scenarios. The effects of BSPC on energy structures, pollutant emissions, $PM_{2.5}$ concentrations, and control costs have been evaluated in our recent study (Xu et al., 2020). More details regarding the calculation principles, descriptions of the input parameters, calculation process, and parameters determinations for BSPC are shown in section 1 of supporting information.

2.1.2 The IMED/HEL model

The IMED/HEL model evaluates the health effects due to $PM_{2.5}$ exposure on six morbidity endpoints and chronic mortality using a concentration-response function (CRF) (Apte et al., 2015; Tian et al., 2018; Wu et al., 2017; Xie et al., 2016a; Xie et al., 2018). Besides, it can also quantify the monetary value of these health endpoints. The IMED/HEL model is continuously updated, and the documents of detailed information on the model are available online (http://scholar.pku.edu.cn/hanchengdai/imedhel). In our study, a non-linear concentration-response function is applied to assess the six morbidity endpoints, premature deaths with different causes (ischemic heart disease, stroke, cerebrovascular disease, chronic obstructive pulmonary disease, lung cancer, and acute lower respiratory infection), and work time loss. Work time loss includes premature deaths between 15–65 and morbidity for labor. This study uses the population data from the sixth census to conduct the calculation. Besides, to monetize the health effects, medical expenditures and the VSL losses attribute to $PM_{2.5}$ pollution are quantified by assuming a linear relationship with the $PM_{2.5}$-related premature deaths by using health service price (Xie et al., 2016a). Health expenditures are calculated by multiplying outpatient and hospital admission prices with total health endpoints. VSL are evaluated through the willingness to pay method in China (Jin et al., 2020), calculated by certain regions' current GDP per capita values relative to the national average per capita GDP in 2010 and the income elasticity of 0.5. The model is set about our previous analyses (Wu et al., 2017; Xie et al., 2016a; Xie et al., 2020). Details of the calculation principles and calculation process can be found in section 2 in the supporting information.

2.1.3 Cost-benefit analysis

This study also estimates the net benefits of implementing BSPC in the BTH region. The monetized benefits include health expenditure savings associated with reduced morbidities and economic savings due to avoided premature deaths. Total costs equal to emission control costs from BPSC estimated by the GAINS IV Asia model, including the implementation costs of all pollutant control measures (i.e., upfront investments and operating costs).

2.2 Scenarios setting

GAINS IV Asia model simulates emission scenarios at five-year intervals. The baseline is 2015. The primary target year of BSPC is 2020. The years 2025 and 2030 are also included as the secondary target years to show the long-term health and economic benefits of air quality improvements.

Two scenarios are developed to simulate policy effects: the baseline scenario and the policy scenario. The baseline scenario assumes there is no BSPC implementation for air quality improvement in the BTH region. Firstly, we obtain the original 2015 data from the World Energy Outlook 2018 Current Policy Scenario (WEO-2018-CPS) projected by the GAINS IV Asia model and then update parameters of the default baseline scenario of 'WEO-2018-CPS'. The key updating parameters have been described in section 1.4.3 in supporting information. Besides, it's worth noting that the GAINS IV Asia model has some inaccuracies in its data on renewable energy for 2015, we calibrate it using data from the renewable energy report for China and the BTH region. Secondly, based on the recalibrated data for 2015, we project the activities of energy, agricultural, and industrial processes for 2020 based on the trend from the 'WEO-2018-CPS' and the 13th Five-Year Plan (FYP) targets of some macro economy indexes published by the BTH regional government and China's renewable report (NDRC 2016, NEA 2017). The energy demands in 2025 and 2030 in the baseline scenario are estimated based on the growth rate in the scenarios from 2020 to

2030 of the 'WEO-2018-CPS'. The policy scenario assumes that the BTH region implemented BSPC. The key sub-policy package of BSPC can be found in Table S1 in supporting information. Specifically, the policy packages are divided into four categories: the power and industry sector (with core content such as improving the industrial structure and the associated distribution for steel, cement, coke, glass, and coal power plants); the transport sector (with core content such as increasing the number of new energy vehicles and implementing national vi (B) standard gasoline and diesel for traffic vehicles); the building sector (with core content such as replacing untreated coal of heating by households); and the cross-sector (such as the pollution controls for stationary sources). The policy packages of the BSPC and its corresponding emission control measures in the GAINS IV Asia model are summarized in Table S2 in the supporting information. From 2020 to 2030, each region of the BTH will maintain the same policy strictness levels, and the governments will continue to implement specific policy measures at the same rate. The setting of scenarios refers to our previous studies (Meng et al., 2020). The detailed parameters and default parameters of the GAINS IV Asia model used in our study are shown in sections 1.4.3 and 1.4.4 of the supporting information.

2.3 Data sources

Data for this study was obtained from the China Guidebook for Air Pollution Emission Inventory (MEEC 2015), the Provincial Economic Yearbooks (BSB 2016, HSB 2016, TSB 2016), the China Statistical Yearbook (NBS 2016), the 13th FYP of Energy Development (NEA 2017a), the Clean Heating Plan for Winter in North China (2017–2021) (NEA 2017b), the 13th FYP of Renewable Energy Development (NDRC 2016), the 13th FYP of Industrial Transformation and Upgrading (GOHB 2016), the 13th FYP for the Comprehensive Development of Transportation Systems (GOBJ 2016, GOHB 2016, GOTJ 2016), the 13th FYP of Power Sector Development (PGC 2016), and several state-of-the-art studies (Xiong *et al* 2015, Zhang *et al* 2015, Su *et al* 2018).

3 Results

3.1 $PM_{2.5}$ concentration

Table 1 shows the projected $PM_{2.5}$ concentrations under different scenarios, which have been concluded in our previous study (Xu et al., 2020). During the last study, $PM_{2.5}$ concentrations up to 2020 were quantified, and no longer-term $PM_{2.5}$ changes have been investigated. In this study, we extend it to 2030 to better evaluate the health and economic impacts. $PM_{2.5}$ concentrations projected here are used as the basis for subsequent studies focusing on health and economic impacts. The results show that the emission of pollutants in Beijing in 2015 was not high, but Beijing and Tianjin are adjacent to Hebei, and a large number of pollutants disperse from Hebei to Beijing and Tianjin area. Also, the particular geographical locations of Beijing and Tianjin lead to the poor diffusion of air pollutants, so the $PM_{2.5}$ concentrations of Beijing and Tianjin in 2015 were higher than that of Hebei. This study projected that the $PM_{2.5}$ concentrations were 78.7μg/m^3, 69.1μg/m^3, and 65.2μg/m^3 in 2015 for Beijing, Tianjin, and Hebei. According to the Environment Statement of 2015 in the BTH region (BJES, 2015; HBES 2015; TJES, 2015), $PM_{2.5}$ concentrations were 80.6μg/m^3, 70μg/m^3, and 77μg/m^3 for Beijing, Tianjin, and Hebei, respectively. Our simulation for Beijing and Tianjin is comparable to the results from the Environment Statement. $PM_{2.5}$ concentrations for Hebei is lower than Environment Statement. Because we aggregate and average the grid concentrations belonging to the region's longitude and latitude and the spatial resolution of concentration and area of the region may cause some differences in the results. Our projections are all comparable to the results from Zhang et al. (2019), which calculated the $PM_{2.5}$ concentrations for Beijing, Tianjin, and Hebei in 2015 to be 85μg/m^3, 72μg/m^3, and 69μg/m^3, respectively.

After implementing the BSPC, $PM_{2.5}$ concentration in the BTH region will decrease significantly. By 2030, Tianjin will have the highest concentration of $PM_{2.5}$, followed by Hebei and Beijing. Compared with the baseline scenarios, $PM_{2.5}$ concentration in policy scenarios will decrease by 8.7% (Hebei 2030) to 32.1% (Beijing 2020). However, $PM_{2.5}$ concentration under the policy scenarios will still be higher than the national standard of 35 μg/m^3 and will still have impacts the exposed population.

3.2 Health impacts

3.2.1 Morbidity

The main morbidities associated with $PM_{2.5}$ pollution involve asthma, cardiovascular hospital admissions, cerebrovascular hospital admissions, chronic bronchitis, respiratory hospital admissions, and upper respiratory (Dockery et al., 1993; Iii et al., 2002; Pope et al., 2002), which are the primary health endpoints we evaluate in this study. Fig. 2A1-A3 (left Y-axis) presents the physical impacts on morbidities attributed to $PM_{2.5}$ pollution in BTH. In 2015, the total morbidities due to $PM_{2.5}$ exposure amounted to 5208 thousand cases in BTH. The morbidity cases show a decreasing trend in both the baseline and the policy scenarios, and the more significant $PM_{2.5}$ decreases under the policy scenario are more effective in reducing morbidity cases. By 2020, morbidity cases in the BTH region under the policy scenario will decrease significantly to 3561 (equivalent to a 24% reduction in the baseline scenario) thousand cases. It will reduce to 3242 (25%) and 2943 (18%) thousand cases by 2025 and 2030. Upper respiratory is the dominating morbidity endpoint, followed by asthma and chronic bronchitis. These three diseases account for more than 96% of total morbidity in all scenarios.

At the regional level, provinces with higher population density suffer more morbidities (Xie et al., 2019). Beijing presented the highest $PM_{2.5}$ concentration in 2015. Hebei had the highest $PM_{2.5}$-related morbidity cases, accounting for 68% of morbidity cases in BTH in 2015. Hebei has higher morbidity risks due to the aging population. Specifically, the aging population of Hebei has exceeded the national average level for the first time since 2015 (Li, 2019). By the end of 2017, it accounted for 18% of the total population in Hebei. The aging population will reach 15 million by 2020, indicating a moderately aging society on the horizon. The bars in Fig. 3 indicate the absolute reductions (thousand cases) in morbidity between the baseline scenarios and the policy scenarios for each year. After implementing the BSPC, 378

(38%), 105 (20%), and 644 (20%) thousand cases of morbidity will be avoided by 2020 in Beijing, Tianjin, and Hebei, respectively. The avoided morbidities cases will amount to 266 (34%), 141 (29%), and 268 (11%) thousand by 2030. Zhang et al. (2019) evaluated the health benefits of the residential 'coal-to-electricity' policy in BTH. They found that with the implementation of the policy, 0.20 (19.7%), 0.07 (13.1%), and 0.40 (11.2%) million cases of morbidity could be avoided in BTH, respectively. The avoided morbidity is higher than other studies of other clean air policies. Beijing improves the most in terms of $PM_{2.5}$ concentrations and the proportions of reductions in morbidity cases. Hebei benefits the most in total morbidity population due to its large exposure population.

The number of morbidity cases is lower in the policy scenarios than in the baseline scenarios due to implementing the BSPC. The morbidity cases decrease in the 2020 baseline scenario compared to 2015 because of the continuous decline in $PM_{2.5}$ concentrations (Fan et al., 2020; Li et al., 2020; Maji et al., 2020; Meng and Zhou, 2020). Similar reductions in morbidity cases without implementing the BPSC are also found in other researches in the BTH region (Huang and Zhang, 2013; Zhang et al., 2019) and other provinces (Liying et al., 2014; Wu et al., 2017). For instance, Huang and Zhang (2013) presented that significant health improvements would be achieved since the implementation of Air Quality Standards in 2012. Therefore, it indicates that even if BPSC is not implemented (as suggested in the baseline scenario), the morbidity cases in the 2020 baseline scenario will be lower than that of 2015. The morbidity reductions in Tianjin are lower than in Beijing and Hebei due to $PM_{2.5}$ concentration reduction potentials are more significant than those of Tianjin under BSPC.

3.2.2 Mortality

The red triangles in Fig. 2A1-A3 indicate the impacts on mortalities associated with $PM_{2.5}$ exposure in BTH. The mortalities were estimated to be 206 thousand in the BTH region of 2015. There will be slight downward trends of the mortality cases in both the baseline and policy scenarios. Mortality cases will significantly decrease in the policy scenarios due to reductions in $PM_{2.5}$ pollution under the BSPC. Mortalities will amount to 204 thousand and 180 thousand in the baseline and policy scenarios, respectively. BSPC will reduce 24 thousand premature deaths in BTH in 2020. Mortality in BTH under the policy scenarios will decrease significantly by 20 (12%) thousand and 20 (9%) thousand by 2025 and 2030, respectively.

It has been concluded that regions with a larger population have more mortalities (Xie et al., 2019). In Hebei, the mortality cases were 145 thousand in 2015. The yellow triangles in Fig. 3 indicate the absolute reductions (thousand cases) in mortality between the baseline scenarios and the policy scenarios for each year. Compared with the baseline scenario, the BSPC will avoid approximately 14 (10%) thousand premature deaths by 2020 under the policy scenario. It will decrease by 16 (11%) thousand and 8 (5%) thousand cases by 2025 and 2030. In Beijing and Tianjin, after implementing the BSPC, the mortality cases will decrease by 8 (19%) thousand and 2 (9%) thousand by 2020. The avoided mortality in Beijing and Tianjin is 6.6 (17%) thousand and 3.2 (14%) thousand cases of mortalities by 2030. Many studies have assessed premature mortality due to $PM_{2.5}$ exposure. If the residential "coal-to electricity" policy in BTH is fully implemented, 6700, 2500, and 13200 cases of premature deaths can be avoided in 2020 (Zhang et al., 2019). Huang et al. (2018) assessed the health effects of the APPCAP in 74 cities of China and found 47,240 fewer mortalities in 2017 compared with 2013. Our study shows implementing BSPC can significantly reduce morbidity in the BTH. The avoided premature deaths in Hebei is much higher than in Beijing and Tianjin. Beijing benefits the most from BSPC in the percentage of reductions in mortality cases.

The mortality cases in the 2020 baseline scenario will be comparable or even higher than the 2015 level. A slight decrease of $PM_{2.5}$ concentration between 2015 and the 2020 baseline scenario will have little impact on the mortality cases. The results could also explain this from Wang et al. (2014). These volunteers with longer exposure histories present higher contaminant levels in serum while not cause acute deaths (Wang et al., 2014). The declining trends in mortality cases between the reference year and the baseline scenario are consistent with the conclusions drawn from Zhang et al. (2019). Therefore, it demonstrates that even if BPSC is not implemented, the mortality cases in the 2020 baseline scenario will be even higher than that of 2015. Consequently, it is necessary to implement the BSPC to achieve health benefits to reduce mortality cases.

3.2.3 Work time loss

Morbidities and mortalities lead to work time loss, as indicated by the bars below the X-axis in Fig. 2B1-B3. The purple circles in Fig. 3 indicate the absolute reductions (hour/cap/year) in work time loss between the baseline scenarios and the policy scenarios. The work time loss is calculated as the hours a person aged 15-64 stays off work due to morbidities and mortalities. In 2015, the total annual work time loss in BTH was 7.7×10^8 hours; this will drop to 6.9×10^8 and 5.3×10^8 hours by 2020 and 2030 under the baseline scenarios. Under the policy scenarios, work time loss will be approximately 5.2×10^8 hours and 4.3×10^8 hours by 2020 and 2030. Work time loss presents a downward trend in the BTH region due to air quality improvement under all scenarios. $PM_{2.5}$ decrease has a positive effect in decreasing work time loss by 1.7×10^8 hours (24%) in the BTH region by 2020.

At the provincial level, the annual per capita work time loss in 2015 was 11.98 hours, 10.30 hours, and 9.63 hours in Beijing, Tianjin, and Hebei. Under the policy scenario, per capita work time loss in 2020 will drop to 6.69 hours (38%) in Beijing, 8.11 hours (20%) in Tianjin, and 6.91 hours (20%) in Hebei. The per capita work loss will decrease to 5.52 hours (34%), 6.76 hours (29%), and 5.92 hours (11%). We calculated the percentages in the brackets as the absolute avoided work time loss ratio between the baseline scenario and the policy scenario to the absolute value of work time loss in the corresponding baseline scenario, representing the percentage of the avoided absolute work time loss caused by implementing the BSPC in the baseline scenario.Tian et al. (2018) evaluated $PM_{2.5}$ pollution-related health impacts of road transport in China. They found the most strict control strategy scenario would decrease the hours of work time loss by 42.65% in China. Their result is comparable to our study. In 2015, Beijing lost the most working hours in 2020. The regional disparities in work time loss are consistent with the regional disparities in $PM_{2.5}$ concentrations.

3.3 Economic impacts

3.3.1 Health expenditures

$PM_{2.5}$ pollution also causes additional medical expenditures, as indicated by the bars above the X-axis in Fig. 2B1-B3. In 2015, additional medical expenses related to air exposure in the BTH region amounted to 134 million USD. In the baseline scenarios, the additional health expenditure for the BTH region will be 121 million USD and 92 million USD by 2020 and 2030. It will drop to 91 million USD and 75 million USD under the policy scenarios by 2020 and 2030. The expenditures present slightly downward trends in the BTH region due to improved air quality under all scenarios. However, the reductions in policy scenarios are more significant than their respective baseline. The monetized benefits of avoided morbidity cases are 29 million USD and 17 million USD in the BTH region, accounting for 24% and 18% of their perspective baseline expenditures. The costs of treating respiratory symptoms are relatively low. Because of the large number of cases, respiratory symptoms are the first contributor to total morbidity expenditures, accounting for more than 50% of total expenditure in all the scenarios.

At the regional level, the additional medical expenditures in 2015 were 29 million USD, 14 million USD, and 91 million USD for Beijing, Tianjin, and Hebei, respectively. Under the policy scenario, the additional medical expenditures in 2020 will drop to 16 million USD (38%) in Beijing, 11 million USD (20%) in Tianjin, and 65 million USD (20%) in Hebei. The expenditures will be even lower by 2030, which will decrease to 13 million USD (34%), 8.9 million USD (29%), and 53 million USD (11%), respectively. Hebei encounters the highest additional medical spending in the BTH region and benefits the most in reducing health expenditures. Zhang et al. (2019) assessed the monetized benefits of morbidity reduction under the implementation of the coal-to-electricity policy in the residential sector in BTH. They concluded that the morbidity benefits of reducing morbidity cases from $PM_{2.5}$ pollution are 0.23, 0.07, and 0.26 billion yuan in the BTH region, respectively, by 2020, accounting for 22%, 18.2%, and 11.1% of their respective morbidity losses. The reduction of $PM_{2.5}$ concentration due to implementing the BSPC will help reduce the additional medical expenditures in the BTH region. The decreasing trends of additional medical spending on both the baseline scenarios and the policy scenarios are consistent with the declining trends of morbidity cases in different scenarios. Our result is consistent with the conclusions drawn from Xie et al. (2016b), which indicated that the medical expenditures would be lower in the scenarios with low $PM_{2.5}$ concentration.

3.3.2 VSL

The benefits of avoided deaths are monetized using VSL, shown by the scatter triangles in Fig. 2B1-B3. Mortality losses are significantly higher than morbidity losses. Mortality losses in 2015 were 395 billion USD in the BTH region. In the baseline scenarios, the mortality losses due to uncontrolled $PM_{2.5}$ pollution will increase to 473 billion USD and 624 billion USD in the BTH region by 2020 and 2030. The mortality losses of implementing the BPSC will increase to 413 billion USD and 561 billion USD by 2020 and 2030. The benefits will be 60 billion USD and 63 billion USD from reducing $PM_{2.5}$ concentration in 2020 and 2030. With the per capita GDP and income increase, total VSL will increase significantly in the future.

At the regional level, VSL is significantly higher in Hebei than in Beijing and Tianjin, which was estimated to be 198 billion USD, 125 billion USD, and 72 billion USD in 2015, respectively. Under the policy scenarios, VSL in 2020 will increase to 81 billion USD (10%) and 222 billion USD (10%) in Tianjin and Hebei, with an absolute increase of 9 billion USD and 24 billion USD. By 2030, VSL will be 105 billion USD and 331 billion USD under Tianjin and Hebei's policy scenarios. For Beijing, VSL also presents an increasing trend in both the baseline and policy scenarios. However, in the policy scenario, the VSL in 2020 will be lower than that in 2015. It will present an upward trend from 2020 to 2030. Some studies have monetized the benefits of mortality reduction due to $PM_{2.5}$ exposure. Zhang et al. (2019) suggested that if the "coal-to electricity" policy is fully implemented in BTH by 2020, there will be 20.10, 4.84, and 15.60 billion yuan in health benefits for Beijing, Tianjin, and Hebei, respectively. The health benefits of VSL in our study are higher than that study, and BSPC in BTH has higher economic benefits in our study. Our analysis also indicates that the economic benefits are dominated by VSL savings (avoided premature deaths) that far exceed the health expenditure savings. Our result is consistent with other studies (Garcia-Menendez et al., 2015; Turner et al., 2015; West et al., 2012).

3.4 Cost-effectiveness analysis

Our results indicate that the BSPC entails co-benefits in reducing morbidities, mortalities, work time loss, medical expenditures, and VSL. A cost-benefit evaluation of $PM_{2.5}$-polluted health effects due to implementing the BPSC is shown in Fig. 4 and Fig. 5. The emission control costs are estimated using the GAINS IV Asia mode. The costs under different scenarios of each region are shown in Table 2 below. The health benefit mainly comprises two aspects of health expenditure savings attributed to reductions in morbidity and reductions in VSL associated with decreased mortality. VSL savings dominate the economic benefits. Therefore, the detailed benefit-cost evaluation of the BSPC is conducted by comparing the monetized health benefits (including VSL-related monetary savings) with pollutant terminal technology costs.

A closer look at the provincial level shows that the costs in policy scenarios are lower than those in the baseline scenarios from each region. The technological improvements in the BPSC will improve air quality and reduce the control costs simultaneously. In 2020, the cost and benefit ratio will amount to 94, 70, and 12 of Beijing, Tianjin, and Hebei, respectively. By 2030, the Δ benefit/Δ cost ratios are about 502, 85, and 8 in Beijing, Tianjin, and Hebei, respectively. Beijing has higher cost-effectiveness of BPSC. Hebei has a relatively lower ratio due to a large number of pollutant emissions and reduction pressure. Our result is consistent with the conclusions drawn from Xie et al. (2016b). They found the benefit-cost ratios in the

BTH region will be the highest in Beijing, followed by Tianjin and Hebei in 2020.

The benefit-cost ratios will increase from 2020 to 2030 in Beijing because of the cumulative effects (shown in Fig. 5), presenting increasing benefits obtained through implementing control measures. For Hebei, it is less significant due to its industrialization processes and the aging population society. Further, the efficiencies of pollutant controls under the BPSC in Beijing are higher than those of Tianjin and Hebei due to different sources of air pollutant emissions in the BTH region. Therefore, to effectively control air pollution, the BTH region needs unified planning and joint control.

4 Discussion

Our results clearly show that the BSPC can significantly benefit air quality and health improvement in BTH. In 2015, Beijing presented the highest $PM_{2.5}$ concentration, followed by Tianjin and Hebei, comparable with previous studies (Zhang et al.,, 2019). After implementing the BSPC, in 2020, Tianjin will have the highest $PM_{2.5}$ concentration, followed by Hebei and Beijing, with 55.1 μg/m^3, 48.4 μg/m^3, and 47.1μg/m^3, respectively. Even in 2030, the average annual $PM_{2.5}$ concentrations from Beijing, Tianjin, and Hebei in policy scenarios far exceed the national standard of 35 μg/m^3. BSPC is not enough to achieve air quality standards in the BTH region. More attention and efforts are needed to achieve better air quality.

Air pollution will inevitably pose severe health impacts on people (Dockery et al., 1993 ; Iii et al., 2002; Pope et al., 2002). The health and economic impacts of air pollution cannot be ignored (Wu et al., 2017). The results show that the $PM_{2.5}$ concentration reductions due to implementing BSPC will reduce morbidity cases and health expenditures in BTH. After implementing the BSPC, by 2020, the reduced morbidity cases and health expenditures will be 378 thousand cases and 10 million USD in Beijing, 105 thousand cases and 2.7 million USD in Tianjin, and 644 thousand cases and 16.6 million USD in Hebei. The provinces with higher population density and more heavy industry could benefit the health and economy after implementing the clean air policies (Xie et al., 2020). By 2030, these reduced morbidity cases and health expenditures would be 266 thousand cases and 6.8 million USD in Beijing, 141 thousand cases and 3.6 million USD in Tianjin, and 260 thousand cases and 6.7 million USD in Hebei, which are equivalent to 34.0 % and 34.0%, 28.8% and 28.8%, and 11.1% and 11.1% of the 2015 levels in Beijing, Tianjin, and Hebei, respectively.

The most concerning health effects are mortalities (Zhang et al., 2019). In 2020, the reduced mortality cases and VSL due to implementing the BSPC will be 7.6 thousand cases and 26.7 billion USD in Beijing, 2.1 thousand cases and 8.7 billion USD in Tianjin, and 14.3 thousand cases and 24.8 billion USD in Hebei. In 2030, the reduced mortality cases and VSL will be 6.6 thousand cases and 26.6 billion USD in Beijing, 3.2 thousand cases and 17.9 billion USD in Tianjin, and 6.7 thousand cases and 18.5 billion USD in Hebei, which are equivalent to 16.3 % and 21.2%, 15.4% and 24.8%, and 4.7% and 9.4% of the 2015 levels for Beijing, Tianjin, and Hebei, respectively. It is worth noting that the absolute mortality cases have been keeping relatively stable from 2020 to 2030 under the policy scenarios, while the VSL has shown a significant increasing trend from 2020 to 2030 under the policy scenarios. Our results show that the benefits are dominated by VSL savings that far exceed the benefits in health expenditure savings, consistent with many other studies (West et al., 2013; Garcia-Menendez et al., 2015).

In 2020, the reduced work loss time due to implementing the BSPC will be 4.0 hour/cap/year of Beijing, 2.0 hour/cap/year of Tianjin, and 1.8 hour/cap/year of Hebei, which are equivalent to 33.5%, 19.6%, and 18.4% of the 2015 levels in Beijing, Tianjin, and Hebei, respectively. In 2030, the reduced work loss time would be 2.8 hour/cap/year of Beijing, 2.7 hour/cap/year of Tianjin, and 0.74 hour/cap/year of Hebei, which are equivalent to 23.7%, 28.8%, and 7.7% of the 2015 levels in Beijing, Tianjin, and Hebei, respectively.

On the other hand, controlling air pollution needs a lot of capital and technology investments. The costs in our study are calculated based on the GAINS IV Asia model, which represents the costs of terminal treatment technology (Amann et al., 2011).

Overall, compared with the 2015 level, the pollutant emission controls cost in 2020 and 2030 will be about 1.3 times and 2.4 times higher for Beijing, 1.4 times and 1.9 times higher for Tianjin, 1.4 times and 1.6 times higher for Hebei, respectively.

Based on the consideration of health benefits and investments in 2020, the benefit-cost ratios of air pollution control in BTH will be the highest in Beijing (94), followed by Tianjin (70) and Hebei (12). Similar trends are for the year 2030. Our results reveal the benefits of pollution controls in Beijing are significantly higher than those in Tianjin and Hebei. This is in line with a prior study which suggests that the benefit-cost ratios of air pollution controls in BTH in 2020 is the highest in Beijing, followed by Tianjin, and Hebei is the lowest (Xie et al., 2016a). The formulation of BSPC is most beneficial to Beijing, but the net benefit to Hebei is low. But this does not mean that pollution in Hebei will not be controlled. To effectively control air pollution, the BTH region needs unified planning and joint control. Cooperation with the surrounding areas to actively introduce air pollution control technology should be encouraged (Xie et al., 2020).

5 Conclusion

In this study, we combine GAINS IV Asis model and IMED/HEL model to quantify the benefits of implementing the BSPC in the BTH region. Our integrated assessment reveals that the BSPC can significantly benefit air quality and health improvement in the BTH region. Substantial reduction of mortalities and morbidity related to $PM_{2.5}$ will be achieved in the BTH region, and Hebei will have the majority in Hebei. $PM_{2.5}$ reductions due to BSPC are highly effective in reducing work time loss.

We also conduct a detailed benefit-cost evaluation of the BSPC in the BTH region by comparing the monetized health benefits (VSL-related savings) with pollutant control technology costs. Substantial health gains can be obtained due to $PM_{2.5}$ reductions, and the benefits can offset the control costs in the BTH region. It presents a solid framework for evaluating the effectiveness of control measures from a public health perspective. The applicability can be broadened to other areas to assist in policy-making and determine the strategies needed to achieve ambitious air quality objectives.

There are some limitations to this study. The BSPC has co-benefits on CO_2 mitigation, which have been identified by our previous analysis (Meng et al., 2020). Therefore, the CO_2 reduction due to the implementation of BSPC may have other benefits. Secondly, we only consider the effects on labor supply for the health evaluation, while different conclusions have shown that $PM_{2.5}$ pollution can influence labor productivity. If we can assess productivity effects in the future, the benefits will be higher than our calculation. However, our conclusion will still hold if we take into account productivity effects. Thirdly, we ignore the impact of indoor $PM_{2.5}$ pollution. Therefore, future researches are necessary to achieve comprehensive policy insights.

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Figures

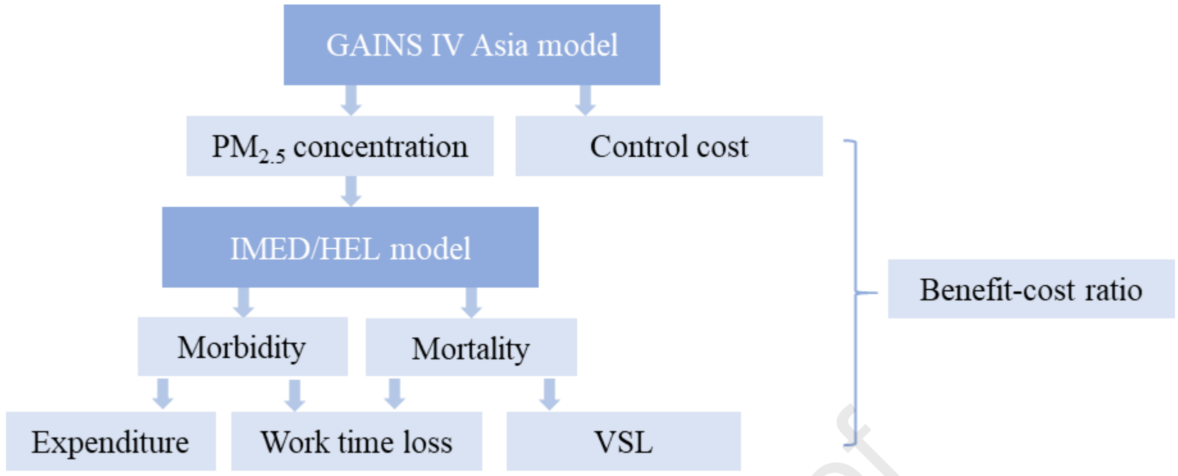

Fig. 1. Research framework.

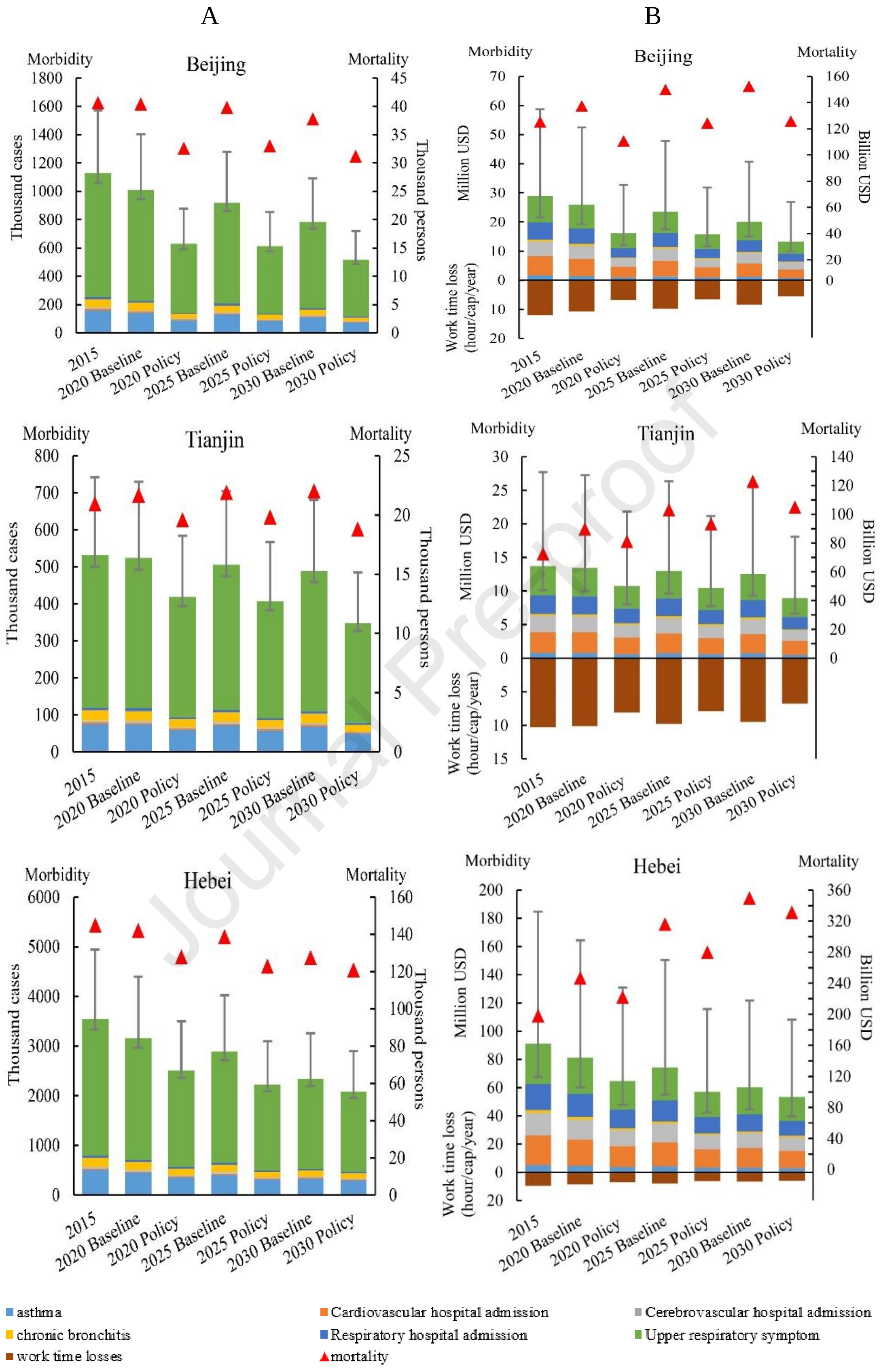

Fig. 2. Health effects of morbidities and mortalities (A) and expenditures, VSL and work time loss (B) in the BTH region. (Bars refer to the left Y-axis and scatter triangles refer to the right Y-axis.

Lines in the middle of bars are error lines of morbidity and expenditures acquired from the 95% confidence interval of response functions.)

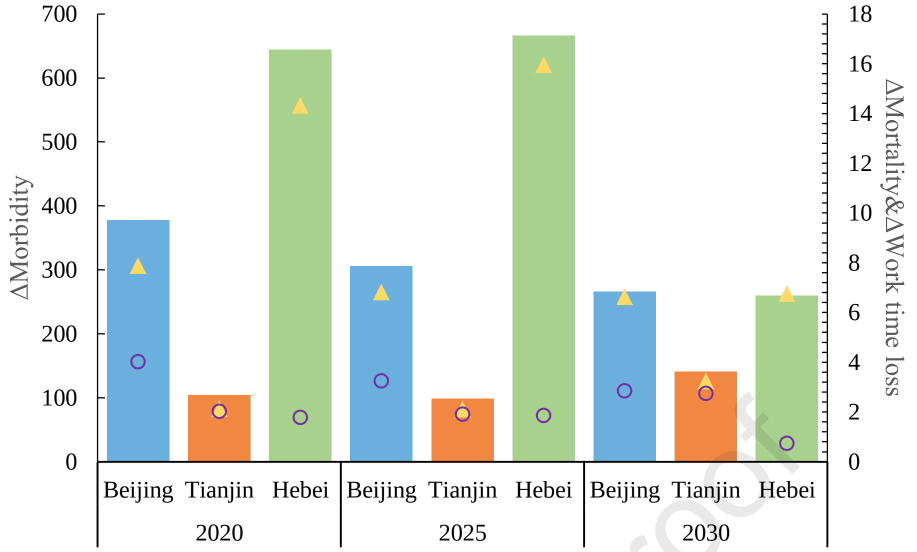

Fig. 3. Comparisons of absolute reductions (Thousand cases) in morbidity and mortality and absolute reductions (hour/cap/year) in work time loss between the baseline scenarios and the policy scenarios for 2020, 2025, and 2030, respectively. (Bars refer to the left Y-axis while triangles and circles refer to the right Y-axis.) (Detailed results are presented as supplementary tables in Table S4.)

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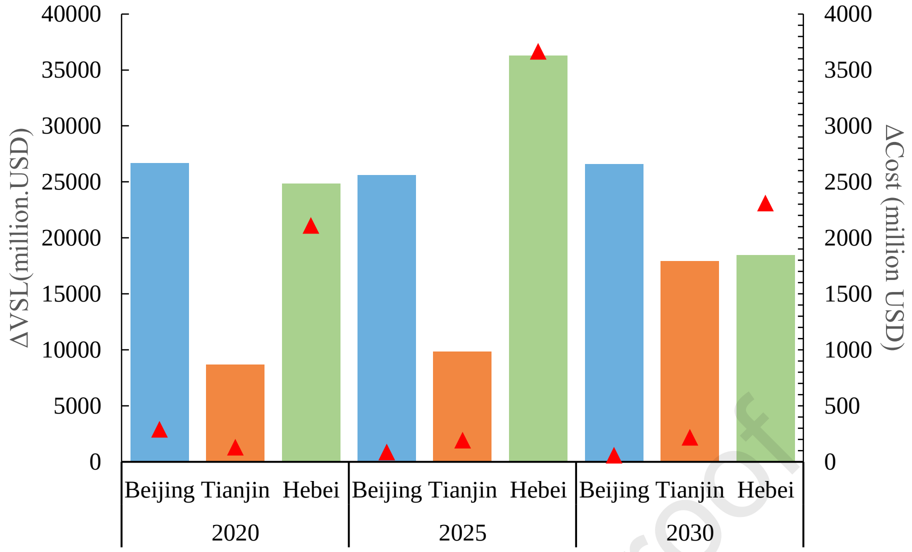

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816 Fig. 4. Co-benefit analysis of ΔVSL and ΔCost in the BTH region. (Bars refer to the
817 left Y-axis while triangles refer to the right Y-axis.) (Detailed results are presented as
818 supplementary tables in Table S5.)

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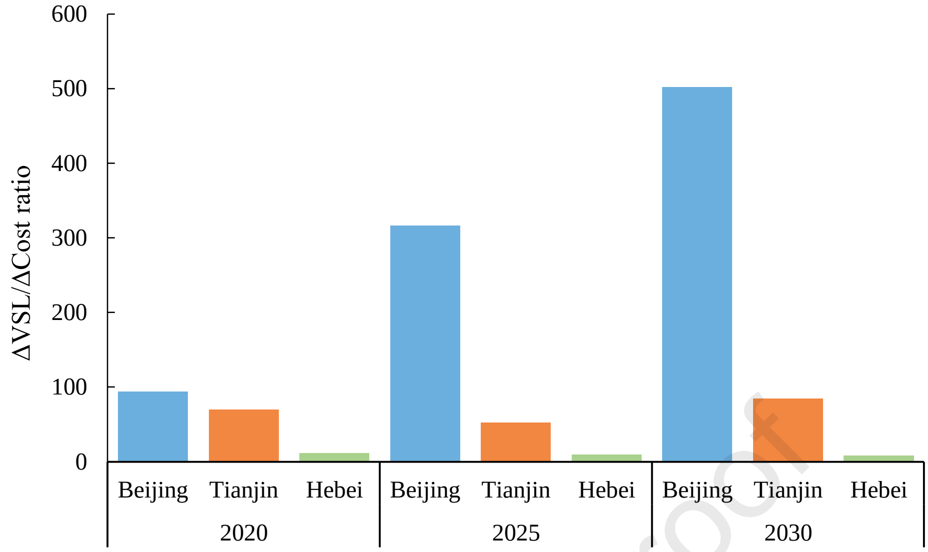

Fig. 5. The ΔVSL/ΔCost ratio in the BTH region. (Detailed results are presented as supplementary tables in Table S6.)

Tables

Table 1 $PM_{2.5}$ concentrations in different scenarios in the BTH region ($\mu g/m^3$).

Regions	2015	2020		2025		2030	
		Baseline	Policy	Baseline	Policy	Baseline	Policy
Beijing	78.7	69.5	47.1	63.2	45.5	54.5	39.4
Tianjin	69.1	66.3	55.1	63.3	52.9	60.6	46.0
Hebei	65.2	58.3	48.4	54.0	43.8	45.4	41.5

Table 2 Emission control costs in different scenarios in the BTH region (million USD/yr)

Regions	2015	2020		2025		2030	
		baseline	policy	baseline	policy	baseline	policy
Beijing	970.8	1506.2	1222.0	2075.1	1994.1	2411.3	2358.3
Tianjin	1476.3	2158.9	2034.9	2660.0	2473.1	2963.0	2751.9
Hebei	6951.3	11558.8	9454.1	13778.4	10119.2	13252.5	10947.0

•Implementing Blue Sky Protection Campaign has positive health and economic impacts.

•The $PM_{2.5}$ reductions are highly effective in reducing work time loss.

•A sum of 60 billion USD in value of statistical life will be avoided in BTH by 2020.

•The Δ benefit/Δ cost ratio in Beijing is the highest, followed by Tianjin and Hebei.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: