Chinese Medical Journal®

Related health burden with the improvement of air quality across China

Huaiyue Xu[1], Qing Wang[1], Huanhuan Zhu[1], Yayi Zhang[1,2], Runmei Ma[1], Jie Ban[1], Yiting Liu[1], Chen Chen[1], Tiantian Li[1]

[1]Department of Environmental Health Risk Assessment, China CDC Key Laboratory of Environment and Population Health, National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing 100021, China;

[2]School of Geomatics and Marine Information, Jiangsu Ocean University, Lianyungang, Jiangsu 222005, China.

Abstract

Background: Substantial progress in air pollution control has brought considerable health benefits in China, but little is known about the spatio-temporal trends of economic burden from air pollution. This study aimed to explore their spatio-temporal features of disease burden from air pollution in China to provide policy recommendations for efficiently reducing the air pollution and related disease burden in an era of a growing economy.

Methods: Using the Global Burden of Disease method and willingness to pay method, we estimated fine particulate matter ($PM_{2.5}$) and/or ozone (O_3) related premature mortality and its economic burden across China, and explored their spatio-temporal trends between 2005 and 2017.

Results: In 2017, we estimated that the premature mortality and economic burden related to the two pollutants were RMB 0.94 million (68.49 per 100,000) and 1170.31 billion yuan (1.41% of the national gross domestic product [GDP]), respectively. From 2005 to 2017, the total premature mortality was decreasing with the air quality improvement, but the economic burden was increasing along with the economic growth. And the economic growth has contributed more to the growth of economic costs than the economic burden decrease brought by the air quality improvement. The premature mortality and economic burden from O_3 in the total loss from the two pollutants was substantially lower than that of $PM_{2.5}$, but it was rapidly growing. The O_3-contribution was highest in the Yangtze River Delta region, the Fen-Wei Plain region, and some western regions. The proportion of economic burden from $PM_{2.5}$ and O_3 to GDP significantly declined from 2005 to 2017 and showed a decreasing trend pattern from northeast to southwest.

Conclusion: The disease burden from O_3 is lower than that of $PM_{2.5}$, the O_3-contribution has a significantly increasing trend with the growth of economy and O_3 concentration.

Keywords: Fine particulate matter; Ozone; Long-term mortality; Willingness to pay; Economic burden; Spatio-temporal trends; Air quality

Introduction

Air pollution is a primary environmental risk factor that harms the public health and imposes economic burden.[1–11] As a developing country with a large population, China has achieved considerable economic growth accompanied with severe air pollution and economic burden on health. A series of measures have been made to control and reduce air pollutants to decouple economic growth from air pollution, including the "Air Pollution Prevention and Control Action Plan" (APPCAP) between 2013 and 2017 and the "Blue Sky Defense Battle" between 2018 and 2020.[12] Considerable reduction in fine particulate matter ($PM_{2.5}$) pollution has been achieved after years of efforts, but the ozone (O_3) issue has unexpectedly emerged. In 2020, the burden of disease related to air pollution remained at high levels and continued to increase because of the increasing and aging of population.[13,14] Many studies have investigated the relationship between air pollution and health, but only few have explored the economic loss from the health effects of air pollution, especially their spatial patterns and changing trends across China.[3–6,9] Most existing studies have employed the willingness to pay (WTP) and cost of illness (COI) methods to measure the economic cost of health impacts.[3–6,9,15,16] For example, Maji *et al*[15] adopted the WTP and COI methods to estimate an economic loss of 101.39 billion US dollars in 2016 from $PM_{2.5}$-related

Access this article online

Quick Response Code:

Website: www.cmj.org

DOI: 10.1097/CM9.0000000000002974

Correspondence to: Qing Wang, Department of Environmental Health Risk Assessment, National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing 100021, China
E-Mail: wangqing@nieh.chinacdc.cn

Chinese Medical Journal 2024;137(22)

Received: 07-06-2023; **Online:** 18-01-2024 **Edited by:** Jing Ni and Xuehong Zhang

mortality and morbidity across 338 Chinese cities, which is 0.91% of the national GDP. According to a report by the Organization for Economic Co-operation and Development (OECD, https://stats.oecd.org), the World Bank used WTP methods to calculate the welfare loss due to $PM_{2.5}$ and O_3 in China, which increased from 1.35 trillion US dollars in 2010 to 2.56 trillion US dollars in 2019. Limited by the lack of long-term historical exposure and evaluation parameter data, previous studies have mainly assessed the economic burden from the $PM_{2.5}$ or O_3 pollution in some cities or regions.[1,15,17–20] There is currently no study estimating the spatial patterns and changing trends of the combined economic burden from health effects attributed to the two pollutants in China.

This study quantified the health and economic burden from $PM_{2.5}$ and O_3, explored their spatio-temporal features across China between 2005 and 2017, and determined the regions with high or increasing trends of health and economic burden attributed to $PM_{2.5}$ and/or O_3.

Methods

Data sources

We used the five datasets to assess the economic loss of health effects from ambient $PM_{2.5}$ and O_3: Air pollution exposure, population, cause-specific mortality rates, the concentration-response (C-R) function from epidemiological studies, and socio-economic parameters.

The $PM_{2.5}$ and O_3 concentration were derived from our previous studies, and the annual mean $PM_{2.5}$ and O_3 concentration of each county was used as the exposure.[23,24] We simulated the national-wide 1 km grid ambient $PM_{2.5}$ and O_3 concentration by carrying out the method of multi-parameter-based random-forest model based on the many meteorological, geographic, and socioeconomic parameters. A previous study provided average model-fitting R^2 values of 0.85, 0.88, 0.90, 0.77, 0.77, and 0.69 from the daily, monthly, and annual estimations of $PM_{2.5}$ and O_3-1 h max from test datasets, respectively.[24] The root mean square error (RMSE) and mean absolute error (MAE) of $PM_{2.5}$ simulation were 17.72 μg/m^3 and 9.37 μg/m^3, and O_3 simulation were 15.59 part per billion (ppb) and 9.59 ppb.[23,24] The county-level and age-specific population data were obtained from the sixth demographic census of China in 2010, covering more than 95% of counties across China. The provincial-level cause-specific mortality data for five diseases, including chronic obstructive pulmonary disease (COPD), lung cancer, ischemic heart disease (IHD), stroke in adults aged 25 years or older, and lower respiratory infection for all age groups were obtained from Global Burden of Disease (GBD) studies.[25] The provincial-level socioeconomic data, gross domestic product (GDP), and consumer price index (CPI) were collected from the China Statistical Yearbook (http://www.stats.gov.cn/).

The C-R function described an association between exposure (long-term exposure to $PM_{2.5}$ or O_3) and mortality, including the integrated exposure risk (IER) function (for $PM_{2.5}$)[26] and log-linear (LL) function (for O_3).[27] The relative risks (RRs) of $PM_{2.5}$ to deaths were estimated through the IER function, which can be expressed as follows:

$$RR_{IER} = \begin{cases} 1+\alpha\left\{1-\exp\left[-\beta\left(z-z_0\right)\delta\right]\right\}, z \ge z_0 \\ 1, z < z_0 \end{cases} \quad (1)$$

For O_3-attributed mortality studies, LL function can be expressed as follows:

$$RR_{LL} = \exp\left[\gamma\left(c-c_0\right)\right] \quad (2)$$

In which, z and c are the actual $PM_{2.5}$ and O_3 concentration, respectively; z_0, c_0 refer to the threshold concentration of $PM_{2.5}$ (2.4–5.9 μg/m^3) and O_3 (33.3 ppb), respectively; α, β, and δ determined the relationship between $PM_{2.5}$ and mortality in IER; And γ is the exposure–response coefficient in LL.[26,27]

Estimation of premature mortality

We used the approach developed for the GBD study to estimate the premature mortality attributable to long-term exposure to every air pollutant in each county from 2005 to 2017.

$$M_{i,j} = P_i \times I_{i,j} \times \frac{RR_{i,j}-1}{RR_{i,j}} \quad (3)$$

$M_{i,j}$ indicates the $PM_{2.5}$/O_3 related premature mortality for end point j in county i; P_i is the population in the county i; $I_{i,j}$ is the mortality rate for end point j in county i; $RR_{i,j}$ is the relative risk for end point j in the county i.

Estimation of economic burden

We evaluated the economic burden of air pollution with the varying value of a statistic life (VSL), which represents the WTP value for an individual to reduce the risk of death. Cost-benefit analysis has been widely applied in the United States and Europe to estimate the benefits of savings.[16,28] To investigate the spatial patterns and changing trends of the economic burden from $PM_{2.5}$ and O_3, we applied the province-specific VSL that changes with annual change of GDP and CPI. Assuming that population growth, population aging, and age-specific mortality are constant, we decomposed $PM_{2.5}$ and O_3 were only two driving factors of the changes in economic cost from premature mortality.

As the province-specific VSLs are not entirely available for China and only a few provinces have available VSLs from existing literatures, which are based on different approaches and are not conducive to statistics and comparative analysis among provinces. We derived the different VSLs for 31 provinces in the year 2005–2017 in the two scenarios, using the following equation.[29]

$$VSL_{l,k} = VSL_{B,2010} \times \left(\frac{G_{l,2010}}{G_{B,2010}}\right)^{\beta} \times (1+\%\Delta P_l + \%\Delta G_l)^{\beta} \quad (4)$$

$VSL_{l,k}$ is the value of VSL in province l in year k, $VSL_{B,2010}$ is the reference value for VSL in Beijing in 2010, which equals to RMB 1.68 million yuan.[1,30,31] β is the income elasticity of health cost, representing 0.8 as recommended by OECD (2016).[28] $G_{B,2010}$ is the GDP per capita in Beijing in 2010. $G_{l,2010}$ is the GDP per capita in province l in 2010. $\%_{\Delta}P_l$ and $\%_{\Delta}G_l$ are the percentage change in CPI and GDP per capital in the province l from 2010 to year k, respectively.

$$Economic\ Burden_{l,k} = VSL_{l,k} \times M_{l,k} \quad (5)$$

In which, the $Economic\ Burden_{l,k}$ is the economic loss caused by the premature deaths in province l in year k, $M_{l,k}$ is premature deaths attributed to $PM_{2.5}$ and O_3 exposure in province l in year k.

Results

Spatio-temporal trends of $PM_{2.5}$ and O_3 pollution

The annual mean $PM_{2.5}$ concentration in China showed a substantial downward trend from 2013 (58.82 μg/m^3) to 2017 (44.41 μg/m^3), while it experienced a slight fluctuation trend from 2005 (55.8 μg/m^3) to 2013 (58.82 μg/m^3) [Supplementary Figure 1, http://links.lww.com/CM9/B851]. The high levels of $PM_{2.5}$ concentration were mainly located in densely populated regions, such as the Beijing-Tianjin-Hebei (BTH), Fen-Wei Plain (FWP), Yangtze River Delta (YRD), and Sichuan-Chongqing (SC) regions [Figure 1A]. There was a different pattern from $PM_{2.5}$, with a considerable increase in the annual average O_3 concentration during the 2013–2017 period in China [Figure 1A and Supplementary Figure 1, http://links.lww.com/CM9/B851]. The O_3 concentration in the BTH, FWP, YRD has increased significantly. However, the concentration change of O_3 in the Pearl River Delta (PRD) region is not obvious [Figure 1A].

Spatio-temporal trends of premature mortality caused by $PM_{2.5}$ and O_3

The sum of premature mortality from the two pollutants showed a downward trend between 2005 and 2017 (from 1.01 million [73.457 per 100,000] in 2005 to 0.94 million [68.487 per 100,000] in 2017), especially after the implementation of the APPCAP in 2013 [Figure 2A].The regions with great total premature mortality were densely populated and heavily polluted, such as the BTH, SC, FWP, and YRD regions. After 2013, the total premature mortality declined significantly in all these regions and the relative reduction in total premature mortality was highest in the SC region (10.90%) and lowest in the FWP region (1.71%) [Supplementary Figure 2, http://links.lww.com/CM9/B851]. Some provinces in the central, eastern, and northeast regions were associated with the highest total premature mortality per capita, while the total mortality per capita in the southwestern, southern, and southeastern regions were relatively lowest [Supplementary Figure 3, http://links.lww.com/CM9/B851].

$PM_{2.5}$-related premature mortality (8.47–9.28 million) accounted for majority of the total premature mortality (91.06%–92.29%), its spatial-temporal trends were similar to the total premature mortality between 2005 and 2017 [Figure 2A, Supplementary Figure 2, http://links.lww.com/CM9/B851]. However, the O_3-contribution showed an increasing trend in most regions but showed differences across regions. The highest O_3-contribution occurred in the SC and the FWP regions, while the O_3-contribution in Northeast China and PRD region was relatively lower [Figures 1A, Supplementary Figure 2, http://links.lww.com/CM9/B851]. During the 13-year period, the O_3-related premature mortality increased

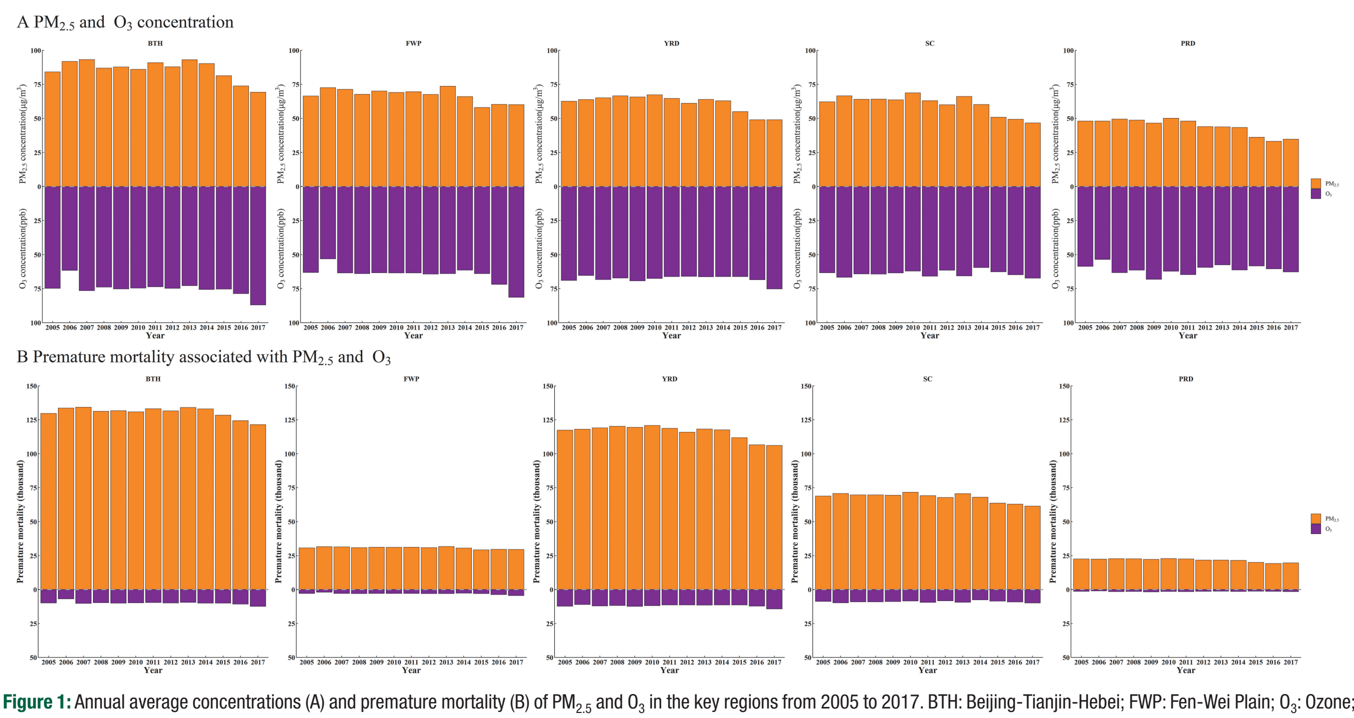

Figure 1: Annual average concentrations (A) and premature mortality (B) of $PM_{2.5}$ and O_3 in the key regions from 2005 to 2017. BTH: Beijing-Tianjin-Hebei; FWP: Fen-Wei Plain; O_3: Ozone; PRD: Pearl River Delta; $PM_{2.5}$: Fine particulate matter; SC: Sichuan-Chongqing; YRD: Yangtze River Delta.

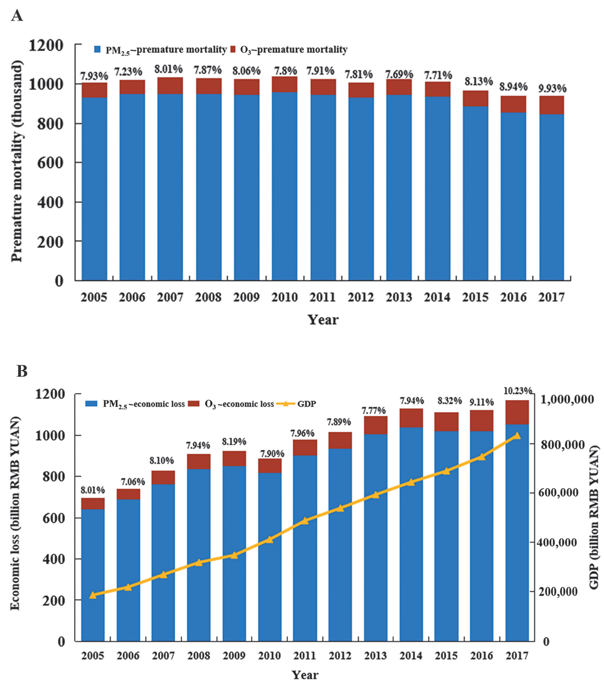

Figure 2: Changing trends of premature mortality (A) caused by $PM_{2.5}$ and O_3 and its economic loss (B) across China (the marked percentages indicate the contribution of O_3 to the overall premature mortality and economic loss). O_3: Ozone; $PM_{2.5}$: Fine particulate matter.

significantly in the five typical regions, in which the highest increase was in the FWP region (56.46%), and the lowest was in the SC region (12.23%) [Figure 1A, 1B].

Spatio-temporal patterns of economic loss from $PM_{2.5}$ and O_3

Due to economic growth, the changing trend of the sum of economic loss from mortality caused by ambient $PM_{2.5}$ and O_3 was different from that of the mortality [Figure 2]. The total economic burden was estimated to rise from RMB 695.96 yuan in 2005 to RMB 1170.31 billion yuan in 2017, representing 3.72% and 1.41% of the national GDP, respectively [Figures 2B, 3, and Supplementary Figure 4, http://links.lww.com/CM9/B851]. Between 2013 and 2017, the decreased exposure to ambient $PM_{2.5}$ and O_3 avoided the economic loss of RMB 101.29 billion yuan, but the economic growth in GDP and CPI raised RMB 166.57 billion yuan of economic cost [Figure 3]. In contrast, the proportion of total economic loss to GDP showed a stable declining trend.

The higher total economic loss was observed in the provinces with the heavy pollution and high GDP, such as Shandong, Guangdong, Henan, Hebei, and Sichuan provinces [Figure 4D]. Lower total economic burden was found in the western regions such as Xizang, Ningxia, and Qinghai [Figure 4D]. The number of high-burden provinces with the total economic loss of more than RMB 50.00 billion yuan increased from one (Shandong) in 2005 to eight (including Shandong, with a burden of more than RMB 100.00 billion yuan) in 2017 [Figure 4A–D]. In 2017, the spatial feature of the proportion of O_3-related economic loss to the total loss was coincided with that of the mortality [Figure 2]. But lower O_3-contributions

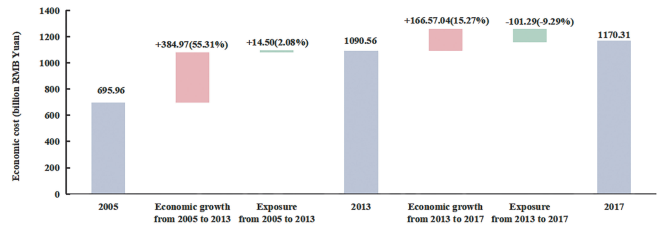

Figure 3: Contribution of each driving factor to the change in economic cost of premature mortality due to ambient $PM_{2.5}$ and O_3 (the lengths indicate the contribution of each driving factor to the change in the economic loss; the marked percentages show the contribution as a proportion of the cost in 2005 or 2013). O_3: Ozone; $PM_{2.5}$: Fine particulate matter.

were observed in several northern regions with substantially heavier air pollution, such as Hebei [Supplementary Figure 5, http://links.lww.com/CM9/B851].

The greatest proportion of economic loss from the two pollutants to GDP was mainly distributed in the northeast and northern China over the 2005–2017 period. The proportion of total economic burden to GDP showed a gradient pattern, increasing from the southwest to the northeast. In 2017, the highest proportion was observed in the northeast and BTH region. The lowest proportion occurred in the south and southwest provinces, such as Hainan (0.61%), Xizang, and Yunnan [Figure 5A–D].

Discussion

This study comprehensively explored the spatial patterns and changing trends of premature deaths and economic loss attributable to $PM_{2.5}$ and O_3 pollution across China, aggregating the economic development and the concentration change of the air pollutants. We confirmed that air pollution control measures significantly improved air quality and achieved health and economic benefits, but the disease burden was still heavy. In 2017, the sum of premature mortality from the two pollutants was 0.94 million (decreased by 6.93% from 2005), of which the total economic loss was RMB 1170.31 billion yuan (about two times the number in 2005) with the national economic development [Figure 2A–B]. The premature mortality in this study was consistent with some existing studies.[32,33] However, the economic loss was higher than those in previously published studies,[34–36] and its proportions of GDP was near the range of the available estimates (2.9–5.9% in previous studies).[4,8,16,37,38] These differences may come from the various data sources, the C-R function, different methods of assessing economic burden, and studying periods [Supplementary Table 1, http://links.lww.com/CM9/B851]. The $PM_{2.5}$ and O_3-related premature mortality in 2017 that Xiao *et al*[39] assessed was slightly higher than that in this study, due to the various sources of exposure and population data. The exposure data from the tracking air pollution in China (TAP) and the population from the LandScan Global Population Database set, have slightly different spatial and temporal characteristics to our study.[39] Maji *et al*[15,40] and OECD (https://stats.oecd.org) estimated that the number of premature deaths associated with $PM_{2.5}$ and O_3 was in accordance with the results of this study. However, the total economic burden of this study was

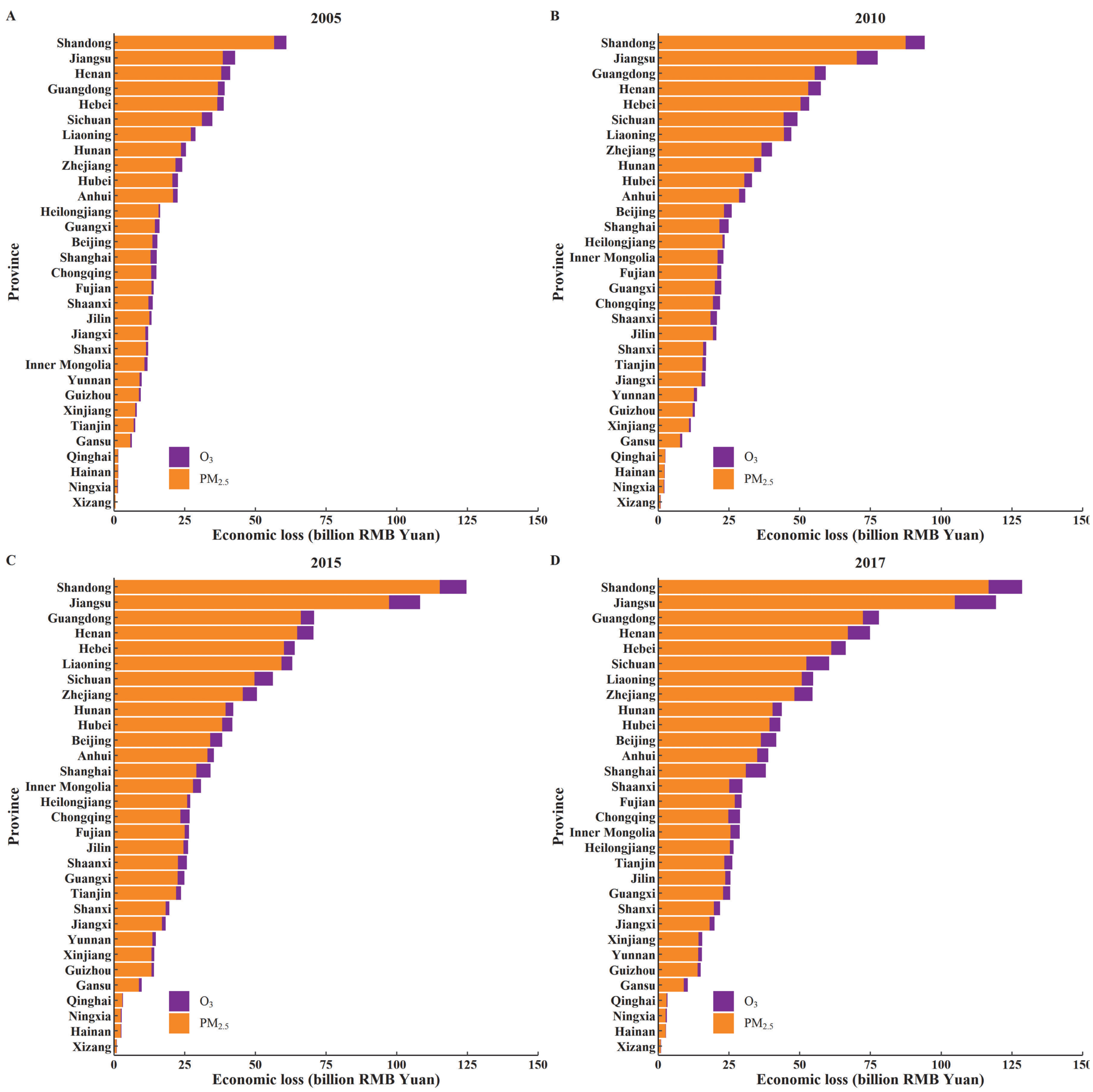

Figure 4: Economic burden of premature mortality due to ambient $PM_{2.5}$ and O_3 of each province in 2005 (A), 2010 (B), 2015 (C), and 2017 (D). O_3: Ozone; $PM_{2.5}$: Fine particulate matter.

higher than that Maji *et al*[15,40] estimated (108.99 million US dollars), and lower than that of OECD (2.15 trillion US dollars). This is mainly because of the different VSL values of WTP methods. Furthermore, many studies are prospective, so they could not take into account historical spatio-temporal patterns of health and economic burden or benefits of two pollutants after clean air policies.[4,38] To minimize these uncertainties, we made estimates by using county-level statistics like county-level population and county-level exposure, as well as province-level variables like provincial CPI and GDP per capita to adjust the VSL. To assess the data, we aggregated the health and economic burden from the two pollutants and created a coarse scale description and discussion to gain comprehension to aid macro decision-making, especially after the implementation of clean air policies.

Recently, China has implemented a series of national and regional air quality improvement policies and measures, achieving the significant reduction in $PM_{2.5}$ concentration and the great health benefits. However, the annual average $PM_{2.5}$ concentration was still higher than that of WHO Air Quality Guidelines (5 $\mu g/m^3$), and its related premature deaths and economic burden were still great [Figure 2 and Supplementary Figure 1, http://links.lww.com/CM9/B851].[13] The $PM_{2.5}$-related premature mortality for cardiovascular disease accounted for the majority, especially IHD and stroke. These findings are consistent with reports reported in the literature.[18,41–44] Moreover, some previous studies indicated that $PM_{2.5}$-related premature mortality remained high in China even at the low concentration.[39,41] Therefore, China still must improve the management of $PM_{2.5}$ pollution as well as the prevention and control of reducing the morbidity and mortality rates of cardiovascular diseases, in order to significantly lower the burden of disease. However, as O_3 concentrations rose, the O_3-related premature mortality and its economic burden increased, particularly in the YRD, FWP and SC

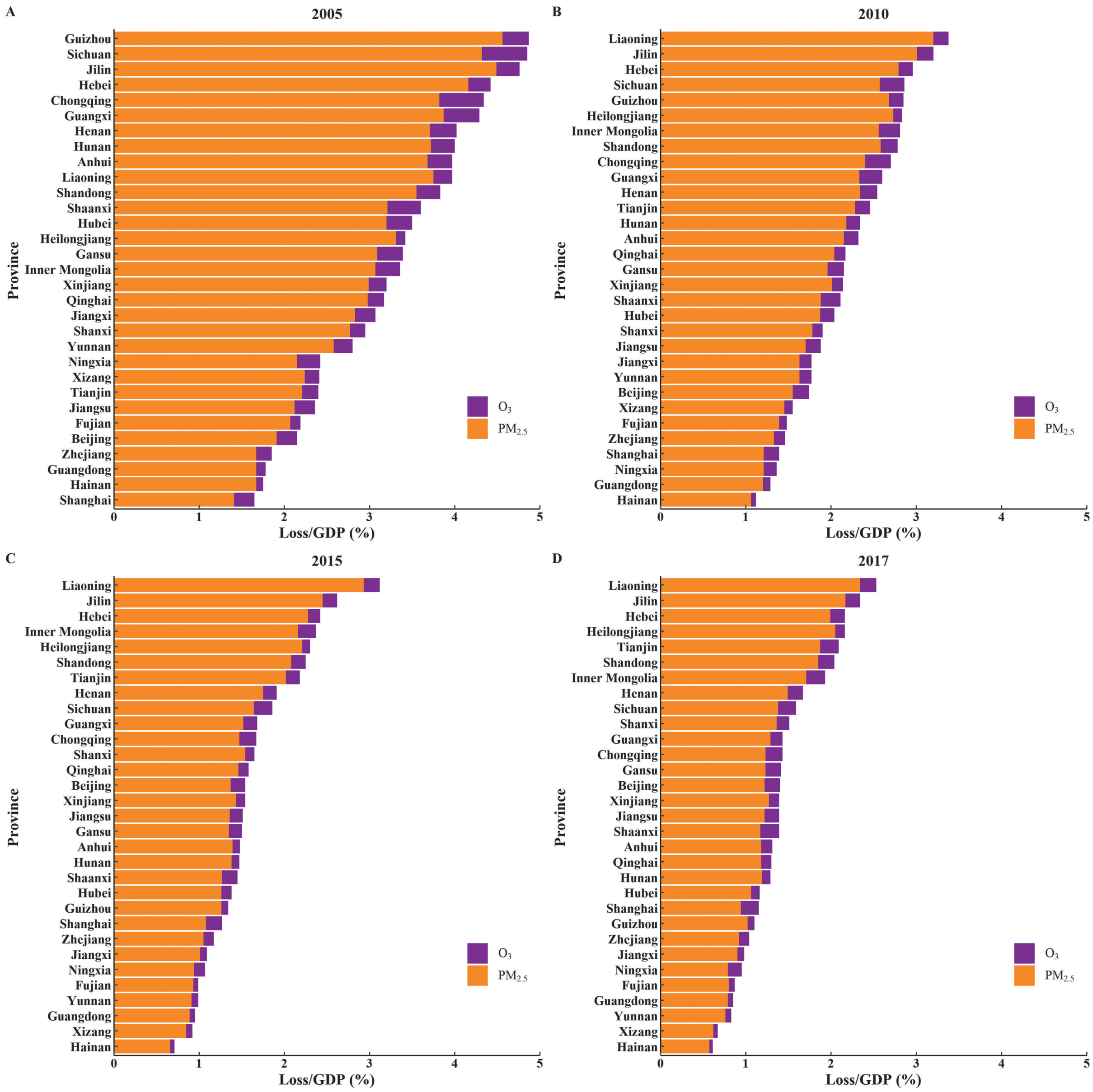

Figure 5: Proportion of economic loss from deaths caused by ambient $PM_{2.5}$ and O_3 to GDP of each province in 2005 (A), 2010 (B), 2015 (C), and 2017 (D). GDP: Gross domestic product; O_3: Ozone; $PM_{2.5}$: Fine particulate matter.

regions. [Figures 1, 2, and Supplementary Figure 1, http://links.lww.com/CM9/B851]. Many studies have demonstrated that after implementing the APPCAP, several cities or regions had strived to address the $PM_{2.5}$ issue, but the O_3 concentrations were unexpectedly growing because of the complex chemical interactions.[12,45,46] These findings emphasized that the great progress has been made in reducing $PM_{2.5}$ concentrations across China in recent years, but the adverse effects of growing in O_3 pollution could not be ignored. Therefore, the regions with higher $PM_{2.5}$ concentration should pay attention to cutting down the $PM_{2.5}$ pollution and, at the same time, keeping the O_3 concentration from increasing. Some regions with both higher $PM_{2.5}$ and O_3 concentrations, such as the BTH, YRD, FWP, and SC regions were recommended to coordinately control the two pollutants. Nowadays, the 14th Five-Year Plan for National Economic and Social Development (2021–2025) includes the coordinated control of $PM_{2.5}$ and O_3 pollution. It is important to adopt coordinated management measures that are based on the spatio-temporal patterns of two pollutants, the disease burden associated with them, population growth, and socioeconomic development.

The disproportionate health at the regional and province level were influenced by the concentration changes of air pollutant, population density, and baseline mortality. However, due to the economic growth, the economic burden in China showed an increasing trend. In the central China (such as Hubei and Hunan provinces), the premature deaths were relatively slight, but the economic losses were relatively higher due to the high GDP [Figure 4A–D]. Hence, China must continue to make great efforts on air pollution prevention and control while maintaining economic growth. Greater targets and tougher regulations of air quality improvement must be implemented in densely inhabited and economically developed areas. The proportion of the economic burden of $PM_{2.5}$ and O_3 in GDP decreased significantly in all provinces of China, with the highest decline occurring in the southeast region between 2005 and 2017 [Figure 5A–D]. This indicated that the speed of economic development was higher than the growth of economic burden from air pollution issues as the Chinese government has been paying more and more attention to environmental protection while fostering economy growth. The area with the highest proportion mainly shifted from southwest China (Sichuan and Guizhou) to northeast China (Liaoning and Jilin) [Figure 5A–D]. These findings suggested that the ability of each region across China to withstand and respond with the economic losses attributed with air pollution was different due to the economic growth. The southeast region (Guangdong Province) with high economy and rapid economic growth, has a higher capacity to cope with its great economic burden. The economic losses in the northeastern provinces were relatively small, but the economic burden had a greater impact in these regions compared to their overall GDP. Compared with other regions, the northeastern provinces have realized economic growth through heavy industry, leading to serious air pollution. And this region with great mortality rate of chronic diseases and slow economic development, caused higher disease and economic burden.[41] It is urgent for the northeast China to optimize the industrial structure, encourage new energy development, and reduce the morbidity and mortality, in order to economic growth and burden reduction.

This study demonstrated significant advantages in assessing the changing trends and regional patterns of the economic burden of premature deaths attributed to long-term $PM_{2.5}$ and O_3 exposure in China, but there are a few limitations. First, our estimation used the 6th census data in 2010 and did not consider the population change during the 13 years. Moreover, the spatial features of any sociodemographic aspects might not change over time. Therefore, we used the 2010 census data for all the 13 years in this study. Because our pollutant exposure data were based at the county-level and collected yearly from 2005 to 2017, we believe that our study provides a scientific and reasonable estimation and crucial information related to the economic burden associated with air pollution. Second, the health risks caused by air pollution also leads to medical cost and economic loss in the form of labor loss and lack of working hours. However, due to the lack of widely accepted exposure-response associations between hospitalization and air pollution, and labor loss and air pollution, we estimated the economic burden from premature deaths associated with long-term $PM_{2.5}$ and O_3 exposure and estimate the medical cost and economic loss from labor loss and lack of working hours related to air pollution. The comprehensive estimation will be considered in our future studies based on the progresses of above relationships.

In conclusion, the clean air policy in China brought significant health and economic benefits but the disease burden from $PM_{2.5}$ and O_3 pollution remained at high levels and kept increasing during 2005–2017. Although the health and economic burden from O_3 is lower than that of $PM_{2.5}$, it has a significant increase along with the economic development and the rising of O_3 concentration while the $PM_{2.5}$ concentration has decreased thanks to the years of efforts. In an era to achieve the target of carbon peaking and neutrality, China has been taking a synergistic pathway and continuous efforts to curb pollution and mitigate climate change, which could hopefully bring great health benefits.

Funding

This work was supported by a grant from the National Natural Science Foundation of China (No. 42071433).

Conflicts of interest

None.

References

1. Diao B, Ding L, Zhang Q, Na J, Cheng J. Impact of urbanization on $PM_{2.5}$-related health and economic loss in China 338 cities. Int J Environ Res Public Health 2020;17:990. doi: 10.3390/ijerph17030990.
2. Guo XR, Cheng SY, Chen DS, Zhou Y, Wang HY. Estimation of economic costs of particulate air pollution from road transport in China. Atmos Environ 2010;44:3369–3377. doi: 10.1016/j.atmosenv.2010.06.018.
3. Xie Y, Dai H, Dong H, Hanaoka T, Masui T. Economic impacts from $PM_{2.5}$ pollution-related health effects in China: A provincial-level analysis. Environ Sci Technol 2016;50:4836–4843. doi: 10.1021/acs.est.5b05576.
4. Xie Y, Dai H, Zhang Y, Wu Y, Hanaoka T, Masui T. Comparison of health and economic impacts of $PM_{2.5}$ and ozone pollution in China. Environ Int 2019;130:104881. doi: 10.1016/j.envint.2019.05.075.
5. Yao M, Wu G, Zhao X, Zhang J. Estimating health burden and economic loss attributable to short-term exposure to multiple air pollutants in China. Environ Res 2020;183:109184. doi: 10.1016/j.envres.2020.109184.
6. Yin H, Pizzol M, Xu L. External costs of $PM_{2.5}$ pollution in Beijing, China: Uncertainty analysis of multiple health impacts and costs. Environ Pollut 2017;226:356–369. doi: 10.1016/j.envpol.2017.02.029.
7. Yin P, Brauer M, Cohen A, Burnett RT, Liu J, Liu Y, *et al*. Long-term fine particulate matter exposure and nonaccidental and cause-specific mortality in a large national cohort of Chinese men. Environ Health Perspect 2017;125:117002. doi: 10.1289/EHP1673.
8. Liu T, Cai Y, Feng B, Cao G, Lin H, Xiao J, *et al*. Long-term mortality benefits of air quality improvement during the twelfth five-year-plan period in 31 provincial capital cities of China. Atmos Environ 2018;173:53–61. doi: 10.1016/j.atmosenv.2017.10.054.
9. Maji KJ, Arora M, Dikshit AK. Burden of disease attributed to ambient $PM_{2.5}$ and PM_{10} exposure in 190 cities in China. Environ Sci Pollut Res Int 2017;24:11559–11572. doi: 10.1007/s11356-017-8575-7.
10. Cai W, Zhang C, Suen HP, Ai S, Bai Y, Bao J, *et al*. The 2020 China report of the Lancet Countdown on health and climate change. Lancet Public Health 2021;6:e64–e81. doi: 10.1016/s2468-2667(20)30256-5.
11. Murray CJL, Aravkin AY, Zheng P, Abbafati C, Abbas KM, Abbasi-Kangevari M, *et al*. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. Lancet 2020;396:1223–1249. doi: 10.1016/s0140-6736(20)30752-2.
12. Lu X, Zhang S, Xing J, Wang Y, Chen W, Ding D, *et al*. Progress of air pollution control in China and its challenges and opportunities in the ecological civilization era. Engineering 2020;6:1423–1431.

doi: 10.1016/j.eng.2020.03.014.
13. World Health Organization. WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization, 2021.
14. Ministry of Ecology and Environment of the People's Republic of China. Bulletin on the State of the Ecological Environment in China. In: Ministry of Ecology and Environment of the People's Republic of China, 2020. Available from: https://www.mee.gov.cn. [Last accessed on April 24, 2023].
15. Maji KJ, Ye WF, Arora M, Shiva Nagendra SM. $PM_{2.5}$-related health and economic loss assessment for 338 Chinese cities. Environ Int 2018;121(Pt 1):392–403. doi: 10.1016/j.envint.2018.09.024.
16. Niu Y, Chen R, Kan H. Air pollution, disease burden, and health economic loss in China. Adv Exp Med Biol 2017;1017:233–242. doi: 10.1007/978-981-10-5657-4_10.
17. Luo G, Zhang L, Hu X, Qiu R. Quantifying public health benefits of $PM_{2.5}$ reduction and spatial distribution analysis in China. Sci Total Environ 2020;719:137445. doi: 10.1016/j.scitotenv.2020.137445.
18. Zhang X, Ou X, Yang X, Qi T, Nam KM, Zhang D, *et al*. Socioeconomic burden of air pollution in China: Province-level analysis based on energy economic model. Energy Econ 2017;68:478–489. doi: 10.1016/j.eneco.2017.10.013.
19. Shi Y, Zhu Y, Gong S, Pan J, Zang S, Wang W, *et al*. $PM_{2.5}$-related premature deaths and potential health benefits of controlled air quality in 34 provincial cities of China during 2001–2017. Environ Impact Assess Rev 2022;97:106883. doi: 10.1016/j.eiar.2022.106883.
20. Wang J, Gao A, Li S, Liu Y, Zhao W, Wang P, *et al*. 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. J Environ Sci (China) 2023;130:75–84. doi: 10.1016/j.jes.2022.06.036.
21. Yin P, Brauer M, Cohen A, Burnett RT, Liu J, Liu Y, *et al*. Long-term Fine Particulate Matter Exposure and Nonaccidental and Cause-specific Mortality in a Large National Cohort of Chinese Men. Environ Health Perspect. 2017 Nov 7;125(11):117002. doi: 10.1289/EHP1673 .
22. Zhang M, Song Y, Cai X, Zhou J. Economic assessment of the health effects related to particulate matter pollution in 111 Chinese cities by using economic burden of disease analysis. J Environ Manage 2008;88:947–954. doi: 10.1016/j.jenvman.2007.04.019.
23. Zhao C, Wang Q, Ban J, Liu Z, Zhang Y, Ma R, *et al*. Estimating the daily $PM_{2.5}$ concentration in the Beijing-Tianjin-Hebei region using a random forest model with a 0.01 degrees x0.01 degrees spatial resolution. Environ Int 2020;134:105297. doi: 10.1016/j.envint.2019.105297.
24. Ma R, Ban J, Wang Q, Zhang Y, Yang Y, Li S, *et al*. Full-coverage 1 km daily ambient $PM_{2.5}$ and O_3 concentrations of China in 2005–2017 based on a multi-variable random forest model. Earth Syst Sci Data 2022;14:943–954. doi: 10.5194/essd-14-943-2022.
25. Kassebaum NJ, Bertozzi-Villa A, Coggeshall MS, Shackelford KA, Steiner C, Heuton KR, *et al*. Global, regional, and national levels and causes of maternal mortality during 1990–2013: A systematic analysis for the Global Burden of Disease Study 2013. Lancet 2014;384:980–1004. doi: 10.1016/s0140-6736(14)60696-6.
26. Apte JS, Marshall JD, Cohen AJ, Brauer M. Addressing global mortality from ambient $PM_{2.5}$. Environ Sci Technol 2015;49:8057–8066. doi: 10.1021/acs.est.5b01236.
27. Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, *et al*. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. Lancet 2017;389:1907–1918. doi: 10.1016/s0140-6736(17)30505-6.
28. OECD. The economic consequences of outdoor air pollution. Paris: OECD Publishing, 2016. Available from: https://www.oecd-ilibrary.org. [Last accessed on April 24, 2023].
29. Xie, P, Liu, X. Y., Liu, Z. R., Li, T. T. & Bai, Y. H. Exposure-response functions for health effects of ambient particulate matter pollution applicable for China. China Environ Sci 2009;29:1034–1040. Available from: https://kns.cnki.net [Last accessed on April 24, 2023].
30. Yang Z, Liu P, Xu X. Estimation of social value of statistical life using willingness-to-pay method in Nanjing, China. Accid Anal Prev 2016;95(Pt B):308–316. doi: 10.1016/j.aap.2016.04.026.
31. Aldy JE, Viscusi WK. Adjusting the value of a statistical life for age and cohort effects. Rev Econ Stat 2008;90:573–581. doi: 10.1162/rest.90.3.573.
32. Yin P, Brauer M, Cohen AJ, Wang H, Li J, Burnett RT, *et al*. The effect of air pollution on deaths, disease burden, and life expectancy across China and its provinces, 1990-2017: An analysis for the Global Burden of Disease Study 2017. Lancet Planet Health 2020;4:e386–e398. doi: 10.1016/S2542-5196(20)30161-3.
33. Guan Y, Xiao Y, Wang Y, Zhang N, Chu C. Assessing the health impacts attributable to $PM_{2.5}$ and ozone pollution in 338 Chinese cities from 2015 to 2020. Environ Pollut 2021;287:117623. doi: 10.1016/j.envpol.2021.117623.
34. Zeng X, Ruan F, Peng Y. Health effects' spatial distribution analysis of $PM_{2.5}$ pollution in China based on spatial grid scale. China Environ Sci 2019;39:2624–2632.doi: 10.19674/j.cnki.issn1000-6923.2019.0312
35. OECD. The cost of air pollution: Health impacts of road transport. Paris: OECD Publishing, 2014. Available from: https://www.oecd-ilibrary.org. [Last accessed on April 24, 2023].
36. Zhang X, Cheng C, Zhao H. A health impact and economic loss assessment of O_3 and $PM_{2.5}$ exposure in China from 2015 to 2020. Geohealth 2022;6:e2021GH000531. doi: 10.1029/2021GH000531.
37. Chen F, Yamashita K, Kurokawa J, Klimont Z. Cost–benefit analysis of reducing premature mortality caused by exposure to ozone and $PM_{2.5}$ in East Asia in 2020. Water Air Soil Pollut 2015;226:108. doi: 10.1007/s11270-015-2316-7.
38. Wang Y, Hu J, Zhu J, Li J, Qin M, Liao H, *et al*. Health-burden-and-economic-impacts-attributed-to-$PM_{2.5}$-and-O_3-in-China-from-2010-to-2050-under-different-representative-concentration-pathway-scenarios. Resourc Conservat Recycl 2021;173:105731. doi: 10.1016/j.resconrec.2021.105731.
39. Xiao Q, Geng G, Xue T, Liu S, Cai C, He K, *et al*. Tracking $PM_{2.5}$ and O_3 pollution and the related health burden in China 2013-2020. Environ Sci Technol 2022;56:6922–6932. doi: 10.1021/acs.est.1c04548.
40. Maji KJ, Ye WF, Arora M, Nagendra SMS. Ozone pollution in Chinese cities: Assessment of seasonal variation, health effects and economic burden. Environ Pollut 2019;247:792–801. doi: 10.1016/j.envpol.2019.01.049.
41. Qing W, Zhu H, Xu H, Lu K, Ban J, Ma R, *et al*. The spatiotemporal trends of $PM_{2.5}$- and O_3-related disease burden coincident with the reduction in air pollution in China between 2005 and 2017. Resourc Conservat Recycl 2022;176:105918. doi: 10.1016/j.resconrec.2021.105918.
42. Ministry of Ecology and Environment of the People's Republic of China. 2017 Report on the Status of the Ecology and Environment in China. In: Ministry of Ecology and Environment of the People's Republic of China: Ministry of Ecology and Environment of the People's Republic of China, 2018.
43. Health Effects Institute. State of global air 2020. Special Report. Boston, MA: Health Effects Institute, 2020.
44. Huang J, Pan X, Guo X, Li G. Health impact of China's air pollution prevention and control action plan: An analysis of national air quality monitoring and mortality data. Lancet Planet Health 2018;2:e313–e323. doi: 10.1016/S2542-5196(18)30141-4.
45. Li K, Jacob DJ, Liao H, Zhu J, Shah V, Shen L, *et al*. A two-pollutant strategy for improving ozone and particulate air quality in China. Nat Geosci 2019;12:906–910. doi: 10.1038/s41561-019-0464-x.
46. Nichol JE, Bilal M, Ali MA, Qiu Z. Air pollution scenario over China during COVID-19. Remote Sens 2020;12:2100. doi: 10.3390/rs12132100.

How to cite this article: Xu HY, Wang Q, Zhu HH, Zhang YY, Ma RM, Ban J, Liu YT, Chen C, Li TT. Related health burden with the improvement of air quality across China. Chin Med J 2024;137:2726–2733. doi: 10.1097/CM9.0000000000002974