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Regional joint $PM_{2.5}$-O_3 control policy benefits further air quality improvement and human health protection in Beijing-Tianjin-Hebei and its surrounding areas

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ABSTRACT

Beijing-Tianjin-Hebei and its surrounding areas (hereinafter referred to as "2+26" cities) are one of the most severe air pollution areas in China. The fine particulate matter ($PM_{2.5}$) and surface ozone (O_3) pollution have aroused a significant concern on the national scale. In this study, we analyzed the pollution characteristics of $PM_{2.5}$ and O_3 in "2+26" cities, and then estimated the health burden and economic loss before and after the implementation of the joint $PM_{2.5}$-O_3 control policy. During 2017–2019, $PM_{2.5}$ concentration reduced by 19% while the maximum daily 8 hr average (MDA8) O_3 stayed stable in "2+26" cities. Spatially, $PM_{2.5}$ pollution in the south-central area and O_3 pollution in the central region were more severe than anywhere else. With the reduction in $PM_{2.5}$ concentration, premature deaths from $PM_{2.5}$ decreased by 18% from 2017 to 2019. In contrast, premature deaths from O_3 increased by 5%. Noticeably, the huge potential health benefits can be gained after the implementation of a joint $PM_{2.5}$-O_3 control policy. The premature deaths attributed to $PM_{2.5}$ and O_3 would be reduced by 91.6% and 89.1%, and the avoidable economic loss would be 60.8 billion Chinese Yuan (CNY), and 68.4 billion CNY in 2035 compared with that in 2019, respectively. Therefore,

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it is of significance to implement the joint $PM_{2.5}$-O_3 control policy for improving public health and economic development.

Introduction

$PM_{2.5}$ (particles ≤ 2.5 μm in aerodynamic diameter) and ozone (O_3) pollution have become a severe air pollution problem in China, which does considerable harm to human health (Cakmak et al., 2016; Chen et al., 2017a; Chen et al., 2017d; Crouse et al., 2015; Yin et al., 2017) and restricts economy development (Maji et al., 2019; Maji et al., 2018; Zhang et al., 2015). The Beijing-Tianjin-Hebei (BTH) and its surrounding areas ("2+26" cities) are the typical area where severe air pollution has arisen in recent years, owing to massive anthropogenic emissions, adverse geographical conditions, and high population density (Liu et al., 2019; Xiang et al., 2020). In January 2013, Beijing (a core city of the BTH region) suffered from a long-lasting haze event which the monthly average $PM_{2.5}$ concentration was higher than 170 μg/m^3 (Gao et al., 2015). In addition, the serious health burden and considerable economic losses due to air pollution aroused wide attention among the public. The premature mortality due to $PM_{2.5}$ exposure was up to 74,000 deaths in the BTH region (Ji et al., 2019) and led to $28.1 billion of the economic losses (1.52% of the gross domestic product, GDP) (Xie et al., 2019b).

To improve air quality in "2+26" cities, the Ministry of Ecology and Environment (MEE) issued the Air Pollution Prevention and Control Action Plan (APPCAP) on September 10, 2013. With the implementation of the regulation, air quality in "2+26" cities has significantly improved (Song et al., 2020). The annual $PM_{2.5}$ concentration in the BTH region declined by ~29 μg/m^3 from 2013 to 2017 (Ding et al., 2019). However, O_3 concentrations showed were with an increasing trend. The annual O_3 concentration increased by 38 μg/m^3 in the same period (Xiang et al., 2020). Wang et al. (2021) also reported that the O_3 concentration increased significantly as $PM_{2.5}$ concentration decreased in China after a series of control measures were implemented. From the above results, the problem of ozone pollution is becoming more prominent. Air pollution in "2+26" cities is exhibiting new characteristic that $PM_{2.5}$ and O_3 affect air quality at the same time. The variation characteristics of a single pollutant have been unable to reveal air pollution status in the whole area, which will not supply enough information to make air pollution control policies. Therefore, it is necessary to study the spatial-temporal variation characteristics of $PM_{2.5}$ and O_3 pollution based on a long-term dataset in "2+26" cities.

Health impact assessments have always been one of the most concerning issues in air pollution (Guo et al., 2018; Huang et al., 2018; Sun et al., 2018). These assessments nicely assist the public and policy-makers in understanding the health benefits associated with air quality improvement (Faridi et al., 2018). At present, a few previous studies have estimated health benefits due to air quality improvement after implementing a series of control policies. For instance, Chen et al. (2017c) showed that the avoidable all-cause deaths were almost 8000/year in the BTH region assessing the benefits of the Air Pollution Prevention and Control Action Plan. Zhang et al. (2019) found that GDP would gain 0.24% in 2030 by improving air quality with the implementation of a coal-to-electricity policy in the BTH region, and this policy would bring substantial benefits to the BTH. In sum, these results quantified the potential health benefits resulting from air quality improvement under air pollution control policies, which help the government to establish reasonable and targeted policies on air pollution control. However, after implementing a joint $PM_{2.5}$-O_3 control policy in "2+26" cities, the health benefits attributed to the common improvement of ozone pollution have not been quantified. Hence, in this study, we assessed the potential health benefits caused by the common decrease of two pollutants ($PM_{2.5}$ and O_3) concentrations, which is conducive to the formulation of the joint $PM_{2.5}$-O_3 control policy.

For the above reasons, this study carried out a comprehensive study on air quality and health assessment in "2+26" cities. The main aims of this study are: (1) to investigate the characteristics of $PM_{2.5}$ and O_3 in the "2+26" cities, (2) to quantify the health effects and economic loss attributed to $PM_{2.5}$ and O_3 exposure, and (3) to assess health benefits from air quality improvement using scenario analysis. Our study evaluated the air quality and the related health benefits, intending to provide effective $PM_{2.5}$ and O_3 coordinated control policies in "2+26" cities.

1. Materials and methods

1.1. *Study areas and air pollutants*

Our study area was "2+26" cities including cities in Beijing (BJ), Tianjin (TJ), Hebei (SHB), Shanxi (SSX), Shandong (SSD), and Henan (SHN) (Appendix A Fig. S1 and Appendix A Table S1). MDA8 O_3 and hourly $PM_{2.5}$ concentrations in these cities from January 2017 to December 2019 were collected from the China National Environmental Monitoring Center (http://113.108.142.147:20035/emcpublish/, last access: 10/26/2021). 131 valid air pollutants monitoring stations were available, which were mainly located in the urban and suburban areas (Fig. 1 and Appendix A Fig. S1). Based on Ambient Air Quality Standard (GB 3095-2012) and Ambient Air Quality Evaluation Technical Specification (On trial) (HJ 663- 2013) (https://doi.org/10.5281/zenodo.F5790372, last access: 02/03/2022), we developed the following criteria to filter the observation data. The daily average $PM_{2.5}$ concentrations were calculated only if the valid data is more than or equal to 20 hr during the day. The MDA8 O_3 concentrations were calculated only if valid data is more than or equal to 6 hr for every 8 hr.

1.2. *Spatial distribution of $PM_{2.5}$ and O_3*

The Kriging interpolation method (Rohde and Muller, 2015) was adopted to simulate the spatial distribution of air pol-

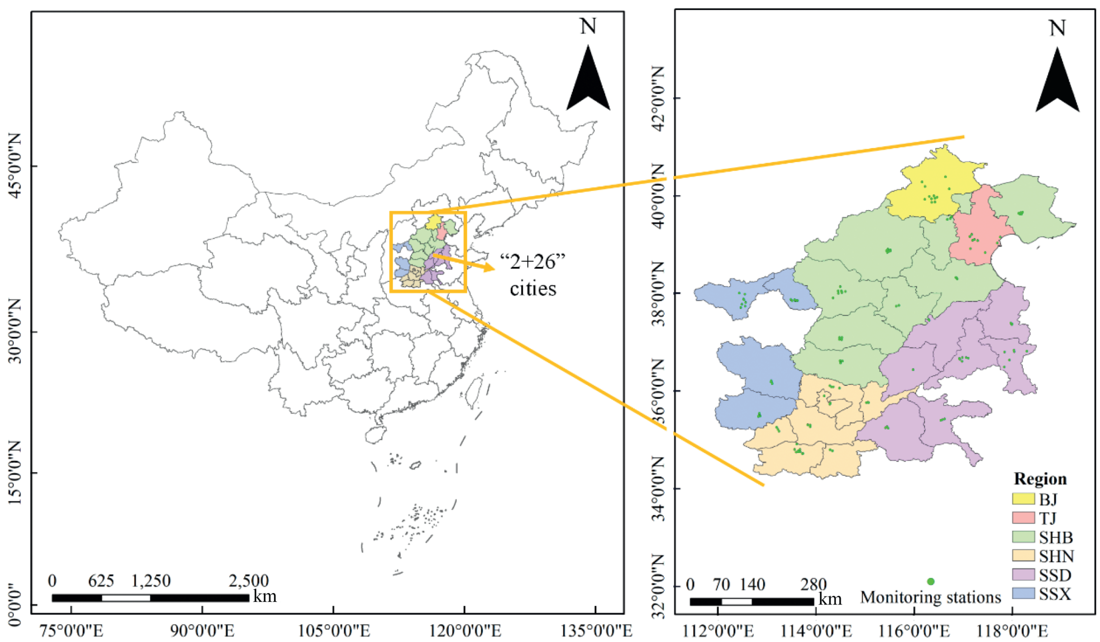

Fig. 1 – Study area and air pollutants monitoring stations.

lutants through the software ArcMap 10.6 in this study. This interpolation is generally used in simulating the spatial distribution of air pollutants (Ma et al., 2019). In this paper, we interpolated air pollutant concentration in every county to reflect individual exposure situations (Appendix A Table S2).

To better illustrate the connection of air pollution ($PM_{2.5}$ and O_3) in each city, Moran's I was adopted to analyze the spatial autocorrelation of $PM_{2.5}$ and O_3 in the studied area (Jiang et al., 2020; Ye et al., 2018). The calculation of Global Moran's I formula is shown in Eq. (1).

$$I = \frac{n}{S_0} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(y_i-\bar{y})(y_j-\bar{y})}{\sum_{i=1}^{n}(y_i-\bar{y})^2} \tag{1}$$

In which $S_0 = \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}$, n is the total number of space cells; y_i and y_j stand for i-th and j-th space cell, respectively; y is the average of all space cell values; W_{ij} is spatial weight value. Global Moran's I ranges from −1 to 1. In case Moran's I > 0, it shows a positive spatial autocorrelation, and with the increase of value, spatial autocorrelation will be more intensive. It exhibits the negative spatial autocorrelation if Moran's I <0. Besides, space is considered as a random state when Moran's I is equal to 0. In the end, local Moran's I index was adopted to further analyze spatial heterogeneity. In this paper, we applied GeoDa 1.12 (https://github.com/GeoDaCenter, last access: 10/26/2021) to carry out spatial autocorrelation analysis.

1.3. *Health-related benefits assessment*

1.3.1. *Health effect assessment*

Mortality attributable to air pollutants exposure was estimated by the log-linear exposure-response function. It is shown as Eq. (2) (Lu et al., 2016; Voorhees et al., 2014).

$$\Delta Y = Pop \times Y_0 \times (e^{\beta \Delta c} - 1) \tag{2}$$

where, ΔY is the health burden caused by air pollutants exposure; Pop represents the number of population in each county (Appendix A Table S2); Y_0 stands for the baseline incidence rate per unit population, obtained from the Global Burden of Disease results tool (ghdx.healthdata.org/gbd-results-tool), as listed in (Appendix A Table S3); β is the exposure-response coefficient, representing the excess risk of mortality per unit increase of each air pollutant from the epidemiological study. To improve the accuracy of the assessment result, we adopted the β value from the meta-analysis that better represents China's real situation (Shang et al., 2013), and β was listed in Appendix A Table S4; Δc (μg/m^3) is equal to the differential value of c (the real exposure concentration) and c_0 (the threshold concentration). According to the previous studies on the threshold of air pollutants concentration (Apte et al., 2015; Atkinson et al., 2012; Chen et al., 2017b; Fiore, 2002; Veira et al., 2013; Yang et al., 2012), 5.8 and 65 μg/m^3 were adopted as $PM_{2.5}$ and O_3 concentration threshold, respectively.

1.3.2. *Economic loss estimation*

In this study, economic loss is referred to as the loss of human health caused by air pollution, which mainly includes personal medical expenses, loss of human resources, and mental loss of negative health effects caused by air pollution (Bayat et al., 2019; Liu et al., 2021). The Value of Statistical Life (VSL) is a general approach to economically quantify health effects attributed to ambient air pollutants exposure. We used the benefit conversion method to adjust VSL (Xie et al., 2019a), as shown in Eq. (3).

$$VSL_{in} = VSL_b \times \left(\frac{\text{income}_{\text{in}}}{\text{income}_{\text{base}}}\right)^{\beta} \tag{3}$$

where, VSL_b is the baseline value of VSL. We selected VSL in 2010 (1.68 million CNY) as VSL_b (Xie, 2011); VSL_{in} stands for the value of statistical life of city i in the year of n; $income_{in}$ is income per capita value in city i of the n year; $income_{base}$ is the income per capita value in 2010. β is the income elasticity, 0.5 was adopted (Viscusi, 2003). Detailed disposable income and VSL values were summarized in Appendix A Table S5 and Appendix A Table S6, respectively.

2. Results and discussion

2.1. Spatial-temporal variation of $PM_{2.5}$ and MDA8 O_3

Annual $PM_{2.5}$ concentration in "2+26 cities" decreased continuously from 70 μg/m^3 in 2017 to 57 μg/m^3 in 2019 (Appendix A Fig. 2 and Appendix A Table S7), with an average annual decrease of 6.5 μg/m^3. The decreased trend was consistent with previous studies. Wang et al. (2019a) studied that $PM_{2.5}$ concentration in the BTH region showed a significant decrease trend where $PM_{2.5}$ concentration decreased from 98.9 μg/m^3 in 2013 to 55.6 μg/m^3 in 2018. Ding et al. (2019) also reported that the annual $PM_{2.5}$ concentration in the BTH region declined by ~29 μg/m^3 from 2013 to 2017. But it is worth noting that $PM_{2.5}$ concentration in 2019 still did not meet China Ambient Air Quality Standard (CAAQS) Grade II standard (35 μg/m^3) and should be further reduced. Among 28 cities, Baoding had the most remarkable reduction (26 μg/m^3), followed by Shijiazhuang (22 μg/m^3) and Hengshui (21 μg/m^3). The spatial distributions of $PM_{2.5}$ during 2017–2019 are shown in Fig. 3. The highest $PM_{2.5}$ annual average concentration was found in Anyang City (71.5 μg/m^3), followed by Handan (66.3 μg/m^3) and Xingtai (64.7 μg/m^3). The $PM_{2.5}$ pollution was relatively severe in the above cities, located in the south-central section of the whole study scope. These cities are in the Southwest Plain Area of the Taihang Mountains which can obstacle the diffusion of air pollutants, and are typically heavy industrial cities mainly including coal energy and smelting steel. Industrial emissions and residential coal combustion were the main cause of $PM_{2.5}$ heavy pollution (Hua et al., 2016; Ma et al., 2017). These power plants released masses of SO_2 and NO_2 in the BTH region (Wang et al., 2016b), resulting in a lot of SO_4^{2-} and NO_3^-, and an increase in $PM_{2.5}$ concentration (Peng et al., 2019). Therefore, more stringent measures need to be adopted to decrease $PM_{2.5}$ concentration. Fig. 4 illustrates the seasonal variation of $PM_{2.5}$ concentrations for the whole area from 2017 to 2019. During the study period, the maximum peak of $PM_{2.5}$ concentration appeared in winter (above 87 μg/m^3) and the minimum peak value of $PM_{2.5}$ concentration came out in summer. Our result is comparable with some previous works (Li et al., 2017a; Li et al., 2017b).

MDA8 O_3 concentration kept generally stable during the study period and even increased in some cities (Figs. 2 and 3, and Appendix A Table S7), and even some cities increased during 2017–2019. Among 28 cities, Jinan had the most remarkable increase (18 μg/m^3), followed by Binzhou (17 μg/m^3) and Tianjin (15 μg/m^3). Similarly, Zhao et al. (2021) even found that MDA8 O_3 concentration showed an upward trend with 5.4 μg/(m^3·year) from 2014 to 2018, and BTH was the most severe region with 42–71 days suffering O_3 pollution each year. Ma et al. (2021) also illustrated that ambient O_3 concentration in the BTH region showed an overall increasing trend from 2010 to 2017. The average MDA8 O_3 concentration in "2+26" cities in 2019 is 197.5 μg/m^3 (Appendix A Table S7). No one city met the CAAQS Grade II standard (160 μg/m^3 for O_3). These results indicated that O_3 pollution increased and the problem of O_3 pollution was also prominent in recent years. From the spatial variation, O_3 pollution in the central region and some counties of the eastern region always remained relatively severe. The three severest cities of O_3 pollution were Liaocheng (214 μg/m^3), Xingtai (210 μg/m^3), and Binzhou (209 μg/m^3). There were some potential reasons for the whole area with high O_3 pollution. A huge number of key chemical precursor (eg., NO_x and VOC_s) emissions lead to O_3 pollution in the region (Wang et al., 2019b; Wei et al., 2022) because the reaction of NO_x and VOCs is deemed to be the major pathway of O_3 generation (Wang et al., 2014). Also, meteorological conditions are not a negligible factor in the formation of O_3 pollution, including high temperature, solar radiation, wind, atmospheric stability, and so on (Wang et al., 2016a; Wang et al., 2019c; Wang et al., 2017). For seasonal variation, the O_3 pollution is relatively severe in summer. The MDA8 O_3 concentration in the summer during 2017–2019, was 167 μg/m^3, 171 μg/m^3, and 167 μg/m^3, respectively (Fig. 4). Maji et al. (2019) also found that O_3 pollution showed a remarkable seasonal variability, which was higher in summer and lower in winter in Chinese cities. Significantly, the characteristic variation of O_3 and $PM_{2.5}$ pollution is different, which becomes the main challenge in joint $PM_{2.5}$-O_3 control.

Appendix A Fig. S3 illustrates the Moran's I scatter plots and LISA (local indicators of spatial association) cluster map for $PM_{2.5}$ and MDA8 O_3 in 2019. The global Moran's I for $PM_{2.5}$ and MDA8 O_3 were 0.95 and 0.91 ($P \leq 0.01$), respectively. The results indicated that the positive spatial autocorrelation was extremely strong for the spatial distribution of $PM_{2.5}$ and MDA8 O_3 in the whole area. Four quadrants in Appendix A Fig. S3 represent four different spatial relationships. H (L)-H (L) type represents these cities with high (low) pollution nearing the other high (low) pollution areas, exhibiting the positive spatial autocorrelation. Most spots occur in the first and third quadrants, implying that spatial distributions of $PM_{2.5}$ and MDA8 O_3 showed significant aggregation. Our results are consistent with previous research (Jiang et al., 2020; Li et al., 2019; Zeng et al., 2019). The local Moran's I showed that $PM_{2.5}$ (Appendix A Fig. S3c) and MDA8 O_3 (Appendix A Fig. S3d) both exhibited H-H (L-L) positive autocorrelation aggregation, indicating spatial clustering in the region of higher (lower) concentrations. The Moran's I result showed that $PM_{2.5}$ and O_3 pollution had significant spatial autocorrelation. For instance, an increase in O_3 concentrations in neighboring areas may result in aggravating O_3 pollution in local areas. Thus, regional joint prevention and control are better measures to improve air quality.

2.2. Health burden and economic loss

During the study period, premature mortalities attributed to $PM_{2.5}$ pollution in the whole area declined by 5865 (95% CI: 4750–6985) cases, with a significant downward trend (Fig. 5 and Appendix A Table S8). The declining trend of premature

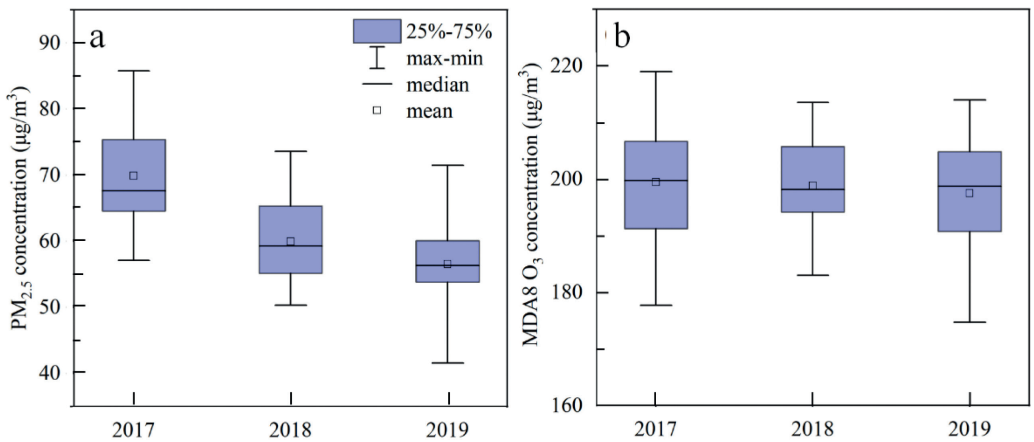

Fig. 2 – Observed $PM_{2.5}$ (a) and O_3 MDA8 O_3 in the 90th percentile (b) concentration from 2017 to 2019 in "2+26" cities.

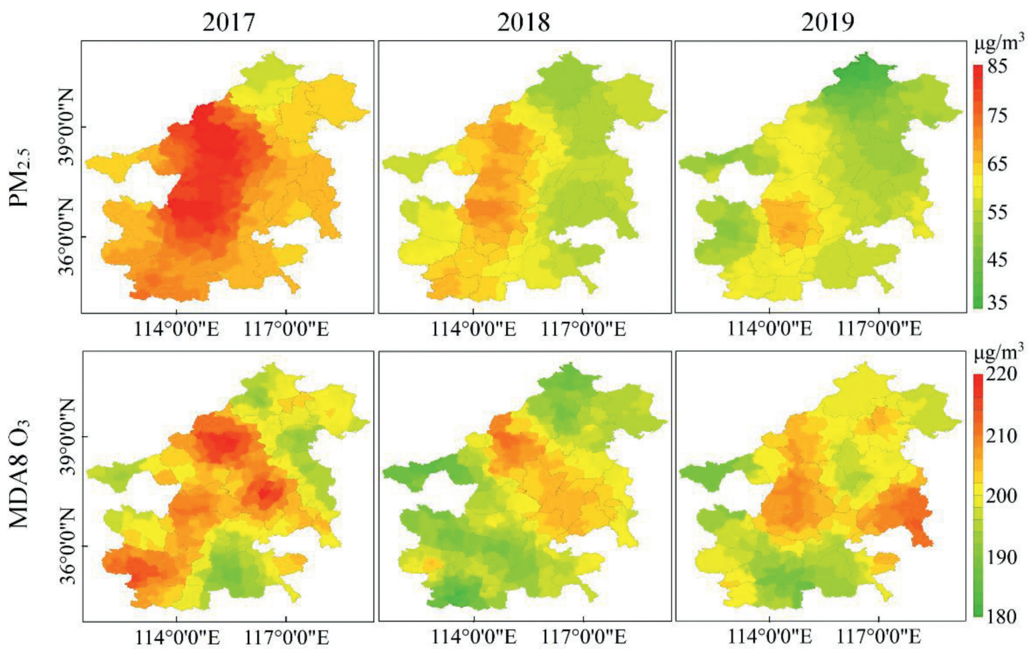

Fig. 3 – Spatial distribution of $PM_{2.5}$ and MDA8 O_3 in the 90th percentile concentration from 2017 to 2019 in "2+26" cities.

deaths in Baoding was the most significant, decreasing by 660 cases from 2017 to 2019, followed by Beijing (declines by 530 cases) and Shijiazhuang (declines by 495 cases). Economic loss caused by $PM_{2.5}$ pollution showed a significant reduction as the same as health burden, which avoided the economic cost of 5.2 (95% CI: 4.2–6.2) billion CNY compared with that in 2017 (Fig. 5 and Appendix A Table S9). However, premature mortalities attributed to MDA8 O_3 exposure displayed a generally increasing trend from 2017 to 2019, which caused a very serious health consequence. Relative to that in 2017, mortalities due to MDA8 O_3 exposure increased by 1520 (95% CI: 1207–1807) cases in 2019. The largest increase in premature deaths was in Tianjin (increasing 193 cases), followed by Jinan (180 cases) and Handan (166 cases). The economic loss of deaths resulting from MDA8 O_3 exposure increased by 6.9 (95% CI: 5.4–8.9) billion CNY from 2017 to 2019. Our result is consistent with previous works (Wang et al., 2021; Xue et al., 2019; Zhang et al., 2019).

The premature mortality from MDA8 O_3 exposure was higher than death due to $PM_{2.5}$ exposure in 2019 (Appendix A Table S8). Around the whole area, the total premature deaths due to $PM_{2.5}$ and MDA8 O_3 exposures were 26,653 (95% CI: 21,712–31,608) and 30,871 (95% CI: 24,380–37,371), respectively. Similarly, the economic loss from MDA8 O_3 (52 (95% CI: 41–63) billion CNY) was more remarkable relative to that of $PM_{2.5}$ (45 (95% CI: 37–53) billion CNY) (Appendix A Table S9). Our result was comparable with some previous studies (Lu et al., 2016; Yao et al., 2020). Health burden and economic loss linked to $PM_{2.5}$ and MDA8 O_3 exposures were both considerable. We should take the joint $PM_{2.5}$-O_3 control policy to reduce $PM_{2.5}$ and O_3 concentrations, which protect human health and promote economic development.

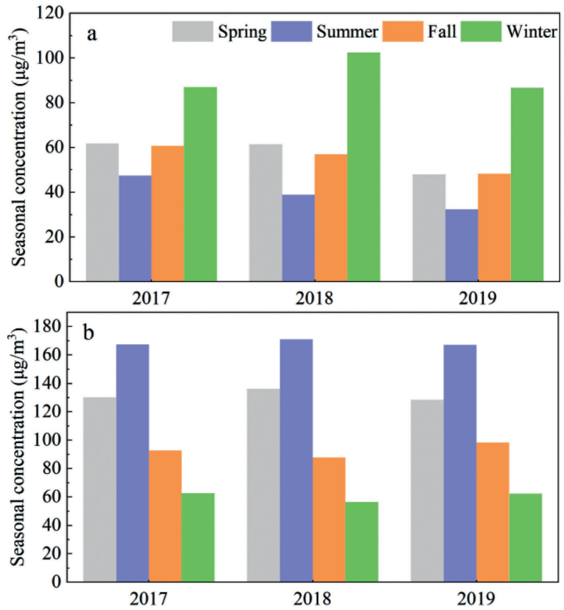

Fig. 4 – Seasonal variation of $PM_{2.5}$ (a) and MDA8 O_3 (b) concentration during 2017–2019 in "2+26" cities.

2.3. *Avoidable health benefits attributed to air quality improvement in the future (year 2035)*

To reveal the potential health benefits of air quality improvement in the future (year 2035), we set up two scenarios (Table 1): BCT1 and BCT2. The BCT1 scenario takes the "Beautiful China" targets in 2035 into account. The BCT2 was more rigorous management and stricter control than BCT1. The population growth and economic growth were considered in SI Appendix Text S1 (Liu and Bin, 2020; Guo and Zhang, 2019; Zhai et al., 2017).

Table 1 – Two scenarios setting of future air quality.

Scenario	Target concentration in 2035	
	$PM_{2.5}$ (μg/m³)	MDA8 O_3 (μg/m³)
BCT1	35	100
BCT2	10	70

BCT: the "Beautiful China" targets; MDA8: the maximum daily 8 hr average.

The health burden and avoidable health burden in 2035 are shown in Fig. 6, Appendix A Table S10, and Appendix A Table S11. Mortalities attributed to $PM_{2.5}$ exposure under the BCT1 and BCT2 scenarios in 2035 were 15,652 (95% CI: 12,761–18,548) and 2246 (95% CI: 1821–2648), respectively, reducing 11,001 and 24,407 premature deaths contrast against in 2019. The avoidable mortality from $PM_{2.5}$ exposure in the BCT2 scenario was two times more than that in the BCT1 scenario. In 2035, mortalities attributed to MDA8 O_3 exposure under the BCT1 and BCT2 scenarios were 23,776 (95% CI: 18,789–28,772) and 3370 (95% CI: 2662–4078), avoiding 7195 and 27,501 cases. The avoidable mortality of MDA8 O_3 under the BCT2 scenario was four times more than that under the BCT1 scenario. The avoidable mortalities under air quality improvement are remarkable, especially in the BCT2 scenario. These results indicated that it was necessary and valuable for human health protection to further improve air quality. Meanwhile, economic loss and avoidable economic loss are shown in Fig. 6, Appendix A Table S12, and Appendix A Table S13. The avoidable economic loss from $PM_{2.5}$ under the BCT1 and BCT2 scenarios were 26.9 and 60.8 billion CNY in 2035. Avoidable economic loss attributed to mortality of MDA8 O_3 were 17.3 and 68.4 billion CNY. It was not difficult to see that the potential health benefits in the BCT2 were much bigger than those in the BCT1.

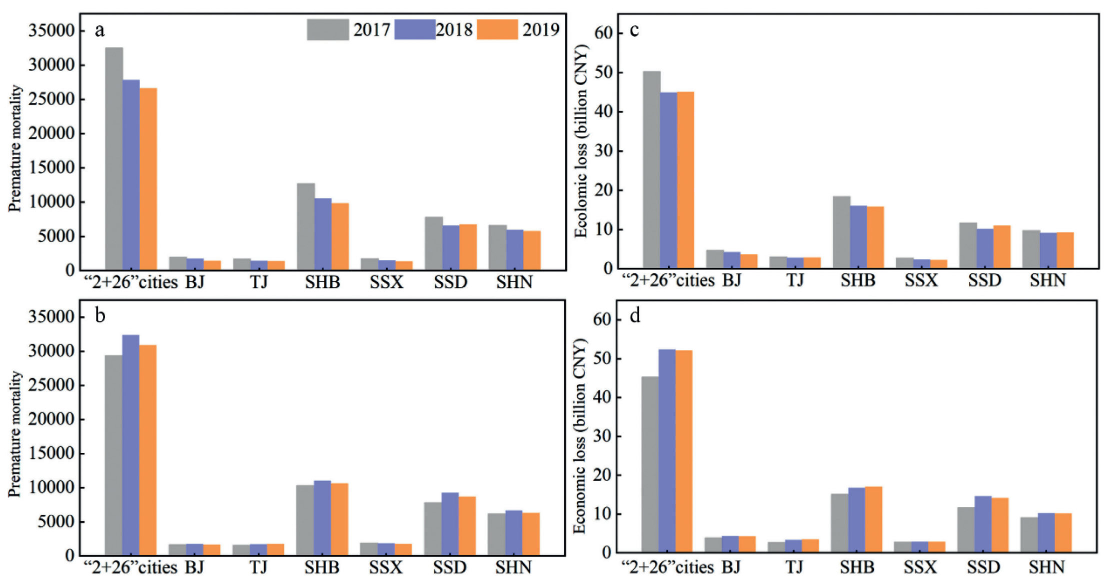

Fig. 5 – The variation of premature mortality and economic loss attributed to $PM_{2.5}$ (a and c) and MDA8 O_3 (b and d) exposure from 2017 to 2019 in "2+26" cities.

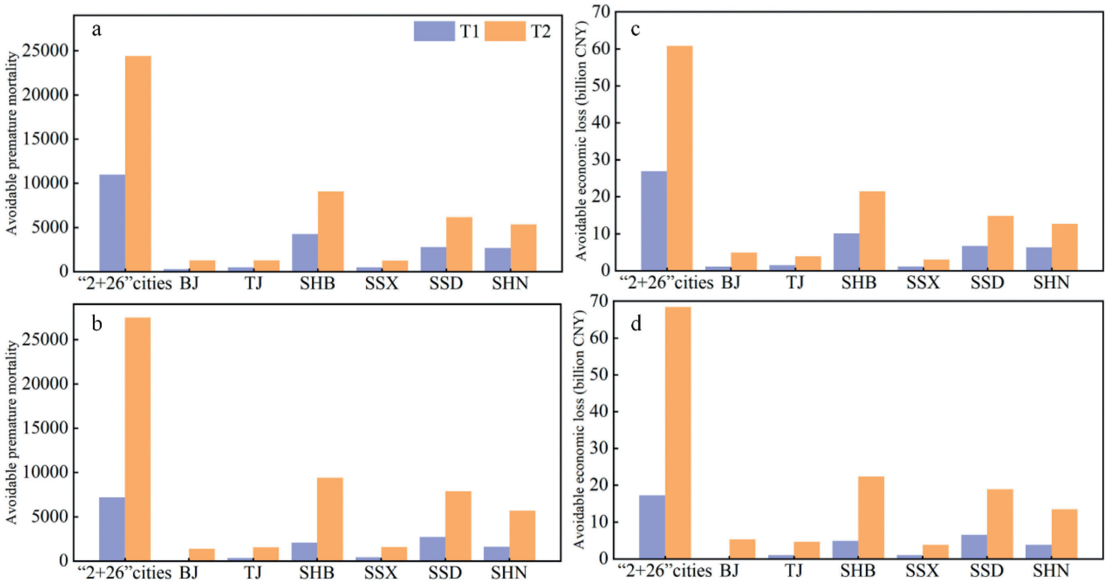

Fig. 6 – The avoidable premature mortality and economic loss attributed to $PM_{2.5}$ (a and c) and O_3 (b and d) under the BCT1 and BCT2 scenarios in 2035.

These results indicated that economic benefits positively correlated with the degree of air quality improvement. That is to say, more remarkable health-related economic benefits can be obtained by using more stringent strategies for air quality improvement. Two pollutants coordinated control ought to be an effective strategy for human health protection and economic development.

From the city level, three cities (Beijing, Handan, and Tianjin) with the topmost considerable potential health benefits due to $PM_{2.5}$ exposure, avoided by 4.87, 3.95, and 3.89 billion CNY in the BCT2 scenario, respectively. For MDA8 O_3, Beijing, Tianjin, and Baoding were the topmost considerable potential health benefits attributable to MDA8 O_3 pollution, avoided by about 5.26, 4.65, and 3.92 billion CNY under the BCT2 scenario. Instestinngly, these cities are with higher pollution, dense population, and economically developed level, and will have more potential health benefits for air quality improvement. Our studies are comparable to previous studies (Xie et al., 2019a; Xing et al., 2020; Yang et al., 2019). For example, Xing et al. (2020) demonstrated that avoidable premature mortality was more remarkable in the dense population due to the decrease of $PM_{2.5}$ concentrations area in 2035. Yang et al. (2019) indicated that remarkable health benefits can be gained in regions with dense populations and rapid urbanization. So, cities with high population density and high economic levels can gain more health benefits under the joint $PM_{2.5}$-O_3 control policy.

2.4. *Uncertainties analysis*

Some limitations existed in this study. For health effect assessment, the exposure-response coefficient (β) is a key parameter, which was obtained from the results of the national meta-analysis without the consideration of the spatial variation of each region. Air pollutant composition, detailed population data (eg., age, socioeconomic, race), and climatic factors are significantly different in various cities, which may cause a difference in the exposure-response coefficient in various cities (Hubbell et al., 2009). Yin et al. (2017) observed the association between mortality and O_3 was significantly different in different regions. The association between ozone and mortality in the North and South regions of China is more significant than that in the Northwest region. Therefore, β values we adopt in this work may cause the uncertainty of estimated results, more work should be made in the future to reduce uncertainties caused by the difference in exposure-response coefficients of each region. The estimated results also are influenced by $PM_{2.5}$ and O_3 threshold values. There is no consistent conclusion for threshold values. In this study, 5.8 and 65 $\mu g/m^3$ were adopted as $PM_{2.5}$ and O_3 threshold values. Some previous studies have suggested that adverse health effects still can be observed at low $PM_{2.5}$ pollution levels (less than 5 $\mu g/m^3$ or even zero) (Chen and Hoek, 2020; Chen et al., 2017b; WHO, 2021). That is, the $PM_{2.5}$ threshold values we adopted possibly are relatively high compared with the previous study (Chen et al., 2017a; Yao et al., 2020). This could explain why there were relatively lower premature deaths in this study. In addition, VSL was used to quantify the economic loss. The method, including not only personal medical expenses and loss of human resources but also the mental loss, was considered as the upper limit of statistical premature death value, which may cause an overestimation of economic loss (Gao et al., 2022). These factors would have some impacts on the results of health benefits and then would affect the formulation of the joint $PM_{2.5}$-O_3 control policy in the future. To reduce uncertainty, modeling and other observational studies may be used in "2+26" cities to improve the assessment of the health burden of $PM_{2.5}$ and O_3 pollutants.

3. Conclusions

In the light of air pollutants concentration data from the monitoring points and Kriging interpolation, we comprehensively illustrated the spatial-temporal variation characteristics of $PM_{2.5}$ and O_3 in "2+26" cities in recent years and estimated potential health benefits under different scenarios. $PM_{2.5}$ (57 μg/m^3) and MDA8 O_3 (197.5 μg/m^3) pollution are still severe in "2+26" cities in 2019, failing to meet the national standard, which presents both $PM_{2.5}$ and O_3 compound atmospheric pollution. $PM_{2.5}$ and MDA8 O_3 pollution in the whole area showed significant spatial aggregation, mainly by H-H and L-L positive spatial autocorrelation, further indicating that regional joint defense and control of $PM_{2.5}$ and O_3 is urgently needed. The avoidable premature deaths and economic loss due to $PM_{2.5}$ exposure under BCT1 and BCT2 scenarios will be 11,001 cases, 24,407 cases, 26.9 billion CNY, and 60.8 billion CNY, respectively. The corresponding values of MDA8 O_3 will be 7195 cases, 27,501 cases, 17.3 billion CNY, and 68.4 billion CNY, respectively. Potential health benefits under BCT2 were more remarkable than those under BCT1, which indicated that more significant improvements in air quality would bring more considerable health benefits. In conclusion, not only demonstrates this study the necessity and rationality of collaborative governance of $PM_{2.5}$ and O_3 to ameliorate air quality, but it calls out the Chinese government and all the residents in the study area jointly strive to bet blue sky battle as well.

Declaration of Competing Interest

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.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2022.06.036.

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