Health impact of China's Air Pollution Prevention and Control Action Plan: an analysis of national air quality monitoring and mortality data

Jing Huang, Xiaochuan Pan, Xinbiao Guo, Guoxing Li

Summary

Background **To mitigate the serious levels of air pollution in China, the State Council of China issued the Air Pollution Prevention and Control Action Plan (APPCAP) in 2013. This policy is a milestone in air quality control in China. We aimed to evaluate the effects of the APPCAP on long-term air quality management and the related health impacts in China.**

Methods **We did an analysis of national air quality monitoring and mortality data to estimate the health impact of the APPCAP from 2013 to 2017 in 74 key cities in China. Changes in mortality and in years of life lost (YLL), an indicator that considers life expectancy at death, were calculated to assess the health impact of air quality management during the 5-year period.**

Findings **Between 2013 and 2017, annual average concentrations of $PM_{2\cdot5}$ decreased by 33·3% (95% CI 16·3–50·3), PM_{10} by 27·8% (8·0–47·5), sulphur dioxide by 54·1% (28·2–80·0), and carbon monoxide by 28·2% (3·1–53·3) in the 74 key cities. However, no significant change was seen in annual average concentrations of nitrogen dioxide (9·7% reduction; 95% CI –23·0 to 42·4) or ozone (20·4% increase; –30·1 to 71·0). In 2017, as a result of substantial improvements in air quality, there were 47 240 (95% CI 25 870–69 990) fewer deaths and 710 020 (420 230–1 025 460) fewer YLL in the 74 key cities in China than in 2013.**

Interpretation **Substantial reductions in mortality and YLL related to control of ambient air pollution were achieved from 2013 to 2017 in China, indicating appreciable effectiveness of China's APPCAP. However, emissions control efforts for ozone and nitrogen dioxide should be strengthened in the future.**

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Introduction

Exposure to ambient air pollution increases mortality and morbidity, and is a leading cause of the global disease burden.[1] As the largest developing country in the world, China has experienced rapid economic growth over several decades. However, energy consumption in the form of coal combustion, as well as increases in industrial waste and motor vehicles use, and city planning and construction accompanied by rapid economic growth have all contributed to China's ambient air pollution, making it a country with one of the most serious levels of air pollution in the world.[2,3]

The Global Burden of Disease 2015 study[1] revealed that approximately 1·1 million people died prematurely and 21·8 million disability-adjusted life-years (DALYs) were lost because of ambient air pollution in China in 2015. China is at its most important stage of ambient air pollution control, and the unaddressed health consequences at regional and global levels pose major policy challenges.[4]

In the past century, high-income countries including the USA and the UK also faced severe air pollution problems.[5,6] Legislation for air pollution prevention and control was implemented to address these challenges, including promulgation of the Clean Air Acts in the UK and USA. Appreciable health benefits have been achieved as a result, as confirmed by long-term evaluation.[7,8] These previous efforts provide useful insights and perspectives for air pollution prevention and control efforts in China.

To mitigate the serious levels of air pollution and the related adverse health impacts in China, the State Council of China issued the Air Pollution Prevention and Control Action Plan (APPCAP) in 2013, which comprises ten specific measures, and specific concentration goals were proposed for achievement by 2017.[9] This action was considered to be the most stringent air pollution control policy in China to date, and is a promising step for China to improve its air quality and attempt to achieve substantial health benefits for the population. Expected improvements in air quality over time provide a natural

Research in context

Evidence before this study

China is at its most important stage of ambient air pollution control. Air quality management and control policies have been promulgated to alleviate the serious levels of air pollution in China. However, the effects of these policies are still unclear. We searched PubMed, Web of Science, Embase, Google Scholar, China Biological Medicine, and China National Knowledge Infrastructure (CNKI) using the search terms "air pollution control", "air quality improvement", "health benefits", "mortality benefits", and "China" for English and Chinese language studies published up to Jan 30, 2018. Although several previous studies have assessed the health benefits of air quality improvement in China, most have focused on short-term effects, or on a single city or one key region; limited long-term evaluations assessed only several types of air pollutants or were based on hypothetical data. To our knowledge, there has been no comprehensive evaluation of the long-term impact of air pollution control at the national level in China.

Added value of this study

To the best of our knowledge, this is the first study to comprehensively evaluate the long-term health impact of China's air pollution control policy at the national level. The State Council of China issued the Air Pollution Prevention and Control Action Plan (APPCAP) in 2013, which comprises ten specific measures, and specific concentration goals were proposed for achievement by 2017. In the present study, national air quality monitoring and mortality data were used to assess the health impact of the APPCAP in 74 key cities in China. Health impact was assessed by calculating years of life lost (YLL), which provided a complementary way to estimate disease burden by taking both premature deaths and life expectancy at death into consideration. Annual average concentrations of $PM_{2·5}$ decreased by 33·3%, PM_{10} by 27·8%, sulphur dioxide by 54·1%, and carbon monoxide by 28·2% between 2013 and 2017. However, no significant changes were observed for nitrogen dioxide or ozone concentrations. In 2017, as a result of substantial improvements in air quality, there were 47 240 fewer deaths and 710 020 fewer YLL in the 74 key cities in China.

Implication of all the available evidence

The results of our study show appreciable declines in annual average concentrations of air pollutants from 2013 to 2017, and substantial accompanying health benefits. Combined with existing evidence, these effects indicate that it is worthwhile for China to shift its development strategy from economic growth to environmental and economic sustainability. Meanwhile, emissions control efforts for ozone and nitrogen dioxide should be strengthened. Since ambient air pollution contributes substantially to the global burden of disease, these findings are crucial for air quality management and public health interventions both in China and in other countries.

backdrop to examine the potential beneficial health effects of this policy.

Although several previous studies have assessed the health benefits of air quality improvement in China, most have focused on the short-term effects, or on a single city or one key region;[10–16] limited long-term evaluations assessed only several types of air pollutants[17,18] or were based on hypothetical data.[19] To our knowledge, there has been no comprehensive evaluation of the long-term impact of air pollution control at the national level in China.[20] The APPCAP is a milestone in air quality control efforts in China, and offers an excellent opportunity to evaluate the effects of long-term air quality management and the related health impacts at the national level.

We aimed to comprehensively estimate the health impact of the APPCAP from 2013 to 2017 in 74 key cities in China. Changes in mortality and in the years of life lost (YLL), an indicator that considers life expectancy at death,[21] were calculated to assess the health impact of air quality management during the 5-year period.

For more on the **China Statistical Yearbook** see http://www.stats.gov.cn/english/statisticaldata/annualdata/

Methods

Study setting

We did an analysis of national air quality monitoring and mortality data from 74 key cities located in 31 provinces (including municipalities and autonomous regions) in mainland China (figure 1). These cities were selected on the basis of their geographical distribution, data availability, and population size. They were the first to conduct regular monitoring of ambient $PM_{2·5}$ since 2012, as required by the central government. Additionally, the total population in these cities amounted to 0·5 billion in 2017, accounting for approximately 41·2% of China's population. This study was approved by the Institutional Review Board of Peking University Health Science Center (Beijing, China).

Three key regions for air pollution control defined by the State Council of China were also selected: the Beijing-Tianjin-Hebei region, the Yangtze River Delta region, and the Pearl River Delta region. These three regions are considered the most developed regions of China. Air pollution improvement targets for these three regions have been highlighted in the APPCAP (panel).

Estimation of exposure

Exposure estimates of the six criteria air pollutants in this study—$PM_{2·5}$, PM_{10}, sulphur dioxide, nitrogen dioxide, carbon monoxide, and ozone—are described below.

We obtained exposure data first by searching the China Statistical Yearbook from 2013 to 2016 to obtain annual concentrations of air pollutants. The annual six air pollutant concentrations of 52 cities from 2013 to 2016 were obtained from the China Statistical Yearbook. However, these data were unavailable for 22 cities

Figure 1: **Locations of the 74 key cities in China**

from 2013 to 2016 and for all 74 cities in 2017. Therefore, we used an alternative approach to obtain the remaining data. From 2013, regular air quality monitoring has been carried out in the 74 key cities, and hourly data are released on China's National Urban Air Quality Real Time Publishing Platform. On the basis of these publicly available data, we calculated city-level annual concentrations of air pollutants. Because the air pollutant concentrations in the China Statistical Yearbook were provided by China's National Urban Air Quality Real Time Publishing Platform, these two methods of data collection were consistent.

For $PM_{2.5}$, PM_{10}, sulphur dioxide, nitrogen dioxide, and carbon monoxide, we validated the effectiveness of city-level data using the criteria of 324 days or more daily mean concentration data per year and 27 days or more daily mean concentration data per month (≥25 days daily mean concentration in February).

For ozone, we validated the effectiveness of city-level data using the criteria of 324 days or more daily 8-h moving average concentration data per year and 27 days or more daily 8-h moving average concentration data per month (≥25 days daily mean concentration in February). In China, the annual concentration of ozone is reported as an 8-h moving average concentration. To ensure comparisons with Chinese Ambient Air Quality Standards, we used the 8-h moving average concentration for ozone.

Monitoring of the six criteria air pollutants was done in accordance with the Chinese Ambient Air Quality Standards (GB 3095–2012) and the Chinese Technical Regulation for Ambient Qir Quality Assessment (HJ 663–2013). The related methodology has been described previously.[22,23]

For more on **China's National Urban Air Quality Real Time Publishing Platform** see http://106.37.208.233:20035/

Population and mortality data

Data about the annual average population size from 2013 to 2016 were collected from the China Statistical Yearbook. City-level proportions of different age groups were obtained from the 2010 census (appendix). The 2017 population size was estimated on the basis of the population growth rate of China cited by the Population Division of the UN.[24] This estimation might have resulted in some uncertainty, but the degree of uncertainty should be relatively small because population growth was slow.

See Online for appendix

We obtained mortality data from the China Centers for Disease Control and Prevention. Since 2004, the China Centers for Disease Control and Prevention has established 161 death surveillance points. On the basis of these death surveillance points, age-specific and cause-specific mortality were estimated. The proportions of cause-specific mortality in different districts and age groups were obtained from the China Death Surveillance Dataset in 2013 (appendix).

Risk estimation

Air pollution is a mixture of gases and particles. Because of high collinearity among air pollutants, we could not assess independent associations between the health

***Panel*: Targets and tasks of China's Air Pollution Prevention and Control Action Plan (2013–17)**

Air quality improvement targets

- By 2017, urban concentrations of PM_{10} shall be decreased by 10% compared with 2012; the annual number of days with fairly good air quality will gradually increase
- $PM_{2.5}$ concentrations for the Beijing-Tianjin-Hebei region shall be lowered by 25%, the Yangtze River Delta region lowered by 20%, and the Pearl River Delta region lowered by 15% in 2017 compared with 2013
- The annual average $PM_{2.5}$ concentration in Beijing shall be controlled below 60 μg/m³ in 2017

Ten tasks

- Increase efforts towards comprehensive control and reduce emissions of multi-pollutants
- Optimise the industrial infrastructure and promote industrial restructuring
- Accelerate technology transformation and improve innovation capability
- Adjust the energy infrastructure and increase clean energy supply
- Strengthen environmental thresholds and optimise industrial layout
- Promote the role of market mechanisms and improve environmental economic policies
- Improve legal and regulatory systems and continue supervision and management based on law
- Establish regional coordination mechanisms and integrated environmental management
- Establish monitoring and warning systems to cope with air pollution episodes
- Clarify the responsibilities of the government, enterprises, and society, and mobilise public participation

impacts and each of these air pollutants.[25] In the Global Burden of Disease studies,[1,26] only $PM_{2.5}$ and tropospheric ozone were selected as indicators to quantify the health impact of air pollution.

We estimated the burden attributable to $PM_{2.5}$ for chronic obstructive pulmonary disease (COPD), ischaemic heart disease, lung cancer, and stroke, along with the burden attributable to ozone for COPD. To assess the effects of ambient annual $PM_{2.5}$ concentration, we used the integrated exposure–response functions (IER) for each cause of death, which were used in a Global Burden of Disease study[27] and are based on studies of ambient air pollution, household air pollution, and second-hand smoke exposure and active smoking.[28]

The equations are as follows:

$$z<z_{cf},\ RR_{IER}(z)=1$$

$$z\geq z_{cf},\ RR_{IER}(z)=1+\alpha\{1-\exp[-\gamma(z-z_{cf})^{\delta}]\}$$

where z is the exposure to $PM_{2.5}$ concentrations (μg/m³); z_{cf} is the counterfactual concentration below which no adverse health effect is observed; RR is relative risk; and α, γ, and δ are unknown parameters that can be estimated by non-linear regression methods. The central (50%) value of the results of 1000 sets of parameters was used as the mean, and to calculate 95% CIs of $PM_{2.5}$-related cause-specific mortality, the lower (2·5%) and upper (97·5%) values were used as the lower and upper CIs.

For estimation of the relative risk of COPD mortality from ozone exposure, we used a linear exposure–response function for respiratory mortality that was reported by one US study.[29]

Estimation of health benefits

We calculated deaths and YLL attributable to ambient air pollution by applying the year-specific, location-specific, and age-specific population-attributable fraction to the number of deaths and YLL.

First, the deaths attributable to $PM_{2.5}$ and ozone were calculated as follows:

$$\Delta Mort_a=\left(\frac{(RR_a-1)}{RR_a}\right)\times\gamma_{0,a}\times Pop_a$$

where $\Delta Mort_a$ is the excess mortality attributable to $PM_{2.5}$ and ozone exposure at a specific age; $\gamma_{0,a}$ is the baseline mortality of a specific health outcome at a specific age, Pop_a is the size of the exposed population at a specific age, and RR_a is the grid-level relative risk at a specific age. Unless indicated, the excess mortality mentioned in this Article refers to the estimated excess mortality attributable to ambient $PM_{2.5}$ and ozone.

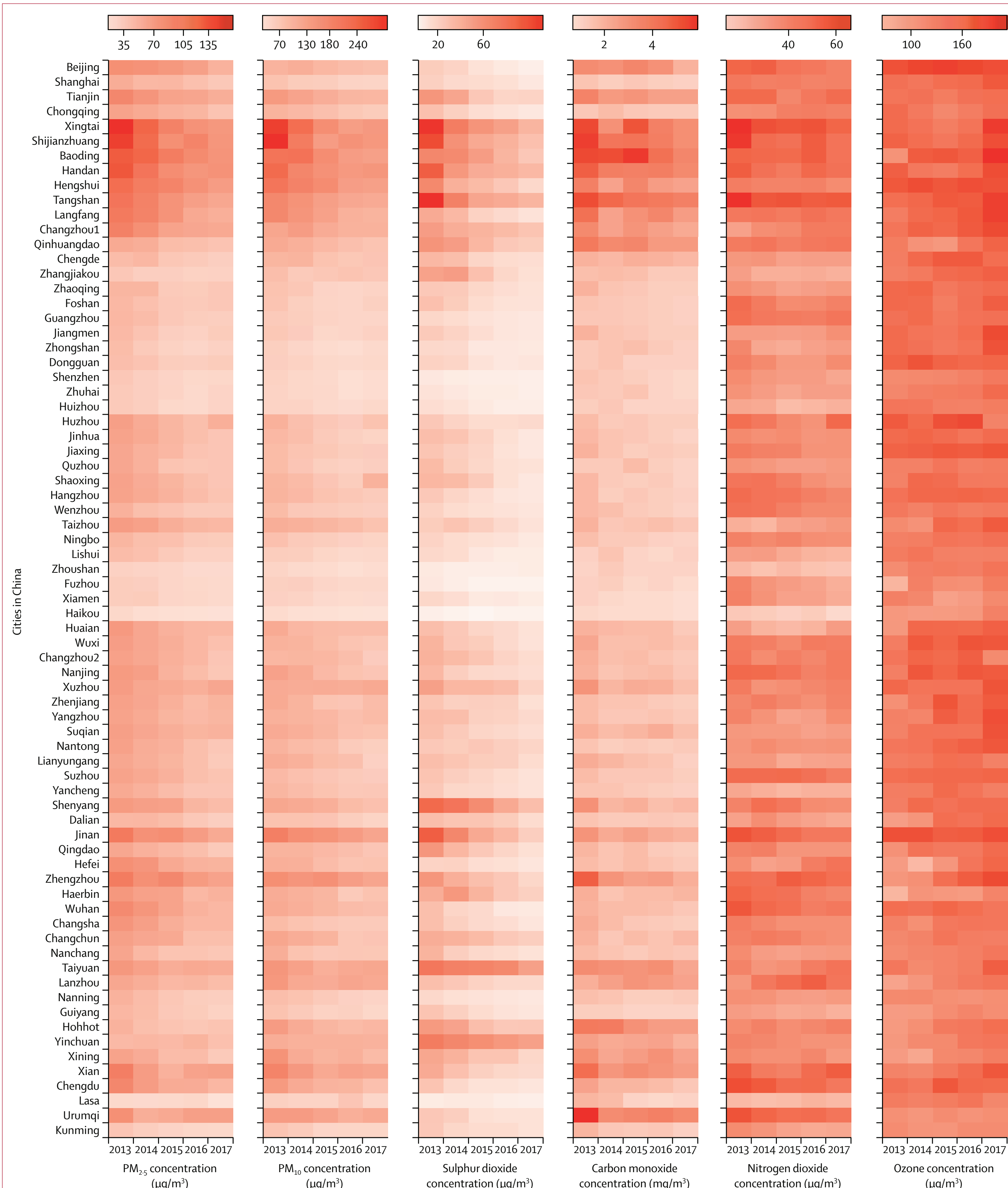
Second, the corresponding YLL were calculated as follows:

$$\Delta YLL_a=\Delta Mort_a\times L_t$$

where ΔYLL_a is the YLL attributable to $PM_{2.5}$ and ozone exposure at a specific age; $\Delta Mort_a$ is the excess mortality attributable to $PM_{2.5}$ and ozone exposure in a specific age group, and L_t is the life expectancy in a specific age group. In this analysis, we used the Chinese residents' life table in 2013 from the report of Chinese residents' life expectancy and risk factors (appendix). The YLL measure is the sum of life expectancy and excess mortality attributable to $PM_{2.5}$ and ozone exposure in all age groups.

Considering that the population size varied by year (appendix), and that this variable might affect annual effect

***Figure 2:* Annual concentrations of six criteria air pollutants in the 74 key cities in China, 2013–17**
The colour change from light red to deep red indicates that the concentration of the air pollutants increased, while the colour change from deep red to light red indicates that the concentrations of the air pollutants decreased.



35 70 105 135
70 130 180 240
20 60
2 4
40 60
100 160
Cities in China
Beijing
Shanghai
Tianjin
Chongqing
Xingtai
Shijianzhuang
Baoding
Handan
Hengshui
Tangshan
Langfang
Changzhou1
Qinhuangdao
Chengde
Zhangjiakou
Zhaoqing
Foshan
Guangzhou
Jiangmen
Zhongshan
Dongguan
Shenzhen
Zhuhai
Huizhou
Huzhou
Jinhua
Jiaxing
Quzhou
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Xiamen
Haikou
Huaian
Wuxi
Changzhou2
Nanjing
Xuzhou
Zhenjiang
Yangzhou
Suqian
Nantong
Lianyungang
Suzhou
Yancheng
Shenyang
Dalian
Jinan
Qingdao
Hefei
Zhengzhou
Haerbin
Wuhan
Changsha
Changchun
Nanchang
Taiyuan
Lanzhou
Nanning
Guiyang
Hohhot
Yinchuan
Xining
Xian
Chengdu
Lasa
Urumqi
Kunming
2013 2014 2015 2016 2017
PM2.5 concentration (µg/m3)
PM10 concentration (µg/m3)
Sulphur dioxide concentration (µg/m3)
Carbon monoxide concentration (mg/m3)
Nitrogen dioxide concentration (µg/m3)
Ozone concentration (µg/m3)

	Mean (SD)	Range	Median (IQR)
$PM_{2·5}$ (μg/m³)			
2013	72·2 (27·8)	26·0–160·0	70·0 (53·0–81·0)
2014	63·6 (23·1)	23·0–130·0	62·5 (47·2–73·5)
2015	55·2 (19·5)	22·0–107·0	54·5 (41·0–64·8)
2016	49·7 (17·4)	21·0–99·0	46·0 (37·2–56·8)
2017	47·0 (15·8)	19·0–86·0	42·5 (37·0–56·8)
PM_{10} (μg/m³)			
2013	118·4 (50·7)	47·0–305·0	108·0 (85·0–130·0)
2014	105·3 (40·8)	42·0–232·0	102·5 (73·2–121·8)
2015	92·6 (34·1)	40·0–175·0	87·5 (66·8–107·8)
2016	84·9 (30·8)	39·0–164·0	79·5 (62·2–101·0)
2017	83·3 (29·8)	37·0–157·0	79·5 (60·0–99·0)
Nitrogen dioxide (μg/m³)			
2013	43·9 (11·1)	17·0–69·0	43·0 (36·2–52·0)
2014	41·4 (10·5)	16·0–62·0	41·0 (35·0–49·8)
2015	39·1 (10·4)	14·0–61·0	39·5 (31·0–46·8)
2016	39·2 (10·4)	16·0–61·0	38·5 (32·0–46·0)
2017	39·2 (10·1)	11·0–59·0	39·5 (33·0–47·8)
Sulphur dioxide (μg/m³)			
2013	39·9 (24·3)	7·0–114·0	33·0 (26·0–47·5)
2014	32·1 (18·1)	6·0–82·0	26·0 (20·2–40·2)
2015	25·0 (14·6)	5·0–71·0	21·0 (15·2–30·8)
2016	20·9 (12·5)	6·0–68·0	17·0 (13·0–25·8)
2017	17·0 (9·8)	6·0–52·0	14·0 (11·0–19·8)
Carbon monoxide (mg/m³)			
2013	2·5 (1·2)	1·0–5·9	2·1 (1·6–3·1)
2014	2·0 (0·9)	0·9–5·4	1·6 (1·5–2·4)
2015	2·1 (1·0)	0·9–5·8	1·7 (1·4–2·7)
2016	1·9 (0·9)	0·9–4·4	1·6 (1·3–2·5)
2017	1·7 (0·8)	0·8–3·8	1·4 (1·2–2·1)
Ozone (μg/m³)			
2013	139·2 (25·9)	72·0–190·0	141·0 (122·2–158·8)
2014	145·4 (26·0)	69·0–200·0	147·0 (128·0–165·0)
2015	150·6 (23·2)	95·0–203·0	149·0 (137·8–168·8)
2016	154·0 (21·1)	102·0–199·0	154·5 (141·8–167·8)
2017	162·9 (24·0)	118·0–211·0	163·5 (143·5–183·0)

Table 1: **Annual concentrations of the six criteria air pollutants in 74 key cities in China, 2013–17**

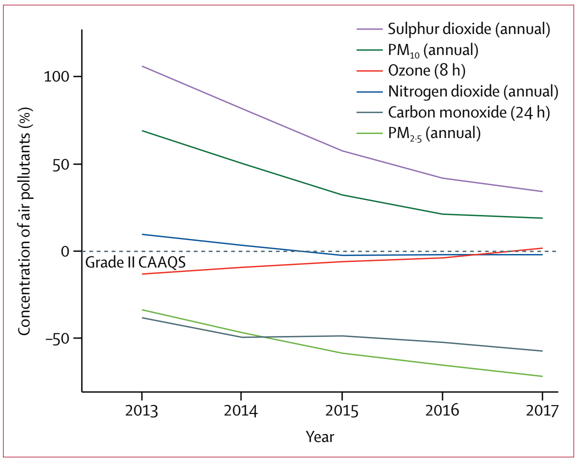

Figure 3: **Average concentrations of the six criteria air pollutants in the 74 key cities, as percentages of the grade II levels set by the CAAQS, 2013–17**
The dashed line denotes the Grade II criteria set by the Chinese Ambient Air Quality Standards (CAAQS). Values were calculated as percentages higher or lower than the Grade II CAAQS.

estimates of air pollution, avoided deaths and YLL per 100 000 people were also calculated by use of population size as the denominator. In addition, since meteorological conditions are also important determinants of air pollution, meteorological trends—including mean wind velocity, mean temperature, and mean relative humidity—were explored over the 5-year study period.

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.

Results

The distribution of the 74 key cities is shown in figure 1. The selected cities are capital cities of provinces or major cities located in the most developed regions of China. According to the China Statistical Yearbook, these 74 cities contributed 63% of the country's national gross domestic product (GDP) in 2013. There is some overlap between the 74 cities and the three regions. Among the 74 cities, 13 cities were in the Beijing-Tianjin-Hebei region, 19 in the Yangtze River Delta region, and nine in the Pearl River Delta region.

Annual concentrations of the six criteria air pollutants in the 74 key cities in China from 2013 to 2017 are shown in figure 2. Concentrations of $PM_{2·5}$, PM_{10}, sulphur dioxide, and carbon monoxide decreased overall during the 5-year period.

There were large reductions in $PM_{2·5}$ concentrations (table 1), which occurred in a non-linear pattern, with a rapid reduction at first, followed by slower reductions. The average annual $PM_{2·5}$ concentration in the 74 key cities was reduced from 72·2 μg/m³ (SD 27·8) to 47·0 μg/m³ (15·8), a reduction of 33·3% (95% CI 16·3–50·3) in 2017 compared with 2013. The reduction in average annual $PM_{2·5}$ concentration was 37·3% (95% CI 21·3–53·2) for the Beijing-Tianjin-Hebei region, 35·2% (19·7–50·7) for the Yangtze River Delta region, and 26·1% (35·6–16·6) for Pearl River Delta region (appendix). Furthermore, the annual average $PM_{2·5}$ concentration in Beijing was 57·0 μg/m³ (SD 55) in 2017. These three regions and Beijing therefore achieved the targets set out in the APPCAP (panel).

The average annual reduction in PM_{10} concentration was 27·8% (95% CI 8·0–47·5) in the 74 key cites, 32·0% (9·7–54·3) in the Beijing-Tianjin-Hebei region, 27·6% (7·8–47·3) in the Yangtze River Delta region, and 22·4% (11·9–32·9) in the Pearl River Delta region. $PM_{2·5}$

and PM_{10} concentrations were both highest in the Beijing-Tianjin-Hebei region at the baseline year, and the largest reductions in both air pollutants were found in the Beijing-Tianjin-Hebei region in 2017. However, the annual average concentrations of $PM_{2·5}$ and PM_{10} in the 74 key cities still exceed the Grade II levels set by the Chinese Ambient Air Quality Standards (figure 3), as did annual $PM_{2·5}$ and PM_{10} concentrations in the Beijing-Tianjin-Hebei and the Yangtze River Delta regions (appendix).

The average annual sulphur dioxide concentration decreased from 39·9 µg/m³ (SD 24·3) in 2013 to 17·0 µg/m³ (9·8) in 2017 in the 74 key cities, a reduction of 54·1% (95% CI 28·2–80·0). Average annual carbon monoxide concentration decreased from 2·5 mg/m³ (SD 1·2) to 1·7 mg/m³ (0·8) in the 74 key cities, a reduction of 28·2% (95% CI 3·1–53·3; table 1). The largest reductions in annual sulphur dioxide and carbon monoxide concentrations occurred in the Beijing-Tianjin-Hebei region, with reductions of 63·5% (95% CI 46·6–80·5) for sulphur dioxide and 30·5% (12·9–48·0) for carbon monoxide (appendix).

No significant change in nitrogen dioxide concentrations was evident. The average annual concentration was only reduced from 43·9 µg/m³ (SD 11·1) to 39·2 µg/m³ (10·1) from 2013 to 2017, a reduction of 9·7% (95% CI –23·0 to 42·4). Average annual concentrations of ozone increased from 139·2 µg/m³ (SD 25·9) to 163·0 µg/m³ (24·0) from 2013 to 2017 in the 74 key cities, but this increase was not significant (20·4%; 95% CI –30·1 to 71·0).

The adverse effects of air pollution during the 5-year period were estimated on the basis of the burden attributable to $PM_{2·5}$ and ozone exposure in the Global Burden of Disease studies.

The attributable number of deaths and YLL because of ambient $PM_{2·5}$ pollution each year from 2013 to 2017 were estimated (figure 4). From 2013 to 2017, there was a general decrease in the attributed number of deaths and YLL because of ambient $PM_{2·5}$ exposure. In 2013, it was estimated that the health loss associated with $PM_{2·5}$ in the 74 leading cites in China included 420 320 premature deaths, which comprised 64 810 cases of COPD, 106 010 cases of ischaemic heart disease, 55 360 cases of lung cancer, and 194 140 cases of stroke. In 2017, the estimates decreased to 365 400 premature deaths attributable to $PM_{2·5}$ pollution, which comprised 50 470 cases of COPD, 97 790 cases of ischaemic heart disease, 43 000 cases of lung cancer, and 174 140 cases of stroke (appendix). It was estimated that 6 512 330 YLL from premature deaths were attributed to ambient $PM_{2·5}$ exposure in the 74 key cites in China in 2013; this number continued to decrease throughout the 5-year period, with 5 735 040 YLL from premature deaths observed in 2017. Among those, the YLL from COPD, ischaemic heart disease, lung cancer, and stroke all decreased (appendix).

However, the ozone-attributable deaths and YLL from COPD increased from 2013 to 2017, as a result of increases in concentrations of ozone. Exposure to ozone contributed to 49 120 premature deaths and 432 930 YLL from COPD in 2013 in the 74 key cities; this number increased to 56 800 deaths and 500 200 YLL in 2017 (figure 4).

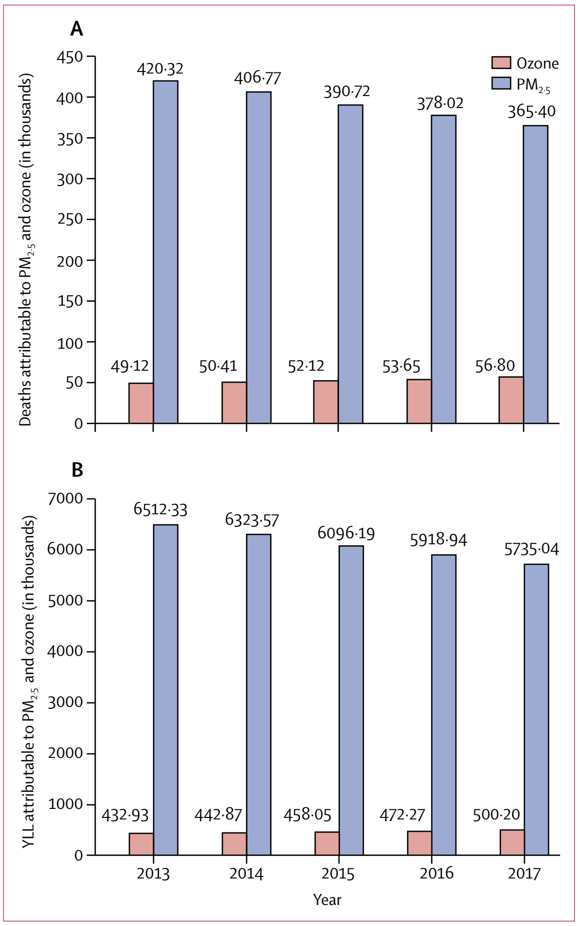

Figure 4: **Number of deaths and YLL attributed to $PM_{2·5}$ and ozone pollution in the 74 key cities in China, 2013–17**
(A) Deaths attributed to ambient $PM_{2·5}$ and ozone pollution (in thousands). (B) Years of life lost (YLL) attributed to ambient $PM_{2·5}$ and ozone pollution (in thousands).

The number of avoided deaths and YLL attributable to air quality improvements in the 74 key cities in China from 2014 to 2017 compared with 2013 are presented in table 2. The number of avoided deaths and YLL increased from 2014 to 2017 compared with 2013. In 2017, as a result of substantial improvements in air quality, there were 47 240 (95% CI 25 870–69 990) fewer deaths and 710 020 (420 230–1 025 460) fewer YLL in the 74 key cities in China. When divided by the baseline death counts and YLL in 2013, the death counts decreased by 10·1% and YLL by 10·2% in the 74 key cities in 2017. The reduced death counts per 100 000 people were 9·0 years (95% CI 4·9–13·4) and reduced YLL per 100 000 people were 135·5 years (80·2–195·7) in 2017 compared with 2013 (table 2).

	Avoided deaths (95% CI)	Avoided deaths (95% CI) per 100 000 people	Avoided YLL (95% CI)	Avoided YLL (95% CI) per 100 000 people
2014	12 260 (–6700 to 34 090)	2·4 (–1·3 to 6·6)	178 820 (–157 850 to 510 250)	34·7 (–30·6 to 98·9)
2015	26 600 (4880 to 50 340)	5·1 (0·9 to 9·7)	391 020 (73 130 to 711 410)	75·4 (14·1 to 137·1)
2016	37 770 (15 640 to 60 400)	7·2 (3·0 to 11·6)	554 050 (233 510 to 872 740)	106·1 (44·7 to 167·2)
2017	47 240 (25 870 to 69 990)	9·0 (4·9 to 13·4)	710 020 (420 230 to 1 025 460)	135·5 (80·2 to 195·7)

YLL=years of life lost. The year 2013 was used as the baseline.

Table 2: **Number of avoided deaths and YLL attributable to air quality improvements in 74 key cities in China from 2014 to 2017 compared with 2013**

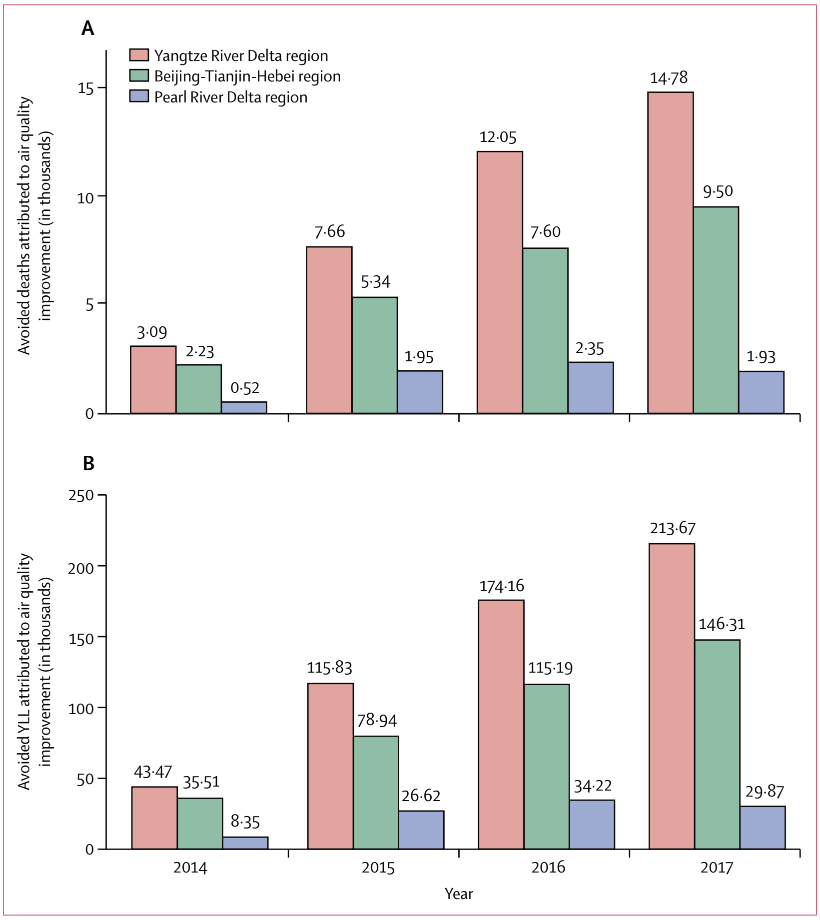

Figure 5: **Number of avoided deaths and YLL attributable to air quality improvements in the three key regions in China from 2014 to 2017 compared with 2013**
YLL=years of life lost.

The number of avoided deaths and YLL attributable to air quality improvements in the Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta regions are shown in figure 5. In general, the avoided deaths and YLL increased from 2014 to 2017. There were 26 210 (95% CI 540–50 920) fewer deaths and 389 850 (26 010–737 620) fewer YLL in the three key regions in 2017, which accounted for 55·5% of deaths and 55·0% of YLL in the 74 key cities. The death counts and YLL per 100 000 people in the three key regions from 2013 to 2017 are provided in the appendix. We found no obvious change in meteorological conditions for different years during the study period in the 74 key cities (appendix). However, data for daily mean wind direction and for the number and intensity of wintertime inversions were not available.

Discussion

In this study, we evaluated changes in concentrations of six criteria air pollutants and assessed the mortality and YLL benefits attributed to promulgation of China's APPCAP during 2013 to 2017. To our knowledge, this is the first study to comprehensively evaluate the long-term health impact of China's air pollution control policy at the national level.

Appreciable reductions in concentrations of air pollutants were observed from 2013 to 2017. A study done in the Beijing-Tianjin-Hebei region also indicated that the APPCAP was effective in lowering concentrations of $PM_{2·5}$ in this region.[30] The targets of the APPCAP were achieved, and noteworthy health benefits were observed during the 5-year period. In 2017, as a result of significant improvements in air quality, there were 47 240 fewer deaths and 710 020 fewer YLL in the 74 key cities in China, and the reduction in the three key regions (Beijing-Tianjin-Hebei, Yangtze River Delta and Pearl River Delta) accounted for more than 55% of the total. The improvements in ambient air quality and the health benefits observed demonstrate the effectiveness of China's air pollution control policy from 2013 to 2017.

Public concern and awareness about ambient air pollution and health have risen to an unprecedented level in China. Studies have been done to assess the health benefits during certain periods of air pollution control, such as during the 2008 Beijing Olympics,[10,11] the APEC Blue and Parade Blue periods in Beijing,[12] and the 2010 Guangzhou Asian Games.[13] The improvements in ambient air quality and related health benefits during these periods demonstrate China's ability to control air pollution emissions through high-priority policies.

However, some of the air quality control policies during these short-term periods were temporary measures that were implemented and enforced by unconventional methods. Continuous and persistent efforts to improve ambient air quality in the long run are urgently needed in China. Promulgation of the APPCAP in China therefore offered an excellent opportunity to evaluate the effects of long-term air quality management and the related health impacts at the national level. Compared with previous studies that focused on a single city,[14,15] one key region,[16] or only a few kinds of air pollutants,[17,18] or those that were based on hypothetical data,[19] our study provides, for the first time, a comprehensive assessment of the health impacts of long-term air pollution control policy in China based on the national air quality monitoring and mortality data.

The problem of air pollution alongside economic expansion seems inevitable. Historically, high-income countries such as the USA and the UK also experienced severe air pollution during their industrialisation process and have substantially improved their air quality from the smog-laden days in the early and mid-20th century. Lessons learned from these countries can provide insights and perspectives for air pollution prevention and control in China.[31]

The British Parliament passed the world's first clean air legislation—the Clean Air Act—in 1956. This Act addressed the problem of smoke pollution and created smoke-free zones to address the burning of coal for heating, a potent source of pollution in the densely settled cities of the UK. Subsequent legislation addressed industrial sources. The clean air legislation has proven effective not only in preventing severe problems of air pollution but has also been accompanied with apparently substantial health benefits.[32–34]

The USA has also made substantial efforts to improve air quality since the 1970s.[7] The Clean Air Act was initially passed in 1970, and aided by amendments passed in 1977 and 1990, and has been the foundation for air quality management in the USA. Concentrations of the criteria air pollutants have dropped substantially, with annual $PM_{2·5}$ reduced by 37%, 24-h PM_{10} by 39%, 1-h sulphur dioxide by 81%, 8-h carbon monoxide by 77%, annual nitrogen dioxide by 54%, and 8-h ozone by 22% in 2015 compared with 1990. The Clean Air Act Amendments have also achieved substantial health benefits, with death counts related to $PM_{2·5}$ reduced by 160 000 and those related to ozone reduced by 4300 in 2010 compared with 1990.[35]

The APPCAP in China is similar to the Clean Air Act. It sets quantitative air quality improvements goals for key regions within a clear time limit and lists ten key actions covering all major aspects of air quality management.[9] Although direct comparisons of its effects with those of Clean Air Acts in the UK and the USA are difficult because the APPCAP was only introduced in 2013, a key strength of the legislation is that it demonstrates China's ability to control air pollution. The APPCAP has, in a 5-year period, achieved noteworthy improvements, including significant reductions in $PM_{2·5}$, PM_{10}, sulphur dioxide, and carbon monoxide concentrations between 2013 and 2017, and annual death counts and YLL have also dropped by approximately 10% in the 74 key cities.

These benefits have arisen largely from changes to the energy infrastructure, including changing fuel consumption from coal to natural gas or electricity, application of coal desulphurisation technologies, and promotion of new energy vehicles. Total coal consumption in China has decreased from 42 million tonnes in 2013 to 38 million tonnes in 2016, with corresponding proportions of coal consumption reduced from 67·4% to 62·0%.[36] Clean energy supply is increasing, from 15·5% in 2013 to 19·7% in 2016, which is equivalent to reducing the use of coal by 2·4 million tonnes.[36] Also noteworthy is the strict emissions control, such as reduced emissions from road dust, construction dust, vehicle exhausts, and cooking fumes. For instance, 17·1 million vehicles that failed to meet emission standards were eliminated during 2014–16.[36] Additionally, measures to optimise the industrial infrastructure and promote industrial restructuring, as well as joint prevention and control of air pollution in key regions, establish a monitoring and warning system, and improve legal and regulatory systems are all contributing to the effectiveness of air quality management in China.[9] Considering the health benefits to be achieved from air quality improvement, it is worthwhile for China to shift its development strategy from economic growth to environmental and economic sustainability.

However, our findings indicate that emissions control efforts for ozone and nitrogen dioxide require further attention and should be strengthened, because average annual ozone concentrations increased from 139·2 μg/m³ in 2013 to 162·9 μg/m³ in 2017 in the 74 key cities, while average annual nitrogen dioxide concentrations only decreased from 43·9 μg/m³ in 2013 to 39·2 μg/m³. The complex formation mechanism of ozone, including the non-linear association between ozone and its precursors (namely, volatile organic compounds and nitrogen oxides), which is associated with meteorological conditions, emission distributions, and land use types, has made it a difficult component of air pollution control.[37] Ozone pollution poses an ongoing challenge for researchers and policy makers.[38] Strengthening investigations into the formation of ozone, and exploration of the optimal proportion of volatile organic compounds and nitrogen oxides in the key regions will provide empirical evidence for ozone control efforts in China and other countries.

Additionally, although reductions in $PM_{2·5}$ and PM_{10} have met the APPCAP targets, annual $PM_{2·5}$ and PM_{10} concentrations in the 74 key cities still exceed the Grade II criteria of the Chinese Ambient Air Quality Standards. Furthermore, the reductions in air pollutants occurred rapidly at first, followed by slower changes. These observations are similar to the effects of the Clean Air Act in the USA,[8] indicating that long-term air quality management is an arduous and complex task once the concentrations of air pollutants are reduced to a certain level.

To the best of our knowledge, this is the first study to comprehensively evaluate the long-term health impact of China's air pollution control policy at the national level. Considering the geographical distribution, data availability, and population size of the 74 key cities and three key regions selected, we feel our study provides a realistic reflection of the policy effects of China's APPCAP. Additionally, use of YLL as the indicator for assessing health impacts provided a complementary way to estimate the disease burden by taking both premature deaths and life expectancy at death into consideration, instead of only considering mortality.

However, our study had several limitations. First, we could not assess the health effects of all air pollutants because of the strong collinearity between air pollutants. Second, we only selected mortality attributed to COPD, ischaemic heart disease, stroke, and lung cancer; previous studies have shown that air pollution exposure is also associated with low birthweight and preterm birth,[39] asthma,[40] and type 2 diabetes.[41] Future studies should consider these other causes of mortality and morbidity. Second, when estimating the influence of the APPCAP in China, we should be aware of other factors that are expected to substantially reduce emissions independently of government policy, such as technological progress and industrial restructuring accompanied by economic growth. However, this is not a challenge unique to this study.[25] Further investigations should explore the role of China's APPCAP by also considering the influence of factors such as economic development and meteorological conditions.

In conclusion, the APPCAP in China led to a significant decrease in levels of air pollution in the 5-year period from 2013 to 2017, and the reduction in air pollution has been accompanied by substantial health benefits, especially in the key regions. Since ambient air pollution contributes substantially to the global burden of disease, these findings are crucial for air quality management and public health interventions both in China and in other countries.

Contributors

GL and JH designed the study and developed the analysis plan. GL collected and analysed the data. JH did the literature search, interpreted the data, and wrote the manuscript. XP and XG gave suggestions for implementation and reviewed and edited the manuscript. GL is the guarantor of this work and had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Declaration of interests

We declare no competing interests.

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