PNAS Nexus, 2024, **3**, pgae142
https://doi.org/10.1093/pnasnexus/pgae142
Advance access publication 30 April 2024
Research Report

Accountability analysis of health benefits related to National Action Plan on Air Pollution Prevention and Control in China

Tiantian Li[a,b,c], Chen Chen[a,b], Mengxue Zhang[a,b,c], Liang Zhao[a], Yuanyuan Liu[a,b], Yafei Guo[a,b], Qing Wang[a,b], Hang Du[a,b], Qingyang Xiao[d], Yang Liu[e], Mike Z. He[f], Patrick L. Kinney[g], Aaron J. Cohen[h], Shilu Tong[a,i] and Xiaoming Shi[a,b,c,*]

[a]China CDC Key Laboratory of Environment and Population Health, National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, No.7 Panjiayuan South, Chaoyang District, Beijing 100021, China
[b]National Key Laboratory of Intelligent Tracking and Forecasting for Infectious Diseases, National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, No.7 Panjiayuan South, Chaoyang District, Beijing 100021, China
[c]School of Public Health, Nanjing Medical University, No.101 Longmian Avenue, Jiangning District, Nanjing 211166, China
[d]State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Haidian District, Tsinghua University, Beijing 100084, China
[e]Department of Environmental Health, Rollins School of Public Health, Emory University, 201 Dowman Drive, Atlanta, GA 30322, USA
[f]Department of Environmental Medicine and Public Health, Icahn School of Medicine at Mount Sinai, 1 Gustave L. Levy Place, New York, NY 10029, USA
[g]Department of Environmental Health, Boston University School of Public Health, 715 Albany Street, Boston, MA 02118, USA
[h]Health Effects Institute, 75 Federal Street, Boston, MA 02110, USA
[i]School of Public Health and Social Work, Queensland University of Technology, 2 George Street, Brisbane, QLD 4001, Australia
*To whom correspondence should be addressed: Email: shixm@chinacdc.cn
Edited By: Junguo Liu

Abstract

China is one of the largest producers and consumers of coal in the world. The National Action Plan on Air Pollution Prevention and Control in China (2013–2017) particularly aimed to reduce emissions from coal combustion. Here, we show whether the acute health effects of $PM_{2.5}$ changed from 2013 to 2018 and factors that might account for any observed changes in the Beijing–Tianjin–Hebei (BTH) and the surrounding areas where there were major reductions in $PM_{2.5}$ concentrations. We used a two-stage analysis strategy, with a quasi-Poisson regression model and a random effects meta-analysis, to assess the effects of $PM_{2.5}$ on mortality in the 47 counties of BTH. We found that the mean daily $PM_{2.5}$ levels and the SO_4^{2-} component ratio dramatically decreased in the study period, which was likely related to the control of coal emissions. Subsequently, the acute effects of $PM_{2.5}$ were significantly decreased for total and circulatory mortality. A 10 μg/m^3 increase in $PM_{2.5}$ concentrations was associated with a 0.16% (95% CI: 0.08, 0.24%) and 0.02% (95% CI: −0.09, 0.13%) increase in mortality from 2013 to 2015 and from 2016 to 2018, respectively. The changes in air pollution sources or $PM_{2.5}$ components appeared to have played a core role in reducing the health effects. The air pollution control measures implemented recently targeting coal emissions taken in China may have resulted in significant health benefits.

Keywords: $PM_{2.5}$ and components, acute effect, mortality, temporal variation, clean air actions

Significance Statement

Extremely high levels of $PM_{2.5}$ exposure and its health hazards in China have become a major concern worldwide. Nationwide clean air actions implemented in 2013–2018 have led to a remarkable decrease in $PM_{2.5}$ pollution. However, there is little evidence to show whether acute health effects of $PM_{2.5}$ have changed under these actions. This study aimed to fill this knowledge gap by conducting an accountability analysis of the health benefits associated with significant reductions in $PM_{2.5}$ pollution in the Beijing–Tianjin–Hebei region and surrounding areas. We found that the acute effects of $PM_{2.5}$ were significantly decreased for total and circulatory mortality. The changes in air pollution sources or $PM_{2.5}$ components appeared to have played a core role in reducing the health effects.

Introduction

The extremely high levels of $PM_{2.5}$ exposure have become a major public concern in China (1). In 2019, over 90% of the world's population was exposed to annual average $PM_{2.5}$ concentrations that exceeded the WHO Air Quality Guideline of 10 μg/m^3 (2). Coal combustion contributed to more than 60% of $PM_{2.5}$ emissions in China in 2012 (3), which was estimated to have caused 710,000 deaths in the entire country (4). In 2012, China was the largest

Competing Interest: The authors declare no competing interest.
Received: May 24, 2023. **Accepted:** March 22, 2024

consumer of coal in the world, accounting for more than half of the world's coal consumption for the first time (5). With the rapid economic growth since the initiation of market reforms in 1978, energy consumption in China increased sharply by more than 6-fold from 0.57 billion tce (tons of standard coal) in 1978 to 3.51 billion tce in 2012 (6). China's energy structure was primarily coal-dominated, which shared 76.2% of the national total energy consumption in 2012 (6). Within this context, China's demand for energy, particularly for coal, has been dramatically increasing, as have China's pollutant emissions (7).

To control air pollution, especially $PM_{2.5}$ pollution from coal combustion sources, in 2013, the State Council of China issued the "China National Action Plan on Air Pollution Prevention and Control" (8). These actions were part of a long-term plan (from 2013 to 2017) with multiple action measures, particularly aiming to reduce emissions from coal combustion (Table S1). The top objective of the National Action Plan was to comprehensively control air pollutant emissions, especially those from coal-based sources, which included plans such as renovating small coal heating stoves, accelerating the construction of central heating systems, implementing coal-to-electricity and coal-to-gas projects, applying ultralow emission technology to retrofit existing coal-fired power plants (9) and promoting the application of high-efficiency, energy-saving, and environmentally friendly stoves in areas uncovered by central heating. The Action Plan also established quantitative goals for key regions within a certain time frame, outlined multiemission control actions for all major emitting industries (10, 11), and set key regional coal consumption caps in the short and long terms (12). The Beijing–Tianjin–Hebei (BTH) region is one of the largest economic zones in northern China, which covers 2.3% of China's land and accounts for 8.1% of total population and 10.4% of national GDP. It was also the most heavily polluted region with a key target for air pollution control in China (13). Coal consumption in the BTH region totaled 0.36 billion tons, accounting for 13.0% (0.36/2.77 billion tons) of the total consumption in China in 2015 (5, 14). The Action Plan clearly stated that the BTH region should achieve negative growth in the total coal consumption, and markedly/gradually increase the proportion of clean energy usage (10). In addition, the Action Plan not only focused on controlling emissions from coal but also took other measures to control heavy air pollution, specifically including actions to quickly activate emergency plans based on the early warning of high air pollution levels and to promptly guide public health protection (8, 15).

Since the promulgation of the National Action Plan in China, there have been marked reductions in coal combustion emissions, as well as improvements in ambient air quality across the whole country, particularly the BTH region. The proportion of coal in total energy consumption decreased from 67.4% in 2013 to 60.4% in 2017 nationwide, and total coal consumption reduced from 3.94 to 3.86 billion tons between 2013 and 2017 (16, 17). In the BTH region, the total coal consumption decreased by nearly 70 million tons during 2012–2017 (18). In the meantime, annual average $PM_{2.5}$ concentrations decreased from 106 $\mu g/m^3$ to 64 $\mu g/m^3$ in BTH during 2013—2017 (8, 19). In 2018, the central government issued the "Three-Year Action Plan for Winning the Blue Sky Defense Battle" (20), which aimed to further reduce the number of days of heavy air pollution and to significantly improve ambient air quality in China, especially in the BTH region. Once again, $PM_{2.5}$ concentrations decreased by 9.3% in 2018, compared to that in 2017 (21).

In the context of decreasing coal emissions and improving air quality, an assessment of the public health impacts of related policies or plans, termed "accountability analysis", plays an essential role in elucidating whether the considerable cost of implementing policies to control coal emissions does indeed yield noticeable improvements in public health and provides relevant data to inform future policy initiatives (22). Several studies have reported a long-term reduction in air pollution emissions and the estimated disease burden under this action plan (23, 24). However, direct short-term epidemiologic evidence of the health benefits from this coal-focused National Action Plan is still lacking.

The effective implementation of the National Action Plan on Air Pollution Prevention and Control in China, especially the substantial reduction in the coal emissions and $PM_{2.5}$ concentrations in the BTH region (25), provides a unique opportunity to explore whether the acute health effects of $PM_{2.5}$ exhibited any changes from 2013 to 2018 and to consider potential factors accounting for observed changes. To address these issues, we assessed dynamic trends in $PM_{2.5}$ concentrations and health outcomes as well as the major determinants of $PM_{2.5}$-related health effects before and after the implementation of air pollution control measures in BTH and the surrounding areas. The most serious health outcomes were considered, including mortality, hospitalizations, and outpatient visits. We found a decreasing trend in $PM_{2.5}$ concentrations by year after the implementation of air pollution control measures in BTH and the surrounding areas. We also found that the effect estimates of mortality in BTH and the surrounding area were lower in 2016–2018 than in 2013–2015. In particular, the effects of total and circulatory-related mortality were significantly decreased in the latter period. These findings provide initial evidence of health benefits that may have resulted from implementing the National Action Plan on Air Pollution Prevention and Control.

Results

Impact on $PM_{2.5}$ concentrations and $PM_{2.5}$ components

Our study focused on the highly polluted BTH region and the surrounding areas, including Beijing, Tianjin, Hebei, Shandong, Shanxi, and Henan (Fig. S1). Guangdong, Fujian, Southern Hunan, and Southern Jiangxi, which experienced relatively low $PM_{2.5}$ concentrations, served as control areas (Fig. S1). Figure 1 indicates the annual $PM_{2.5}$ pollution in BTH and the surrounding area from 2013 to 2018, showing a decreasing trend by year, especially in the southern area of Hebei Province. Table 1 reveals that the average level of $PM_{2.5}$ was 85.6 ± 67.7 $\mu g/m^3$ in the 47 counties in BTH and the surrounding areas from 2013 to 2015. However, the mean daily $PM_{2.5}$ level was reduced by 20 $\mu g/m^3$ in the period of 2016–2018. The average total mortality, circulatory-related mortality, and respiratory-related mortality in the 47 counties over the two periods, i.e. from January 1, 2013–December 31, 2015 to January 1, 2016–December 31, 2018, were similar. Table S2 shows the descriptive statistics of outpatient visits to the 29 hospitals in BTH and the surrounding areas, hospital admissions, and children's hospital outpatient visits in Beijing. $PM_{2.5}$ concentrations decreased by approximately 10 $\mu g/m^3$ (Table S3) in the control areas from 2013–2015 (45.7 ± 33.3 $\mu g/m^3$) to 2016–2018 (35.0 ± 23.9 $\mu g/m^3$).

$PM_{2.5}$ component concentrations in Beijing and Shijiazhuang are shown in Tables S4 and S5. Of these, the other category mainly includes heavy metal elements such as lead, zinc, cadmium, as well as microorganisms, bacteria, viruses, and other substances. $PM_{2.5}$ component concentrations of OC and SO_4^{2-} in Beijing markedly decreased from 2013 to 2018 (Fig. 2B). The SO_4^{2-} component

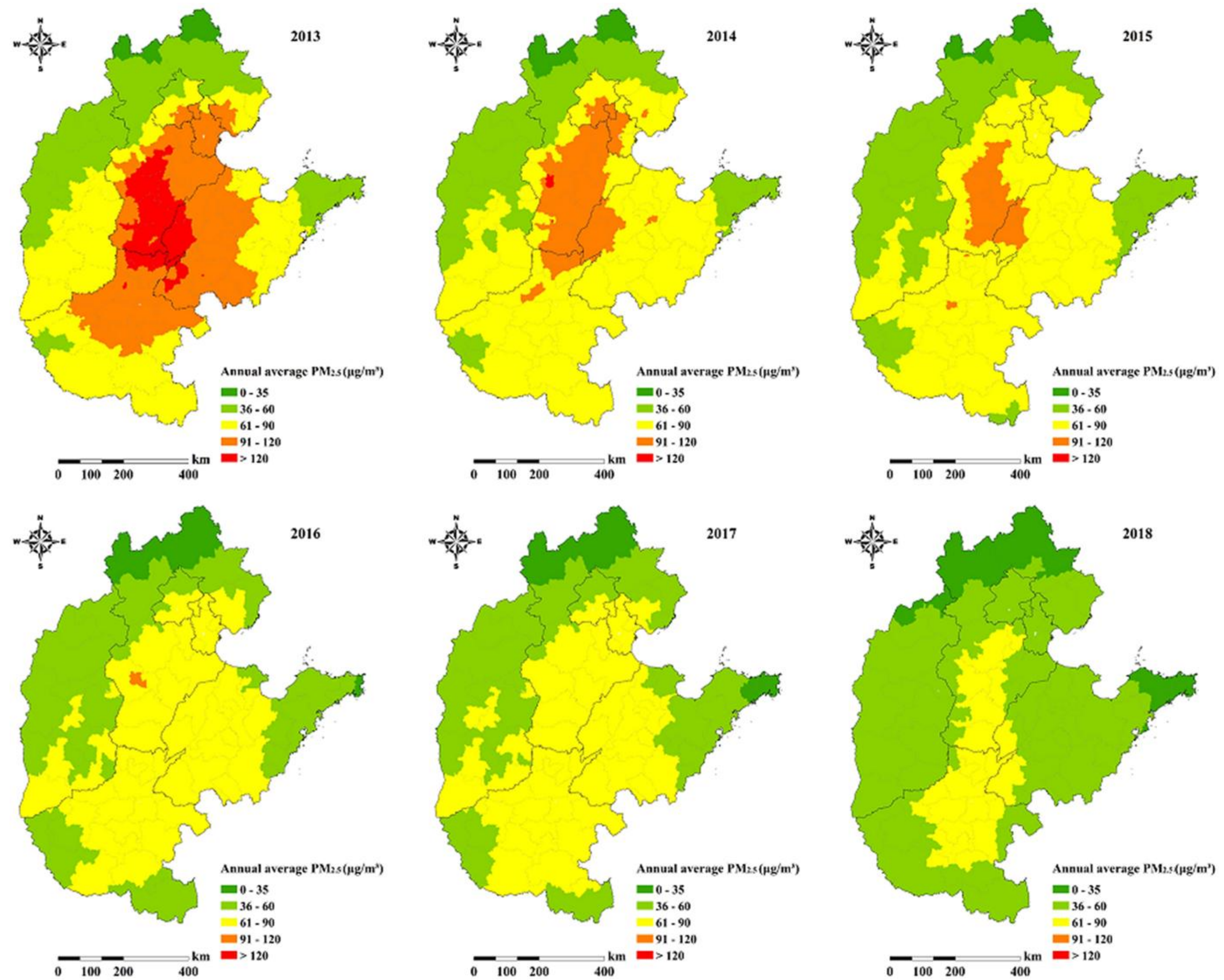

Fig. 1. Annual $PM_{2.5}$ concentrations in BTH and surrounding areas from 2013 to 2018.

ratio fell substantially from 23% in 2013 to 14% in 2018, while the OC component ratio remained almost unchanged at 10–17%. $PM_{2.5}$ component concentration of SO_4^{2-} in Shijiazhuang also decreased from 2014 to 2018 (Figs. S2 and S3). The SO_4^{2-} component ratio decreased from 18% in 2014 to 12% in 2018 (Figs. S4 and S5).

Impact on mortality and morbidity

The percentage changes in mortality for total, circulatory, and respiratory diseases associated with each 10 $\mu g/m^3$ increase in $PM_{2.5}$ in BTH and the surrounding areas are shown in Fig. 3 and Table S6. A 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentrations was associated with an increase of 0.16% (95% CI: 0.08, 0.24%) and 0.02% (95% CI: −0.09, 0.13%) in mortality from 2013 to 2015 and from 2016 to 2018, respectively. In BTH and the surrounding areas, the percent changes in rates of total and circulatory mortality and total and circulatory outpatient visits due to daily exposure to $PM_{2.5}$ were significantly decreased during 2016–2018 relative to 2013–2015 (Figs. 3 and Fig S6, Tables S6 and S7). In Beijing, there was a marked reduction in the effect of $PM_{2.5}$ on the total number of outpatient visits at Beijing Children's Hospital in 2016–2018 compared to that of 2013–2015. We found significant reductions in the effects on hospital admissions for circulatory and respiratory diseases, and a decreasing trend of the estimated effects in 2016–2018 compared to those of 2013–2015 (Figs. S7 and S8, Table S8). In contrast to the findings for BTH and the surrounding areas, in the control areas, the effect of $PM_{2.5}$ concentrations on mortality was not significantly changed from 2013–2015 to 2016–2018 (Fig. 3A and B). In our sensitivity analyses, we found that all of the main results remained robust after adjusting for ozone as a second pollutant and varying the degrees of freedom for temperature, humidity, and time (Tables S9, S10, and S11).

The exposure–response curves of $PM_{2.5}$ concentrations and daily all-cause mortality in BTH and the surrounding areas for the period of 2013 to 2018 show a monotonic increase in the excess relative rate until approximately 250$\mu g/m^3$, after which the excess relative rate monotonically decreased (Fig. 3C). However, the exposure–response curves for 2013–2015 showed a monotonically linear increase, whereas the exposure–response curves for 2016–2018 had an inverted J shape, with nearly no apparent effect. There were similar results for cardiovascular mortality, but not for respiratory mortality during 2013–2015 (Fig. S9). The nonlinear curves of the $PM_{2.5}$ concentrations and morbidity in BTH and the surrounding area or in Beijing are shown in Figs. S10–S12. The exposure–response curves during the 2016–2018 period all tended to

Table 1. Descriptive statistics of mortality and outpatient visits in BTH and surrounding areas by the study period.

	2013–2015							2016–2018						
	n	Mean ± SD	Minimum	P25	P50	P75	Maximum	*n*	Mean ± SD	Minimum	P25	P50	P75	Maximum
Total	51,465	10 ± 8	0	4	8	13	99	51,512	11 ± 8	0	5	9	14	84
Circulatory	51,465	5 ± 4	0	2	4	7	51	51,512	6 ± 4	0	2	5	8	43
Respiratory	51,465	1 ± 1	0	0	1	1	12	51,512	1 ± 1	0	0	1	2	13
Air pollutants														
$PM_{2.5}$ (μg/m^3)	40,392	85.6 ± 67.7	3.0	40.5	67.9	107.8	825.6	49,611	64.1 ± 51.5	3.0	31.7	50.3	79.7	661.4
O_3 (μg/m^3)	41,024	49.9 ± 36.4	2.1	21.7	41.6	71.7	495.1	49,611	63.0 ± 39.0	2.1	32.3	57.0	88.0	236.5
Meteorological parameters														
Temperature (°C)	51,451	14.0 ± 10.6	−15.7	4.4	15.3	23.3	34.6	51,497	14.2 ± 10.9	−19.0	4.6	15.5	23.9	34.6
Relative humidity (%)	51,459	60.0 ± 18.9	0.0	46.0	61.0	74.0	100	51,497	58.7 ± 19.2	8.0	44.0	59.0	74.0	100

have a decreased slope compared to those for the 2013–2015 period.

Discussion

This study explored whether the acute health effects of $PM_{2.5}$ changed and potential factors related to any observed changes in the BTH and the surrounding areas where there were major reductions in $PM_{2.5}$ concentrations from 2013 to 2018. We found that the mean daily $PM_{2.5}$ levels and the SO_4^{2-} component ratio dramatically decreased in the study period, which was likely due to coal emissions control. Subsequently, the effects of $PM_{2.5}$ were significantly decreased for total and circulatory mortalities in the period of 2016–2018 compared to the period of 2013–2015.

Comparison with other studies in the literature

A gradual air quality improvement caused by air pollution control measures has been observed in the United States and Europe, and related changes in health risks per unit exposure to particulate matter (exposure–response relationship) have been reported (12, 22, 26), which is consistent to our findings. However, there are some mixed research results. For example, Dominici et al. evaluated the changes in short-term exposure related mortality risk due to airborne particles from 1986 to 2000 in the United States, during which increasingly stringent regulations to control air pollution were put in place (27). Nevertheless, the degree of the reduction in particulate matter was much smaller than that in BTH and the surrounding areas in China, and additionally, they only found a weak association between decreased PM_{10} concentrations and related health gains, which occurred mostly in the eastern United States. They also reported that the relative rate estimates for PM_{10}–mortality relationship in 1987–1994 were not significantly different from that in 1995–2000 (27). In Germany, where NO_2 and CO were the main air pollutants, emission control and fuel replacement policies were implemented after unification in 1990, and subsequent reductions in air pollution concentrations were observed from 1995 to 2002. Moreover, the study found that the effect of air pollution on mortality decreased from the mid-1990s to the late 1990s (28). In general, both the United States and Germany had better air quality and less reductions of coal emissions than China. Correspondingly, $PM_{2.5}$ reduction levels in these countries were much smaller than those in China. Therefore, the abovementioned studies observed weaker associations between decreased PM_{10} concentrations and related health benefits than we did. Furthermore, the very long study periods of these two studies (both more than 10 years) may also confound some changes in other contemporary factors associated with health outcomes (e.g. healthcare improvement).

Changes of the exposure–response relationship

The nonlinear exposure–response relationship was considered to be largely due to some competing factors (e.g. ozone, nitrogen oxides, and other air pollution) which may explain the changes in effect estimates. One is the possible influence of a nonlinear exposure–response relationship (29, 30), in which lower $PM_{2.5}$ exposure might explain reduced effect estimates following reductions in $PM_{2.5}$ concentrations. All evidence from exposure–response curves in recent Chinese and global studies suggests that the rate of effect per unit change increases more rapidly at low concentrations and higher effects at high concentrations (31–33). In 2013–2015, we found that there were higher mortality effects in the control area with a lower $PM_{2.5}$ exposure level, and

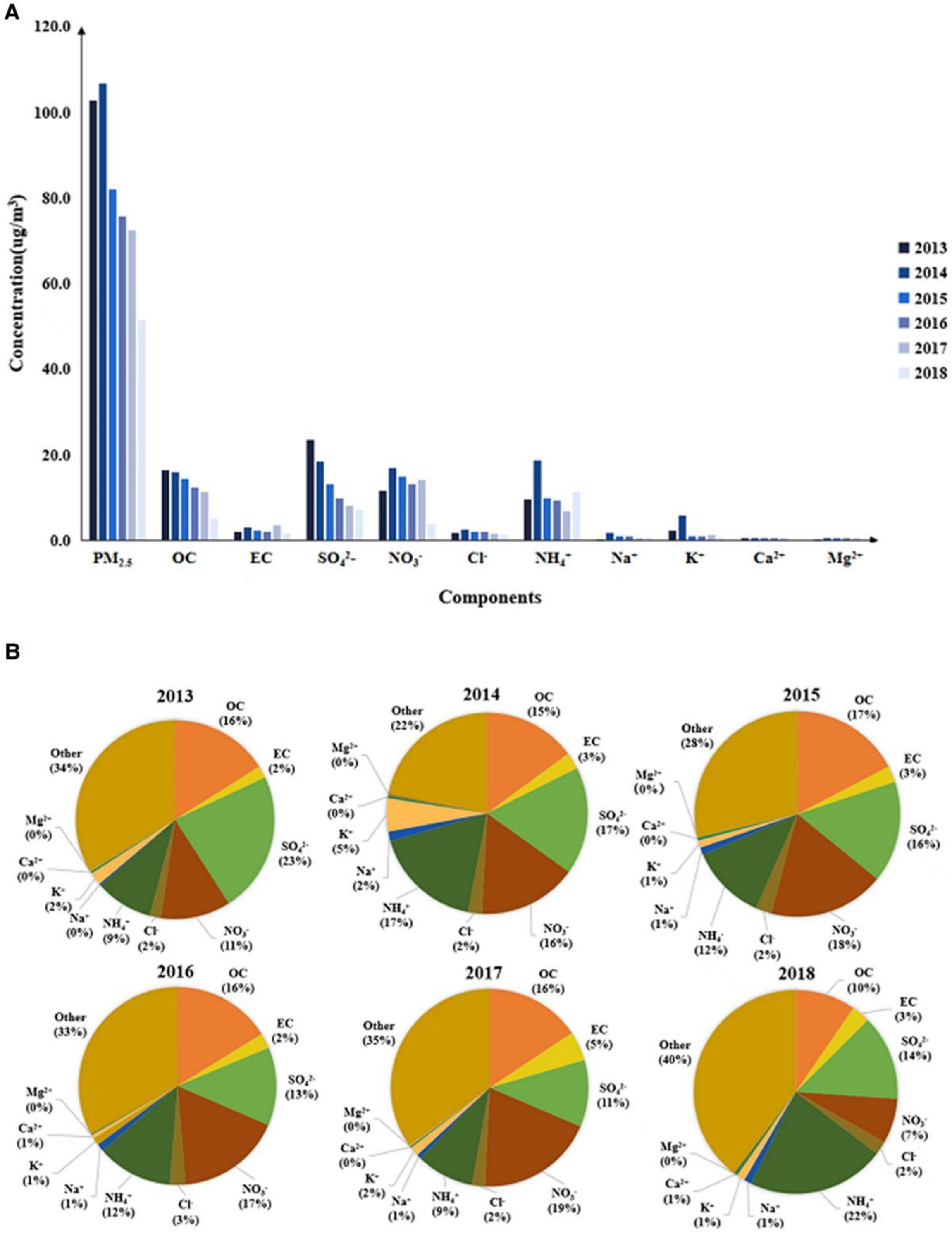

Fig. 2. Concentrations A) and proportions B) of $PM_{2.5}$ components in Beijing from 2013 to 2018.

lower mortality effects in BTH and the surrounding area with a higher $PM_{2.5}$ exposure level, which is consistent with other nationwide studies in China (31, 32). Furthermore, our 2013–2015 effect estimates are very similar to those in a nationwide study of the relationship between $PM_{2.5}$ and mortality in 272 Chinese cities (31). Based on all the evidence, we conclude that nonlinearity in the exposure–response function can explain our findings.

Influence of changing $PM_{2.5}$ components

Another potential explanation for the changing health impacts of $PM_{2.5}$ in the BTH region is that the toxicity of air pollution differed due to changes in pollution sources and particle mixtures (29, 30, 34). Our observation of a reduced exposure–response relationship in the second period suggests that the particle toxicity changed between 2013 and 2018. Recent epidemiologic studies

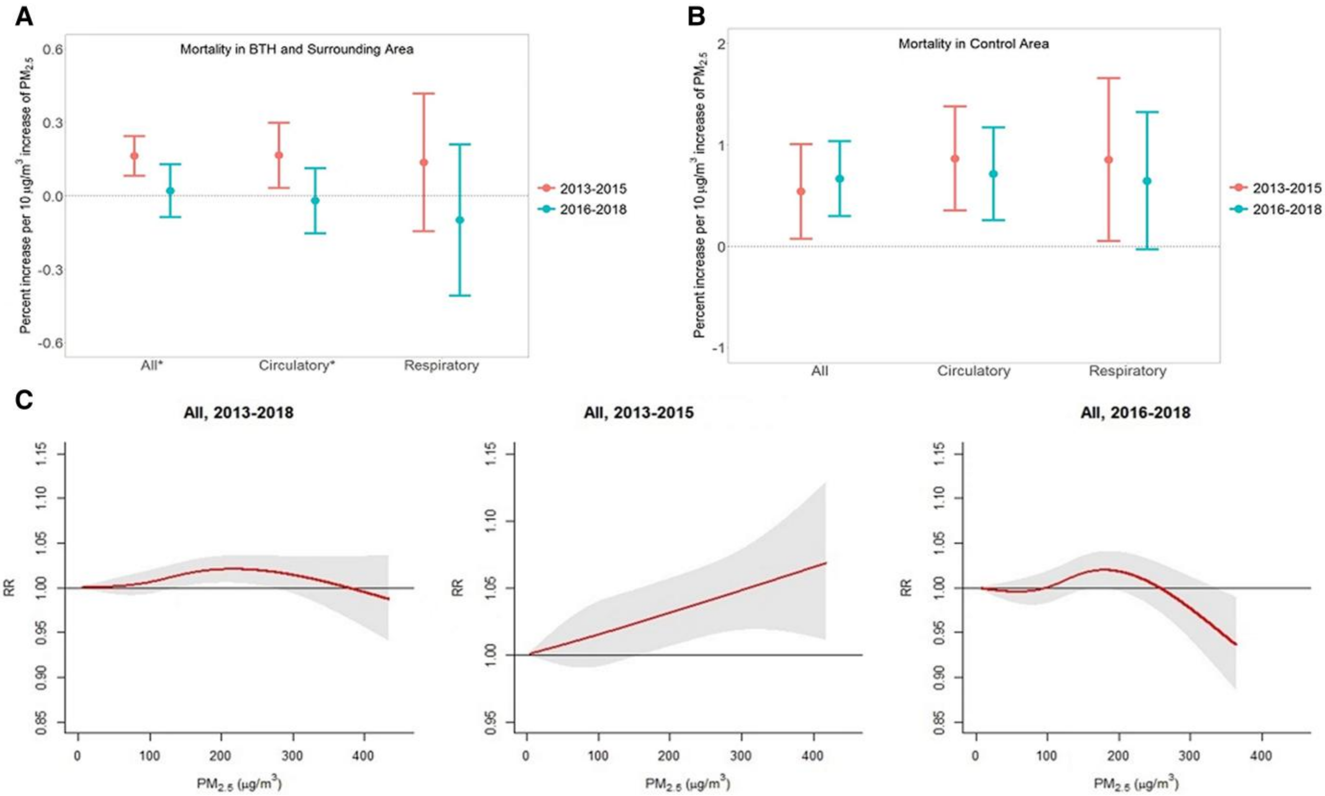

Fig. 3. The effect of $PM_{2.5}$ on mortality in BTH and surrounding areas A) and control areas B) during 2013–2015 and 2016–2018, and exposure–response curves (curves and shading indicate RR and 95% CI) in different study periods C). * indicates that the difference between the groups was statistically significant.

have shown that $PM_{2.5}$ from coal emission sources is more toxic than $PM_{2.5}$ from other noncoal emission sources, and that the health effects of $PM_{2.5}$ from coal emission sources can be more than twice the health effects of overall $PM_{2.5}$ (35–37). In the BTH and the surrounding areas, concentrations of $PM_{2.5}$ altered after multiple air pollution control measures, specifically targeting coal emission sources, were implemented (23, 38, 39). A national modeling study estimated a 37% reduction in primary $PM_{2.5}$ emissions associated with steel and cement production, which are strongly correlated with coal emission. Particularly in the BTH region, $PM_{2.5}$ emissions associated with steel and cement production declined by about 59% from 2013 to 2017, well above the national $PM_{2.5}$ reduction rate (23). Coal emission is the major source of EC (elemental carbon), OC (organic carbon), and other charcoal-containing components, and these components are key components of $PM_{2.5}$ (40), which have been shown to significantly increase the risk of mortality from all-cause, cardiovascular, and respiratory diseases (41–45). For example, Yang et al. showed that for an IQR (interquartile range) increase in EC (0.16 $\mu g/m^3$), the risk of nonaccidental, cardiovascular and respiratory mortality increase 0.45% (95% CI: 0.21–0.69%), 0.68% (95% CI: 0.18–1.18%), and 0.59% (95% CI: 0.09–1.09%), and for an IQR increase in OC (1.0 $\mu g/m^3$), the risk of nonaccidental, cardiovascular and respiratory mortality increase 1.43% (95% CI: 0.97–1.89%), 1.73% (95% CI: 1.04–2.42%), and 1.30% (95% CI: 0.33–2.28%) (43). The evidence of decreased $PM_{2.5}$ concentrations, and stable OC and EC proportions in the BTH area during this study period indicate a similar pace in the decreases of $PM_{2.5}$, OC, and EC, and thus it suggests that the decreased $PM_{2.5}$ concentrations are likely attributable to the reduced concentrations of the OC and EC. Therefore, we consider that the altered health effects of $PM_{2.5}$ are likely attributable to the coal emission and the reduction in the OC and EC.

Influence of changing personal exposure

The reasons for reduced health effects of ambient air pollution might also include decreased personal exposures. During the study period, individual exposure to $PM_{2.5}$ might gradually decrease, especially for heavily polluted areas as a result of the implementation of governmental health promotion actions and residential energy substitution actions against coal, which were two of the important public participation aspects of the National Action Plan. Since several remarkably large haze events occurred in 2013, the Chinese government has made the daily air quality index (AQI) and real-time concentrations of six monitored air pollutants (i.e. CO, O_3, SO_2, NO_2, PM_{10}, $PM_{2.5}$) available to the public (https://air.cnemc.cn:18007/).

Furthermore, information on potential health effects and recommended public protective measures, including the guidance on outdoor activities that correspond to the AQI, has also been disseminated to the public. All of this information has been widely publicized not only in traditional media, such as television, radio, and newspapers, but also on social media platforms, such as Weibo (Chinese Twitter), WeChat, and other mobile phone applications (46). These platforms have played a critical role in increasing the relevant knowledge about air pollution-induced health impacts and relevant behavioral guidelines. In addition, the emergence of social media has prompted widespread public attention to air pollution (46, 47) and has promoted a public behavioral response for health protection from the effects of air pollution in China, especially in regions with heavy pollution (48). A recent study provided evidence that severe ambient air pollution issues induced an increased perception of air pollution risks and positive changes in the personal protective behaviors of the population, leading to decreased personal $PM_{2.5}$ exposure (48). In general, residents in China and particularly in heavily polluted areas have a strong willingness to take personal protective actions during pollution days, such as reducing outdoor activities, wearing masks, and using indoor air purifiers (48). Since 2013, sales of antipollution masks and air purifiers have surged in China; in particular, sales of air purifiers have had a strong increase since 2015 according to the latest electronic equipment market report (49). Furthermore, since 2015, a campaign has been launched to substitute coal with electricity or pipeline-based natural gas (PNG) for heating in rural residences in BTH and the surrounding areas (50). By the end of 2017, more than 3.94 million households covering more than 20,000 villages substituted coal with electricity and PNG in these areas, which reduced the consumption of bulk coal by about 10 million tons (50). In 2018, coal use in another 4 million households was substituted by clean energy in BTH and the surrounding areas. $PM_{2.5}$ from coal combustion sources is associated with an increased risk of hospital admissions or deaths (44), and rural residential coal burning is one of the major components of coal combustion in China and leads to high indoor exposure to $PM_{2.5}$. A recent study in Beijing showed that eliminating coal use in households in high- and middle-income districts markedly reduced indoor $PM_{2.5}$ exposure and increased life satisfaction compared to untreated homes (12). A modeling study in BTH and the surrounding areas showed that even under the 60% substitution scenario, which is projected to be achieved as planned by the clean heating plan for Northern China, indoor $PM_{2.5}$ concentration is expected to significantly decrease from 209 (95% CI: 190–230) $\mu g/m^3$ to 125 (99–150) $\mu g/m^3$ in winter in BTH and the surrounding areas (51).

Strengths

This study has several strengths. First, this is the first study to comprehensively evaluate the health benefits related to the National Action Plan on Air Pollution Prevention and Control in China. Second, we observed a relatively large reduction in $PM_{2.5}$ concentrations and the SO_4^{2-} component ratio in heavily polluted areas. Subsequently, we found a significant decrease in total and circulatory mortalities associated with $PM_{2.5}$ concentrations. Third, we selected control areas with low exposure concentrations and a smaller reduction in $PM_{2.5}$ levels for the additional comparison analysis, which addresses one of the major weaknesses in previous studies, i.e. the lack of a suitable control group. This study demonstrates that there were no significant changes in the mortality risk associated with $PM_{2.5}$ in the control areas, which may strengthen the robustness of our results. Moreover, this study explored the health benefits of the national clean air action over a relatively short period (only 6 years in total) with stable socioeconomic patterns, which provided a good opportunity to identify whether the improved air quality was associated with any health benefits (30).

Limitations

There are also some limitations in our study. First, exposure measurement errors are inevitable in ecological research (52). In order to minimize potential measurement errors, we included all monitoring stations in the area where the target population was located. For the $PM_{2.5}$ composition, we collected $PM_{2.5}$ composition concentration data from three sites in BTH compared to previous studies that could only include a single site. Second, control areas with low $PM_{2.5}$ exposure and fewer concentration changes during the study period were also included in the analysis. However, these areas were also targeted, albeit less intensely, by the National Action Plan. No area in China has been targeted to date. Third, in order to compare the variations of PM2.5-related effects before and after the policy implementation, we divided the study period into two parts, 2013–2015, and 2016–2018. Since it is not possible to capture the exact timing of policy implementation, we conducted a comparative analysis reference to previous studies (27, 28). It is likely that we were unable to capture all the policy impacts since the study period was subjectively divided into two equal parts. To comprehensively evaluate the health benefits of the National Action Plan on Air Pollution Prevention and Control in China, we will continue to gather policy-related data for further analysis. Finally, this study could not avoid the bias effect of planned hospital admission on model fitting results. In order to reduce uncertainty, the fluctuation pattern of daily outpatients of hospitals was evaluated, and hospitals with stable fluctuation patterns and mainly local residents were included.

Public health implications

This study may have important public health implications. High-intensity, long-term, continuous coal emission control measures can result in a significant reduction in $PM_{2.5}$ levels. Long-term policies designed to reduce emissions from major air pollution sources may ultimately reduce adverse health effects such as mortality and morbidity, in addition to the subclinical endpoints that have been mostly frequently studied. This successful experience China has gained may provide useful references for low- and middle-income countries with high ambient air pollution caused by coal burning. The health benefits obtained in the BTH region may guide policy-making on air pollution prevention and control in other regions across China and other similar countries undergoing rapid industrialization.

Conclusions

The study suggests that air pollution control measures implemented recently targeting coal emissions control in China had resulted in significant health benefits. From 2013 to 2018, the average daily $PM_{2.5}$ levels and SO_4^2 component ratio decreased significantly in the BTH region, which was related to coal emission control. Subsequently, the effects of $PM_{2.5}$ on total and circulatory mortalities were significantly reduced. The findings of this study may provide impetus for more accountability research in the future. In particular, further studies should focus on the link of health effects with changes in air pollution sources and/or in personal exposure over time and space.

Materials and methods

Study area and study period

Our study focused on a highly polluted region, which the government designated as a key air pollution control area and named "BTH and the surrounding area" (53), which includes Beijing, Tianjin, Hebei, Shandong, Shanxi, and Henan, where air quality has changed dramatically since the implementation of the National Action Plan (8, 19) (Fig. S1). In this analysis, Guangdong, Fujian, Southern Hunan, and Southern Jiangxi, which had experienced relatively low $PM_{2.5}$ pollution, served as a control area (Fig. S1). Like BTH, this region had a high population density but the $PM_{2.5}$ concentration decreased only moderately—by approximately 10 μg/m^3—from 2013 to 2017 (23).

To quantitatively analyze the health effects of air pollution over time, we selected January 1, 2013 to December 31, 2018 as the study period. We divided the entire study period into two subperiods, 2013–2015 and 2016–2018, to estimate $PM_{2.5}$-related health effects separately and to examine whether the health effects of air pollution had changed during these two subperiods.

Data collection

Here, we primarily focused on the data collection methods in BTH and the surrounding area. Detailed information on the data collection in the control area is shown in the supplementary material.

Mortality and morbidity data

We collected data on mortality, hospital outpatient visits, and hospital admissions between January 1, 2013 and December 31, 2018 in six provinces from BTH and the surrounding area in China. We collected daily mortality data from 47 counties and daily hospital outpatient visits data from 29 general hospitals in BTH and the surrounding area. We also collected daily hospital admission data from all hospitals, and outpatient visits data from one specialized children's hospital in Beijing. The locations of the counties and hospitals are shown in Fig. S1.

Daily county-specific mortality data were obtained from the disease surveillance point system of the Chinese Center for Disease Control and Prevention. We used the International Classification of Disease, tenth revision (ICD-10) codes to categorize the daily counts of cause-specific mortality. The classifications included nonaccidental mortality (ICD-10 codes: A00–R99), circulatory disease mortality (ICD-10 codes: I00–I99), and respiratory disease mortality (ICD-10 codes: J00–J99).

Daily data on hospital-specific outpatient visits were collected from each hospital's information system. ICD-10 codes were also used to categorize the daily counts of cause-specific outpatient visits, including the total outpatient visits, circulatory disease outpatient visits (ICD-10 codes: I00–I99), and respiratory disease outpatient visits (ICD-10 codes: J00–J99).

Daily data on hospital admissions from all hospitals in Beijing were collected from the Beijing Municipal Health Commission Information Center. The daily counts of cause-specific hospital admissions included total nonaccidental hospital admissions (ICD-10 codes: A00–R99), circulatory disease admissions (ICD-10 codes: I00–I99), and respiratory disease admissions (ICD-10 codes: J00–J99). Daily data on hospital outpatient visits were collected from the information system of the Capital Institute of Pediatrics and were categorized into total counts of outpatient visits and respiratory disease outpatient visits (ICD-10 codes: J00–J99).

The study was approved by the Ethics Committee of the National Institute of Environmental Health and Chinese Center for Disease Control and Prevention (201816). Informed consent was obtained from all participants.

Air pollution and meteorological data

Daily ambient $PM_{2.5}$ and O_3 data for the study period were collected from the National Environmental Monitoring System (https://air.cnemc.cn:18007/). The qualified stations were defined as sites with missing records <25% throughout the study period. The daily mortality counts were matched with air pollution data for each of the 47 counties in BTH and the surrounding area. We matched fixed-site environmental monitoring stations with counties by the closest spatial distance to the county center. The daily counts of hospital outpatient visits and hospital admissions were matched with air pollution data for the location (city) of hospitals. All of the available monitoring data from each city were averaged to calculate daily city-level air pollutant concentrations. Daily mean temperature and relative humidity data for the study period were obtained from the Chinese Meteorological Data Sharing Service System (http://data.cma.cn). We matched city-level meteorological data with the mortality and hospital data.

In order to understand the changing trends in air quality, we also obtained gridded annual $PM_{2.5}$ concentrations in BTH and the surrounding area from 2013 to 2018 to describe the interannual changes in $PM_{2.5}$ exposure (Fig. 1), which were estimated from Level-2 Collection 6 Moderate Resolution Imaging Spectroradiometer aerosol optical depth $PM_{2.5}$ data at 10 km resolution. Detailed information on this dataset can be found in Xiao et al. (54).

We collected data on $PM_{2.5}$ components (OC, EC, SO_4^{2-}, NO^{3-}, Cl^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}) in BTH and the surrounding area during the 2013–2018 period. We collected daily $PM_{2.5}$ component data in January, April, July, and October in Chaoyang district in Beijing from 2013 to 2018 with an online monitoring instrument (MARGA ADI 2080, Metrohm and Applikon) and a real-time EC/OC analyzer (US Sunset Lab RT-4) to further explain the causes of changes in $PM_{2.5}$ concentrations and the potential changes in effect estimates. We also collected $PM_{2.5}$ component data in Chang'an and Yuhua districts in Shijiazhuang (the capital of Hebei Province) from 2014 to 2018. The consecutive 24-h sampling was performed from 10:00 AM to 10:00 AM of the next day using a high-volume particle collector with a flow rate of 100 L/min (Thermo Anderson, USA). Routine filter samples of seven days from the 10th to the 16th of each month were collected for $PM_{2.5}$ component laboratory analysis.

The relationship between $PM_{2.5}$ and health outcomes

The relationships between $PM_{2.5}$ and health outcomes were estimated for two separate periods: 2013–2015 and 2016–2018. A two-stage analysis strategy was developed to assess the effects of $PM_{2.5}$ on mortality in the 47 counties. In stage 1, we employed a quasi-Poisson regression model to estimate the associations between $PM_{2.5}$ concentrations and mortality for each county; the model included a natural cubic spline of time with five degrees of freedom (*df*) per year to exclude long-term and seasonal trends in mortality and hospital outpatient visits, a natural cubic spline of three *df* for the potential confounder of temperature, and a natural cubic spline of three *df* for the potential confounder of relative humidity. The days of the week was served as an indicator variable. We estimated the association between $PM_{2.5}$ concentrations and mortality with a maximum lag of 0–1 days, which was the average of the concentrations on the current day (lag 0) and the previous day (lag 1). In stage 2, a random effects meta-analysis was conducted with maximum likelihood estimation to pool the county-specific results into an overall estimated effect. The effects of $PM_{2.5}$ on mortality were expressed as excess risks with corresponding 95% CIs associated with a 10 μg/m^3 increase in $PM_{2.5}$ concentration.

We performed sensitivity analyses to examine the robustness of the results. We adjusted for same-day O_3 concentrations in the two pollutants model. We also modified the *df* of the meteorological variables ($df = 5$) and time of year ($df = 7$). The data were analyzed using the R statistical software (version 3.6.6); the "metafor" package was used for the meta-analysis.

Similar analysis was used to estimate the effect of $PM_{2.5}$ on hospital outpatient visits, including the two-stage analysis and sensitivity analysis strategy. Public holidays were added as an indicator variable in the first-stage model.

In addition, we explored a nonlinear effect model for the combined exposure–response relationship curves to further understand the shape of the $PM_{2.5}$ and mortality or morbidity curves during different periods in BTH and the surrounding area. The detailed methods of the nonlinear effect model are shown in the supplementary materials.

The statistical analysis of hospital admissions and hospital outpatient visits in the children's hospital in Beijing is also shown in the supplementary materials.

Test of the differences in the effect estimates

We tested for significant differences in the health effect estimates associated with $PM_{2.5}$ concentrations between the two subperiods (2013–2015 and 2016–2018) using the following equation:

$$Z = \frac{\beta_{2013-2015} - \beta_{2016-2018}}{\sqrt{se(\beta_{2013-2015})^2 + se(\beta_{2016-2018})^2}} \quad (1)$$

where $\beta_{2013-2015}$ and $\beta_{2016-2018}$ are the coefficients of the exposure–response relationship between $PM_{2.5}$ and health effects for 2013–2015 and 2016–2018, respectively, and $se(\beta_{2013-2015})$ and $se(\beta_{2016-2018})$ are the standard errors of the coefficients for 2013–2015 and 2016–2018, respectively. We performed a one-tailed test with a significance level of $\alpha = 0.05$ because we previously observed decreasing effects from 2013–2015 to 2016–2018 (Fig. 2).

Control comparison

In the control area, we analyzed the $PM_{2.5}$–mortality relationship from 2013–2015 and from 2016–2018; the statistical methods for this analysis were the same as those described for the 47 counties in BTH and the surrounding area. We then compared the changes in the effect estimates in the two subperiods between BTH and the surrounding area and the control area.

Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

Funding

This study was supported by the National Research Program for Key Issues in Air Pollution Control (grant nos. DQGG0401 and DQGG0401-04) and the National Key Research and Development Program of China (grant nos. 2016YFC0206500 and 2022YFC3702700).

Author Contributions

T.L. and X.S. designed research. T.L., C.C., M.Z., L.Z., Y.L., Y.G., Q.W., H.D., Q.X., Y.L., and M.Z.H. analyzed data. P.L.K., A.J.C., and S.T., critically reviewed and provided significant intellectual input into the manuscript. T.L. wrote the paper. All authors revised the paper.

Data Availability

The datasets supporting the current study cannot be directly shared in a public repository because they contain personally identifable information from human subjects. These data and R codes may be made available from the corresponding author on reasonable request. A proposal with a detailed description of the study objectives and statistical analysis plan will be needed to evaluate the reasonability of the requests.

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