Environmental Research 200 (2021) 111457

Contents lists available at ScienceDirect

Environmental Research

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

Reduction of air pollutants and associated mortality during and after the COVID-19 lockdown in China: Impacts and implications

Guimin Chen [a,b], Jun Tao [c], Jiaqi Wang [a], Moran Dong [a,b], Xuan Li [d], Xiaoli Sun [e], Shouzhen Cheng [f], Jingjie Fan [g], Yufeng Ye [h], Jianpeng Xiao [a], Jianxiong Hu [a], Guanhao He [a], Jiufeng Sun [a], Jing Lu [a], Lingchuan Guo [i], Xing Li [a], Zuhua Rong [a], Weilin Zeng [a], He Zhou [a], Dengzhou Chen [a], Jiali Li [a], Lixia Yuan [a,j], Peng Bi [k], Qingfeng Du [l], Wenjun Ma [a,m], Tao Liu [a,m,*]

[a] *Guangdong Provincial Institute of Public Health, Guangdong Provincial Center for Disease Control and Prevention, Guangzhou, China*
[b] *School of Public Health, Southern Medical University, Guangzhou, China*
[c] *Institute for Environmental and Climate Research, Jinan University, Guangzhou, China*
[d] *Guangxi College of Physical Education, Nanning, China*
[e] *Gynecology Department, Guangdong Women and Children Hospital, Guangzhou, China*
[f] *Nursing Department, The First Affiliated Hospital, Sun Yat-sen University, Guangzhou, China*
[g] *Department of Prevention and Health Care, Shenzhen Maternity & Child Healthcare Hospital, Southern Medical University, Shenzhen, Guangdong, China*
[h] *Guangzhou Panyu Central Hospital, Guangzhou, China*
[i] *State Environmental Protection Key Laboratory of Ecological Effect and Risk Assessment of Chemicals, State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, China*
[j] *School of Public Health, Sun Yat-sen University, Guangzhou, China*
[k] *School of Public Health, The University of Adelaide, Adelaide, South Australia, Australia*
[l] *Nanhai Hospital, Southern Medical University, Foshan, 528200, China*
[m] *Department of Public Health, School of Medicine, Jinan University, Guangzhou, China*

ARTICLE INFO

Keywords:
COVID-19 lockdown
Air pollutants
Mortality
Years of life lost
Air quality index

ABSTRACT

Although strict lockdown measurements implemented during the COVID-19 pandemic have dramatically reduced the anthropogenic-based emissions, changes in air quality and its health impacts remain unclear in China. We comprehensively described air pollution during and after the lockdown periods in 2020 compared with 2018–2019, and estimated the mortality burden indicated by the number of deaths and years of life lost (YLL) related to the air pollution changes. The mean air quality index (AQI), PM_{10}, $PM_{2.5}$, NO_2, SO_2 and CO concentrations during the lockdown across China declined by 18.2 (21.2%), 27.0 μg/m^3 (28.9%), 10.5 μg/m^3 (18.3%), 8.4 μg/m^3 (44.2%), 13.1 μg/m^3 (38.8%), and 0.3 mg/m^3 (27.3%) respectively, when compared to the same periods during 2018–2019. We observed an increase in O_3 concentration during the lockdown by 5.5 μg/m^3 (10.4%), and a slight decrease after the lockdown by 3.4 μg/m^3 (4.4%). As a result, there were 51.3 (95%CI: 32.2, 70.1) thousand fewer premature deaths (16.2 thousand during and 35.1 thousand after the lockdown), and 1066.8 (95%CI: 668.7, 1456.8) thousand fewer YLLs (343.3 thousand during and 723.5 thousand after the lockdown) than these in 2018–2019. Our findings suggest that the COVID-19 lockdown has caused substantial decreases in air pollutants except for O_3, and that substantial human health benefits can be achieved when strict control measures for air pollution are taken to reduce emissions from vehicles and industries. Stricter tailored policy solutions of air pollution are urgently needed in China and other countries, especially in well-developed industrial regions, such as upgrading industry structure and promoting green transportation.

1. Introduction

At the end of 2019, an emerging infectious disease named coronavirus 2019 (COVID-19) caused by the novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was reported, and has now affected more than 210 countries and regions worldwide (HOPKINS, 2020). The pandemic has led to unprecedented economic and

* Corresponding author. Guangdong Provincial Institute of Public Health, Guangdong Provincial Center for Disease Control and Prevention, Guangzhou, China.
E-mail address: liut@gdiph.org.cn (T. Liu).

https://doi.org/10.1016/j.envres.2021.111457
Received 23 January 2021; Received in revised form 11 May 2021; Accepted 30 May 2021
Available online 2 June 2021

social disruption. It was suggested that the COVID-19 pandemic leads to at least $1 trillion loss to world's economy during 2020, which is even worse than the 2008 Great Financial Crisis (Kabir et al., 2020).

Abbreviations

COVID-19	Coronavirus disease 2019
SARS-CoV-2	Respiratory syndrome coronavirus 2
AQI	Air quality index
YLL	Years of life lost
CVD	Cardiovascular diseases
RESP	Respiratory diseases
GBD	The global burden of disease
RR	Relative risk
DALY	Disability-adjusted life years

To avert the COVID-19 pandemic, various measurements have been implemented across the world, such as restriction in large-scale social movement and gathering, closing international and interstate borders, travel controls, and implementing partial or full lockdown of cities and regions. These risk reduction measures have significantly affected the local and global socio-political relations and economic growth (Kabir et al., 2020). Meanwhile, such strict measures have dramatically improved the air quality worldwide due to the reduction of anthropogenic-based emissions (Venter et al., 2020; Rodríguez-Urrego and Rodríguez-Urrego, 2020; Chen et al., 2020a; Son et al., 2020). Zander et al. observed 60% decrease in NO_2, and 31% decrease in $PM_{2.5}$ in 34 countries during lockdown (Venter et al., 2020).

China has implemented a series of unprecedented large-scale public health measures to control the spread of COVID-19, including city lockdown and transport freeze in hardest-hit areas, traffic controls in less severe areas, restricting social gathering, and community isolation (China Watch Institute and Ch, 2020). Such restrictions on human and industrial activities had significantly reduced the emission sources of air pollution, which hence decreased the concentrations of air pollutants. Several studies have reported the air quality improvement during the COVID-19 lockdown in China (Wang et al., 2020; Bao and Zhang, 2020; Li et al., 2020; Lian et al., 2020). However, most of these studies were conducted in a single city or region, which not able to provide a comprehensive picture of air pollution change across China. Moreover, a study suggested that the air pollution may not completely resume after the lift of COVID-19 lockdown (Li et al., 2020), but information of air quality after the lockdown was very limited.

The deterioration of global air pollution due to anthropogenic activities is one of the most serious issues in the 21st century. Exposure to air pollution has estimated to cause 6.7 million excess deaths annually worldwide, and most of the access deaths were in low- and middle-income countries including China in which 1.85 million deaths were attributable to air pollution in 2019 (D 2017 Disease and Inju, 2020). Although the health impacts from air pollution have been widely noticed, there have been very few studies estimating the health impacts from air pollutant reduction during and after the COVID-19 lockdown in China (Huang et al., 2020; Chen et al., 2020b; Giani et al., 2020). In this study, we described the changes of key air pollutants during and after the COVID-19 lockdown, and estimated the mortality burden attributable to the air pollutant reductions in China.

2. Methods

2.1. Study settings

This study analyzed the daily air pollution data collected from over 1300 air quality stations and mortality data in a total of 362 cities in China. In particular, we selected four regions as the key study settings: the Beijing-Tianjin-Hebei region, the Yangtze River Delta region, the Pearl River Delta region, and Wuhan city. These four regions are the most economically developed (and air polluted) regions which had only 9.5% land of China, but contributed 45% of Chinese gross domestic product (National bureau of statis, 2018).

2.2. Data collection

2.2.1. Timeline of lockdown and release of lockdown

According to the 'National Emergency Response Plan for Public Emergencies' issued by China State Council, the emergency response has four levels: Level I (extremely serious), Level II (serious), Level III (relatively serious), and Level IV (common) (Ministry of Emergency Management, 2006). During the Level I response period, residents' social movement and gathering were firmly restricted in public places, industrial enterprises, construction sites, catering enterprises, and other large-scale workplaces. Wuhan was the first city which was locked down on the 23rd January 2020. After that, all provinces and municipalities announced their Level I responses. For example, 14 provinces and municipalities announced the Level I response on the 24th January 2020. Tibet was the last Province which announced the Level I response on the 30th January 2020. With the successful control on the COVID-19, the emergency response level was gradually downgraded to a Level II or lower response in all provinces. During days with Level II or lower response, few restriction measures were implemented. The first province downgraded to Level II response was Gansu on 21st February 2020, and the last province was Hubei on the 2nd May 2020. Currently, all provinces and municipalities in mainland China were at Level III or lower response (Figure S1). In this study, we defined days with Level I response as the "lockdown period", and defined days with Level II or lower response as the "after lockdown period".

2.3. Air pollution data

Daily air quality index (AQI) and concentrations of six key air pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3) over 1300 air quality monitoring stations from the 1st January 2018 to 31st July 2020 in China were collected from the National Urban Air Quality Real-time Publishing Platform (http://106.37.208.233:20035/). On the basis of these data, we calculated the weekly mean concentrations of AQI and all pollutants at each monitoring station. The daily mean of all air quality monitoring stations in a city or region was applied to represent the average air quality in that city or region. We assumed that the differences in air pollutant concentrations during and after the lockdown in 2020 versus with the same calendar periods in 2018–2019 was attributable to the lockdown measures. This approach could minimize the influence of the long-term declining trend in air pollution because of China's clean air policy in the past few years (Chen et al., 2020b; National bureau of statis, 2018).

2.4. Population size, mortality, and YLL data

The annual average population size of each province in 2019 was collected from the China National Statistical Yearbook. The age standardized mortality rates and province specific YLL rates (/100,000 population) of all causes, cardiovascular diseases (CVD), and respiratory diseases (RESP) in China were obtained from the Global Burden of Disease (GBD) Study for China (Zhou et al., 2019) ().

2.5. Exposure–response coefficients between air pollutants and mortality

In the GBD studies, only $PM_{2.5}$ and O_3 in six main air pollutants were selected as indicators to assess their health impact (D 2017 Disease and Inju, 2020). Therefore, we estimated the mortality burden attributable to changes in $PM_{2.5}$ and O_3 concentrations for all causes, CVD, and RESP mortality in this analysis. In addition, it was only several months since the beginning of COVID-19 pandemic, the long-term effects of air pollution changes during the epidemic might be not significant. Hence, we only estimated the short-term effects of air pollution changes during COVID-19. The exposure-response relationships (RRs) between short-term exposures to air pollutants and mortality risk were obtained from a meta-analysis across China (Dong, 2017) (Table S4).

2.6. Estimation of health effects caused by air pollution changes

The log-linear exposure-response function below was applied to estimate the short-term health impacts attributable to the changes in $PM_{2.5}$ and O_3 (Huang et al., 2020; Liu et al., 2018).

$$Y_d = Y_0 * (1 - e^{\beta_0 * (x_1 - x_0)}) * \text{pop} \tag{1}$$

$$Y = \sum_{1}^{d} Y_d \tag{2}$$

Where Y_d denotes the daily number of deaths in each province avoided by the air quality improvement; y_0 represents the daily mean total and cause-specific (CVD and RESP) mortality rate (/100,000); β_0 is the regression coefficient derived from the RRs associated with every 1 μg/m^3 change in $PM_{2.5}$ and O_3; x_1 indicates daily mean air pollutant concentration in 2020; x_0 means daily mean air pollutant concentration in the same calendar in 2018–2019; Pop denotes the total population size in each province; d donates the number of days in a period. Y is the cumulative deaths attributable to changes in $PM_{2.5}$ and O_3 exposure during a period in each province. Then, the total excess mortality in China was the sum in all provinces. If the x_1 was lower than x_0, Y would be positive values indicating the mortality benefits from the air quality improvement. Inversely, Y would be negative values indicating the increase in mortality due to air quality exacerbation.

The function below was used to estimate the corresponding YLLs attributable to changes in $PM_{2.5}$ and O_3.

$$YLL_{air} = Y \times \Delta YLL/(y_0 * 100{,}000) \tag{3}$$

where YLL_{air} is the YLL attributable to changes in $PM_{2.5}$ and O_3 in all age groups; Y is the number of deaths attributable to $PM_{2.5}$ and O_3 exposure calculated by equation (2); and ΔYLL represents the mean YLL for all deaths and deaths for CVD and RESP in every 100,000 population in each province, which was obtained from GBD studies for China (Zhou et al., 2019); and y_0 denotes the annual mean total and cause-specific (CVD and RESP) mortality rate (/100,000).

All data analyses were conducted by R software (version 3.6.0, R Foundation for Statistical Computing).

2.7. Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication. This study was approved by the Ethics Committee of Guangdong Provincial Center for Disease Control and Prevention (W96-027E-2020004).

3. Results

3.1. Changes of air pollution in 2020 compared with 2018–2019 in China

We observed lower mean AQI and concentrations of all air pollutants except for O_3 in 2020 compared with those in the same period in 2018–2019 (Table 1). The mean AQI, PM_{10}, $PM_{2.5}$, NO_2, SO_2 and CO concentrations nationwide during the lockdown period in 2020 declined by 17.8 (20.8%), 25.6 μg/m^3 (27.8%), 10.9 μg/m^3 (18.9%), 5.8 μg/m^3 (35.4%), 11.8 μg/m^3 (36.3%) and 0.2 mg/m^3 (20.0%) respectively, when compared to the same periods during 2018–2019. The corresponding reductions in mean AQI, PM_{10}, $PM_{2.5}$, NO_2, SO_2 and CO concentrations after the lockdown period in 2020 were 8.5 (14.1%), 12.0 μg/m^3 (18.5%), 5.5 μg/m^3 (17.1%), 2.0 μg/m^3 (18.2%), 2.7 μg/m^3 (10.6%), and 0.1 mg/m^3 (14.3%), respectively. We observed a different change pattern of O_3 compared to other air pollutants. The mean concentration of O_3 increased by 5.5 μg/m^3 (10.4%) during the lockdown, and decreased by 3.4 μg/m^3 (4.4%) after the lockdown, when compared to the same periods during 2018–2019.

Table 1
Summary statistics of air quality index (AQI) and air pollutants from 1st January 2018 to 31st July 2020.

	2018–2019				2020			
	The same calendar with the lockdown duration in 2020		The same calendar with the duration after lockdown in 2020		During Lockdown		After Lockdown*	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
AQI	85.5	59.1	60.2	41.9	67.7	50.4	51.7	35.2
PM_{10} (μg/m^3)	92.0	65.1	64.8	50.6	66.4	51.9	52.8	40.8
$PM_{2.5}$ (μg/m^3)	57.8	48.2	32.2	26.2	46.9	42.7	26.7	22.3
O_3 (μg/m^3)	53.3	32.9	77.7	48.0	58.9	29.5	74.3	44.1
SO_2 (μg/m^3)	16.4	21.0	11.0	12.9	10.6	13.2	9.0	9.3
NO_2 (μg/m^3)	32.5	23.8	25.5	20.3	20.7	16.4	22.8	18.0
CO (mg/m^3)	1.0	0.6	0.7	0.4	0.8	0.5	0.6	0.3

SD: Standard deviation; *: After lockdown was the duration from the lift date of lockdown to 31st July 2020. The dates for lockdown and lift were different among provinces in China.

Fig. 1 demonstrates the temporal distributions of weekly mean AQI and key air pollutants in 2020 compared with these in 2018–2019. We observed greater reductions in AQI and all pollutants except for O_3 during the period from 23rd January 2020 (date when the first city was locked down) to 2nd May 2020 (date when the last city was lifted lockdown) than that after the lockdown period. The differences in air pollution between 2020 and 2018–2019 almost disappeared by the end of July. Such decreasing trend in air pollution has been observed in both urban and rural areas of China (Table S5).

Figs. 2 and 3 show the spatial distribution of mean $PM_{2.5}$ and O_3 concentrations across China and in the four key study regions and Figure S3 show the frequency distribution of $PM_{2.5}$ and O_3 concentrations in China. We observed severer air pollution in north China and northwest China than in other regions. However, decrease in air pollution during the lockdown period was found across China, with greater decreases in the four key regions. The decreases in $PM_{2.5}$ concentrations in the Beijing-Tianjin-Hebei region, Yangtze River Delta, Pearl River Delta, and Wuhan city were 12.3 μg/m^3 (18.8%), 22.9 μg/m^3 (39.0%), 15.6 μg/m^3 (41.5%) and 15.0 μg/m^3 (29.1%) during the lockdown period respectively, when compared to the same periods during 2018–2019. Smaller decreases in $PM_{2.5}$ were found in the four key regions after the lockdown periods. When it comes to O_3 which had a contrast tendency, the percentages of it increased by 2.6 μg/m^3 (4.3%), 11.5 μg/m^3 (21.8%), 3.2 μg/m^3 (6.1%) and 12.8 μg/m^3 (23.4%) respectively during the lockdown period in the corresponding four areas (Table S5).

The compositions of air pollution in 2020 have slightly changed compared with 2018 and 2019, with higher compositions of O_3, and lower compositions of other air pollutants especially for PM_{10} and $PM_{2.5}$

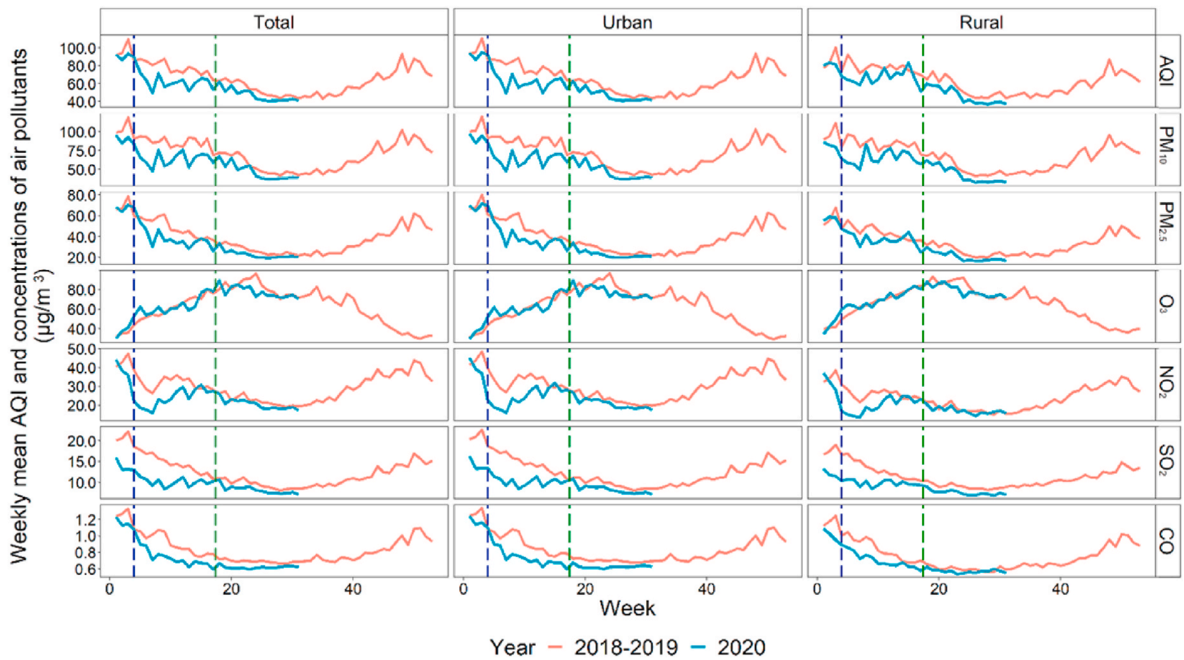

Fig. 1. Weekly mean AQI and air pollutant concentrations in China from 1st January 2018 to 31st July 2020.

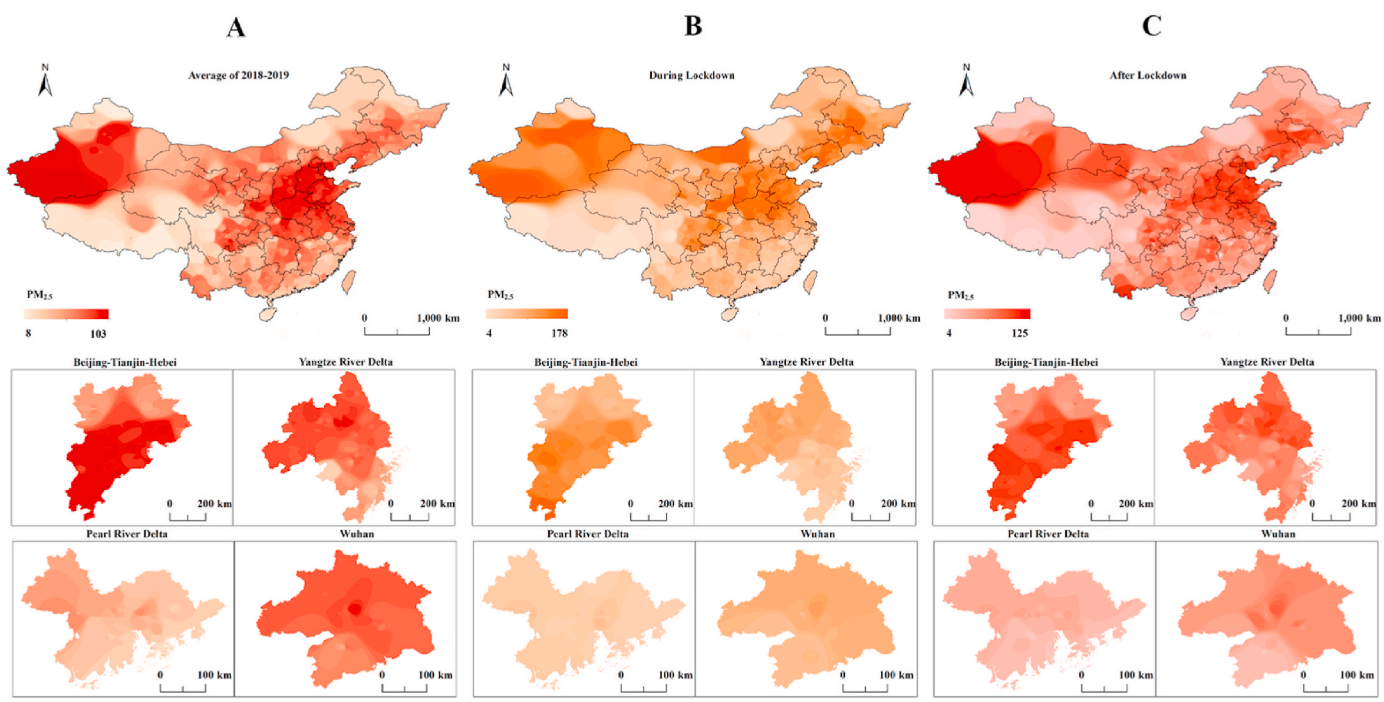

Fig. 2. Comparisons of the mean $PM_{2.5}$ concentrations between 2018 and 2019 and 2020 in China and in four key regions.

(Figure S2).

3.2. Short-term health effects attributable to changes in $PM_{2.5}$ and O_3 in 2020 compared to these in 2018–2019

Table 2 shows the number of deaths and YLLs attributable to changes in $PM_{2.5}$ and O_3 concentrations in 2020 compared to these in 2018–2019 in China. A total of 51.3 (95%CI: 32.2, 70.1) thousand deaths were avoided due to the reduction of $PM_{2.5}$ (48.7, 95%CI: 30.3, 66.7 thousand) and O_3 (2.7, 95%CI: 1.9, 3.5 thousand) during the entire period from January to July in 2020. Among the total benefits, 29.2 (95%CI: 20.1, 37.9) thousand and 3.8 (95%CI: 2.2, 5.4) thousand deaths were avoided from CVD and RESP diseases, respectively. The corresponding total avoided YLLs was 1066.8 (95%CI: 668.7, 1456.8) thousand, in which 1009.9 (95%CI: 628.1, 1383.1) thousand and 56.9 (95%CI: 40.7, 73.7) thousand YLLs were attributable to the decrease in $PM_{2.5}$ and O_3, and 463.9 (95%CI: 324.4, 596.0) thousand and 49.8 (95%CI: 30.0, 69.0) thousand YLLs were related to CVD and RESP diseases, respectively.

During the lockdown period, 19.3 (95%CI: 12.1, 26.0) thousand deaths and 405.6 (95%CI: 255.4, 548.1) thousand YLLs were avoided due to the decrease in $PM_{2.5}$, but the increase in O_3 concentration had led to 3.0 (95%CI: 2.1, 4.0) thousand more premature deaths and 62.3

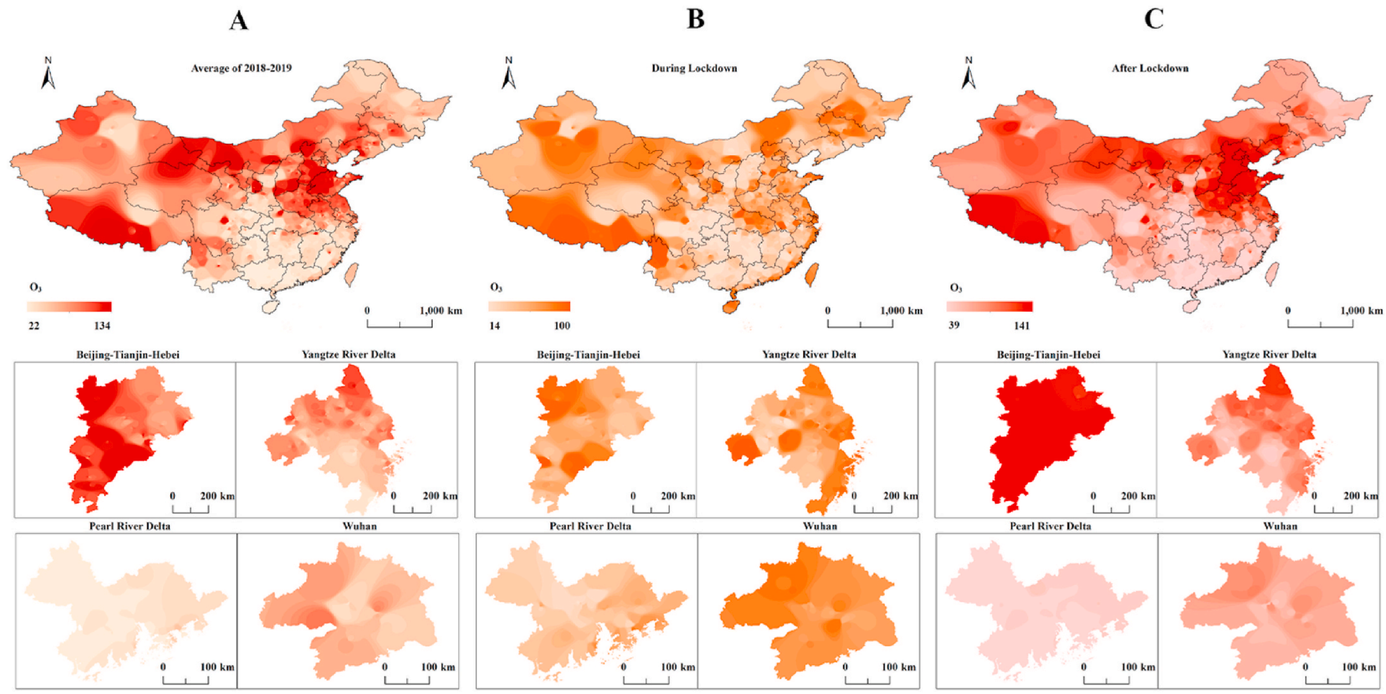

Fig. 3. Comparisons of the mean O_3 concentrations between 2018 and 2019 and 2020 in China and in four key regions.

Table 2
Number of deaths and YLLs (95%CI) attributable to the changes in air pollutants during the period from 23rd January to 31st July 2020 compared to the same periods in 2018–2019 in China.

	The total period from 23rd January to 31st July in 2020			During lockdown			After lockdown		
	$PM_{2.5}$	O_3	$PM_{2.5}$+ O_3	$PM_{2.5}$	O_3	$PM_{2.5}$+ O_3	$PM_{2.5}$	O_3	$PM_{2.5}$+ O_3
Number of deaths (× 1000)									
All causes	48.7(30.3, 66.7)	2.7(1.9, 3.5)	51.3(32.2, 70.1)	19.3(12.1, 26.0)	−3.0(-4.0, −2.1)	16.2(10.0, 22.0)	29.4(18.1, 40.6)	5.7(4.0, 7.5)	35.1(22.2, 48.1)
Cardiovascular diseases	27.9(19.5, 36.0)	1.3(0.6, 1.9)	29.2(20.1, 37.9)	10.9(7.7, 13.8)	−1.5(-2.3, −0.6)	9.4(7.1, 11.5)	17.0(11.8, 22.1)	2.7(1.2, 4.3)	19.8(13.0, 26.4)
Respiratory diseases	3.6(2.2, 4.9)	0.3(0.0, 0.5)	3.8(2.2, 5.4)	1.4(0.9, 2.0)	−0.3(-0.6, 0.0)	1.1(0.8, 1.4)	2.1(1.3, 3.0)	0.6(0.1, 1.0)	2.7(1.4, 4.0)
YLLs (×1000)									
All causes	1009.9(628.1, 1383.1)	56.9(40.7, 73.7)	1066.8(668.7, 1456.8)	405.6(255.4, 548.1)	−62.3(-82.8, −43.5)	343.3(211.8, 465.4)	604.4(372.7, 835.0)	119.2(84.2, 156.5)	723.5(456.9, 991.5)
Cardiovascular diseases	463.9(324.4, 596.0)	23.2(10.5, 35.1)	487.1(334.9, 631.1)	186.9(132.9, 235.9)	−24.8(-39.5, −10.7)	162.1(122.2, 196.3)	277.0(191.5, 360.1)	48.0(21.2, 74.7)	325.0(212.7, 434.8)
Respiratory diseases	49.8(30.0, 69.0)	3.6(0.6, 6.2)	53.4(30.5, 75.2)	20.2(12.3, 27.8)	−3.9(-7.1, −0.6)	16.4(11.7, 20.7)	29.6(17.7, 41.2)	7.5(1.1, 13.3)	37.0(18.8, 54.5)

(95%CI: 43.5, 82.6) thousand more YLLs in China. Overall, the substantial air quality improvement during the lockdown period has led to considerable mortality reduction, including 16.2 (95%CI: 10.0, 22.0) thousand premature deaths fall and 343.3 (95%CI: 211.8, 465.4) thousand YLLs decrease. In addition, we observed health benefits for reduction in both $PM_{2.5}$ [29.4 (95%CI: 18.1, 40.6) thousand deaths and 604.4 (95%CI: 372.7, 835.0) thousand YLLs avoided] and O_3 concentrations [5.7 (95%CI: 4.0, 7.5) thousand deaths and 119.2 (95%CI: 84.2, 156.5) thousand YLLs avoided] after the lockdown was lifted in China. In order to eliminate the influence of different observation days, we also estimated the time-weighted daily mortality burden related to changes in $PM_{2.5}$ and O_3 (Table S6).

In the four key regions, the number of premature deaths avoided in 2020 compared to 2018–2019 were 4933 (95%CI: 3,223, 6441) in the Beijing-Tianjin-Hebei region, 7173 (95%CI: 4,443, 9876) in Yangtze River Delta, 2693 (95%CI: 1,675, 3711) in Pearl River Delta, and 1105 (95%CI: 688, 1521) in Wuhan city. The corresponding avoided YLLs were 112,410 (95%CI: 73,255, 147,297), 130,094 (95%CI: 80,651, 179,129), 37,926 (95%CI: 23,592, 52,273), and 26,817 (95%CI: 16,686, 36,905), respectively (Table S7). The province and city specific health effects of air pollution changes in 2020 can be seen in Tables S8, S9 and Figure S4.

The positive values of deaths and YLLs indicated the health gains from the air quality improvement, while the negative values indicated the number of deaths and YLLs caused by air quality deterioration in 2020 compared with same period in 2018–2019.

The blue dotted line represents the lockdown date (23^{rh} January 2020) of Wuhan which was the first city locked down in China.

The green dotted line indicates the lifting date (2nd May 2020) of lockdown in Wuhan, which was the last city lifted lockdown in China.

Chart A: The mean $PM_{2.5}$ concentration during the period from 23rd January to 31st July in 2018–2019; Chart B: The mean $PM_{2.5}$

concentrations during the lockdown period in 2020; Chart C: The mean $PM_{2.5}$ concentrations after lockdown (until to 31st July 2020);

The dates for lockdown and lift were different among provinces in China.

Chart A: The mean O_3 concentration during the period from 23rd January to 31st July in 2018–2019; Chart B: The mean O_3 concentration during the lockdown period in 2020; Chart C: The mean O_3 concentrations after lockdown (until to 31st July 2020);

The dates for lockdown and lift were different among provinces in China.

4. Discussion

This study comprehensively described the changes of key air pollutants during and after the COVID-19 lockdown compared to the same periods in 2018–2019, and estimated the mortality burden attributable to the air pollutant reductions in China. We observed that the COVID-19 lockdown measures have caused substantial decreases in air pollutants except for O_3 which was significantly increased during the lockdown period. In addition, the substantial improvements in air quality since the lockdown has been accompanied by substantial mortality reductions in China, particularly in the four key regions.

We first observed substantial declines in AQI and concentrations of PM_{10}, $PM_{2.5}$, NO_2, SO_2, and CO during and after the COVID-19 lockdown than these in the same periods during 2018–2019 across China, and the reductions were greater in Wuhan, Beijing-Tianjin-Hebei region, the Yangtze River Delta region, and the Pearl River Delta region. Several previous studies also observed a significant decrease in air quality during the COVID-19 lockdown in China (Wang et al., 2020; Bao and Zhang, 2020; Li et al., 2020; Lian et al., 2020). The decline of air pollution was highly associated with restriction in traffic and reduced industrial activities. During the full lockdown, residents were restricted to go outside, leading to a substantial decrease in vehicle and public transport utilizations. In addition, most medium and small industries except for power plants and large-scale enterprises were closed, which resulted in substantial declines of industrial electricity consumption and industrial productions (Figure S5). The air pollution effects of the lockdown provide a unique opportunity to assess the effects of the reduction of different emission sources on air quality. The governments could implement tailored environmental policies and measurements to reduce the corresponding emission sources in China, particularly in the key regions with severer air pollution as indicated in our findings. For example, public transport systems as well as pedestrian and cycling activities could be promoted at city level. Economically and socially sustainable alternations to fossil fuel use in industries, transportation, and power plants, and cleaner fuels for use in households should be developed in future.

Although we observed substantial declines of most air pollutants, the extents of lockdown effects on air pollutants may be different. In the past years, Chinese government have implemented rigorous measures to fight against particulate pollution at nationwide, and the fine particulate emissions have been substantially controlled, especially in areas with heavy pollution (Liu et al., 2018). Therefore, PM pollutants may continually decrease even if there is no COVID-19 lockdown in 2020. The similar trend was found for SO_2, which is mainly omitted from the combustion of sulfur-containing fuels (oil, coal and diesel) (Huang et al., 2012). Chinese governments also implemented a series of measures to reduce the emissions of SO_2, including upgrading of key industrial industries (power and steel), elimination of small and medium-sized coal-fired boilers, conversion of rural heating from coal to gas and electricity, etc. By contrast, the annual mean concentration of NO_2 did not substantially decrease from 2018 to 2019, but significantly declined in 2020, which indicates that NO_2 may be the most affected by lockdown, which has been echoed by several studies (Venter et al., 2020; Lian et al., 2020; Tobías et al., 2020). The mechanism for possible contribution of NO_2 reduction to the health gains need to be further researched.

Similar to other recent studies (Li et al., 2020; Lian et al., 2020; Tobías et al., 2020), we also observed increase in ambient O_3 concentration during the lockdown period. The mechanisms of increase in O_3 were associated with the changes in NO_2, VOCs and $PM_{2.5}$, meteorological conditions, and photochemical mechanisms. On the one hand, ambient O_3 usually increase in spring and summer seasons due to the higher insolation and temperatures (Tobías et al., 2020). On the other hand, the O_3–VOC–NO_x system was a complicated non-linearity system. The reduction of NO_x during lockdown period could change the ozone concentration in multiple ways. For example, the decrease in NO_x, while the amount drop of VOC is not as large as NO_x, could lead to a drop in titration effect towards ozone (Venter et al., 2020). In recent years, as the significant control on ambient $PM_{2.5}$ in China, ambient ozone has become the primary air pollutant in many regions. The surface O_3 concentration has increased at the rate of 2–4 ppb/year during 2013–2019 across China (Lu et al., 2019). Chinese governments have recently implemented rigorous measures, such as the summer ozone control special action in 2020, to control air O_3 across China, which may be the major reason for the lower ozone concentrations during June and July in 2020 than that in 2018–2019. Nevertheless, the change of O_3 concentrations affected by the lockdown provides a good opportunity to understand the drivers of ozone increase, which is crucial for effective controlling the ozone pollution in China.

The substantial improvements in air quality since the lockdown may have brought down 51.3 thousand premature deaths and 1066.8 thousand YLLs in China, and most benefits were obtained in the four key regions. Three previous studies have estimated the health impacts from air pollution changes during COVID-19 lockdown in China (Huang et al., 2020; Chen et al., 2020b; Giani et al., 2020). Huang et al. observed that the $PM_{2.5}$ reduction during the lockdown was associated with 42.4 thousand less premature deaths over the Yangtze River Delta region, China (Huang et al., 2020). Giani et al. estimated that the improved air quality during the lockdown period (from 1st February to 31st March 2020) has reduced 24,200 deaths in China (Giani et al., 2020). Several previous studies also assessed the health benefits during certain periods of air pollution control in China, such as the 2008 Beijing Olympics (Rich et al., 2012), during the Air Pollution Prevention and Control Action Plan period (Huang et al., 2018), and the 2010 Guangzhou Asian Games (Ding et al., 2016). Our findings suggest the substantial human health benefits that can be achieved when strict control measures for air pollution are taken to reduce emissions from vehicles and industries particularly in the key regions with severer pollution and high density of population.

In addition to mortality, we also employed YLL to assess the health impacts of air quality improvement during the lockdown, which could provide more precise information for understanding the mortality burden from air pollution. YLL is an important component of disability-adjusted life years (DALY) (Liu et al., 2021). It considers both premature deaths and life expectancy at death, and can therefore complementally estimate the disease burden (Steenland and Armstrong, 2006). Some studies suggested that the YLL is better than deaths as an indicator of the mortality burden (D 2016s andC, 2017). The YLL has been widely applied in assessing the mortality burden from air pollution (D 2017 Disease and Inju, 2020; Huang et al., 2018). This is the first study that has used YLL to assess the mortality burden from air quality improvement during the COVID-19 lockdown, which could provide more useful information for policy-makers in their decision-making process. More such studies are warranted in the future.

The limitations of this study should be acknowledged. First, we are not able to estimate the health effects from all air pollutants, because of the strong collinearity between various air pollutants. Second, we only used the mortality indicator in this study because morbidity data were not available across different regions of China during and after COVID-19 lockdown. Previous studies have shown that air pollution is also associated with morbidity (Tian et al., 2018). Future studies should consider both mortality and morbidity. Third, we directly applied the ambient air pollutant concentrations to represent people's exposure level. However, people spent most time indoor especially during the lockdown period, which could lead to lower air pollution exposure. In addition, we did not assess other health impacts from the lockdown. For instance, the health-care systems were seriously disrupted during the lockdown because most of health service facilities and human resources were transferred to fight against COVID-19, which may affect the diagnosis and treatment of patients with other diseases (Chen et al., 2020b; Zhang, 2020). Such impacts also need to be assessed in the future.

5. Conclusion

The COVID-19 lockdown in China has led to significant changes in air pollutant concentrations, with significant decrease in most air pollutants except for Ozone. The reduction in air pollution has been accompanied by substantial mortality reduction that create the co-benefits in population health and environment. Our findings have important implications for air pollution management and public health interventions both in China and other countries, especially in well-developed industrial regions as identified in this study. Several aspects of measures are urgently needed to control air pollution and reduce the health impacts: (1) upgrading industry structure, such as upgrading power and steel industries, and elimination of small and medium-sized coal-fired boilers; (2) upgrading energy structure, such as developing economically and socially sustainable alternations to fossil fuel use in industries, transportation, and power plants, developing cleaner fuels for use in households, and conversion of heating from coal to gas and electricity; (3) promoting green transportation, such public transportation, electric transportation, pedestrian, and cycling activities; (4) improving protective measurements for air pollution, such as wearing mask in heave polluted days.

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.

Acknowledgments

We thank all members from health departments, designated hospitals and Centers for Disease Control and Preventions in Guangdong Province for their contribution in data collection, COVID-19 control, and prevention.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.111457.

Credit author statement

Guimin Chen: Conceptualization, Formal analysis, Writing – original draft. Jun Tao: Methodology, Project administration, Writing – review & editing. Jiaqi Wang: Formal analysis, Investigation. Moran Dong: Formal analysis, Investigation. Xuan Li: Writing – review & editing. Xiaoli Sun: Resources. Shouzhen Cheng: Resources. Jingjie Fan: Resources. Yufeng Ye: Resources. Jianpeng Xiao: Methodology, Data curation. Jianxiong Hu: Investigation, Data curation. Guanhao He: Funding acquisition, Data curation. Jiufeng Sun: Investigation. Jing Lu: Investigation. Lingchuan Guo: Investigation. Xing Li: Investigation. Zuhua Rong: Investigation. Weilin Zeng: Investigation. He Zhou: Investigation. Dengzhou Chen: Investigation. Jiali Li: Investigation. Lixia Yuan: Investigation. Peng Bi: Project administration, Writing – review & editing. Qingfeng Du: Writing – review & editing. Wenjun Ma: Conceptualization, Funding acquisition, Writing – review & editing. Tao Liu: Conceptualization, Formal analysis, Methodology, Writing – original draft.

Data sharing

The data used for this study are available upon request from the authors.

Funding sources

This work was supported by the Key-Area Research and Development Program of Guangdong Province (2019B111103001, 2020111107001), Chinese Postdoctoral Science Foundation (2020T130020ZX), and the Foshan Key Technology Project for COVID-19 (2020001000376).

References

Bao, R., Zhang, A., 2020. Does lockdown reduce air pollution? Evidence from 44 cities in northern China. Sci. Total Environ. 731, 139052.
Chen, L.A., Chien, L.C., Li, Y., Lin, G., 2020a. Nonuniform impacts of COVID-19 lockdown on air quality over the United States. Sci. Total Environ. 745, 141105.
Chen, K., Wang, M., Huang, C., Kinney, P., Anastas, P.T., 2020b. Air pollution reduction and mortality benefit during the COVID-19 outbreak in China. Lancet Planet Health 4 (6), e210–e212.
China Watch Institute, 2020. China Daily, Institute of Contemporary China Studies. In: Chinadaily. Tsinghua University, School of Health Policy and Management, Peking Union Medical College. China's Fight Against COVID-19.
GBD 2016 DALYs, HALE Collaborators, 2017. Global, regional, and national disability-adjusted life-years (DALYs) for 333 diseases and injuries and healthy life expectancy (HALE) for 195 countries and territories, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016. Lancet 390 (10100), 1260–1344.
GBD 2017 disease and injury incidence and prevalence collaborators. 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 396 (10258), 2020, 1223–1249.
Ding, D., Zhu, Y., Jang, C., et al., 2016. Evaluation of health benefit using BenMAP-CE with an integrated scheme of model and monitor data during Guangzhou Asian Games. J. Environ. Sci. 42, 9–18.
Dong, G.H., 2017. Ambient Air Pollution and Health Impact in China, vol. 1017. Springer.
Giani, P., Castruccio, S., Anav, A., Howard, D., Hu, W., Crippa, P., 2020. Short-term and long-term health impacts of air pollution reductions from COVID-19 lockdowns in China and Europe: a modelling study. Lancet Planet Health 4 (10), e474–e482.
Hopkins, J., 2020. COVID-19 Case Tracker. Follow Global Cases and Trends. accessed Aug 15, 2020. https://coronavirus.jhu.edu/.
Huang, Q., Cheng, S., Perozzi, R., Perozzi, E., 2012. Use of a MM5–CAMx–PSAT modeling system to study SO2 source apportionment in the beijing metropolitan region. Environ. Model. Assess. 17 (5), 527–538.
Huang, J., Pan, X., Guo, X., Li, G., 2018. 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 2 (7), e313–e323.
Huang, L., Liu, Z., Li, H., et al., 2020. The silver lining of COVID-19: estimation of short-term health impacts due to lockdown in the Yangtze River Delta region, China. Geohealth 4 (9), e2020GH000272.
Kabir, M., Afzal, M.S., Khan, A., Ahmed, H., 2020. COVID-19 pandemic and economic cost; impact on forcibly displaced people. Trav. Med. Infect. Dis. 35, 101661.
Li, L., Li, Q., Huang, L., et al., 2020. Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: an insight into the impact of human activity pattern changes on air pollution variation. Sci. Total Environ. 732, 139282.
Lian, X., Huang, J., Huang, R., Liu, C., Wang, L., Zhang, T., 2020. Impact of city lockdown on the air quality of COVID-19-hit of Wuhan city. Sci. Total Environ. 742, 140556.
Liu, T., Cai, Y., Feng, B., et al., 2018. Long-term mortality benefits of air quality improvement during the twelfth five-year-plan period in 31 provincial capital cities of China. Atmos. Environ. 173 (jan), 53–61.
Liu, T., Zhou, C., Zhang, H., et al., 2021. Ambient temperature and years of life lost: a national study in China. Innovation 2 (1), 100072.
Lu, X., Zhang, L., Chen, Y., et al., 2019. Exploring 2016–2017 surface ozone pollution over China: source contributions and meteorological influences. Atmos. Chem. Phys. 19, 8339.
Ministry of Emergency Management, P.R.C., 2006. National Emergency Response Plan for Public Emergencies accessed Aug 20, 2020. http://www.gov.cn/gzdt/2006-02/28/content_213129.htm.
National bureau of statistics, 2018. China Statistical Yearbook. China Statistics Press, Beijing (Chinese).
Rich, D.Q., Kipen, H.M., Huang, W., et al., 2012. Association between changes in air pollution levels during the Beijing Olympics and biomarkers of inflammation and thrombosis in healthy young adults. J. Am. Med. Assoc. 307 (19), 2068–2078.

Rodríguez-Urrego, D., Rodríguez-Urrego, L., 2020. Air quality during the COVID-19: PM (2.5) analysis in the 50 most polluted capital cities in the world. Environ. Pollut. 266 (Pt 1), 115042.

Son, J.Y., Fong, K.C., Heo, S., Kim, H., Lim, C.C., Bell, M.L., 2020. Reductions in mortality resulting from reduced air pollution levels due to COVID-19 mitigation measures. Sci. Total Environ. 744, 141012.

Steenland, K., Armstrong, B., 2006. An overview of methods for calculating the burden of disease due to specific risk factors. Epidemiology 17 (5), 512–519.

Tian, Y., Liu, H., Liang, T., et al., 2018. Ambient air pollution and daily hospital admissions: a nationwide study in 218 Chinese cities. Environ. Pollut. 242 (Pt B), 1042–1049.

Tobías, A., Carnerero, C., Reche, C., et al., 2020. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Sci. Total Environ. 726, 138540.

Venter, Z.S., Aunan, K., Chowdhury, S., Lelieveld, J., 2020. COVID-19 lockdowns cause global air pollution declines. Proc. Natl. Acad. Sci. U. S. A. 117 (32), 18984–18990.

Wang, P.F., Chen, K.Y., Zhu, S.Q., Wang, P., Zhang, H.L., 2020. Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak. Resour. Conserv. Recycl. 158, 104814.

Zhang, H., 2020. Early lessons from the frontline of the 2019-nCoV outbreak. Lancet 395 (10225), 687.

Zhou, M., Wang, H., Zeng, X., et al., 2019. Mortality, morbidity, and risk factors in China and its provinces, 1990-2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 394 (10204), 1145–1158.