Ecotoxicology and Environmental Safety 222 (2021) 112481

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Health and related economic benefits associated with reduction in air pollution during COVID-19 outbreak in 367 cities in China

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ARTICLE INFO

Edited by Paul Sibley

Keywords:
COVID-19
China
Air pollution
Health burden
Economic benefits

ABSTRACT

Due to the COVID-19 outbreak, the Chinese government implemented nationwide traffic restrictions and self-quarantine measures from January 23 to April 8 (in Wuhan), 2020. We estimated how these measures impacted ambient air pollution and the subsequent consequences on health and the health-related economy in 367 Chinese cities. A random forests modeling was used to predict the business-as-usual air pollution concentrations in 2020, after adjusting for the impact of long-term trend and weather conditions. We calculated changes in mortality attributable to reductions in air pollution in early 2020 and health-related economic benefits based on the value of statistical life (VSL). Compared with the business-as-usual scenario, we estimated 1239 (95% CI: 844–1578) $PM_{2.5}$-related deaths were avoided, as were 2777 (95% CI: 1565–3995) PM_{10}-related deaths, 1587 (95% CI: 98–3104) CO-related deaths, 4711 (95% CI: 3649–5781) NO_2-related deaths, 215 (95% CI: 116–314) O_3-related deaths, and 1088 (95% CI: 774–1421) SO_2-related deaths. Based on the reduction in deaths, economic benefits for in $PM_{2.5}$, PM_{10}, CO, NO_2, O_3, and SO_2 were 1.22, 2.60, 1.36, 4.05, 0.20, and 0.95 billion USD, respectively. Our findings demonstrate the substantial benefits in human health and health-related costs due to improved urban air quality during the COVID lockdown period in China in early 2020.

1. Introduction

COVID-19, the disease caused by the SARS-CoV-2 virus (Huang et al., 2020a), was declared to be a pandemic by the World Health Organization (WHO) on March 11, 2020, and had caused more than 178 million confirmed cases and 3 million deaths world-wide by June 21, 2021 (https://covid19.who.int/). Measures that have been commonly applied to control COVID-19 including quarantine (Nussbaumer-Streit et al., 2020), stay at home orders and ban on large gatherings (Aquino et al., 2020; Mazumder et al., 2020; Xiao et al., 2020). In addition to the effects on transmission of the virus, these actions have cut air pollution due to restrictions on travel and production activities (Chen et al., 2020; Wang et al., 2020). Evidence from environmental monitoring sites and satellite data has been presented in previous studies of improved air quality

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https://doi.org/10.1016/j.ecoenv.2021.112481
Received 2 February 2021; Received in revised form 24 June 2021; Accepted 28 June 2021
Available online 30 June 2021

during the outbreak in China (Chen et al., 2020; Zheng et al., 2020), India (Gautam, 2020), Brazil (Nakada and Urban, 2020), the United States (Son et al., 2020), and Spain (Tobias et al., 2020).

Short-term exposure to air pollutants, including particulate matter with aerodynamic diameters of ≤ 2.5 μm ($PM_{2.5}$) (Chen et al., 2017) and 10 μm (PM_{10}), carbon monoxide (CO) (Liu et al., 2018), ozone (O_3) (Yin et al., 2017), nitrogen dioxide (NO_2) (Chen et al., 2018), and sulfur dioxide (SO_2) (Wang et al., 2018), increases risks of mortality and morbidity. However, little has been published to date on the economic gains from health improvements due to reduced emissions during the COVID-19 outbreak in China. Furthermore, quantifying avoided air pollution-related health costs, using tools such as the value of statistical life (VSL) may illuminate the cost and severity of air pollution impacts for policy makers and researchers (Bai et al., 2018).

China implemented a severe, nation-wide lockdown to control transmission of SARS-CoV-2 between January 23, 2020 and April 8, 2020. Understanding the health and economic changes, due to the improvement of air quality during the lockdown period, would be helpful to guide future public health policy and environmental protection strategies. Chen et al. (2020) have reported decreased deaths associated with reductions in NO_2 and in $PM_{2.5}$ concentrations during the COVID-19 outbreak in China. This study provides useful insights, but was derived from a simple difference-in-difference approach without fully accounting for factors such as long-term trends and the influence of weather conditions on air pollution. In this study, we aimed to comprehensively estimate the changes in mortality and related costs based on the VSL that may be attributed to the reductions in air pollution during the COVID-19 outbreak in 367 cities in China.

2. Material and methods

2.1. Study setting

We performed an analysis of national air quality monitoring data and mortality data from 367 cities located in 31 provinces (including municipalities and autonomous regions) in mainland China (Fig. A1).

2.2. Air pollution exposure

Data for hourly concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, and O_3 concentrations in each city from January 1, 2015 to March 31, 2020 were downloaded from China's National Urban Air Quality Real-time Publishing Platform (http://106.37.208.233:20035/). The 24-hour average concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2, and SO_2, and 8-hour maximum O_3 concentrations were then calculated if less than a third of hourly data were missing on that day for a given pollutant. Otherwise, the concentrations were estimated using the mean values of the daily average concentrations on the day before and after that day.

2.3. Population and mortality data

Data on the annual average population and annual all-cause mortality rate from 2015 to 2019 were collected from the China Statistical Yearbook and Statistical Report of each city. Due to the lack of recent data, daily deaths in February and March 2020 were estimated by the average of the past 5 years. We note that during the study period there has been slow population growth (Huang et al., 2018).

We downloaded data of 24-hour cumulative precipitation, mean ground surface temperature, mean air pressure, mean relative humidity, mean air temperature, sunshine duration, maximum wind speed, and maximum wind direction from 2015 to 2020 in 699 monitoring stations from the National Meteorological Information Center of China Meteorological Data Service Center (http://data.cma.cn/). These meteorological data were matched to the nearest geographic information system (GIS)-delineated city locations.

2.4. Estimating business-as-usual concentrations of air pollutants during the COVID-19 outbreak

We predicted 'business-as-usual' concentrations of air pollutants using a machine learning method with a meteorology normalization technique, to reflect the air quality that would be expected without the lockdown.

Based on previous studies (Breiman, 2001; Hastie et al., 2009), a Random Forests (RF) model was used to estimate the business-as-usual concentrations of the six air pollutants in 2020. The following variables were linked with the city-specific daily pollutant concentration (CO, NO_2, O_3, SO_2, PM_{10}, and $PM_{2.5}$, respectively) to fit the RF model: *doy* and *year* are day of the year and calendar years, respectively; *citycode* is a unique encoding scheme that defines the city administrative division; *rain* is city-specific daily cumulative precipitation (mm); *meanGst* is city-specific daily mean ground surface temperature (°C); *meanPres* is daily mean air pressure (hPa); *meanRH* is daily mean relative humidity (%); *meanTemp* daily is mean air temperature (°C); *sunshine* is the daily sunshine duration (h); *MWS* is daily maximum wind speed (m/s); and *MWD* is daily wind direction at maximum wind speed (16 directions). Data from 2015 to 2019 were utilized as training sets and then the daily city-specific estimates for the concentration of each pollutant in February and March, 2020 were predicted using the trained RF model.

To validate the model performance, a city-stratified 10-fold cross-validation (CV) process was performed using data from 2015 to 2019 (year-round data). This process was repeated 500 times. The overall adjusted R^2 and Root Mean Square Error (RMSE) were calculated (Fig. A2).

2.5. Estimating the health benefits due to improvement of air quality during COVID-19 outbreak

The mortality on day i in city j, representing the health burden (HB_{ij}) attributed to a specific air pollutant, was calculated as:

$$HB_{ij} = (e^{\beta \times \Delta x_{ij}} - 1) \times N_{ij}$$

$$\beta = \frac{\text{In}\ (1 + ER)}{\Delta\ u} \quad (1)$$

where, ER is the estimated risk indicating the percentage increase of mortality with Δμ increment in concentration of a specific air pollutant. β is the log relative risk per unit (1 mg/m^3 for CO and 10 μg/m^3 for other pollutants) change in concentration of air pollutant. Δx is the excess daily concentration over the threshold (We assumed the threshold was zero as several studies have indicated the lack of a safe threshold level for air pollution and health (Brook et al., 2010; Schwartz and Zanobetti, 2000; Ye et al., 2019; Zhang et al., 2017).). N_{ij} is the count of deaths on day i in city j. Due to the lack of daily death counts at city level, N_{ij} was calculated by multiplying the baseline overall mortality rate and size of the exposed population in each year in each city, then divided by 365 days.

The ER was extracted from previous studies which estimated exposure-response relationships between short-term exposure to air pollutants and mortality (Table 1) (Chen et al., 2011, 2017, 2018, 2019; Tao et al., 2011; Wang et al., 2018; Yin et al., 2017). Because of the lack of a national study on association between the CO concentration and all-cause mortality, we utilized a pooled coefficient drawn from work in seven Chinese cities (Anshan (Chen et al., 2011), Taiyuan (Chen et al., 2011), Shanghai (Chen et al., 2011), Guangzhou (Tao et al., 2011), Foshan (Tao et al., 2011), Zhongshan (Tao et al., 2011), and Zhuhai (Tao et al., 2011)).

The health benefit due to air pollution reduction in February and March in 2020 was defined as the difference in health burden (ΔHB_{ij}).

$$\Delta HB_{ij} = HB_{BAU2020} - HB_{observed2020} \quad (2)$$

Table 1
Percentage increase of all-cause mortality associated per specified unit increment of the air pollutant and its 95% confidence interval (CI).

Air pollutant	Increase unit	Percentage increase (%)	95% CI (%)	
			Lower	Upper
$PM_{2.5}$(Chen et al., 2017)	10 μg/m^3	0.22	0.15	0.28
PM_{10}(Chen et al., 2019)	10 μg/m^3	0.23	0.13	0.33
Carbon monoxide(Chen et al., 2011;Tao et al., 2011)	1 mg/m^3	1.76	0.11	3.42
Nitrogen dioxide(Chen et al., 2018)	10 μg/m^3	0.90	0.70	1.10
Ozone(Yin et al., 2017)	10 μg/m^3	0.24	0.13	0.35
Sulfur dioxide(Wang et al., 2018)	10 μg/m^3	0.59	0.42	0.77

Where $HB_{BAU2020}$ and $HB_{observed2020}$ were daily mortality calculated by model [1] with business-as-usual (BAU) and observed concentrations of air pollutants on day i in city j, respectively. This was summed by days to get city-specific health benefits during the lockdown period in 2020.

2.6. Estimating economic impact of avoided mortalities

We estimated the economic impact of the avoided mortalities as calculated in Section 2.5. The non-market VSL lost was monetized to capture the impact of the change of air pollution due to the COVID-19 outbreak, based on the method applied by West et al. (2013). Details of this method have been described elsewhere (Kim et al., 2020; Tian et al., 2018, 2019, Xie et al., 2016, 2018, 2019, 2020). Although the value of life was reported to range from 8.2 to 31.1 million USD in a previous study (Matus et al., 2012), we adopted here a much lower number, $250,000 USD based on willingness to pay estimates in empirical Chinese research (Jin, 2017; Jin et al., 2020). The VSLs in all cities were adjusted using city-specific Gross Domestic Production (GDP) per capita values relative to the national average per capita GDP in 2010 and an elasticity of 0.5 (Viscusi and Aldy, 2003).

All the analyses were performed by the R software (v. 3.6.1). The "ranger" package was used to perform the random forests model (Wright and Ziegler, 2017), the "sampling" package was used to conduct 10-CV and stratified sampling without replacement, and the "metafor" package was used to conduct the meta-analyses (Viechtbauer, 2010). For all statistical tests, a p value of 0.05 (two-tailed) was considered significant.

3. Results

There were considerable reductions in PM_{10}, $PM_{2.5}$, CO, and SO_2 concentrations over 2015–2019, but reductions in NO_2 were only found during 2017–2019 (Fig. 1), which occurred in a non-linear pattern. The average (± SD) PM_{10} concentration in February and March reduced from 106.09 ± 47.22 μg/m^3 in 2015–64.44 ± 45.92 μg/m^3 in 2020, $PM_{2.5}$ from 59.39 ± 20.66 μg/m^3 to 37.37 ± 16.42 μg/m^3, CO from 1.25 ± 0.50 mg/m^3 to 0.75 ± 0.21 mg/m^3, and SO_2 from 32.10 ± 22.35 μg/m^3 to 10.28 ± 5.31 μg/m^3.

Table A2 includes more details of descriptive statistics (the mean, median, maximum, minimum, and quartiles of the observed concentrations of the six air pollutants in 367 Chinese cities during February and March from 2015 to 2020).

As shown in Fig. 2 and Table A3, significant reductions were found in the observed concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2, O_3, and SO_2 in 2020, compared with the estimated business-as-usual concentrations in 2020 and the average concentrations during 2015–2019. As this figure shows, long-term trends indicate declines in air pollution (see differences in the red and blue lines), but a larger decline for 2020 (green line).

Compared to the business-as-usual scenario, health benefits from air pollution improvement during the quarantine period were substantial (Table 2). At a national level across all cities, NO_2 led to the greatest reduction on deaths, followed by PM_{10}, CO, $PM_{2.5}$, SO_2, and O_3 as shown in Table 2. At a city level (Fig. 3), Beijing (136 deaths), Chongqing (116), Chengdu (69), Shanghai (77), and Suzhou (74, in Jiangsu Province) experienced most of the NO_2-related avoided deaths. Overall, cities in east, north, and central provinces such as Jiangsu, Hebei, and Zhejiang accounted for most of the health benefits.

Estimated economic benefits from reductions in $PM_{2.5}$, PM_{10}, CO, NO_2, O_3, and SO_2 at a city level were shown in Fig. 4, which amounts to a total of 1.22, 2.60, 1.36, 4.05, 0.20, and 0.95 billion USD at a national level, respectively (Table 2). Among the 31 provinces, the highest VSL from the six air pollutants was observed in Jiangsu province (Fig. 5 and Table A4). Higher VSLs from NO_2 and $PM_{2.5}$ were found in Shandong, Beijing, Hebei, and Zhejiang than other cities/provinces.

4. Discussion

This study estimated the changes in mortality and associated VSL caused by the changes of six air pollutants during the early stages of the COVID-19 outbreak in 367 cities in China, comparing observed levels with those expected under a business-as-usual scenario.

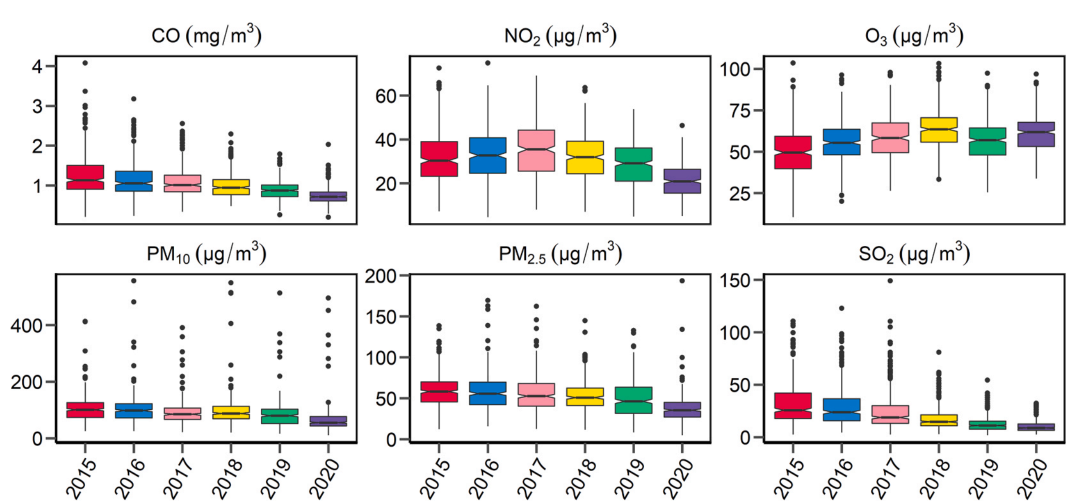

Fig. 1. Observed concentrations of the six criteria air pollutants in 367 Chinese cities during February and March from 2015 to 2020 (Please refer to Table A.1 for details).

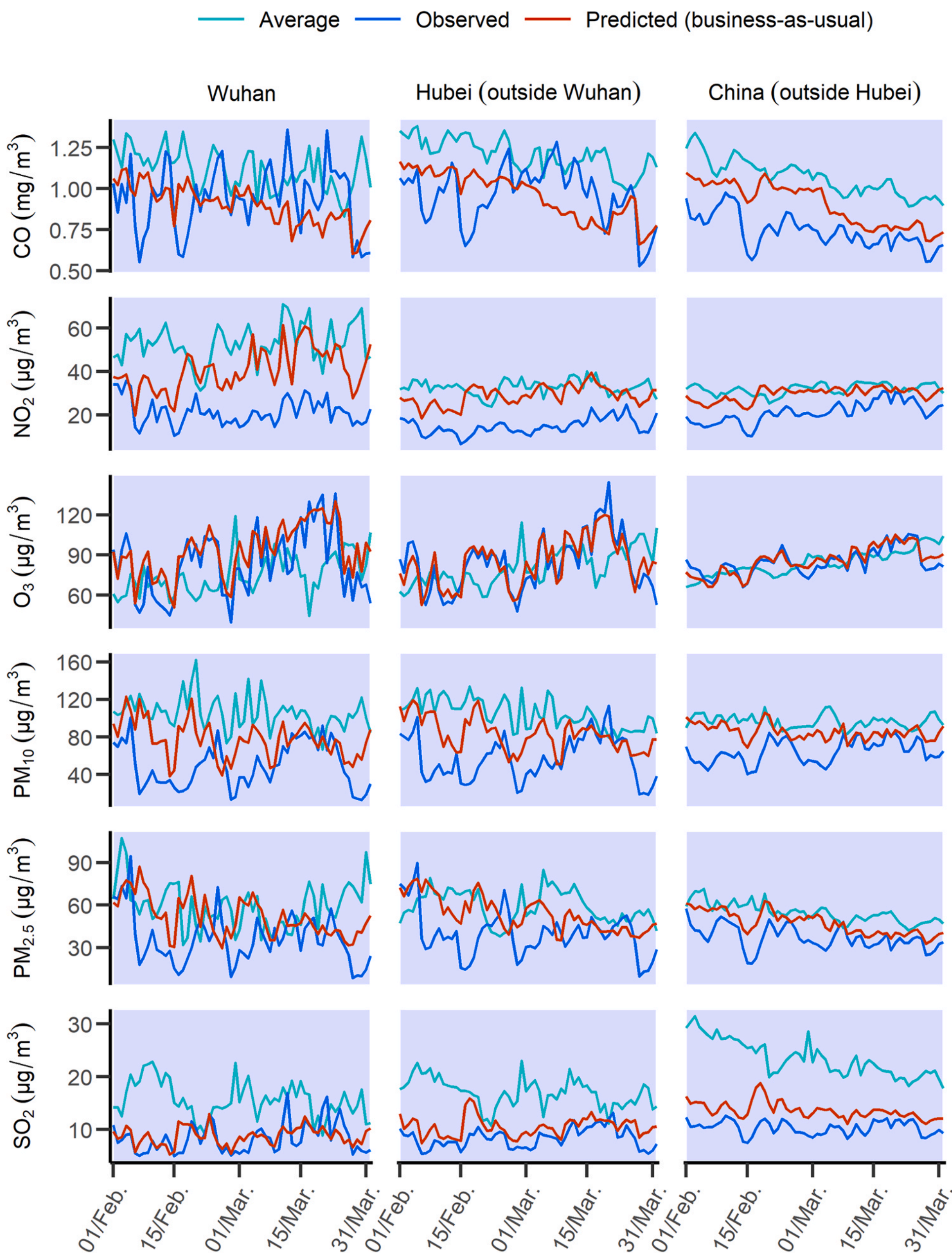

Fig. 2. Daily air pollution concentrations from February 1 to March 31 in 2020 (red line represents predicted business-as-usual concentrations and blue line represents observed concentrations) and 2015–2019 (average value in green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The national (across 367 cities) reduced health burden (deaths) and associated economic benefits (value of statistical life) attributed to the change of six ambient air pollutants during COVID-19, compared to the business-as-usual scenario.

Air pollutants	Reduced death counts (95% CI)	Value of statistical life in billion USD (95%CI)
CO	1587 (98, 3104)	1.36 (1.00, 2.26)
NO_2	4711 (3649, 5781)	4.05 (2.97, 6.75)
O_3	215 (116, 314)	0.20 (0.15, 0.34)
PM_{10}	2777 (1565, 3995)	2.60 (1.90, 4.33)
$PM_{2.5}$	1239 (844, 1578)	1.22 (0.90, 2.04)
SO_2	1088 (774, 1421)	0.95 (0.70, 1.58)

The concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2, and SO_2 in February and March 2020 were substantially lower than the average concentration in the same months during 2015–2019. One possible reason for the overall decline in pollution across time, as demonstrated by business-as-usual estimates lower than the 2015–2019 levels, could be the effective air pollution control policy, issued by the State Council of China in 2013, known as the Air Pollution Prevention and Control Action Plan (APPCAP). Previous studies reported the APPCAP has been effective in decreasing ambient concentrations of $PM_{2.5}$, PM_{10}, SO_2, and CO in the past few years (Huang et al., 2018; Maji et al., 2020). It should be also noted that the observed O_3 concentration tended to increase from 2015 to 2018. Another study also reported an increasing trend of O_3 3 $\mu g/m^3$/year in North and Southwest China from 2013 to 2017(Liu et al., 2020), while there was a decrease in NOx emissions in the same period (Li et al., 2019). Changes in volatile organic compounds (Alghamdi et al., 2014; Song et al., 2020) and solar radiation reaching

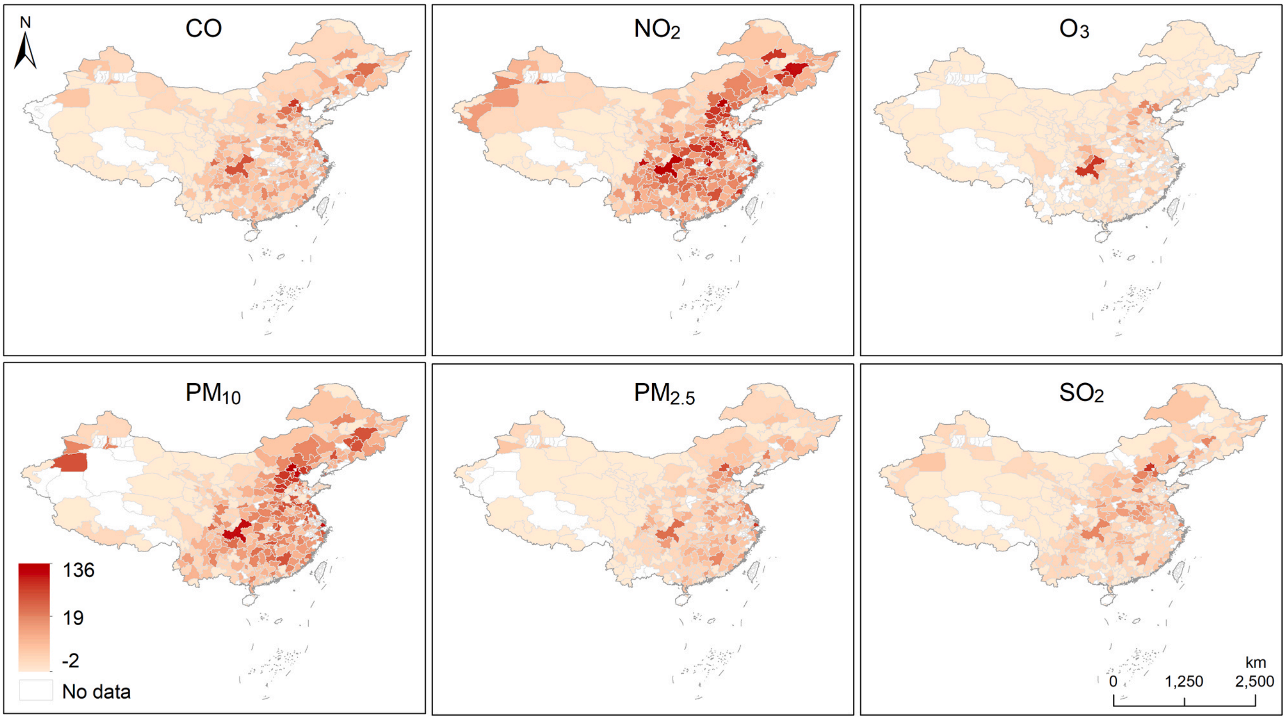

Fig. 3. The reduced health burden (death count) due to the decrease in concentrations of air pollutants in 367 cities during COVID-19, compared to the business-as-usual scenario.

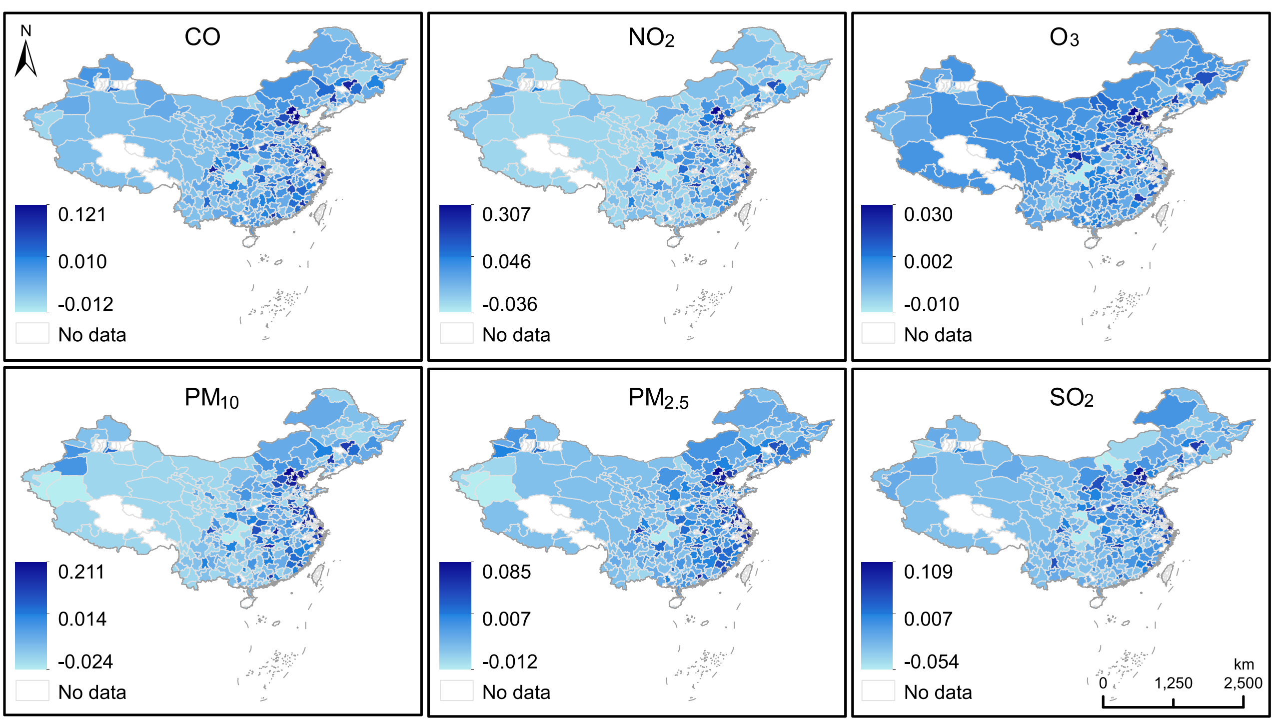

Fig. 4. Value of statistical life (unit: billion USD) saved due to avoided mortalities from decrease in air pollutants for February and March 2020 in 31 provinces during COVID-19, comparing to the business-as-usual scenario.

the surface (Chang et al., 2019; Huang et al., 2020b) may have played a part in these trends. Note that we compared air pollutant levels in the months immediately preceding the outbreak and found a sudden decrease after the lockdown which was unlikely due to changes in APPCAP.

We conclude the key reason for air pollution levels being lower in February and March 2020 compared to business-as-usual estimates is likely to be the restriction during the COVID-19 outbreak, which impacted transportation and other economic sectors, cutting emissions of air pollutants as well as pollutant precursors. The observed ambient concentrations of all the six air pollutants in February and March, 2020 were markedly lower than the predicted values (business-as-usual

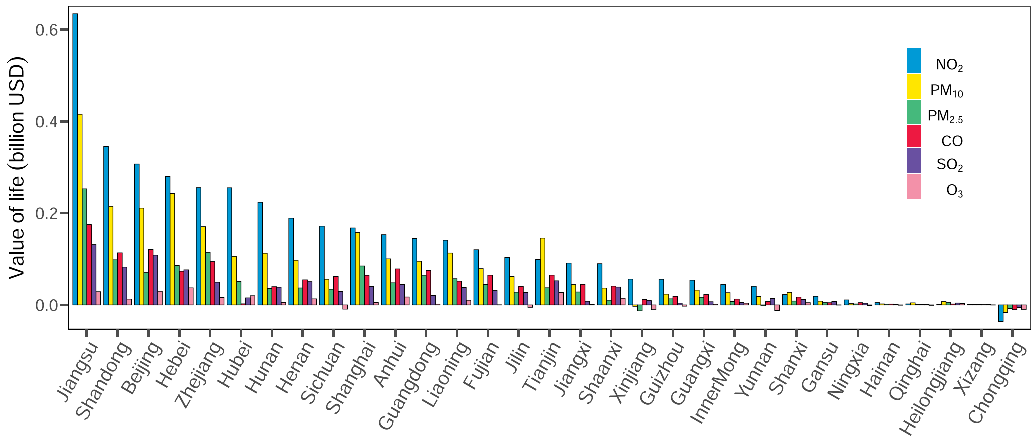

Fig. 5. Values of statistical life (unit: billion USD) saved due to decrease in air pollutants in 367 cities during COVID-19.

concentrations), and this is consistent with previous studies about the change of air quality in China and other countries during the epidemic (Rodríguez-Urrego and Rodríguez-Urrego, 2020).

We conclude that after adjusting for the impact of long-term trends and weather conditions on air pollution in the 367 Chinese cities, thousands of deaths were avoided due to improvements in air quality, especially the improvement in NO_2 and PM_{10}. Another study (Chen et al., 2020) estimated that a total of 8911 (95%CI: 6950–10866) NO_2-related (89% higher than our estimates) and 3214 (95%CI: 2340–4087) $PM_{2.5}$-related (159% higher than our estimates) deaths were avoided for 367 cities by the improved air quality during the study period. In that study, the impact of seasonality conditions on air pollution were adjusted using a different approach (difference-in-difference). They directly calculated the avoided deaths on the basis of the average pollution concentration of the past four years and the mortality data from 2018, only. Our models have adjusted for weather and long-term trend and suggested that pollutant concentrations would have been less than the 2016–2019 average in the absence of the quarantine policy for COVID-19. In this context, Chen et al. may have overestimated the health benefits.

Considerable economic benefits, as estimated by VSL, were estimated from the reduced mortality burden attributed to the decrease in six air pollutants during the epidemic outbreak, with improved NO_2 concentrations contributing the most. To our knowledge, this is one of the first studies assessing the health economic impacts due to the change in air pollution during COVID-19. Previous studies estimated the effect of heavy air pollution on economic development (Diao et al., 2020; Xie et al., 2016). While there are many economic costs from the pandemic (e.g., extra costs carried by the health service, loss of industry), the response to COVID also had economic benefits, including those that flowed from improved air quality. These findings can aid policy makers when they make decisions about restrictions on sectors such as manufacturing industry and transport, and illustrate what can achieved by efforts to address the public health burden from air pollution. We suggest provinces such as Jiangsu, Hebei, and Zhejiang, where the economic benefits in our study were greatest, should pay special attention to air quality management and related interventions, given the experience with COVID.

There are some limitations in this study. First, as in other time-series studies, individual-level confounding could not be fully excluded. However, we anticipate that differential changes at the level of individuals would not lead to substantial bias in the association between the COVID response and mortality at a population level. Ideally, indoor exposures should be measured in further studies, because people spend more time at home during the lockdown period. Second, the effect estimates for associations between air pollutants and mortality were modelled by single-pollutant models. We cannot model the independent effects of six air pollutants because of their co-linearity and lack of epidemiological does-response functions that account for the full suite of pollutants; thus some mortalities may be double counted. Third, air pollution is associated with other adverse health outcomes besides mortality, such as morbidity of many kinds and lower labor productivity (Xie et al., 2019). Costs of the full range of health outcomes should also be included, in order to gain a full picture of economic gains associated with lower air pollution. The avoided deaths that we counted in this study do not represent the full suite of health benefits from better air quality.

5. Conclusions

In conclusion, with a large data set covering 367 Chinese cities, significant reduction in observed concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2, O_3, and SO_2 due to the lockdown were found during February and March, 2020, comparing with an estimated business-as-usual scenario of air pollution concentrations. As a result, a total of 1587 CO-related, 4711 NO_2-related, 215 O_3-related, 2777 PM_{10}-related, 1239 $PM_{2.5}$-related, and 1088 SO_2-related deaths were estimated to be avoided. Benefits of 1.22 billion USD from $PM_{2.5}$, 2.60 from PM_{10}, 1.36 from CO, 4.05 from NO_2, 0.20 from O_3, and 0.95 from SO_2 are estimated from these avoided mortalities. Cities in the eastern, northern, and central provinces accounted for higher health and economic benefits. While the pandemic lockdown is clearly not an appropriate path to long-term air quality control, these findings suggest that substantial health and economic benefits associated with reduction in air pollution could be achieved, if strict air pollution control measures are carried out.

CRediT authorship contribution statement

Tingting Ye: Formal analysis, Writing - original draft **Suying Guo**: Formal analysis, Writing - original draft **Yang Xie**: Formal analysis **Zhaoyue Chen**: Formal analysis **Michael Abramson:** Writing - review & editing **Jane Heyworth:** Writing - review & editing **Simon Hales:** Writing - review & editing **Alistair Woodward:** Writing - review & editing **Michelle Bell:** Writing - review & editing **Yuming Guo:** Conceptualization, Supervision, Writing - review & editing **Shanshan Li:** Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: MJA holds investigator initiated grants from Pfizer and Boehringer-Ingelheim for unrelated research. He has undertaken an unrelated consultancy for and received assistance with conference attendance from Sanofi. He has also received a speaker's fee from GSK. There are no potential conflicts of interests for other authors.

Acknowledgements

This work was supported by the Australian National Health and Medical Research Council [#APP1109193 to SL and #APP1107107 to YG] and the China Scholarship Council [#201906320051 to TY].

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2021.112481.

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