

The dual impact of carbon neutrality and population aging on PM_{2.5}-related mortality and economic burden in China

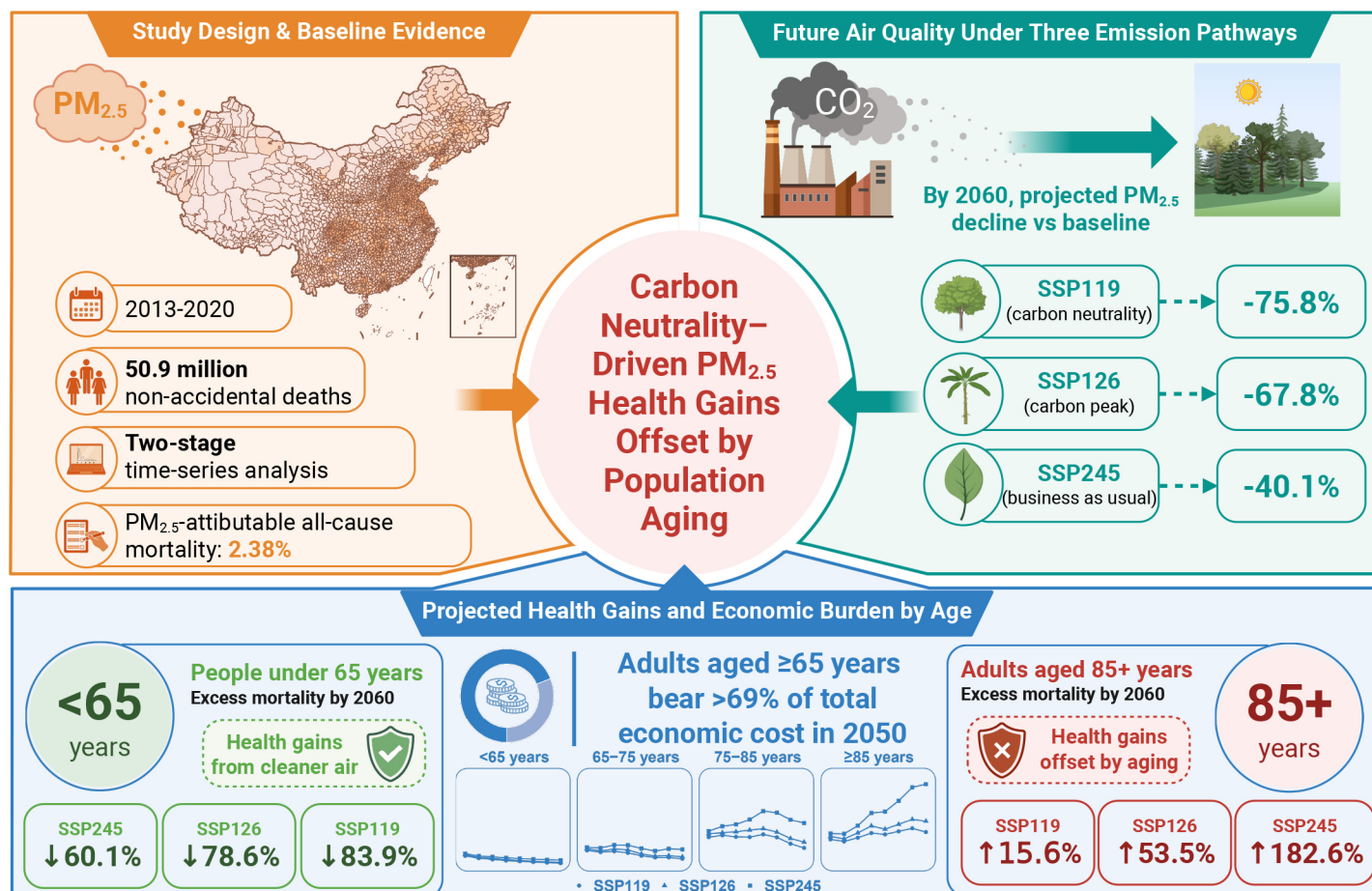
Jianhui Guo,^{1,2,10} Lin Lin,^{3,10} Petros Koutrakis,⁴ Jianlin Hu,⁵ Shaocong Xie,^{6,7,11} Carolina L. Zilli Vieira,⁴ Yi Fan,^{8,9} Zhaokun Wang,^{8,9} Yaqi Wang,^{1,2} Xinyao Lian,^{1,2} Jinling You,³ Lijun Wang,³ Maigeng Zhou,^{3,11} Jing Li,^{1,2,*} Shaodan Huang,^{8,9,*} and Peng Yin^{3,*}

*Correspondence: yinpeng@ncncd.chinacdc.cn (P.Y.); shhuang@bjmu.edu.cn (S.H.); jing.li@hsc.pku.edu.cn (J.L.)

Received: February 18, 2026; Accepted: September 10, 2026; Published Online: September 12, 2026; <https://doi.org/10.59717/j.xinn-med.2026.100259>

© 2026 The Author(s). This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>).

GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Achieving carbon neutrality could reduce PM_{2.5}-related mortality by about 84% among those aged <65 years.
- By 2050, older adults are expected to account for more than 69% of PM_{2.5}-related economic losses.
- Rapid aging will offset health gains from carbon neutrality in older adults.

The dual impact of carbon neutrality and population aging on PM_{2.5}-related mortality and economic burden in China

Jianhui Guo,^{1,2,10} Lin Lin,^{3,10} Petros Koutrakis,⁴ Jianlin Hu,⁵ Shaodong Xie,^{6,7,11} Carolina L. Zilli Vieira,⁴ Yi Fan,^{8,9} Zhaokun Wang,^{8,9} Yaqi Wang,^{1,2} Xinyao Lian,^{1,2} Jinling You,³ Lijun Wang,³ Maigeng Zhou,^{3,11} Jing Li,^{1,2,*} Shaodan Huang,^{8,9,*} and Peng Yin^{3,*}

¹Institute of Child and Adolescent Health, School of Public Health, Peking University, Beijing 100191, China

²National Health Commission Key Laboratory of Reproductive Health, Peking University, Beijing 100191, China

³National Center for Chronic and Noncommunicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention, Beijing 100050, China

⁴Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston MA 02115, USA

⁵School of Environmental Science and Engineering, Nanjing University of Information Science & Technology, Nanjing 210044, China

⁶State Key Joint Laboratory of Environment Simulation and Pollution Control, Peking University, Beijing 100871, China

⁷College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China

⁸Department of Occupational and Environmental Health Sciences, School of Public Health, Peking University, Beijing 100191, China

⁹Key Laboratory of Epidemiology of Major Diseases (Peking University), Ministry of Education, Beijing 100191, China

¹⁰These authors contributed equally

¹¹The senior author supervised the work

*Correspondence: yinpeng@nncdc.chinacdc.cn (P.Y.); shuang@bjmu.edu.cn (S.H.); jing.li@hsc.pku.edu.cn (J.L.)

Received: February 18, 2026; Accepted: September 10, 2026; Published Online: September 12, 2026; <https://doi.org/10.59717/j.inn-med.2026.100259>

© 2026 The Author(s). This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>).

Citation: Guo J, Lin L, Koutrakis P, et al. (2026). The dual impact of carbon neutrality and population aging on PM_{2.5}-related mortality and economic burden in China. *The Innovation Medicine* 4:100259.

Despite considerable regulatory interventions to mitigate air pollution, fine particulate matter (PM_{2.5}) remains a critical health threat across China. Carbon neutrality strategies, though primarily aimed at mitigating climate change, may also yield substantial co-benefits for air quality and public health. However, the scale of these benefits may be undermined by rapid population aging. Here, we used a two-stage time-series analysis to quantify the exposure-response relationship between short-term PM_{2.5} exposure and mortality, using 50.9 million non-accidental deaths in mainland China. We then applied an air quality model to project future PM_{2.5} concentrations and estimate the associated disease burden under three carbon emissions scenarios. From 2013 to 2020, short-term PM_{2.5} exposure was attributable to 2.38% of all-cause mortality. By 2060, PM_{2.5} concentrations are projected to decline by 75.8%, 67.8%, and 40.1%, respectively, under three emission pathways: SSP119 (carbon neutrality), SSP126 (carbon peaking), and SSP245 (business as usual), compared with the baseline period. Consequently, excess mortality among individuals under 65 years of age is expected to decrease by 83.9%, 78.6%, and 60.1%, respectively. However, among adults aged 85 and over, PM_{2.5}-attributable mortality is projected to increase by 15.6%, 53.5%, and 182.6%, respectively. By 2050, older adults are expected to account for more than 69% of PM_{2.5}-related economic costs under the SSP119 scenario, reflecting the growing age-related burden in all scenarios. These findings underscore the health and financial benefits of achieving carbon neutrality and highlight the need to integrate demographic change into future climate and air quality policy frameworks.

INTRODUCTION

China has implemented stringent air pollution control policies, most notably the Air Pollution Prevention and Control Action Plan (2013), which reduced national fine particulate matter (PM_{2.5}) concentrations by over 30% within five years and substantially lowered air pollution-related morbidity.^{1,2} Despite this progress, nearly all regions in China still exceed the WHO Air Quality Guidelines (AQG) for PM_{2.5}.³ The public health and economic burdens associated with PM_{2.5} are still expected to intensify due to population aging and growth in China.⁴⁻⁶ Evidence suggests that the economic costs of air pollution for elderly populations doubled between 2000 and 2016.⁷ However, due to rapid population aging and ongoing population growth, the public health and financial burdens associated with PM_{2.5} are projected to persist or even worsen, despite cleaner air.⁷

Carbon emissions are closely linked to air pollution, as carbon dioxide (CO₂)-emitting processes typically co-emit hazardous pollutants, including PM_{2.5} and ozone (O₃).^{8,9} Substantial evidence indicates that decarbonization strategies, particularly reductions in fossil fuel combustion, can simultaneously reduce greenhouse gas emissions and air pollutants, and potentially prevent

millions of premature deaths globally through the associated decline in PM_{2.5} exposure.¹⁰⁻¹² As the world's leading carbon emitter, China has adopted comprehensive carbon-reduction policies that not only align with global mitigation trends but also address its domestic air pollution challenges. In September 2020, the Chinese government unveiled its carbon neutrality strategy, committing to achieving a peak in carbon emissions before 2030 and achieving carbon neutrality by 2060.¹³ Given the dual benefits of carbon neutrality policies for both climate and air quality, it is essential to further quantify their potential health impacts from improved air quality, particularly on PM_{2.5}-related burdens, to inform the evaluation of current mitigation measures and guide future policy development.

Some existing studies have projected PM_{2.5}-related mortality under various climate and air pollution control scenarios.¹⁴⁻²⁰ For example, one study used climate projections from the Coupled Model Intercomparison Project Phase 6 and national-level mortality rates from the Global Burden of Disease Study to estimate long-term PM_{2.5}-related deaths worldwide.¹⁴ Another study applied a regional air quality model to project PM_{2.5} levels in China in 2030 and calculated mortality based on national statistics and long-term exposure-response functions from previous studies.¹⁶ However, many challenges remain.²⁰ First, few have focused on the short-term health burden attributable to PM_{2.5} within the policy of carbon neutrality.²¹ In addition, estimates of PM_{2.5}-reduction benefits predominantly rely on exposure-response relationships derived from prior studies, often involving non-local populations, which may introduce systematic biases and compromise the validity of both policy decisions and public health interventions.^{14-17,22} Moreover, few studies have integrated future demographic transitions, especially population aging, into scenario-based projections of PM_{2.5}-related health burdens.^{14,20} Failure to incorporate demographic transitions, especially population aging, may result in systematic overestimation of the health co-benefits of emission reductions, particularly among vulnerable age groups.

To address these knowledge gaps, we comprehensively assessed excess mortality and the associated economic burden resulting from short-term PM_{2.5} exposure across all-cause, cardiovascular, and respiratory mortality, spanning both historical and projected future periods. First, age-specific exposure-response relationships were derived using a two-stage time-series model. Second, future PM_{2.5} concentrations were projected under three carbon-emission scenarios: SSP119 (carbon neutrality), SSP126 (carbon peaking), and SSP245 (business-as-usual), while demographic changes were considered independently. Third, integrating pollution levels, population structures, and exposure-response functions, we estimated future excess mortality and corresponding economic costs. Particular attention was given to the potential influence of population aging on excess mortality risks and their financial burdens.

MATERIALS AND METHODS

Study and population

This study included 50.9 million non-accidental deaths recorded in 351 cities across 31 provinces, autonomous regions, and municipalities in mainland China, spanning January 2013 to December 2020 (Figure S1). Among these, 25.3 million deaths were attributed to cardiovascular diseases and 5.8 million to respiratory diseases. Mortality data were obtained from the cause-of-death surveillance system managed by the Chinese Center for Disease Control and Prevention (CDC), which recorded the underlying cause of death, date of death, usual residential address, and socio-demographic details of the deceased. Causes of death were coded according to the 10th revision of the International Classification of Diseases (ICD-10): non-accidental deaths (A00-R99), cardiovascular diseases (I00-I99), and respiratory diseases (J00-J98). This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guideline.

PM_{2.5} and meteorological data

Daily PM_{2.5} concentrations from 2013 to 2020 were retrieved from the China High Air Pollutant (CHAP) dataset, which provides high-resolution data at a 1 km × 1 km grid.²³ Daily sulfur dioxide (SO₂) and nitrogen dioxide (NO₂) concentrations were also obtained from the CHAP dataset, with a spatial resolution of 10 km × 10 km for 2013-2018 and 1 km × 1 km for 2019-2020.^{24,25} Daily ozone (O₃) concentrations were obtained from the Tracking Air Pollution in China (TAP) dataset at a 10 km × 10 km spatial resolution.²⁶ Temperature and humidity data for the same period were drawn from the ECMWF ReAnalysis 5th generation-Land dataset.²⁷ City-level daily PM_{2.5}, temperature, and humidity were computed to match the mortality data.

Prediction of future PM_{2.5} concentrations

We used CO₂ emission scenarios from the Dynamic Projection Model for Emissions in China (DPEC) to drive simulations of future PM_{2.5} concentrations.²⁸ The DPEC model provides emission projections from 2010 to 2060 based on varying socio-economic conditions, climate strategies, and pollution control policies. Three scenarios were selected: SSP119, reflecting China's carbon-neutral policy path; SSP126, representing peak carbon policy targets; and SSP245, a business-as-usual trajectory. We applied the offline-coupled Weather Research and Forecasting (WRF; version 3.9.1)-Community Multiscale Air Quality (CMAQ; version 5.2) modeling system to simulate future PM_{2.5} levels through 2060 for each scenario. The simulations covered mainland China at a horizontal resolution of 36 km; WRF used 28 vertical layers for meteorological fields, while CMAQ used 14 vertical layers for chemical transport.

Prediction of population

Future population data were obtained from a previous study that reanalyzed China's projected annual population using global population forecasts and incorporated the potential impact of recent fertility-promoting policies.²⁹ Three scenarios were considered: SSP1 (low fertility), reflecting a sustainable development pathway; SSP2 (medium fertility), representing a continuation of historical trends; and SSP3 (high fertility), a scenario driven by regional competition. Population projections were aggregated for each province and age group, with additional breakdowns by sex and education level.

Exposure-response relationship between short-term exposure to PM_{2.5} and mortality, and its excess mortality risk

We assessed the relationship between short-term PM_{2.5} exposure and mortality using a two-stage analytical approach commonly employed in multi-regional epidemiological studies, which accounts for both within-region statistical error and between-region variability.³⁰⁻³² In the first stage, we used a generalized linear model with quasi-Poisson regression to estimate the city-specific linear association between PM_{2.5} exposure and mortality. The optimal exposure window was selected using the Quasi-Akaike Information Criterion (QAIC). Covariates in the model included long-term trends (adjusted using a natural cubic spline with 7 degrees of freedom [df] per year), day-of-week, 4-day average temperature (lag 0-3 days, natural cubic spline with 6 df), and 4-day average humidity (lag 0-3 days, natural cubic spline with 3 df), based on parameters informed by prior studies.^{30,31,33} The 2-day average

exposure (lag 0-1), representing PM_{2.5} levels on the day of death and the preceding day, was identified as the optimal exposure window by QAIC and supported by earlier research. We also conducted sensitivity analyses using two-pollutant models with additional adjustment for the 2-day moving-average concentrations (lags 0-1) of SO₂, O₃, and NO₂, respectively.

In the second stage, we performed a random-effects meta-analysis to pool the city-specific estimates; the corresponding heterogeneity statistics are shown in Table S1. Additionally, we applied the same two-stage framework to derive a nonlinear exposure-response curve by replacing the linear pollutant term with a natural spline function (3 knots at the 25th, 50th, and 75th percentiles of PM_{2.5} exposure) in the first-stage model.

Future excess mortality associated with short-term PM_{2.5} exposure under different carbon emission scenarios and population growth patterns

We estimated future excess mortality associated with short-term PM_{2.5} exposure using a two-stage analytical protocol based on cumulative relative risk (RR) over a lag of 0-1 days. The number of excess deaths was calculated using the following equation:

$$ED_{jt} = (1 - \exp(-\beta_j(x_{jt} - c)_+)) \times d_{jt} \quad (1)$$

where ED_{jt} denotes the attributable excess deaths in city j on day t . β_j denotes the log relative risk (log RR) per 1 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5}, defined as the best linear unbiased prediction for city j ; d_{jt} and x_{jt} denote the number of daily mortalities on day t , and the average PM_{2.5} concentration on that day and the previous day, respectively. $(x_{jt} - c)_+$ denotes the PM_{2.5} concentration that exceeds the limit value c .^{30,34,35} In this study, we set the thresholds at 0 $\mu\text{g}/\text{m}^3$ and 37.5 $\mu\text{g}/\text{m}^3$, corresponding to WHO Interim Target-3 (WHO IT-3), because IT-3 is the WHO-recommended and most realistic threshold for PM_{2.5} health impact assessment.

We first calculated baseline mortality rates for each age group at both the national and provincial levels using 2020 data, by dividing the number of deaths in each age group by the corresponding age-specific population across the 31 provinces. These 2020 baseline mortality rates were then used to estimate national and province-specific PM_{2.5}-related excess mortality for 2020 and to project excess mortality from 2025 to 2060 at five-year intervals (2025, 2030, 2035, 2040, 2045, 2050, 2055, and 2060). These projections incorporated PM_{2.5} concentrations derived from three emission scenarios (SSP119, SSP126, and SSP245) and three population growth trajectories (SSP1, SSP2, and SSP3). To further examine how population aging and regional pollution levels might influence future excess mortality, we compared mortality trends across age groups and regions under each scenario. Uncertainty intervals (UI) for the projected excess mortality were estimated using a Monte Carlo simulation based on the uncertainty of the exposure-response coefficients.

Economic costs associated with short-term PM_{2.5}-attributable mortality

We estimated the economic costs of mortality from short-term PM_{2.5} exposure using an age-adjusted value for a statistical life-year (VSLY). First, we obtained the age-adjusted VSLY for China from 2011 to 2016, as reported in a previous study.⁷ The baseline VSL was derived from the average value used in OECD countries (US\$3.54 million) and adjusted for each country's per capita GDP. This value was then further refined by applying age-specific wealth weights and remaining life expectancy, yielding the final age-adjusted VSLY. Second, per capita GDP data for 2011-2020 were collected from China's national and provincial statistical yearbooks, while projected GDP per capita values for future years (2025, 2035, and 2050) were taken from the China Energy Foundation.³⁶ Life expectancy figures were obtained from the life table database in the GBD 2021 study.³⁷

To estimate economic losses, we first projected the national age-adjusted VSLY using 2011 GDP per capita as the baseline (Equation 2), then calculated province-specific VSLY values for 2013-2020 based on national VSLY and regional GDP data (Equation 3). Mortality counts, life expectancy, and age-adjusted VSLY were combined by age group and year at both national and provincial levels. Final economic costs were computed by multiplying attributable deaths by the age-adjusted VSLY, expressed in 2011 purchasing power parity (PPP) dollars (Equation 4).

Table 1. Percentage change in all-cause, cardiovascular, and respiratory mortality per 10 µg/m³ increase in 2-day moving average PM_{2.5} concentrations at the national level.

Age group	Pooled estimate (95% confidence interval), %		
	All-cause mortality	Cardiovascular mortality	Respiratory mortality
All participants	0.55 (0.37, 0.74)	0.63 (0.42, 0.83)	0.52 (0.34, 0.71)
<65 years	0.36 (0.25, 0.46)	0.34 (0.22, 0.45)	0.17 (-0.02, 0.35)
65-75 years	0.48 (0.31, 0.65)	0.47 (0.32, 0.63)	0.46 (0.29, 0.63)
75-85 years	0.61 (0.41, 0.81)	0.64 (0.42, 0.87)	0.47 (0.30, 0.64)
≥85 years	0.75 (0.53, 0.97)	0.78 (0.56, 1.00)	0.69 (0.46, 0.92)

$$Age_VSLY_{j,a,c} = Age_VSLY_{2011,a,c} \times \left(\frac{GDP_{j,c}}{GDP_{2011,c}} \right)^e \tag{2}$$

where, $Age_VSLY_{j,a,c}$ is the age-adjusted value of a statistical life year for China, $GDP_{j,c}$ is the GDP per capita for China in year j . e is the elasticity of income in VSL.

$$Age_VSLY_{j,a,i} = Age_VSLY_{j,a,c} \times \left(\frac{GDP_{j,i}}{GDP_{j,c}} \right)^e \tag{3}$$

where, $Age_VSLY_{j,a,i}$ is the age-adjusted value of a statistical life year for each province in China, $GDP_{j,i}$ is the GDP per capita for province i in year j . e is the elasticity of income in VSL. Following previous studies, we assigned an income elasticity of $e = 0.8$ to provinces with per-capita GDP above the national average, and $e = 1.4$ to those with per-capita GDP below the national average.

$$Age_VSLY_EC_{i,j,k,a} = D_{i,j,k,a} \sum_{t=0}^{LE_{c,j,a}-1} \frac{Age_VSLY_{i,j,a+t}}{(1+r)^t} \tag{4}$$

where, $Age_VSLY_EC_{i,j,k,a}$ represents the economic cost of attributable mortality due to cause k on the population age a in province or national i , year j using the age-adjusted VSLY measure ($Age_VSLY_{i,j,a+t}$), and $LE_{c,j,a}$ is life expectancy at age a in year j , and China (c), t refers to t^{th} year after the age of attributable death a , and r is the discount rate. Following previous studies, we applied a differential r based on provincial economic conditions: 0.04 to provinces with per-capita GDP at or above the national average, and 0.06 to those below.⁷

RESULTS
Association between short-term exposure to PM_{2.5} and mortality

This study analysed 50.9 million non-accidental deaths. Findings from the two-stage analytical protocol (Table 1 and Figure 1A) showed that, for the overall population, each 10 µg/m³ increase in the 2-day moving average concentration of PM_{2.5} (identified as the most suitable exposure window) was linked to a 0.55% increase in all-cause mortality risk (95% confidence interval [CI]: 0.37-0.74%), a 0.63% increase in cardiovascular mortality risk (95% CI: 0.42-0.83%), and a 0.52% increase in respiratory mortality risk (95% CI: 0.34-0.71%). The associations of PM_{2.5} with all-cause, cardiovascular, and respiratory mortality were robust to additional adjustment for SO₂, O₃, and NO₂ in the two-pollutant models (Table S2). The exposure-response curve revealed no clear threshold (Figure 1B). Mortality risk associated with PM_{2.5} exposure increased with age (Table 1 and Figure 2A). For all-cause non-accidental deaths, each 10 µg/m³ increase in the 2-day average PM_{2.5} concentration was associated with a 0.36% increase in mortality risk (95% CI: 0.25-0.46%) for individuals under 65, a 0.48% increase (95% CI: 0.31-0.65%) for those aged 65~75, a 0.61% increase (95% CI: 0.41-0.81%) for those aged 75~85, and a 0.75% increase (95% CI: 0.53-0.97%) in those aged 85 and older.

Pooled estimates represent the percentage changes in daily all-cause, cardiovascular, and respiratory mortality per 10 µg/m³ increase in particulate matter concentrations with an aerodynamic diameter of 2.5 µm or less (PM_{2.5}).

PM_{2.5} exposure-related excess mortality from 2013 to 2020

In the overall population, short-term exposure to PM_{2.5} accounted for 2.38% (95% empirical confidence interval [eCI]: 2.28-2.48%) of all-cause excess

mortality, 2.58% (95% eCI: 2.46-2.69%) of cardiovascular mortality, and 2.46% (95% eCI: 2.28-2.62%) of respiratory mortality. The proportion of excess mortality attributed to PM_{2.5} levels above 37.5 µg/m³ (WHO IT-3) is presented in Table S3, with estimates of 1.63% (95% eCI: 1.55-1.69%) for all-cause mortality, 1.73% (95% eCI: 1.66-1.80%) for cardiovascular mortality, and 1.68% (95% eCI: 1.56-1.80%) for respiratory mortality. These results indicate that, a substantial proportion of PM_{2.5}-related excess mortality occurred at exposure levels below the WHO IT-3 threshold during the study period. The excess mortality fraction increased with age (Table S3). For individuals aged 85 years or older, the excess mortality fractions for all-cause, cardiovascular, and respiratory mortality were 2.1-, 2.3-, and 4.3-fold higher, respectively, than for individuals under 65 years (Table S4). Across all age groups and causes, the excess mortality fraction declined over time (Figure 2B). At the provincial level, Chongqing, Ningxia, and Guangdong had the highest excess all-cause mortality fractions, with estimates of 5.88% (95% eCI: 3.80-7.96%), 5.85% (95% eCI: 5.12-6.60%), and 5.06% (95% eCI: 4.89-5.25%), respectively (Table S4). In all provinces, excess mortality fractions from short-term PM_{2.5} exposure also rose with age (Figures 2C & S2). Over time, a general decline in excess mortality fractions was observed at the provincial level (Figures S3 & S4).

Prediction of population growth patterns and PM_{2.5} levels under different carbon emission scenarios

China's aging trend is projected to continue, with individuals aged 65 and older expected to make up 31.9% of the total population by 2060 (Figure 3A). The bias-corrected PM_{2.5} simulations showed good agreement with observations, with $r = 0.897$, $R^2 = 0.805$, $RMSE = 7.793$ µg/m³, $MAE = 4.940$ µg/m³, $MB = -1.551$ µg/m³, and $NMB = -3.89\%$. These results indicate that the bias-corrected model reasonably reproduced the observed PM_{2.5} concentrations. Based on this validated modeling framework, national average PM_{2.5} concentrations are projected to decline under all emission scenarios. By 2060, average concentrations are expected to decline to 7.16 µg/m³ under SSP119, 9.5 µg/m³ under SSP126, and 17.7 µg/m³ under SSP245, corresponding to reductions of 75.8%, 67.8%, and 40.1%, respectively, from baseline levels (Figure 3B). At the provincial level, PM_{2.5} concentrations are projected to decline across all regions, with the most significant improvements under the SSP119 scenario (Figure S5).

Prediction of PM_{2.5} exposure-related excess mortality under different carbon emission scenarios and population growth patterns

We projected temporal trends in excess mortality associated with short-term PM_{2.5} exposure across various emission scenarios, showing lower excess all-cause mortality under SSP119 and markedly higher excess mortality under SSP245, with the burden increasing with age, particularly among older adults (Figure 4, Tables S3-S5, Figures S6 & S7). Specifically, under the SSP119 scenario, by 2060, excess all-cause mortality attributable to PM_{2.5} exposure among individuals aged <65 years is projected to decline by 83.9%, from 19,941.7 (95% UI: 18,976.2 to 20,885.8) to 3,213.8 (95% UI: 2,231.1 to 4,244.5). Mortality is also projected to decrease by 62.0% among those aged 65-75 years and by 40.4% among those aged 75-85 years. In contrast, among individuals aged ≥85 years, excess all-cause mortality is projected to increase by 15.6%, from 44,824.1 (95% UI: 43,012.3 to 46,508.8) to 51,823.5 (95% UI: 36,601.8 to 67,217.0). Under the SSP245 scenario, excess all-cause mortality attributable to PM_{2.5} exposure among individuals

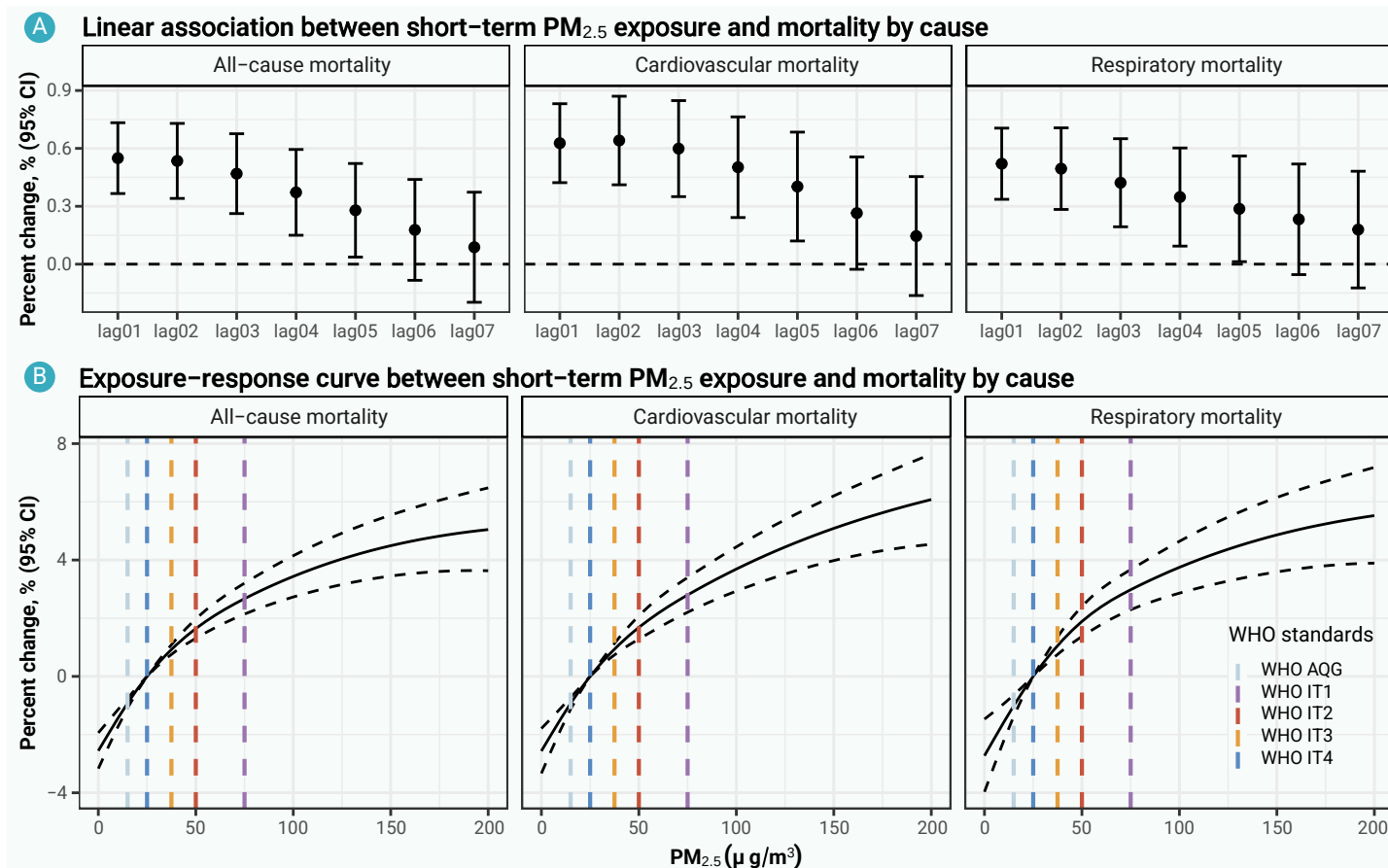


Figure 1. Association between short-term PM_{2.5} exposure and all-cause, cardiovascular, and respiratory mortality (A) Percentage change and 95% confidence interval in all-cause mortality, cardiovascular mortality, and respiratory mortality per 10 μg/m³ increase in the n-day moving average of PM_{2.5} concentrations at the national level. Points represent the estimated percentage changes, and error bars indicate 95% confidence intervals. (B) Pooled exposure-response curves for the associations between 2-day moving average PM_{2.5} concentrations and daily mortality. Solid lines represent the pooled estimates, and black dashed lines indicate the corresponding 95% confidence intervals. Colored vertical dashed lines indicate the World Health Organization (WHO) Air Quality Guideline and the four WHO interim targets (IT-1, IT-2, IT-3, and IT-4).

aged <65 years is projected to decrease by 60.1%, to 7,955.6 (95% UI: 5,439.8 to 10,283.9). By contrast, mortality is projected to decrease by 6.0% among those aged 65–75 years and increase by 45.4% among those aged 75–85 years. Among individuals aged ≥85 years, excess all-cause mortality is projected to rise by 182.6%, reaching 126,666.3 (95% UI: 85,700.7 to 166,300.0) (Table S5). The results for excess circulatory-cause and respiratory-cause mortality were consistent with those for excess all-cause mortality (Table S5, Figures S6 & S7). Figure 4B and Table S6 also present provincial-level changes in PM_{2.5}-related excess mortality across different emission scenarios.

Economic costs associated with short-term PM_{2.5}-attributable mortality in 2020 and under different emission scenarios

We estimated the age-adjusted VSLY at the national level for 2011–2016 and projected these through 2050, along with province-specific age-adjusted VSLY values for 2013–2020 (Figures 5A & S8). In 2020, the economic cost of all-cause mortality attributable to short-term PM_{2.5} exposure reached \$873.1 billion, a 23.4% increase from \$707.6 billion in 2013. Costs increased across all age groups, rising by 6.7% among individuals aged <65 years, from \$505.7 billion (95% UI: 473.9–535.0) to \$539.8 billion (95% UI: 513.7–565.4), with progressively larger increases observed with age. The largest increase occurred among those aged ≥85 years, for whom the cost rose from \$13.7 billion (95% UI: 13.0–14.4) to \$28.1 billion (95% UI: 27.0–29.2), representing a 104.7% increase (Figure 5B and Table S7). Economic costs varied substantially across provinces, with Guangdong, Shandong, and Jiangsu experiencing the highest burdens in 2020 (Figure 5C and Table S7). At lower PM_{2.5} concentrations (WHO IT-3), the relative economic costs of excess mortality increased (Figure S9). By 2050, under the SSP119 scenario, the national

economic costs attributable to PM_{2.5}-related all-cause, cardiovascular, and respiratory mortality are projected to reach \$920.2 billion, \$462.0 billion, and \$61.0 billion, respectively, reflecting increases of 5.4%, 20.3%, and 53.5% relative to 2020 levels. In contrast, under the SSP126 and SSP245 scenarios, economic burdens are expected to increase significantly (Figures 5 & S10–S11, Table S8). When broken down by age group, the economic burden of PM_{2.5}-related mortality is projected to decline by more than 47.3% for individuals under 65. However, for those aged 65 and older, the burden is expected to rise sharply, with increases reaching up to 248.3%. By 2050, people under 65 will account for just 30.9%, 22.5%, and 8.5% of total economic costs for all-cause, cardiovascular, and respiratory mortality, respectively. In contrast, individuals aged 65 and above will bear 69.1%, 77.5%, and 91.5% of the economic burden from all-cause, cardiovascular, and respiratory mortality, respectively (Figures 5 & S10–S11, Table S8).

DISCUSSION

In this nationwide study, we employed a two-stage analysis involving 50.9 million deaths to assess the risks of excess mortality and the economic costs associated with short-term PM_{2.5} exposure, both during the historical period and under projected carbon-emission scenarios. The results indicated that PM_{2.5} exposure was associated with increased risks of all-cause, cardiovascular, and respiratory mortality, with no clear exposure threshold. The magnitude of this association grew with age. By 2060, under the SSP119 scenario, excess all-cause mortality is projected to decline by 83.9%, 62.0%, and 40.4% among individuals aged <65, 65–75, and 75–85 years, respectively, but to increase by 15.6% among those aged ≥85 years. Between 2013 and 2020, the economic burden of all-cause mortality attributable to short-term PM_{2.5} exposure increased by 23.4%. Relative to 2020 levels, these costs are

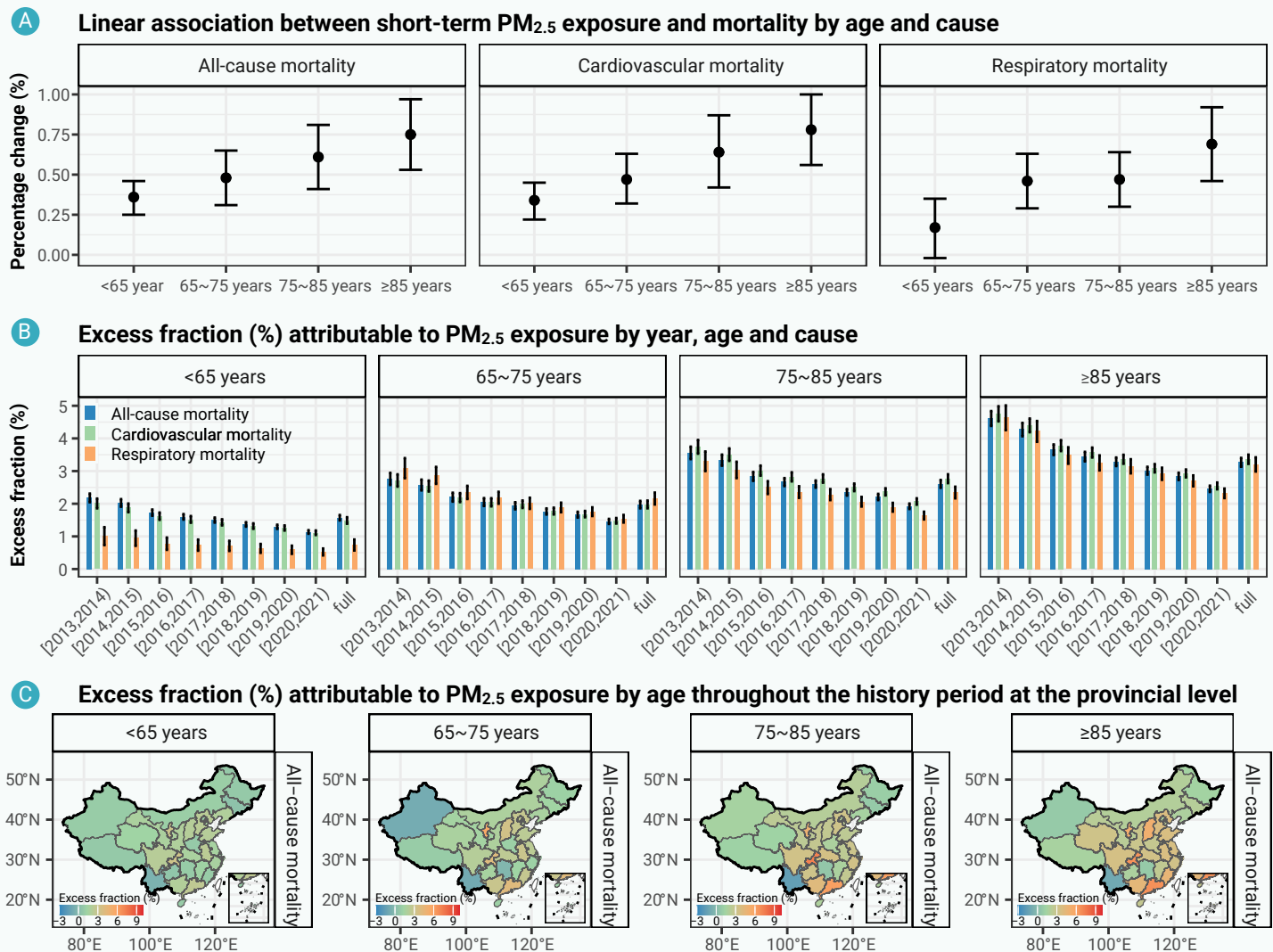


Figure 2. Association between short-term PM_{2.5} exposure and mortality, and excess fraction attributable to PM_{2.5} exposure by age and cause (A) Percentage change in all-cause, cardiovascular, and respiratory mortality per 10 µg/m³ increase in the n-day moving average of PM_{2.5} concentrations by age at the national level. Points represent the estimated percentage changes, and error bars indicate 95% confidence intervals. (B) Excess fraction attributable to PM_{2.5} exposure by age, year, and cause from 2013 to 2020 at the national level, with "Full" indicating the cumulative excess fraction across the entire study period. Bars represent the estimated excess fractions, and error bars indicate 95% empirical confidence interval. "Full" denotes the estimate for the entire study period. (C) Excess all-cause mortality fraction attributable to PM_{2.5} exposure by age throughout the observation period (2013–2020) at the provincial level.

projected to decrease by 47.3% among individuals aged <65 years by 2050 under the SSP119 scenario, but to increase by 16.4%, 161.1%, and 248.3% among those aged 65–75, 75–85, and ≥85 years, respectively. From 2013 to 2020, individuals aged 65 and older accounted for 28.5–38.2% of the total economic burden. This share is projected to rise to around 69% by 2050 under the SSP119 scenario. These findings highlight the combined benefits of improved air quality and reduced health impacts achievable through carbon-neutral policies. However, the growing share of older adults may limit these health gains and reduce the expected economic benefits from lower PM_{2.5} exposure.

Although the two-stage analytical approach is widely used in multi-regional epidemiological studies, our pooled estimates still exhibited moderate to substantial between-region heterogeneity, particularly for all-cause and cardiovascular mortality. In contrast, the heterogeneity in respiratory mortality was relatively low across several age groups. The attenuation of heterogeneity after age stratification suggests that regional differences in population age structure may partly account for the observed heterogeneity in the associations between short-term PM_{2.5} exposure and mortality. The remaining heterogeneity may be explained by regional variation in PM_{2.5} composition, meteorological conditions, baseline disease burden, exposure patterns, and healthcare resources.^{38–40}

Despite this heterogeneity, our study found that short-term exposure to PM_{2.5} was associated with a 0.55% increase in the risk of all-cause mortality, a 0.63% increase in the risk of cardiovascular mortality, and a 0.52% increase in the risk of respiratory mortality during the period from 2013 to 2020, consistent with previous findings.^{30–33,41–42} A time-series analysis conducted in 96 counties in Jiangsu Province, China, reported that a 10 µg/m³ increase in PM_{2.5} was associated with a 0.60% (95% CI: 0.52–0.67%) rise in all-cause mortality.³⁰ Similarly, a study covering 372 cities across 19 countries and regions estimated a 0.47% (95% CI: 0.26–0.67%) increase in all-cause mortality per 10 µg/m³ increase in PM_{2.5} at a lag of 0–1 day.³² A meta-analysis of 652 cities reported an excess mortality risk of 0.68% (95% CI: 0.59–0.77%) per 10 µg/m³ increase in PM_{2.5} with the same lag structure.³¹ We also observed marked age-related variation in the association between short-term PM_{2.5} exposure and mortality risk, with stronger associations found in older adults. This aligns with prior research showing greater susceptibility in older populations compared to younger ones, for example, 0.69% (95% CI: 0.60–0.78%) versus 0.45% (95% CI: 0.32–0.57%), respectively.³⁰ Our results suggest that older adults bear a relatively higher burden of excess mortality from short-term PM_{2.5} exposure; however, this burden has declined in recent years, coinciding with improved air quality in China. Additionally, we quantified excess mortality using exposure-response functions at both national and provincial

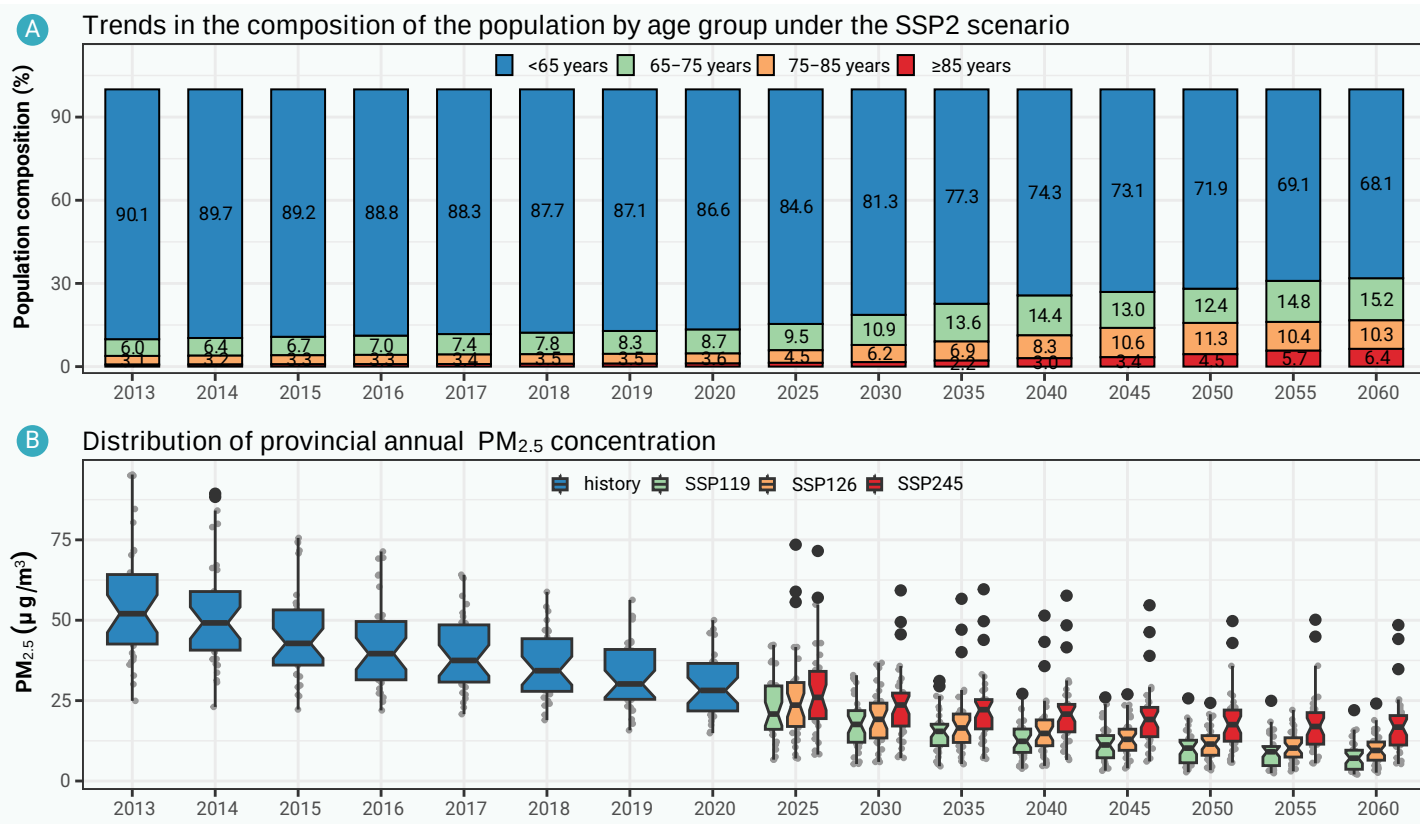


Figure 3. Trends in national population composition by age group (A) and provincial distribution of annual average PM_{2.5} concentrations (B) from 2013 to 2060 (A) National population composition by age group under the SSP2 scenario. (B) Provincial distributions of annual mean PM_{2.5} concentrations under historical and future scenarios. Boxes show the median and interquartile range. SSP119, SSP126, and SSP245 represent China's carbon-neutral policy pathway, peak-carbon policy target pathway, and business-as-usual trajectory, respectively.

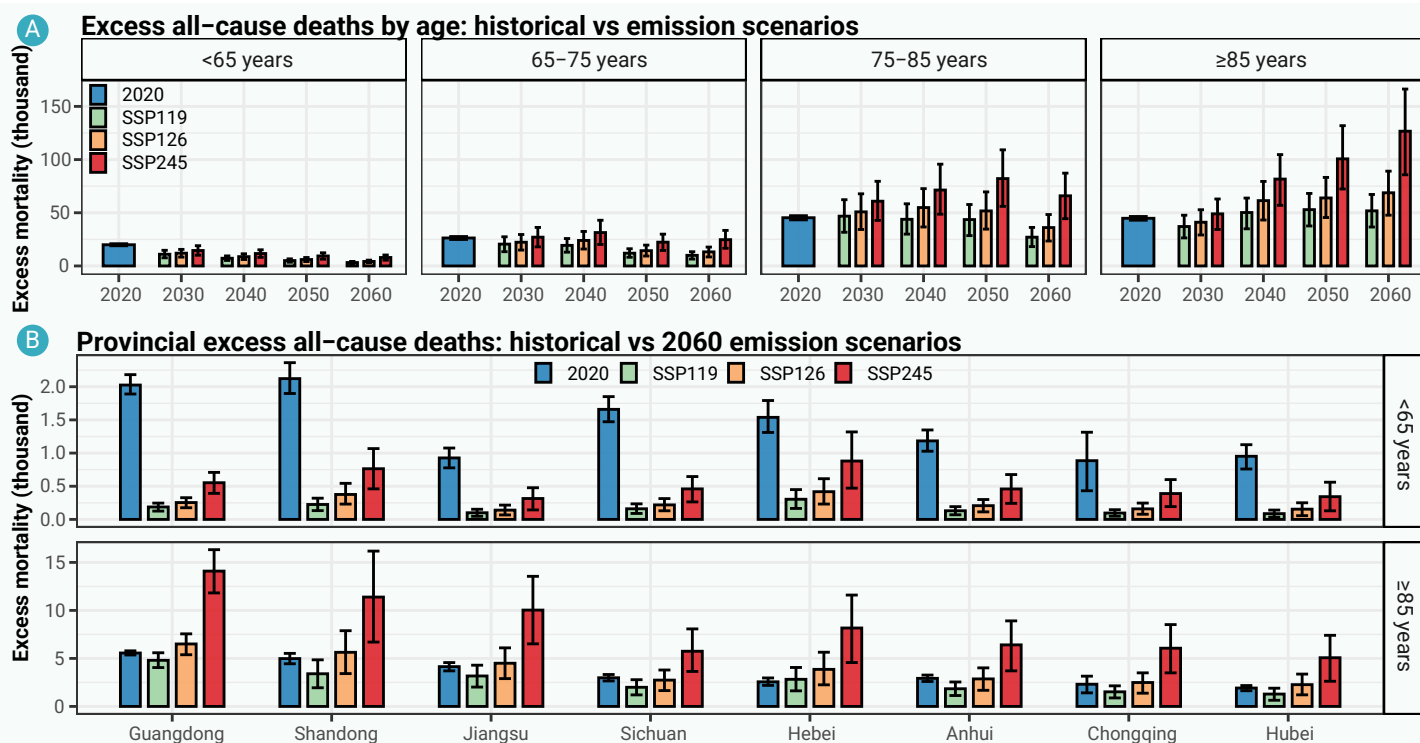


Figure 4. Excess all-cause mortality in 2020 and under different emission scenarios in 2060 (A) Comparison of excess all-cause mortality in 2020 and under various emission scenarios in 2030-2060, stratified by age. (B) Comparison of excess all-cause mortality in 2020 and under different emission scenarios in 2060, stratified by province. Bars represent estimated excess deaths, and error bars indicate 95% uncertainty intervals. SSP119, SSP126, and SSP245 represent China's carbon-neutrality pathway, carbon-peaking pathway, and business-as-usual scenario, respectively.

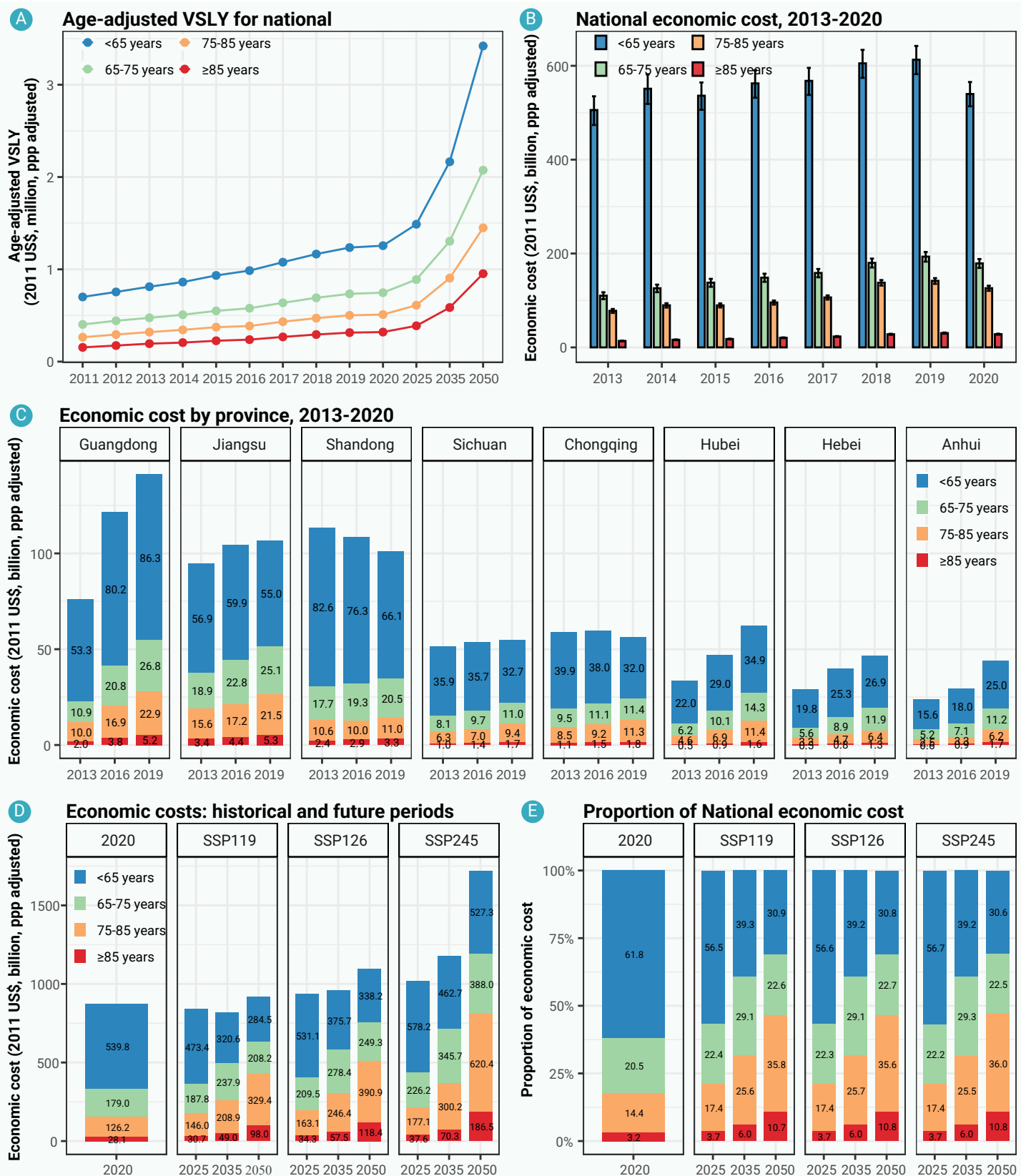


Figure 5. Economic costs of all-cause mortality attributable to short-term $PM_{2.5}$ exposure during the historical and future periods (A) Age-adjusted value of a statistical life year (VSLY) on a national scale from 2011 to 2050. (B) National economic costs associated with mortality from short-term $PM_{2.5}$ exposure during the historical period (2013-2020). Bars represent estimated economic costs, and error bars indicate 95% uncertainty intervals. (C) Provincial-level economic costs associated with mortality from short-term $PM_{2.5}$ exposure in the historical period. (D) Comparison of economic costs attributed to mortality from short-term $PM_{2.5}$ exposure in 2020 and future periods. (E) Age-specific proportion of economic costs attributable to mortality from short-term $PM_{2.5}$ exposure in 2020 and future periods. SSP119, SSP126, and SSP245 represent China's carbon-neutral policy pathway, peak-carbon policy target pathway, and business-as-usual trajectory, respectively.

levels, providing a more geographically specific analysis than most prior studies.⁴³ The mortality burden remains concentrated in areas with high pollution, including the Pearl River Delta, the Beijing-Tianjin-Hebei region, and the Sichuan Basin, which continue to require focused prevention and control efforts.

Our projections indicate a substantial decline in future excess mortality associated with short-term PM_{2.5} exposure, with the most significant reductions anticipated under the near-carbon-neutral SSP119 scenario. By 2060, excess all-cause mortality is projected to drop by 32.5% under SSP119 and by 10.3% under SSP126. In contrast, under the SSP245 scenario, which reflects a business-as-usual pathway, excess all-cause mortality is projected to rise by 65.1%. These trends are consistent with previous studies, which report the largest decreases in PM_{2.5}-related excess incidence under SSP119, followed by SSP126, with minimal reductions under SSP245.^{17,21} These results suggest that China's carbon-neutral strategy could bring considerable health benefits. Age-specific projections indicate that under SSP119, excess mortality among individuals under 65 years is expected to fall by approximately 84% by 2060 compared to 2020 levels. However, the magnitude of this reduction decreases with age and eventually reverses, with excess mortality among individuals aged 85 years and older projected to increase by 13.1–15.6% under different projection assumptions. This pattern suggests that population aging may undermine the health benefits of carbon-neutral policies, underscoring the importance of tailored preventive strategies for older adults. Regionally, the Beijing-Tianjin-Hebei area, the Sichuan Basin, and the Pearl River Delta are expected to remain key areas for air pollution control in the future.

To support air pollution control policy, previous studies have sought to quantify the economic burden of air pollution-related health effects. However, most of these assessments have relied on an age-invariant VSL multiplied by attributable mortality, or an age-invariant VSLY multiplied by years of life lost.^{7,44,45} These approaches assume the same VSL or VSLY across all age groups and do not account for differences in remaining life expectancy, quality of life, or socioeconomic status by age.^{46,47} In this study, we applied an age-adjusted VSLY framework to estimate the economic burden of mortality attributable to short-term PM_{2.5} exposure, accounting for population aging and China's carbon neutrality policy. We estimated that the economic cost of all-cause mortality linked to short-term PM_{2.5} exposure reached US\$873.1 billion in 2020, marking a 23.4% increase from US\$707.6 billion in 2013. Individuals aged 65 and older accounted for 28.5–38.2% of this cost, a share that may be slightly below global estimates.⁷ The increase in expenses observed between 2013 and 2016 was mainly driven by increasing GDP per capita, population growth, and aging. Our findings also suggest that even under SSP119, the economic burden of PM_{2.5}-related mortality will continue to increase by 2050, albeit modestly. Under SSP126 and SSP245, however, the economic burden is projected to rise substantially more, highlighting the importance of stronger mitigation efforts. Therefore, population aging is expected to become the primary factor driving the growing economic burden, with older adults projected to account for approximately 70% of total costs, a proportion similar to that observed in high-income regions.⁷ This disproportionate burden in older age groups likely results from the rapid increase in the older population, higher baseline mortality rates by age and disease category, and sharper declines in mortality and, therefore, economic losses among younger groups. These findings underscore the importance of prioritizing interventions for older adults to mitigate the economic burden of air pollution-related mortality.

By 2060, under the SSP119 scenario, most regions in China are projected to experience substantial reductions in PM_{2.5} concentrations compared to the baseline period. However, several provinces, including Xinjiang, Tibet, Inner Mongolia, Northeast China, and the Beijing-Tianjin-Hebei region, are expected to maintain annual average PM_{2.5} levels above the WHO guideline of 5 µg/m³. This highlights the continued need for focused efforts to address the health burden of PM_{2.5} exposure in these high-risk areas.^{21,48} Our findings also confirm the absence of a significant threshold for PM_{2.5}-related mortality. Prior research has shown that even at low concentrations, PM_{2.5} is associated with an increased risk of mortality.⁴⁹ Moreover, studies have reported that the exposure-response relationship between short-term PM_{2.5} exposure and mortality tends to show a steeper slope at lower concentrations and

a flatter slope at higher concentrations.³⁰ Consistent with these observations, we found that a considerable share of excess mortality was associated with exposure levels below the WHO IT-3 threshold from 2013 to 2020. These results emphasize the ongoing mortality risk associated with PM_{2.5} exposure, even in areas with relatively low concentrations, and suggest that incremental improvements in air quality could yield meaningful health benefits.

This study systematically assessed excess mortality associated with short-term PM_{2.5} exposure under carbon-neutrality policy scenarios, offering critical insights into the potential health benefits of achieving carbon neutrality. Compared with previous studies, our analysis, based on both national and provincial data, provides a more detailed quantification of how China's carbon-neutrality targets and population aging may influence excess mortality and the economic burden associated with short-term PM_{2.5} exposure. We also employed age-adjusted VSLY estimates that account for three key life-span factors: remaining life expectancy, quality of life, and wealth weighting.^{47,50} This approach more accurately reflects the distribution of health-related economic costs across age groups. It provides a rational foundation for pollution control and health system planning, balancing the needs of older adults with the societal value placed on younger populations.

However, the findings should be interpreted with certain limitations in mind. First, limited case counts in some provinces may introduce uncertainty in the regional estimates of excess mortality and economic costs. Second, while estimating age-adjusted VSLY, potential variation in quality of life and wealth across provinces and future periods may affect cost estimates. Third, although age groups were categorized, more granular subdivisions were not applied to preserve model stability. Fourth, because observational data are unavailable for future periods, the projected future PM_{2.5} concentrations could not be directly validated. Moreover, the bias-correction approach was developed using historical simulations and observations, and its application to future scenarios assumes a relatively stable model bias over time, which may introduce uncertainty into the projections. Finally, in the future burden projections, we accounted for changes in population structure but did not incorporate potential temporal changes in baseline mortality. In addition, future improvements in healthcare, disease prevention, and population susceptibility were not explicitly considered, which may have introduced some uncertainty into the estimated PM_{2.5}-attributable mortality burden. Importantly, the 95% uncertainty intervals reported for the future projections mainly reflected the statistical uncertainty in the exposure-response coefficients. Other sources of uncertainty, including future PM_{2.5} simulations, population projections, baseline mortality, and economic parameters, were not fully propagated into the interval estimates; therefore, the reported uncertainty intervals should not be interpreted as capturing the full range of uncertainty in the future projections.

CONCLUSION

In summary, achieving carbon neutrality presents a dual opportunity to improve both air quality and public health. China's carbon-neutrality policies could substantially reduce mortality from short-term PM_{2.5} exposure, delivering wide-ranging health benefits. However, rapid population aging may offset some of these gains and intensify the economic burden. As a result, in regions with a legacy of high pollution and a large elderly population, it is essential to implement strategies that not only reduce air pollution but also strengthen healthcare services for older adults, thereby lowering the health costs associated with environmental air pollution.

REFERENCES

- Huang J., Pan X., Guo X., et al. (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:e313–e323. DOI:10.1016/S2542-5196(18)30141-4
- Yu T., Jiang Y., Chen R., et al. (2025). National and provincial burden of disease attributable to fine particulate matter air pollution in China, 1990–2021: An analysis of data from the Global Burden of Disease Study 2021. *Lancet Planet. Health* 9:e174–e185. DOI:10.1016/S2542-5196(25)00024-5
- World Health Organization. (2022). Billions of people still breathe unhealthy air: new WHO data. <https://www.who.int/news/item/04-04-2022-billions-of-people-still-breathe-unhealthy-air-new-who-data>.
- Wan L., Bambrick H. and Tong M. (2025). Mortality attributable to ambient PM_{2.5}

- pollution in China's aging population. *Environ. Impact Assess. Rev.* 112:107823. DOI:10.1016/j.eiar.2025.107823.
5. Liu Y., Zhu G., Zhao Z., et al. (2022). Population aging might have delayed the alleviation of China's PM2.5 health burden. *Atmos. Environ.* 270:118895. DOI:10.1016/j.atmosenv.2021.118895.
 6. Li C., van Donkelaar A., Hammer M. S., et al. (2023). Reversal of trends in global fine particulate matter air pollution. *Nat. Commun.* 14:5349. DOI:10.1038/s41467-023-41086-z
 7. Yin H., Brauer M., Zhang J., et al. (2021). Population ageing and deaths attributable to ambient PM2.5 pollution: A global analysis of economic cost. *Lancet Planet. Health* 5:e356–e367. DOI:10.1016/S2542-5196(21)00131-5
 8. Brauer M., Roth G. A., Aravkin A. Y., et al. (2024). Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: A systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 403:2162–2203. DOI:10.1016/S0140-6736(24)00933-4
 9. Mora C., McKenzie T., Gaw I. M., et al. (2022). Over half of known human pathogenic diseases can be aggravated by climate change. *Nat. Clim. Chang.* 12:869–875. DOI:10.1038/s41558-022-01426-1
 10. Scovronick N., Buddolfson M., Dennig F., et al. (2019). The impact of human health co-benefits on evaluations of global climate policy. *Nat. Commun.* 10:2095. DOI:10.1038/s41467-019-09499-x
 11. Lelieveld J., Klingmüller K., Pozzer A., et al. (2019). Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proc. Natl. Acad. Sci. U. S. A.* 116:7192–7197. DOI:10.1073/pnas.1819989116
 12. Shindell D., Faluvegi G., Seltzer K., et al. (2018). Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nat. Clim. Chang.* 8:291–295. DOI:10.1038/s41558-018-0108-y
 13. Zhao X., Ma X., Chen B., et al. (2022). Challenges toward carbon neutrality in China: Strategies and countermeasures. *Resources, Conservation and Recycling* 176:105959. DOI:10.1016/j.resconrec.2021.105959
 14. Chen W., Lu X., Yuan D., et al. (2023). Global PM2.5 prediction and associated mortality to 2100 under different climate change scenarios. *Environ. Sci. Technol.* 57:10039–10052. DOI:10.1021/acs.est.3c03804
 15. Yang G., Wang Y., Zeng Y., et al. (2013). Rapid health transition in China, 1990–2010: Findings from the Global Burden of Disease Study 2010. *Lancet* 381:1987–2015. DOI:10.1016/S0140-6736(13)61097-1
 16. Xu J., Yao M., Wu W., et al. (2021). Estimation of ambient PM2.5-related mortality burden in China by 2030 under climate and population change scenarios: A modeling study. *Environ. Int.* 156:106733. DOI:10.1016/j.envint.2021.106733
 17. Wang Y., Liao H., Chen H., et al. (2023). Future projection of mortality from exposure to PM2.5 and O3 under the carbon neutral pathway: Roles of changing emissions and population aging. *Geophys. Res. Lett.* 50:e2023GL104838. DOI:10.1029/2023GL104838
 18. Li N., Chen W., Rafaj P., et al. (2019). Air quality improvement co-benefits of low-carbon pathways toward well below the 2 °C climate target in China. *Environ. Sci. Technol.* 53:5576–5584. DOI:10.1021/acs.est.8b06948
 19. Wang Y., Hu J., Huang L., et al. (2022). Projecting future health burden associated with exposure to ambient PM2.5 and ozone in China under different climate scenarios. *Environ. Int.* 169:107542. DOI:10.1016/j.envint.2022.107542
 20. Xu F., Huang Q., Yue H., et al. (2023). The challenge of population aging for mitigating deaths from PM2.5 air pollution in China. *Nat. Commun.* 14:5222. DOI:10.1038/s41467-023-40908-4
 21. Ban J., Cheng J., Zhang C., et al. (2024). China's carbon-neutral policies will reduce short-term PM2.5-associated excess incidence of cardiovascular diseases. *One Earth* 7:497–505. DOI:10.1016/j.oneear.2024.01.006
 22. Qin Y., Zhou M., Hao Y., et al. (2024). Amplified positive effects on air quality, health, and renewable energy under China's carbon neutral target. *Nat. Geosci.* 17:411–418. DOI:10.1038/s41561-024-01425-1
 23. Wei J., Li Z., Lyapustin A., et al. (2021). Reconstructing 1-km-resolution high-quality PM2.5 data records from 2000 to 2018 in China: Spatiotemporal variations and policy implications. *Remote Sens. Environ.* 252:112136. DOI:10.1016/j.rse.2020.112136
 24. Wei J., Liu S., Li Z., et al. (2022). Ground-level NO2 surveillance from space across China for high resolution using interpretable spatiotemporally weighted artificial intelligence. *Environ. Sci. Technol.* 56:9988–9998. DOI:10.1021/acs.est.2c03834
 25. Wei J., Li Z., Wang J., et al. (2023). Ground-level gaseous pollutants (NO2, SO2, and CO) in China: Daily seamless mapping and spatiotemporal variations. *Atmos. Chem. Phys.* 23:1511–1532. DOI:10.5194/acp-23-1511-2023
 26. Xiao Q., Geng G., Xue T., et al. (2022). Tracking PM2.5 and O3 pollution and the related health burden in China 2013–2020. *Environ. Sci. Technol.* 56:6922–6932. DOI:10.1021/acs.est.1c04548.
 27. Muñoz-Sabater J., Dutra E., Agustí-Panareda A., et al. (2021). ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth Syst. Sci. Data* 13:4349–4383. DOI:10.5194/essd-13-4349-2021
 28. Cheng J., Tong D., Zhang Q., et al. (2021). Pathways of China's PM2.5 air quality 2015–2060 in the context of carbon neutrality. *Natl. Sci. Rev.* 8. DOI:10.1093/nsr/nwab078
 29. Chen Y., Guo F., Wang J., et al. (2020). Provincial and gridded population projection for China under shared socioeconomic pathways from 2010 to 2100. *Sci. Data* 7:83. DOI:10.1038/s41597-020-0421-y
 30. Guo J., Zhou J., Han R., et al. (2023). Association of short-term co-exposure to particulate matter and ozone with mortality risk. *Environ. Sci. Technol.* 57:15825–15834. DOI:10.1021/acs.est.3c04056
 31. Liu C., Chen R., Sera F., et al. (2019). Ambient particulate air pollution and daily mortality in 652 cities. *N. Engl. J. Med.* 381:705–715. DOI:10.1056/NEJMoa1817364
 32. Liu C., Chen R., Sera F., et al. (2023). Interactive effects of ambient fine particulate matter and ozone on daily mortality in 372 cities: Two stage time series analysis. *BMJ* 383:e075203. DOI:10.1136/bmj-2023-075203
 33. Chen R., Jiang Y., Hu J., et al. (2022). Hourly air pollutants and acute coronary syndrome onset in 1.29 million patients. *Circulation* 145:1749–1760. DOI:10.1161/circulationaha.121.057179
 34. Gasparrini A. and Leone M. (2014). Attributable risk from distributed lag models. *BMC Med. Res. Methodol.* 14:55. DOI:10.1186/1471-2288-14-55
 35. O'Brien E., Masselot P., Sera F., et al. (2023). Short-term association between sulfur dioxide and mortality: A multicountry analysis in 399 cities. *Environ. Health Perspect.* 131:37002. DOI:10.1289/ehp11112
 36. China National Information Center. (2021). Medium- and Long-Term Goals, Strategies, and Pathways for China's Economic and Social Development. <https://www.efchina.org/Reports-zh/report-lceag-20210207-4-zh>.
 37. Schumacher A. E., Kyu H. H., Aali A., et al. (2024). Global age-sex-specific mortality, life expectancy, and population estimates in 204 countries and territories and 811 subnational locations, 1950–2021, and the impact of the COVID-19 pandemic: A comprehensive demographic analysis for the Global Burden of Disease Study 2021. *Lancet* 403:1989–2056. DOI:10.1016/S0140-6736(24)00476-8
 38. Baxter L. K., Dionisio K., Pradeep P., et al. (2019). Human exposure factors as potential determinants of the heterogeneity in city-specific associations between PM2.5 and mortality. *J. Expo. Sci. Environ. Epidemiol.* 29:557–567. DOI:10.1038/s41370-018-0080-7
 39. Ma Y., Noble F., Marb A., et al. (2024). Short-term exposure to fine particulate matter and nitrogen dioxide and mortality in 4 countries. *JAMA Netw. Open* 7:e2354607–e2354607. DOI:10.1001/jamanetworkopen.2023.54607
 40. Masselot P., Sera F., Schneider R., et al. (2022). Differential mortality risks associated with PM2.5 components: A multi-country, multi-city study. *Epidemiology* 33:167–175. DOI:10.1097/EDE.0000000000001455
 41. Tian Y., Liu H., Wu Y., et al. (2019). Association between ambient fine particulate pollution and hospital admissions for cause specific cardiovascular disease: time series study in 184 major Chinese cities. *BMJ* 367:l6572. DOI:10.1136/bmj.l6572
 42. Peng S., Li Z., Ji J. S., et al. (2024). Interaction between extreme temperature events and fine particulate matter on cardiometabolic multimorbidity: Evidence from four national cohort studies. *Environ. Sci. Technol.* 58:12379–12389. DOI:10.1021/acs.est.4c02080
 43. Xu R., Huang S., Shi C., et al. (2023). Extreme temperature events, fine particulate matter, and myocardial infarction mortality. *Circulation* 148:312–323. DOI:10.1161/circulationaha.122.063504
 44. Maji K. J., Ye W.-F., Arora M., et al. (2018). PM2.5-related health and economic loss assessment for 338 Chinese cities. *Environ. Int.* 121:392–403. DOI:10.1016/j.envint.2018.09.024
 45. Pimpin L., Retat L., Fecht D., et al. (2018). Estimating the costs of air pollution to the National Health Service and social care: An assessment and forecast up to 2035. *PLoS Med.* 15:e1002602. DOI:10.1371/journal.pmed.1002602
 46. Aldy J. E. and Viscusi W. K. (2007). Age differences in the value of statistical life: Revealed preference evidence. *Rev. Environ. Econ. Policy* 1:241–260. DOI:10.1093/reep/rem014
 47. O'Brien J. (2018). Age, autos, and the value of a statistical life. *J. Risk Uncertain.* 57:51–79. DOI:10.1007/s11166-018-9285-3
 48. Li D., Wu Q., Cheng H., et al. (2024). Numerical study of the future PM2.5 concentration under climate change and best-health-effect (BHE) scenario. *Environ. Pollut.* 357:124391. DOI:10.1016/j.envpol.2024.124391
 49. Shi L., Zanobetti A., Kloog I., et al. (2016). Low-concentration PM2.5 and mortality: Estimating acute and chronic effects in a population-based study. *Environ. Health Perspect.* 124:46–52. DOI:10.1289/ehp.1409111
 50. Viscusi W. K. (2019). Risk guideposts for a safer society: Introduction and overview. *J. Risk Uncertain.* 58:101–119. DOI:10.1007/s11166-019-09307-3

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the National Key Research and Development Program of China (Grant No. 2023YFC3709302), the National Natural Science Foundation of China (Grant Nos. 52478073 and 42307133), and the Young Elite Scientists Sponsorship Program by CAST (Grant No. 2023QNRC001). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The High-performance Computing Platform of Peking University supported this study.

AUTHOR CONTRIBUTIONS

P.Y., S.H., and J.L. conceived and designed the study, jointly supervised the work, and contributed equally as senior authors. J.G. and L.L. contributed equally to this work,

coordinated the study, performed the statistical analyses, interpreted the results, and drafted the manuscript. J.H., J.Y., L.W., and M.Z. contributed to data acquisition and curation. P.K., J.H., S.X., C.L.Z.V., Y.F., Z.W., Y.W., X.L., J.Y., L.W., and M.Z. contributed to the interpretation of the findings and critically revised the manuscript for important intellectual content. P.Y., S.H., and J.L. provided overall scientific guidance and are the guarantors of the study. All authors contributed to and approved the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

ETHICAL STATEMENT AND PATIENT CONSENT

This study was exempt from ethical review, and informed consent was not required because only de-identified data were analysed.

DATA AND CODE AVAILABILITY

All data supporting the findings of this study are included in the main text and Supplementary Information. Individual-level mortality data from the China Cause of Death Reporting System cannot be made publicly available because of privacy considerations and data-use agreements with the relevant authority. Access to eligible de-identified or derived data may be requested from the corresponding author and will be subject to applicable approvals and data-management requirements. Daily PM_{2.5} concentrations were obtained from the China High Air Pollutants dataset, meteorological data were obtained from the ERA5-Land dataset, and future population projections were obtained from the publicly available Figshare dataset. The analytical code is available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.xinn-med.2026.100259>.