

Role of climate goals and clean-air policies on reducing future air pollution deaths in China: a modelling study

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Summary

Background Over 3 million people die every year from diseases caused by exposure to outdoor PM_{2.5} air pollution, and more than a quarter of these premature deaths occur in China. In addition to clean-air policies that target pollution emissions, climate policies aimed at reducing fossil-fuel CO₂ emissions (eg, to avoid 1.5°C of warming) might also greatly improve air quality and public health. However, no comprehensive accounting of public health outcomes has been done under different energy pathways and local clean-air management decisions in China. We aimed to develop an integrated method for quantifying the health co-benefits from different climate, energy, and clean-air policy scenarios and to assess the relationship between climate and clean-air policies and future health burdens in China, where an ageing population will further exacerbate the effects of air pollution.

Methods For this modelling study, we used a China-focused integrated assessment model and a dynamic emission projection model to project future Chinese air quality in scenarios spanning a range of global climate targets (1.5°C, 2°C, national determined contributions [NDC], unambitious, baseline, and 4.5°C) and national clean-air actions (termed 2015-pollution, current-pollution, and ambitious-pollution). We then evaluated the health effects of PM_{2.5} air pollution in the scenario matrix using the air quality model and the latest epidemiological concentration–response functions from the 2019 Global Burden of Diseases, Injuries, and Risk Factors Study.

Findings We found that, without ambitious climate mitigation (eg, under current NDC pledge), Chinese deaths related to PM_{2.5} air pollution might not always decrease—and might often grow—by 2050 compared with the base year of 2015, regardless of clean-air policies and air quality improvements. For example, in the scenario that tracks China's current NDC pledge and uses the best available pollution control technologies (the ambitious-pollution and NDC goals scenario), PM_{2.5}-related deaths in China would decrease slightly by 2030 to 1.23 million per year (95% CI 0.95–1.51) from 1.25 million (1.04–1.46) in 2015, but would not decrease further by 2050 (1.21 million, 0.86–1.60) despite substantial and continuous improvements in population-weighted air quality (from 27.2 µg/m³ in 2030 to 16.0 µg/m³ in 2050). The contrary trends of improving air quality and increasing PM_{2.5}-related deaths in many of our scenarios revealed the extent to which extra efforts are needed to compensate for the increasing age of China's population in the future. With the scenarios that included ambitious clean-air policies and met international climate goals to avoid 1.5°C and 2°C of warming (the ambitious-pollution-2°C goals scenario and the ambitious-pollution-1.5°C goals scenario), we observed substantial decreases in China's PM_{2.5}-related deaths of 0.32–0.55 million deaths compared with NDC goals in 2050, and age-standardised death rates decreased by 10.2–14.2 deaths per 100 000 population per year.

Interpretation Our results show that ambitious climate policies (ie, limiting global average temperature rise to well below 2°C) and low-carbon energy transitions coupled with stringent clean-air policies are necessary to substantially reduce the human health effects from air pollution in China, regardless of socioeconomic assumptions. Our findings could help policy makers understand the crucial links between climate policy and public health.

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Introduction

Outdoor air pollution is currently one of the greatest environmental and public health threats in China, with an estimated 1.42 million deaths in 2019.¹ Although strict emission standards and clean air policies focused on end-of-pipe pollution abatement have substantially reduced the health risks over the past decade, the country's fossil-fuel-dominated energy structure is a barrier to deeper

reductions in pollution emissions and further decreases of the related health burdens.^{2–6} However, it has been shown that the sweeping energy transitions and reductions in fossil fuel entailed by international goals to limit the increase in global mean temperature to well below 2°C, and to pursue efforts to avoid a 1.5°C increase, would also deliver large health co-benefits.^{7–12} In China, such health co-benefits have been estimated under some

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Research in context**Evidence before this study**

We searched Web of Science, Google Scholar, and China National Knowledge Infrastructure for articles in English and Chinese using Chinese and English terms such as “air quality co-benefits”, “air quality improvement”, “health co-benefits”, “PM_{2.5} pollution-related health”, and “China”. The search was done between Oct 1 and 19, 2021. Although previous studies have evaluated the health benefits of China’s adoption of different climate policies to improve air quality, most of these studies have focused on a global scale. Some studies that contained detailed descriptions of China were often based on China’s previous air control policy modelling (before 2013), which are inconsistent with China’s rapid air quality improvements in recent years. The few studies that considered China’s short-term air pollution control policies tended to focus on the health benefit assessment of national determined contributions climate target in the short term (2015–30) and lacked a detailed analysis of different long-term climate targets.

Added value of this study

To the best of our knowledge, this is the first comprehensive assessment of China’s future air pollution-related disease

burden combined with climate policy and local clean-air policy. We have found that adopting strict climate policies or strengthening clean-air policies could achieve tremendous improvements in air quality. However, due to the ageing of China’s population, even with the strongest clean-air policy, PM_{2.5}-related deaths might increase during 2030–50. In this case, only the strongest clean-air policy coupled with ambitious climate targets (the 1.5°C and 2°C targets) were able to always offset an increasing trend of air pollution-related premature deaths driven by an ageing population.

Implications of all the available evidence

As the world’s largest carbon emitter, China’s actions to mitigate climate change affect the achievement of the global climate mitigation target. This study found that the implementation of the 1.5°C and 2°C targets coupled with ambitious pollution controls in China could also substantially improve air quality and offset the negative health benefits of population ageing. The results of this study could help policy makers understand the importance of ambitious climate targets from a health perspective.

climate-energy pathways (eg, national determined contributions [NDC] or avoiding 2°C increase) and pollution control assumptions derived from global databases,^{9,13–18} but a detailed and comprehensive assessment of future public health outcomes (ie, mortality) that includes localised clean-air policies and the full range of plausible energy–emissions trajectories is still needed for China. As China’s national and local clean air policies are constantly being updated, such a comprehensive evaluation could greatly help policy makers to design and implement effective and efficient climate and energy clean-air policies in the context of the country’s steadily ageing and still growing population.¹⁹

We developed an integrated method for quantifying the health co-benefits from different levels of climate and energy ambitions and clean-air policies for China, estimating and resolving scenarios under each specific clean-air and climate policy. In summary, we first build up a scenario matrix across different levels of climate ambition and stringencies of clean-air policies across China (appendix pp 22–24), defining three levels of pollution control technologies: one that would maintain air pollution controls at 2015 levels (the 2015-pollution scenario), one that would continue current clean-air policies (the current-pollution scenario), and one that would deploy the best available technologies (the ambitious-pollution scenario). In turn, these different stringencies of clean-air policy, which focused on end-of-pipe measures to control air pollution emissions alone, were coupled with a range of climate mitigation scenarios that span six levels of economic and climate ambitions created by the integrated global change assessment model

of China (GCAM-China): 1.5°C, 2°C, NDC, unambitious, baseline, and 4.5°C targets. We then modelled future anthropogenic emissions for air pollution by using the dynamic emission projection (DPEC) model and, finally, we evaluated the health impacts of PM_{2.5} air pollution of our scenarios using the weather research and forecasting (WRF) model and the models-3 community multiscale air quality (CMAQ) model and the latest concentration–response functions developed in the Global Burden of Diseases, Injuries, and Risk Factors Study (GBD) 2019.¹

Methods**Scenario design**

We designed scenarios to consider multiple permutations of future socioeconomic development, climate ambition, and clean-air policies, and we used an integrated modelling approach to analyse the health benefits of air quality improvements across all scenarios in both 2030 and 2050 (appendix p 11). In terms of scenario design, we first constructed the different levels of climate ambition by combining shared socioeconomic pathways (SSPs, SSP1 to SSP5) with the representative concentration pathways (RCPs, RCP1.9 to RCP8.5) to represent the climate goal scenarios 1.5°C, 2°C, NDC, unambitious, baseline, and 4.5°C, which are combined in a way that is consistent with the scenarios used in the Scenario Model Intercomparison Project for the Coupled Model Intercomparison Project 6.^{20–22} Noting that SSPs embodied in climate policy scenarios are different, the climate scenarios thus included the driving forces and impacts from different socioeconomic characteristics. We then designed three national clean-air policy scenarios

See Online for appendix

targeting end-of-pipe controls: 2015-pollution, current-pollution, and ambitious-pollution (more detailed description in the appendix, pp 4–6). The 2015-pollution scenario explores the effect of maintaining air pollution control at 2015 levels; the current-pollution scenario is the current policy and its continuation, to meet the national ambient air quality standards ($35 \mu\text{g}/\text{m}^3$) by 2030, with no new policies implemented after 2030; the ambitious-pollution scenario is based on the implementation of current policies, reflecting the additional promotion of the best available pollution control technologies after 2030 to maximise public health benefits by 2050.

Air quality modelling

On the basis of six climate mitigation scenarios and three clean air scenarios, we established a matrix that included 18 scenarios with full ranges of future energy–emission trajectories (appendix pp 22–24). We then used GCAM-China to simulate future energy consumption under the climate ambition scenarios, and we applied the DPEC model in China to project future anthropogenic emissions. GCAM-China is a China-focused version of the GCAM, which can project China's future energy demand and supply under different SSP-RCP scenarios at the provincial level.^{23–25} The DPEC, developed in a previous study, contains sector-based emission projection modules that can simulate the evolution of production technologies and emission control measures under different clean-air policies.²⁶ Using output from DPEC, we simulated $\text{PM}_{2.5}$ concentrations using the WRF-CMAQ models.² More detailed configurations of the simulation can be found in the appendix (pp 2–3).

$\text{PM}_{2.5}$ -attributable deaths

We used the concentration–response functions developed by GBD 2019 to estimate age-specific premature deaths attributable to $\text{PM}_{2.5}$ exposure. These functions were developed to quantify the association between $\text{PM}_{2.5}$ exposure and non-accidental mortality by use of cohort data from different $\text{PM}_{2.5}$ exposures.¹ As GBD 2019 includes several high-level $\text{PM}_{2.5}$ exposure studies from China and India, it is suitable for studies focusing on China.

In this study, we calculated the age-specific $\text{PM}_{2.5}$ -attributable deaths caused by ischaemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and lower respiratory infection. For each disease, we obtained the age-stratified baseline incidence at the national level in 2015 from GBD 2019 and we projected the future baseline incidence by adapting the trends from the World Population Prospects 2019 report (more details in the appendix, pp 3–4).²⁷ We also present the 95% CIs of attributable mortality estimation (more details in the appendix, p 8). Because population, $\text{PM}_{2.5}$ concentration, and baseline incidence will all change in the future, we further assessed the effects of four factors: population size and distribution, population ageing,

improved air quality, and baseline incidence decline. Additionally, by using the proportion of the population in the age bins used in GBD 2019 as a weight, we also estimated the age-standardised $\text{PM}_{2.5}$ -attributable death rates as another indicator of health independent from future age distribution change. Furthermore, because the estimates of $\text{PM}_{2.5}$ -related deaths will change with the demographic assumptions embodied in different socioeconomic policies under the same climate ambition, we did a series of sensitivity analyses across all SSPs to validate the reliability of the crucial conclusions. We used Python, version 3.8.8, for our analyses.

Role of the funding source

The funder had no role in study design, data collection, data analysis, data interpretation, or writing of the manuscript and the decision to submit for publication.

Results

We plotted China's future air quality and $\text{PM}_{2.5}$ -related deaths as a result of climate mitigation scenarios and different national clean air policies in 2030 and 2050 (figure 1). Compared with 2015 ($53.1 \mu\text{g}/\text{m}^3$ of population-weighted $\text{PM}_{2.5}$ concentration and 1.25 million $\text{PM}_{2.5}$ -related deaths [95% CI 1.04–1.46]), current clean-air actions targeting end-of-pipe controls would improve China's future air quality for all climate targets, especially during 2015–30 (ie, the current-pollution scenarios; figure 1A, C). For example, in the current most likely scenario that tracks China's NDC pledge and uses the current clean-air policies (ie, the current-pollution and NDC goals scenario), China's air quality would meet the national standard ($35 \mu\text{g}/\text{m}^3$) by 2030, with $27.6 \mu\text{g}/\text{m}^3$ of population-weighted $\text{PM}_{2.5}$ concentration. The short-term improvement in air quality (during 2015–30) was estimated to be much larger than the long-term improvement (ie, during 2030–50), due to the continuous but insufficient clean-air actions during 2015–30 and no new policies being implemented after 2030 in this scenario. Incorporating best-available pollution control technologies (ie, the ambitious-pollution scenarios) would further improve air quality improvement in 2050 by $5.2 \mu\text{g}/\text{m}^3$, an additional 24.5% decrease from the current-pollution and NDC goals scenario to the ambitious-pollution and NDC goals scenario (figure 1). Air quality improvements also responded to climate mitigation and associated reductions in fossil fuels use; minimising air pollution thus also depends on climate mitigation targets. For example, we estimated that increasingly stringent climate mitigation efforts, from the 4.5°C warming goal to the 1.5°C warming goal, would lead to additional reductions in population-weighted $\text{PM}_{2.5}$ concentrations of 10.2 – $16.3 \mu\text{g}/\text{m}^3$ in 2030 and 12.5 – $25.4 \mu\text{g}/\text{m}^3$ in 2050 across all clean-air actions. As a result, if China were to limit warming to 1.5°C , $\text{PM}_{2.5}$ concentrations could be as low as $9.0 \mu\text{g}/\text{m}^3$ by 2050 (ie, the ambitious-pollution and 1.5°C goals scenario). This is the only one of the

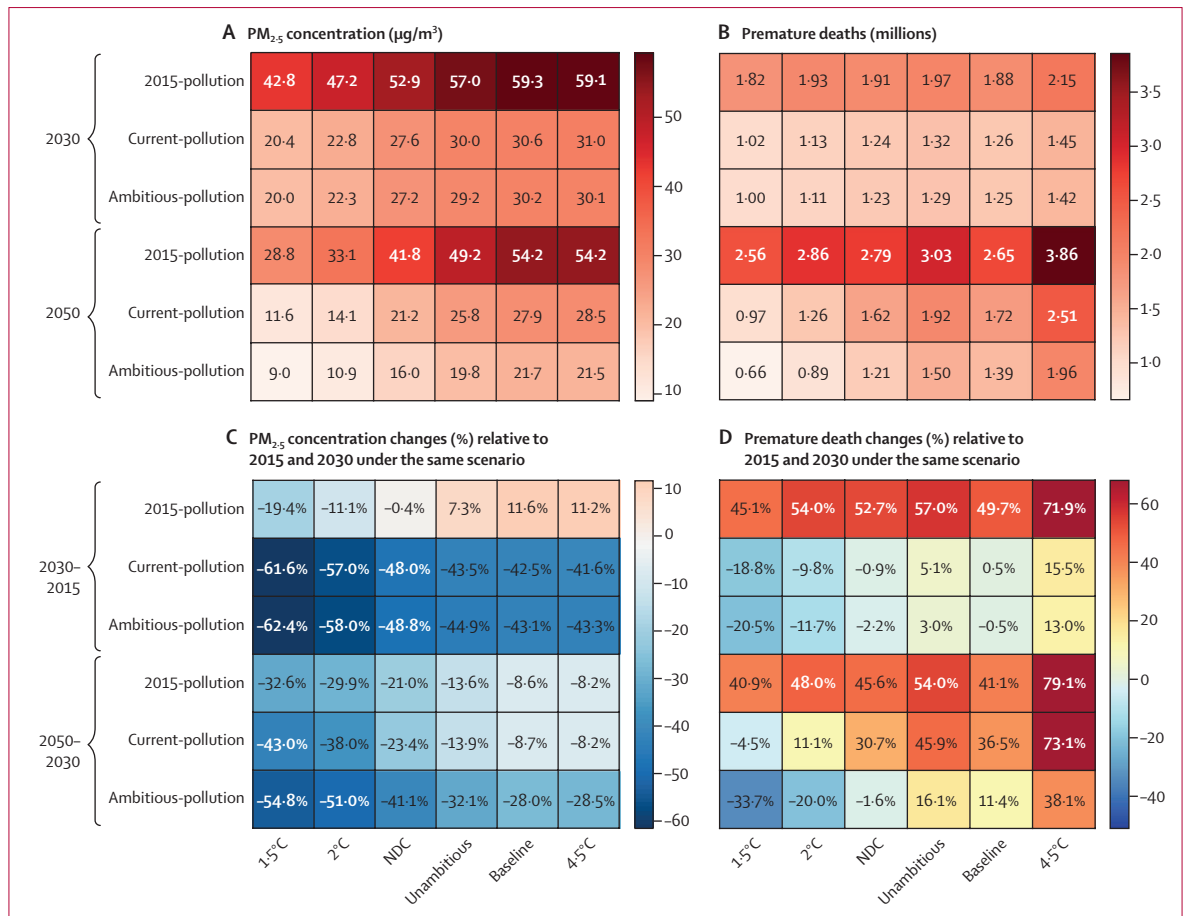


Figure 1: PM_{2.5} exposure and changes in PM_{2.5}-related deaths across all ranges of climate targets and stringency of pollution controls
 (A) Population-weighted PM_{2.5} concentrations in 2030 and 2050. (B) PM_{2.5}-related deaths in 2030 and 2050. (C) PM_{2.5} concentration changes during 2015–30 and 2030–50 compared with 53.1 µg/m³ population-weighted PM_{2.5} concentrations in 2015. (D) PM_{2.5}-related death changes during 2015–30 and 2030–50 compared with 1.25 million PM_{2.5}-related deaths (95% CI 1.04–1.46) in 2015. The populations used in climate target scenarios follow different socioeconomic pathways (ie, shared socioeconomic pathways). NDC=national determined contributions.

18 scenarios that could successfully reach the fourth WHO interim target of 10 µg/m³ on average across China.²⁸

Air pollution leads to health burdens, such as PM_{2.5}-related deaths (figure 1B, D). With the current clean-air policies and 4.5°C climate goal (ie, the current-pollution and 4.5°C goals scenario), PM_{2.5}-related deaths would increase to 1.45 million (95% CI 1.14–1.76) in 2030 and 2.51 million (1.95–3.08) in 2050 (appendix p 35). Ambitious clean-air controls would further decrease PM_{2.5}-related deaths. For instance, with strict end-of-pipe pollution controls, 0.55 million PM_{2.5}-related deaths could be avoided in 2050, 22.0% fewer PM_{2.5}-related deaths in 2050 with the current-pollution and 4.5°C goals scenario compared with the ambitious-pollution and 4.5°C goals scenario (figure 1B). Ambitious climate goals also reduced PM_{2.5}-related deaths. With the roll-out of current clean-air policies, 0.21 million PM_{2.5}-related deaths in 2030 and 0.88 million PM_{2.5}-related deaths in 2050 would be avoided (0.12 million in 2030 and 0.57 million in 2050 if we applied the same SSP1

population and age structure; appendix p 12) by moving from the 4.5°C climate goal to China’s NDC pledge (from the current-pollution and 4.5°C goals scenario to the current-pollution and NDC goals scenario).

However, by contrast with 1.25 million PM_{2.5}-related deaths (95% CI 1.04–1.46) in 2015 (appendix p 13), even when implementing the ambitious clean-air policies, these loose climate targets (NDC, unambitious, baseline, and 4.5°C climate goals) would still result in 1.23–1.42 million PM_{2.5}-related deaths in 2030 and 1.21–1.96 million PM_{2.5}-related deaths in 2050 (figure 1B), with a slight decrease or great increases occurring despite substantial air quality improvements (from –2.2% to 13.0% of changes during 2015–30 and from –1.6% to 38.1% during 2030–50; figure 1D). In these findings, only the combination of ambitious climate goals and clean-air policies would substantially alleviate the health burden during the 2030–50 period, mainly due to future demographic changes (ie, population ageing; appendix p 14) associated with the higher emissions scenarios. This hypothesis was

supported by considering the changes of age-standardised $PM_{2.5}$ -related death rates, which were based on the 2015 population age distribution and were not affected by differences in future age distributions. With the ambitious

clean-air policies and NDC goals scenario, the age-standardised $PM_{2.5}$ -related death rates would decrease from 92.1 per 100000 population (95% CI 76.6–107.6) in 2015 to 25.9 per 100000 population (18.4–34.3), a

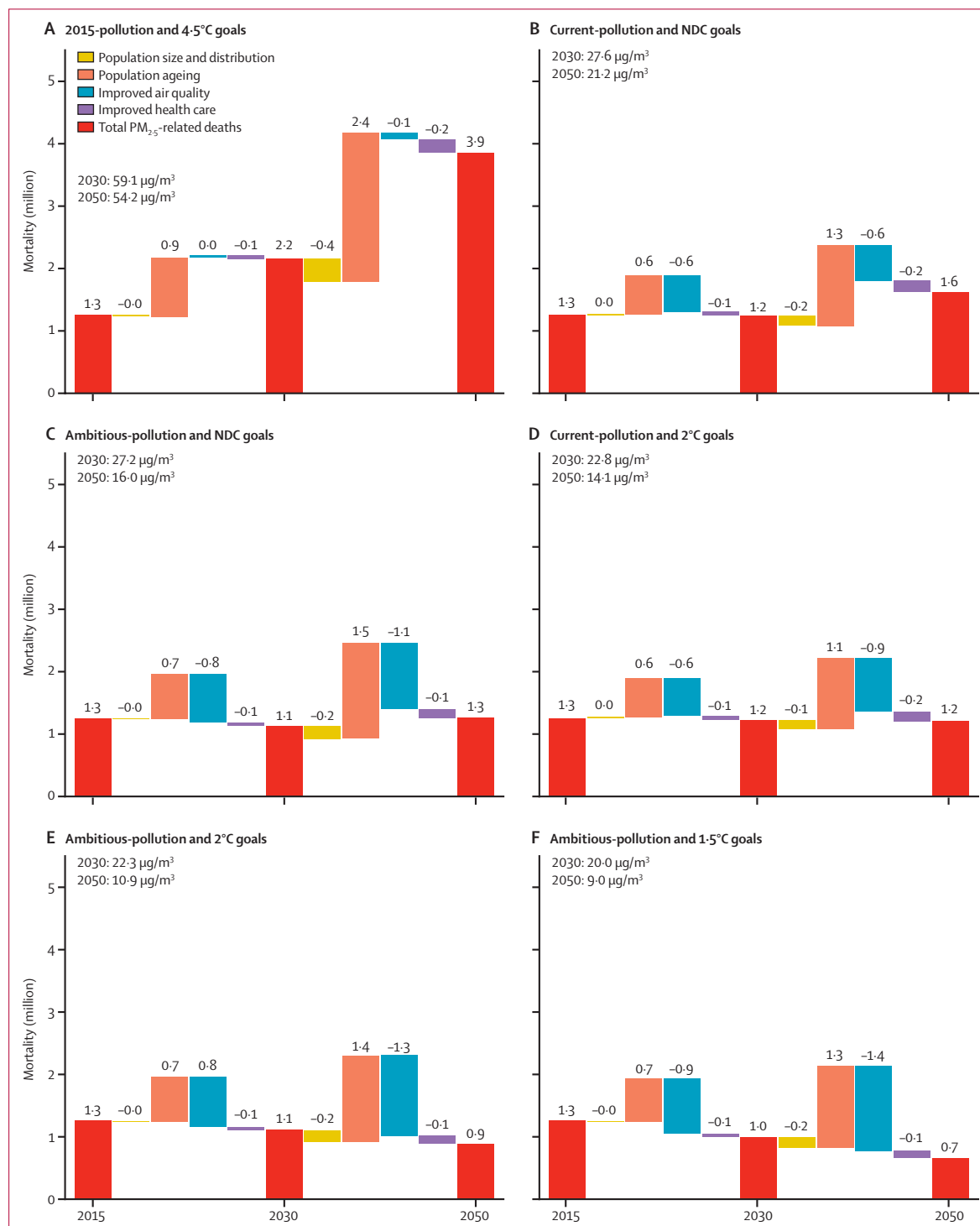


Figure 2: Drivers of changes in premature mortality associated with $PM_{2.5}$ exposure from 2015 to 2050

Each panel presents the population-weighted $PM_{2.5}$ concentrations for 2030 and 2050 under the respective scenario. NDC=national determined contributions.

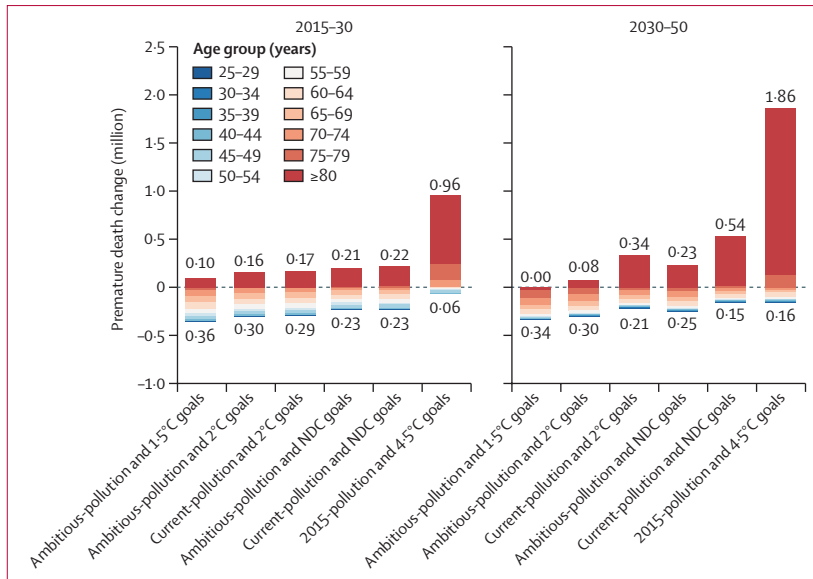


Figure 3: Changes in PM_{2.5}-related deaths by age group during 2015–30 and 2030–50
NDC=national determined contributions.

71.9% decrease during 2015–50, whereas PM_{2.5}-related deaths only decrease 1.6% (appendix p 15). In the ambitious-pollution scenario, with the help of the ambitious climate goals of 2°C and 1.5°C (the ambitious-pollution and 2°C goals scenario and the ambitious-pollution and 1.5°C goals scenario), the improvement in air quality would offset the impact of ageing to some extent, with the PM_{2.5}-related deaths decreasing well below the 2015 1.25 million PM_{2.5}-related deaths by 2050. For example, the climate goal of 1.5°C would help to reduce age-standardised PM_{2.5}-related death rates from 25.9 per 100000 population (95% CI 18.4–34.3) in the NDC scenario to 11.7 per 100000 population (7.0–17.7), a 54.9% reduction (appendix p 36); PM_{2.5}-related deaths would also lower from 1.21 million (0.86–1.60) in the NDC scenario to 0.66 million (0.40–1.00) in the 1.5°C scenario, a striking 45.2% reduction in 2050. It is important to note that the reduction in PM_{2.5}-related deaths from NDC pledges to 1.5°C depended not only on the increased climate mitigation, but also on the socioeconomic differences between the 1.5°C scenarios (SSP1) and the NDC scenarios (SSP2). If we follow the same socioeconomic pathway as the 1.5°C scenario (ie, SSP1) due to the relatively young population structure embodied in the NDC scenarios (SSP2), the PM_{2.5}-related deaths in the NDC scenario with SSP1 would increase to 1.48 million (1.05–1.92) in 2050, an increase of 0.28 million compared with SSP2 (appendix p 12). In other words, the difference would be even larger (0.65 million with SSP2 vs 0.82 million with SSP1 between NDC and 1.5°C) when controlling for the socioeconomic changes in the mitigation scenarios, which in turn emphasises the crucial role of climate mitigation coupled with ambitious pollution controls in reducing future PM_{2.5}-related pollution deaths

in China (appendix p 13). Differences in socioeconomic assumptions also explain why, for example, PM_{2.5}-related deaths under the baseline climate goal (SSP3) would be fewer than those under the unambitious goal (SSP4): 1.50 million deaths (1.11–1.92) under the ambitious-pollution and unambitious goal scenario versus 1.39 million (1.05–1.76) under the ambitious-pollution and baseline goal scenario in 2050.

We disaggregated the drivers of changes in premature mortality associated with PM_{2.5} exposure from 2015 to 2050 (figure 2): population size and distribution, population ageing, improved air quality, and baseline incidence decline. Population size and distribution and baseline incidence decline tended to decrease annual PM_{2.5}-related deaths across different SSPs during 2015–50 (appendix p 16). Ageing and improved air quality dominated the overall changes, and ageing became increasingly important beyond 2030. In the 4.5°C climate scenario with 2015-level pollution control (ie, 2015-pollution and 4.5°C goal scenario; figure 2A), the health benefits from air quality improvement and baseline incidence decline were unable to offset the attributable mortality from ageing from 2015 to 2030, leading to an overall increase in PM_{2.5}-related deaths. By contrast, with current clean-air policies and the 2°C climate mitigation target (ie, the current-pollution and 2°C goals scenario; figure 2D), avoided PM_{2.5}-related deaths from improved air quality (0.6 million) and baseline incidence decline (0.1 million) in 2015–30 could successfully offset increased PM_{2.5}-related deaths from population ageing (0.6 million).

Compared with 2015–30, ageing during 2030–50 posed great challenges for alleviating PM_{2.5}-related health burdens. In many of the scenarios, during 2030–50, the positive effects from all other factors (ie, population size and distribution, improved air quality, and baseline incidence decline) could not effectively offset the influence of an ageing population. Additionally, health benefits from improved air quality alone in all combined 18 scenarios—except strengthening the clean-air policies under the 1.5°C climate target (ie, the ambitious-pollution and 1.5°C goals scenario; figure 2F)—were not able to offset the negative effects from population ageing. Meanwhile, only the ambitious climate targets (ie, limiting warming to 2°C and 1.5°C) coupled with the most stringent clean-air policies (ie, the ambitious-pollution and 2°C goals scenario and the ambitious-pollution and 1.5°C goals scenario) could improve air quality sufficiently and, along with a decline in population size and distribution and baseline incidence decline, offset the effects of an ageing population and substantially reduce PM_{2.5}-related deaths in 2015–50.

As population ageing was the dominant driver of increasing PM_{2.5}-attributable deaths in all scenarios, we assessed the PM_{2.5}-related death changes among different age groups (figure 3). For all scenarios, people older than 55 years in 2030 and older than 70 years in 2050 accounted for most of the increase in PM_{2.5}-related deaths in those

periods. By 2050, more than 40% of the population would be older than 55 years in all socioeconomic pathways (ie, SSP1 to SSP5), compared with only 21% in 2015 (appendix p 14).

Discussion

By comprehensively assessing future mortality attributable to PM_{2.5} in China across a broad range of climate and clean-air scenarios, our results show that current clean-air policies and NDC pledges provide only modest reductions in midterm PM_{2.5}-related deaths (ie, the current-pollution and NDC goals scenario in 2030), with deaths continuing to increase in the long term unless stringent clean-air policies are paired with more ambitious climate targets. Specifically, our findings highlight the crucial role of adopting ambitious climate targets together with stringent clean-air policies for protecting China's public health in 2050, and especially the health of an increasing number of older people. A previous study¹⁹ found that the energy-saving policies and maximum feasible control strategies might not be enough to protect health in 2030 under the population ageing background, whereas our study revealed that the local strongest clean-air policies combined with global 2°C or 1.5°C climate targets could offset the effects of ageing to a greater extent and, more importantly, only the energy transitions driven by ambitious climate targets could fundamentally reduce the PM_{2.5}-related deaths for a long-term future (ie, 2050).¹⁹ For China's local climate mitigation effort with NDC pledges, curbing the increase of CO₂ emissions after 2030 alone (ie, carbon peak before 2030) cannot help reduce PM_{2.5}-related deaths by mid-century through air quality improvement. On Sept 22, 2020, China announced its ambitious climate intention to become carbon neutral by 2060, filling the blank space of local long-term (ie, 2030–60) climate mitigation policies. Compared with global ambitious climate goals of 2°C or 1.5°C, it has been shown that China's carbon neutrality goals lie between the 1.5°C-consistent and 2°C-consistent climate policies and closer to the 1.5°C climate goal.¹⁷ Therefore, carbon neutrality goals could successfully offset the negative effects of population ageing and lead to an overall decrease of PM_{2.5}-related deaths from 2015 to 2050.

Because demographic trends (ie, ageing) are so important for future PM_{2.5}-related deaths, we also did sensitivity tests using a wide range of socioeconomic pathways (SSP1 to SSP5) under different climate, energy, and clean-air policy scenarios. These sensitivity analyses show the importance of future socioeconomic pathways for human health, regardless of climate and environmental policies (appendix p 13). For example, if we follow either SSP1 (sustainability) or SSP5 (fossil-fuelled development) and the NDC climate target with best-available pollution control technologies (eg, the ambitious-pollution and NDC goals scenario), PM_{2.5}-related deaths might not decrease in 2030–50. In turn, under these

socioeconomic pathways, more ambitious climate targets (eg, 2°C and 1.5°C climate target) are the better choices to protect public health. Therefore, although the aggregate population levels and age distributions are not easily manipulated by policy makers, adopting more ambitious climate targets avoided health risks regardless of socioeconomic assumptions in all modelled scenarios.

Additionally, we found that the decline of baseline incidence also contributed to a reduction of PM_{2.5}-attributable deaths, especially during the later period of 2030–50. We used future changes of baseline incidence from the World Population Prospects 2019 report (more details in the appendix, pp 3–4). Because the future baseline incidence is affected by many factors such as income level, education level, health-care quality, and so on, there are usually differences between different projections.²⁹ We did sensitivity tests on different projections of future baseline incidence, and we showed that the more aggressive improvement of baseline incidence reduces PM_{2.5}-related deaths (eg, using the baseline incidence projected by the International Futures model) but much less so than it would be necessary to offset the negative effect of population ageing (appendix p 17). Therefore, although a decline of baseline incidence would always decrease PM_{2.5}-related deaths, such improvements would not obviate the health benefits of ambitious climate, energy, and clean-air policies. Another limitation of the study could be that future air quality improvement is also considered as one of the factors driving future baseline incidence decline,^{1,30} the contributions of which would be partly attributed to the factor of improved air quality. Because of the small contribution of baseline incidence decline to the changes of premature deaths (figure 2), we believe that future air quality improvements embodied in future baseline incidence decline would have little effect on the results of the decomposition, which in turn highlights the importance of air quality improvement from the ambitious climate, energy, and clean-air policies in reducing the health burden.

Some important uncertainties also apply to our findings. For example, the evaluation of air quality and PM_{2.5}-related deaths are based on the integrated models including the emission projection model DPEC, the atmospheric chemical model WRF-CMAQ, and the concentration–response functions, all of which would introduce uncertainties. Additionally, these models incorporate limitations such as incomplete knowledge of base-year emissions, innovation of end-of-pipe control technologies, chemical and physical process of the WRF-CMAQ model, constant meteorological conditions, and the health risk curves based on the low number of studies.³⁰ We present more detailed analyses of these uncertainties in the appendix (pp 8–10). Another limitation is that this study only estimates the deaths attributed to PM_{2.5} ambient exposure, and deaths attributed to household air pollution from solid fuels are

not included, which would underestimate the health burden in rural China, as well as highlight the importance of ambitious climate targets. However, regardless of the various sensitivities and uncertainties, our modelling of a broad range of climate, energy, and clean-air scenarios shows the crucial role of 1.5°C and 2°C climate targets together with ambitious pollution controls for protecting air pollution-related human health in China.

In conclusion, using the integrated method for quantifying future health outcomes under the scenario matrix, we found that PM_{2.5} health risk from ambient PM_{2.5} pollution will greatly increase in the future in the context of population ageing, even with mild air quality improvement. However, the future air quality improvement from the most advanced end-of-pipe pollution controls or ambitious climate actions alone might not always support the continuous and substantial decline of PM_{2.5}-related deaths in some scenarios (eg, under the SSP1 scenario; appendix p 13), which underscores the need for ambitious climate action (eg, 2°C and 1.5°C climate target) together with the strongest clean-air policies to substantially reduce the future health burden across wide ranges of SSP assumptions.

Contributors

QZ and DT conceived the study. YL, DT, JC, SY, and BY developed the integrated model and provided input to the analysis. YL, DT, JC, and QZ analysed and interpreted the results. DT, YL, and SJD wrote the first draft of the manuscript. QZ, LEC, MB, AJC, HK, and TX reviewed the manuscript. All authors contributed to the development of the manuscript and approved the final version for publication. YL and JC have verified the underlying data and have full access to all the data in the study. All authors had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

All data used in this work are available on request from the authors.

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