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Original Research

Increasing life expectancy in China by achieving its 2025 air quality target

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ABSTRACT

China is striving to build a “Beautiful China” characterized by clean air. The country has committed to further reducing its national mean fine particle ($PM_{2.5}$) concentration by 10% from 2020 to 2025, following the substantial improvements in its air quality during the past decade. Meanwhile, the “Healthy China” mission has pledged to increase the national mean life expectancy by one year during the same period. Yet, to what extent will the “Beautiful China” mission contribute to the “Healthy China” vision by reducing the levels of the detrimental $PM_{2.5}$ is still unclear. Here, by coupling the life table approach and an epidemiological concentration-response model, this study quantifies the potential benefits of achieving China's 2025 air quality target on the national life expectancy. The analysis reveals that the Chinese citizen could expect to extend the average life expectancy by 42.5 days by 2025 due to improved air quality. In addition, if the Chinese government outperforms the planned air quality target, as it usually does, the gains would increase to 65.4 days, ~18% of the “Healthy China” life expectancy increment task. Further reductions in $PM_{2.5}$ concentration would lead to accelerated gains in life expectancy both nationally and at the city level, providing strong incentives for the authorities to keep improving air quality. This study reveals the notable benefits on individual life that could be expected from air quality improvement in China and suggests that longer life expectancy is achievable by implementing a health-prioritized air quality management mechanism.

1. Introduction

The rapid industrialization and urbanization in China over the past decades have been driven by intensive fossil fuel consumption; in turn, this consumption has substantially deteriorated air quality in this country [1]. Air pollution has been demonstrated to adversely affect human health and would thus reduce life expectancy [2,3]. The latest Global Burden of Disease Study (GBD) estimates that, in China, exposure to ambient $PM_{2.5}$ pollution may have caused 1.42 million premature mortalities in 2019, ranking third in the leading risk factors for premature mortality [4]. This detrimental effect of air pollution has been a major public concern for both government and people in China.

To tackle the air pollution issue and protect public health, the Chinese government has implemented a series of strict air pollution control policies since 2013, namely, the Air Pollution Prevention and Control Action Plan (the Action Plan) from 2013 to 2017 and the following Three-Year Action Plan for Winning the Blue Sky Defense Battle (the Three-year Action Plan; the second phase of the Action Plan) from 2018 to 2020 [5]. These clean air policies have substantially improved air quality in China, with the estimated national population-weighted annual mean $PM_{2.5}$ concentration decreasing from 63 $\mu g\ m^{-3}$ in 2013 to 33 $\mu g\ m^{-3}$ in 2020, achieving a 48% reduction [6]. These $PM_{2.5}$ reductions are estimated to avoid 0.36 million chronic-exposure-related premature deaths (i.e., a 21% reduction) [6]. Despite great efforts that have been made, the country's national population-weighted annual mean $PM_{2.5}$ concentration in 2020 was still 6.6 times the corresponding World Health Organization (WHO) air quality guideline level (AQG) of 5 $\mu g\ m^{-3}$ [6,7], indicating that much more works are necessary to protect Chinese people from air-pollution-related health issues.

The Chinese government has committed to continuously improving the country's air quality as a vital part of the mission to

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build a "Beautiful China". Specifically, the country has set a target of reducing annual mean $PM_{2.5}$ concentration by 10% between 2020 and 2025 in its 14th Five-Year Plan (the 14th-FYP Action Plan; the third phase of the Action Plan). On the other side, the "Healthy China" mission has pledged to increase the country's life expectancy by one year from 2020 to 2025 [8,9]. The substantial health impacts of air pollution raise the question of to what extent will the "Beautiful China" mission contribute to the "Healthy China" vision by improving air quality and extending the country's life expectancy?

Investigating the interconnections between the goals of the two top-tier missions would convey key information for policymakers to better formulate and implement supporting policies and achieve synergies. The linkage between life expectancy and air pollution exposure has been well studied in China based on empirical experiments [10–12]. The impacts of clean air policies on mortality and morbidity have also been extensively evaluated in China and beyond, based on retrieved or simulated changes in air pollutant concentrations and functions that depict exposure-response relationships [13–18]. Yet, studies evaluating the public health benefits of attaining China's new air quality target and its potential contributions to the "Healthy China" target by 2025 have not been reported.

To provide a better understanding of the full range of impacts of China's 14th-FYP Action Plan and to incentivize the authorities to keep improving air quality, we apply the life table approach [3,19], coupled with an updated epidemiological concentration-response model (the Global Exposure Mortality Model; GEMM) [20] to estimate the potential gains in life expectancy associated with planned air quality targets by 2025 at a city level.

2. Material and methods

2.1. Scenarios of air quality target

China's 14th-FYP Action Plan commits to reducing the country's national annual mean $PM_{2.5}$ concentration by 10% from 2020 to 2025, with stricter requirements applied to key regions with high $PM_{2.5}$ concentrations. Base on historical experiences, in this study, the reduction rate for the Beijing–Tianjin–Hebei and the surrounding regions (BTHS) is set to 20%, while the reduction rate for the Fenwei Plain region (FYP) and the Yangtze River Delta region (YRD) are both set to 15%. For Beijing, the country's capital, an annual mean $PM_{2.5}$ concentration target of 32 $\mu g\ m^{-3}$ is set, equivalent to a 15.8% reduction, compared with the concentration of 38 $\mu g\ m^{-3}$ in 2020. Based on the policy requirements, three prospective scenarios of air quality target are designed: the *Policy*, *Averaged Reduction*, and *Outperform* scenarios, as summarized in Table 1.

***Policy* scenario.** The *Policy* scenario sets varying $PM_{2.5}$ reduction targets for cities in different regions, as described in Table 1. With the targets for the national average (T_a) and targets for key regions/cities (denoted as T_r) confirmed, targets for other regions (denoted as T_o) could be derived following equation (1).

$$T_o = \left(T_a \times P_a \times n_a - \sum_r T_r \times P_r \times n_r\right) \Big/ \left(P_a \times n_a - \sum_r P_r \times n_r\right) \tag{1}$$

where P_a represents the national annual average $PM_{2.5}$ concentration in 2020; n_a represents the number of cities (i.e., 337); P_r represents regional annual average $PM_{2.5}$ concentrations in region r in 2020; and n_r depicts the number of cities in region r. The reduction target for BTHS cities other than Beijing is also reestimated following the same approach, with T_a, P_a, and n_a represent corresponding regional values, and T_r and P_r represent corresponding values for Beijing. It should be noted that the national and regional mean $PM_{2.5}$ concentrations and the corresponding 2025 targets released by the Chinese government are estimated as the arithmetic means of city-level concentrations. This study therefore estimates T_o by adopting the number of cities (i.e., n_r) as the weight in equation (1).

Finally, in the *Policy* scenario, a 20.1% reduction is applied for cities in the BTHS region, with an annual $PM_{2.5}$ concentration of 32 $\mu g\ m^{-3}$ set for Beijing; the reduction ratio for the FYP and YRD regions are both set to 15%; a 5.6% reduction is applied to other cities.

***Averaged Reduction* scenario.** China's clean air policies (for example, the Action Plan) commonly demand greater $PM_{2.5}$ abatements over key regions with high $PM_{2.5}$ concentrations. To evaluate the incremental benefits expected from this key-region-prioritized strategy, a counterfactual *Averaged Reduction* scenario applies a 10% reduction in $PM_{2.5}$ concentration to all 337 prefecture-level (or above) cities, is designed. The incremental gains in life expectancy in the *Policy* scenario relative to the *Averaged Reduction* scenario would show to what extent would the key-region-prioritized strategy helps in protecting public health.

***Outperform* scenario.** Previous practices have shown that the Chinese government traditionally does more than it committed regarding air pollution control. For example, the annual $PM_{2.5}$ concentration over the non-attainment cities from 2015 to 2020 dropped by 28.8%, whereas the target set in the Three-year Action Plan is 18%. We therefore design an *Outperform* scenario to investigate the potential health benefits of air quality improvements from 2020 to 2025, assuming that a reduction rate higher than planned would finally be achieved. In the *Outperform* scenario, the reduction rates of $PM_{2.5}$ concentration in all cities are set as 1.5 times the reduction rate in the *Policy* scenario, based on historical experiences.

To be consistent with China's policy narrative, we conduct our evaluation at a city level: health benefits of air quality improvements are estimated for each of the 337 cities, with statistics of the city's average $PM_{2.5}$ concentration and total population as inputs.

Table 1
Prospective scenarios for $PM_{2.5}$ reduction ratio in China from 2020 to 2025.

Scenario	$PM_{2.5}$ reduction rate	Reason
Base	0	$PM_{2.5}$ concentration in the year 2020.
Policy	• 32 $\mu g\ m^{-3}$ for Beijing, 20.1% for the remaining BTHS cities; • 15% for FWP and YRD; • 5.6% for all other cities.	With the national target set in the 14th-FYP Action Plan, the regional-specific targets are proposed based on historical experiences.
Average Reduction	10% for all the 337 prefecture-level (or above) cities.	The national target set in the 14th-FYP Action Plan.
Outperform	1.5 times the reduction rate in the *Policy* Scenario	From 2013 to 2020, the $PM_{2.5}$ concentration being reduced is generally 50% higher than planned.

2.2. Baseline life expectancy estimation

This study applies the standard life table method to estimate the life expectancy at birth, following Arias et al. (2013) and Apte et al. (2018) [3,19]. A life table documents the probabilities of an individual of a particular population living or dying during a particular age interval, which provides a convenient way to represent a population's life expectancy [21]. A life table can be constructed by converting the age-specific mortality rate to the probability of dying. Two types of life tables exist. The complete life table contains data for every single year of age, while the abridged life table shows data for age groups, typically with intervals of five or ten years [19]. In this study, an abridged life table is constructed because the mortality rates for all causes, noncommunicable diseases (NCD), and lower respiratory infections (LRI) for every single age are not publicly available in China. NCD and LRI are the $PM_{2.5}$-related disease endpoints considered in the GEMM model.

The baseline abridged life table for China is constructed based on the age-specific all-cause mortality incidence rate in 2019 retrieved from the GBD 2019 study, which is the latest GBD study [4]. We do not disaggregate the life table by gender, because the GEMM model that provides the $PM_{2.5}$-mortality relationships is not gender-specific. The population is divided into 20 age groups from 0 to 95+ with an interval (denoted as n) of five years (0–4, 5–9, 10–14, …, 90–94, 95+). For each of the age strata, the probability of dying during the age interval between ages x and $x+ n$ can be calculated as:

$$ {}_nq_x = ({}_nm_x \times n)/(1+(1-\alpha_x)\times {}_nm_x \times n) \tag{2}$$

where ${}_nq_x$ is the probability of dying between the beginning of age x and before reaching the beginning of age $x+n$. For example, for the age group 10–14, ${}_nq_x$ represents the probability of those persons in the life table cohort reaching their 10th birthday and dying before their 15th birthday (i.e., by the end of their age 14). ${}_nm_x$ stands for the GBD 2019 all-cause mortality incidence rate for the age interval x to $x+n$. For persons who die during the age interval x to $x+n$, α_x represents the fraction of the age interval duration that the average dying cohort member survives. Following Apte et al., 2018, we simply assume that mortalities on average occur at the midpoint of each age interval and set $\alpha_x = 0.5$. Based on ${}_nq_x$, the surviving population (denoted as l_x) of a hypothetical birth cohort of N individuals at age x could be calculated as:

$$ l_x = l_{x-1} \times (1 - {}_nq_{x-1}) \tag{3}$$

when x is 0, $l_x = N$. The value of N is independent of the estimated life expectancy.

The surviving population at age x and the probability of death during the age interval $[x,\ x+n)$ together determine the number of cohort members who die during the age interval (denoted as ${}_nd_x$).

$$ {}_nd_x = l_x \times {}_nq_x \tag{4}$$

In a given age interval x to $x+n$, the number of life-years lived by the cohort (denoted as ${}_nL_x$) is estimated as the ratio of the number of deaths to the average death rate:

$$ {}_nL_x = {}_nd_x / {}_nm_x \tag{5}$$

The average life expectancy at birth (denoted as e_0) can finally be calculated as the ratio of the number of life years lived by the life-table cohort in all age intervals, normalized to the individual number at the beginning of the cohort (i.e., N):

$$ e_0 = \left(\sum\nolimits_{x=0}^{95} {}_nL_x \right) \Big/ N \tag{6}$$

2.3. Mortality incidence rate attributable to $PM_{2.5}$ exposure

This study applies the Global Exposure Mortality Model (GEMM) to estimate the premature mortality rate attributable to long-term ambient $PM_{2.5}$ exposure [20]. The GEMM model constructs relationships between $PM_{2.5}$ exposure and risk of premature mortality based on ambient air pollution cohort studies. Unlike previous exposure-response models that were generally constructed based on cohort studies conducted in regions with clean air (e.g., cohort studies in European countries and the U.S.), information from cohort studies conducted in polluting air (i.e., a cohort study of Chinese men) was added when building the GEMM model. The inclusion of the Chinese cohort provides $PM_{2.5}$-mortality relationships observed at a high pollution level (long-term ambient $PM_{2.5}$ exposures up to 84 $\mu g\ m^{-3}$), and hence substantially extends the range of exposures observed in cohort studies conducted in clean regions [22]. In addition, the inclusion of $PM_{2.5}$-mortality relationships observed in China makes the GEMM model a preferable choice when estimating $PM_{2.5}$-related health risks in China. Consequently, the GEMM model has been widely applied in China and beyond [14,23–27].

The GEMM model estimates age-specific $PM_{2.5}$-related non-accidental mortality risk due to noncommunicable diseases and lower respiratory infections (denoted as GEMM NCD + LRI). The dependence of relative risk (RR) of noncommunicable diseases and lower respiratory infections on $PM_{2.5}$ concentration (P) is parameterized as:

$$ \begin{aligned} &RR(P) = exp\{\theta \times \ln(z/\alpha+1)/(1+exp\{-(z-\mu)/\nu\})\}, \\ &\text{where } z = \max(0, P-2.4), \end{aligned} \tag{7}$$

where θ, α, μ and ν determine the exposure-response relationships. In the GEMM model, RRs of NCD + LRI are calculated by age for adults, whose age started from 25 to greater than 85, with a 5-year interval. The age-specific risk estimation provides essential input for the associated life expectancy impact assessment. The attributable fraction (AF) of premature mortality to chronic $PM_{2.5}$ exposure can then be calculated as:

$$ AF(P) = (RR(P)-1)/RR(P) \tag{8}$$

The premature mortality incidence rate (MR) associated with $PM_{2.5}$ exposure for an age strata a in city c is calculated as:

$$ MR_a(P_c) = B_a \times AF_a(P_c) \tag{9}$$

where B_a represents the baseline mortality incidence rate of NCD + LRI for the age strata a; and $AF_a(P_c)$ is the attributable fraction of NCD + LRI to $PM_{2.5}$ exposure at the exposure level P_c for the age strata a.

2.4. Gain in life expectancy associated with $PM_{2.5}$ abatements

Following the cause-deleted life table approach used in Arias et al. (2013), Apte et al. (2018), and Zhao et al. (2022) [3,19,28], we apply a similar “risk-reduced” life table approach to estimate the potential life expectancy increment that could be expected from the improved air quality. Similar to the established cause-deleted life table approach, our approach consists of three steps: (1) estimating the changes in $PM_{2.5}$-attributable age-specific mortality rate due to air quality improvements for each city, based on equation (9); (2) recompiling a counterfactual "risk-reduced" life table that would exist in the circumstance of improved air quality; (3) estimating the counterfactual "risk-reduced" life expectancy at birth. Take scenario *s* as an example, gains in life expectancy could be estimated by applying equations 10–14.

$$\Delta MR^s = MR^{Base} - MR^s \tag{10}$$

$${}_nq_x^s = \left({}_n\Delta MR_x^s \times n\right)/\left(1 + (1-\alpha_x)\times {}_n\Delta MR_x^s \times n\right) \tag{11}$$

$${}_nr_x^s = {}_nq_x^s / {}_nq_x \tag{12}$$

$${}_np_x^s = {}_np_x^{(1-{}_nr_x)} \tag{13}$$

$${}_nq_x^s = 1 - {}_np_x^s \tag{14}$$

where ΔMR^s represents the changes in PM$_{2.5}$-attributable age-specific mortality rate; ${}_nq_x^s$ represents the changes in the probability of dying associated with changes in air quality; ${}_nr_x^s$ is the fractional changes in the probability of dying; ${}_np_x^s$ represents the probability of surviving after the air quality is improved; and ${}_nq_x^s$ represents the counterfactual probability of dying in scenario *s*. By applying equations (3)–(6) with the counterfactual ${}_nq_x^s$ as input, the "risk-reduced" counterfactual life expectancy e_s could be derived. The gain in life expectancy due to the improved air quality in scenario *s* can be estimated as:

$$\Delta LE_s = e_s - e_0 \tag{15}$$

2.5. Data source

In this study, annual mean PM$_{2.5}$ concentrations in 2020 for the 337 cities are retrieved from the China National Environmental Monitoring Centre (CNEMC, http://www.cnemc.cn/en/), which manages the nationwide air quality monitoring network and releases the official air quality observation data. Historical annual mean PM$_{2.5}$ concentrations for each city published by the Chinese government are rounded to integers. To keep consistency with the official data, historical city-level PM$_{2.5}$ concentrations reported in this study are all integers. Decimals are reported for national or regional mean results in all cases or for city-level results in prospective scenarios. City-level population for the year 2020 is obtained from the 2020 census, which is the newly conducted national census. The latest (i.e., for the year 2019) national all-cause and cause-specific baseline mortality incidence rate and population structure are retrieved from the GBD 2019 study [4]. Given the regional-specific mortality rate is not publicly available, the national average mortality rate is applied in our calculation, and therefore, the estimated city-level life expectancy at birth in the *Base* scenario e_0 is the same. Yet, due to the differences in PM$_{2.5}$ levels, gains in life expectancy in different cities vary.

3. Results

In 2020, the city-level annual mean PM$_{2.5}$ concentrations varied from 7 to 63 μg m^{-3}, with a national mean concentration of 32.7 μg m^{-3} (see Supplementary Materials Table S1 for city-level results). Among the 337 cities, 125 cities (37.1%) failed to attain the national air quality standard for PM$_{2.5}$ (35 μg m^{-3}). The three key regions are the most polluting. In 2020, the annual mean PM$_{2.5}$ concentration for the BTHS, FWP, and YRD reached 48.9, 47.8, and 38.1 μg m^{-3}, respectively, 8.8–39.6% higher than the national PM$_{2.5}$ air quality standard. Meanwhile, several cities exhibit high loading of PM$_{2.5}$ concentrations in the west. For example, Wujiaqu, a city located in the northern Xinjiang autonomous region in northwestern China, is the most polluting city in terms of PM$_{2.5}$, with the annual mean PM$_{2.5}$ concentration reaching 63 μg m^{-3}. Wind-blown dust contributes substantially to PM$_{2.5}$ pollution in these northwestern cities.

As shown in Fig. 1a is the premature mortality rate attributable to PM$_{2.5}$ exposure in 2020 at a city level, estimated based on the GEMM model. With the national population structure and baseline mortality rate applied, the variations in city-level premature mortality rate directly follow the PM$_{2.5}$ concentrations. The estimated PM$_{2.5}$-related premature mortality rates for cities range from 486.9 to 2069.8 per million, indicating that the risk of premature mortality for people in the most polluting Chinese city is 4.2 times that in the cleanest city, as a result of a nine times difference in PM$_{2.5}$ concentrations. The smaller disparities in health effects compared with PM$_{2.5}$ concentrations reflect the nonlinear relationships between PM$_{2.5}$ exposure and the associated health risk.

In China, populous regions generally suffer higher health

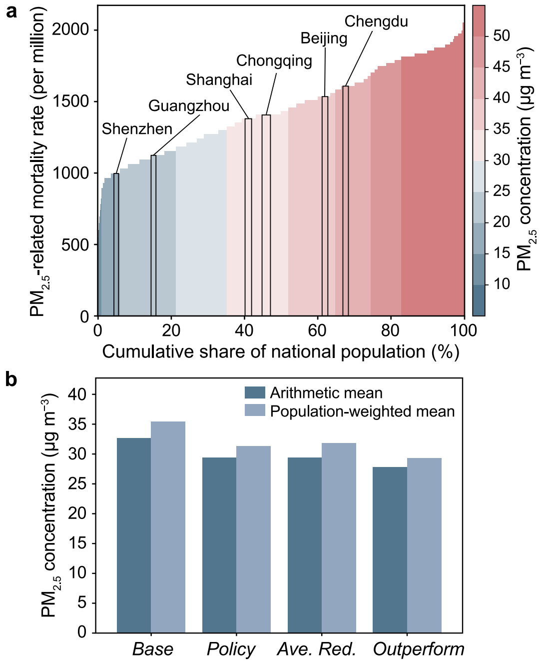

Fig. 1. PM$_{2.5}$-related health risks over China in 2020 and PM$_{2.5}$ concentrations for the three prospective scenarios. **a**, City-level premature mortality rate associated with PM$_{2.5}$ exposure in 2020. **b**, national arithmetic and population-weighted annual mean PM$_{2.5}$ concentration for the *Base* (i.e., the 2020 levels) and three prospective scenarios (i.e., the *Policy*, *Average Reduction*, and *Outperform* scenarios; *Avg. Red.* is the abbreviation of *Average Reduction*). In **a**, cities are sorted by PM$_{2.5}$-related premature mortality rate from the lowest on the left to the highest on the right; the x-axis shows the share of the national population for each city, and the area of each bar represents the city-specific fraction of PM$_{2.5}$-related premature mortality out of the national population. Bars in **a** are shaded by city-level annual mean PM$_{2.5}$ concentration in 2020. Six cities with populations greater than 15 million are labeled in **a**. With the national population structure and baseline mortality rate applied, the variations in city-level premature mortality rate in **a** directly follow the variations in PM$_{2.5}$ concentrations. Arithmetic means are officially adopted by the Chinese government to estimate national and regional mean PM$_{2.5}$ concentration based on city-level results, while population-weighted means better represent average population exposure to air pollution. Therefore, in **b**, the national arithmetic mean and population-weighted mean PM$_{2.5}$ concentrations are both presented. City-level annual mean PM$_{2.5}$ concentrations in each prospective scenario are documented in Supplementary Materials Table S1.

burdens. Six Chinese cities with populations greater than 15 million are labeled in Fig. 1a. $PM_{2.5}$ concentration in these cities varies notably, and so do the associated premature mortality risks. Yet, because of the large population, the health burdens in these cities are all high, indicating that reducing $PM_{2.5}$ concentration in populous cities may yield greater health benefits.

The annual mean $PM_{2.5}$ concentrations in the three prospective scenarios are illustrated in Fig. 1b. As designed, reductions in $PM_{2.5}$ concentration over the three key regions are prioritized in the *Policy* and *Outperform* scenarios, while $PM_{2.5}$ reductions over other regions in these two scenarios are smaller than in the *Average Reduction* scenario. The national annual arithmetic mean $PM_{2.5}$ concentrations decline to 29.4 $\mu g\ m^{-3}$ in both the *Policy* and *Average Reduction* scenarios and 27.8 $\mu g\ m^{-3}$ in the *Outperform* scenario. The population-weighted annual mean $PM_{2.5}$ concentrations in all scenarios are higher than the arithmetic mean concentrations. In 2020 (the *Base* scenario in Fig. 1b), the national population-weighted annual mean $PM_{2.5}$ concentration is estimated as 35.4 $\mu g\ m^{-3}$, 8.3% higher than the arithmetic mean, implying that higher $PM_{2.5}$ loadings tend to occur over regions with a larger population. In 2025, the population-weighted annual mean $PM_{2.5}$ concentrations could be reduced to 31.3 $\mu g\ m^{-3}$ (−11.6%), 31.9 $\mu g\ m^{-3}$ (−9.9%), and 29.3 $\mu g\ m^{-3}$ (−17.2%), respectively, in the *Policy*, *Average Reduction*, and *Outperform* scenarios, assuming the distribution of population fixed. The difference between the *Policy* and the *Average Reduction* scenario is small (0.6 $\mu g\ m^{-3}$), indicating that the key-region-prioritized strategy may not substantially increase health benefits compared with the average reduction strategy as a bunch of populous cities do not belong to any of the key regions. For example, 11 out of 18 cities with a population greater than ten million are located outside the three key regions. However, it should be noted that the current key-region-prioritized strategy has been proven effective with greater $PM_{2.5}$ abatements witnessed over key regions [6,14], which would inevitably help to reduce the imbalances in air pollution exposure in China.

As illustrated in Fig. 2a is the potential gains in life expectancy with China's 2025 air quality target achieved. As expected, the small difference in the national population-weighted mean $PM_{2.5}$ concentration between the *Policy* and the *Average Reduction* scenario would result in a small difference in the national mean benefit (Fig. 2a). In the *Policy* scenario, a key-region-prioritized 10% reduction in national mean $PM_{2.5}$ concentration would lead to a 42.5-day increment in national life expectancy, and vary from 10.9 to 106.2 days by city. In comparison, if a 10% $PM_{2.5}$ reduction applies to all cities (i.e., in the *Average Reduction* scenario), gains in life expectancy would be 38.4 days nationally and 19.7–50.4 days at a city level. In the *Outperform* scenario, if 1.5 times the reduction rate in the *Policy* scenario is achieved, which is possible based on historical experiences, gains in national mean life expectancy would be 65.4 days, and would range from 16.5 to 167.4 days by cities. These national and city-level benefits in the *Outperform* scenario are all larger than 1.5 times the corresponding values in the *Policy* scenario. These disproportionate health benefits indicate the accelerated increment in life expectancy associated with air quality improvement.

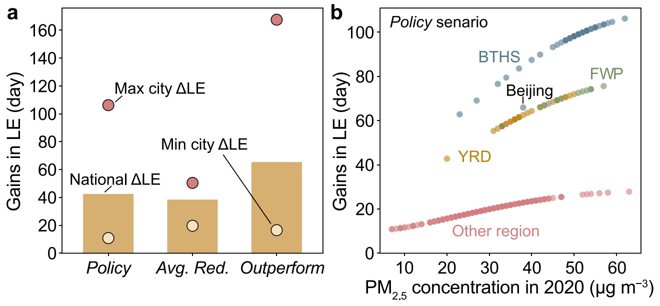

Fig. 2. Potential gains in life expectancy in China with its 2025 air quality target achieved. **a**, Potential gains in national life expectancy for the three prospective scenarios. **b**, Gains in life expectancy for each city in the *Policy* scenario. In **a**, the ranges of increment in life expectancy increment for cities are illustrated by the pink and yellow dots for each scenario. In **b**, cities in different regions are differentiated by colors.

The distribution of gains in life expectancy for cities in the *Policy* scenario is shown in Fig. 2b. Generally, higher gains in life expectancy would be obtained in key regions, because of their higher 2020 $PM_{2.5}$ levels and greater concentration reductions, compared with other regions. In the *Policy* scenario, with 20% reductions in $PM_{2.5}$ concentrations, gains in life expectancy in cities in the BTHS region are estimated to range from 62.8 to 106.2 days. The 15% reduction in $PM_{2.5}$ concentrations would increase city-level life expectancy by 42.8–71.9 days in the YRD region and by 57.5–75.6 days in the FWP region, respectively. For cities in other regions, life expectancy gains are estimated at 10.9–27.8 days.

To test the effects of different reduction rates on potential gains, three cities in different regions with the same 2020 $PM_{2.5}$ levels (45 $\mu g\ m^{-3}$) are selected, namely Zhumadian in the BTHS region (20.1% reduction in $PM_{2.5}$), Suqian in the YRD region (15% $PM_{2.5}$ reduction), and Jinmen in other regions (5.6% $PM_{2.5}$ reduction). In the *Policy* scenario, the estimated gains in life expectancy for the three cities are 93.3, 68.5, and 25.0 days, respectively. Differences in the estimated benefits in different cities are slightly larger than the differences in the $PM_{2.5}$ reduction rates, further suggesting that increasingly gains in life expectancy could be expected from continuous $PM_{2.5}$ reductions.

To check the potential to increase life expectancy by reducing $PM_{2.5}$ concentrations in China, we design a sensitivity test by reducing $PM_{2.5}$ concentrations in all cities at rates from 1% to 100% with an interval of 1% (an average reduction strategy). As shown in Fig. 3a, when the national mean $PM_{2.5}$ concentrations achieve the WHO recommended interim targets 2–4 for annual mean $PM_{2.5}$ concentration, i.e., 25, 15, and 10 $\mu g\ m^{-3}$, respectively, the national mean life expectancy could be expected to increase by 92.2, 244.9, and 342.0 days, respectively. Furthermore, if the WHO AQG value is achieved, the national life expectancy could be expected to increase by 500.4 days (~1.4 years).

As shown in Fig. 3a, the national $PM_{2.5}$ reduction rate (x-axis in Fig. 3a) and gains in life expectancy (y-axis in Fig. 3a) exhibit a superlinear relationship. This superlinear relationship could be explained by the supralinear shape of the exposure-response function, i.e., steeper exposure-response slopes towards low concentration levels [20]. The superlinear “reduction-benefit” relationship highlights the importance of progressively improving air quality to extend the life expectancy of Chinese citizens.

As illustrated in Fig. 3b are the potential gains in city-level life expectancy in the 4 $PM_{2.5}$ reduction cases highlighted in Fig. 3a. For most of the cities (>99%), continuous reductions in $PM_{2.5}$ concentrations at rates from 1% to 85% would keep increasing city-level life expectancy, at an accelerated speed. Taking Anyang, the most polluting BTHS city in 2020, as an example (annual mean $PM_{2.5}$ concentration in 2020 is 62 $\mu g\ m^{-3}$), 10%, 20%, 40%, and 80% reductions in this city's annual mean $PM_{2.5}$ concentration might on average increase the life expectancy by 50, 106, 234, 593 days, respectively, for its citizens, showing a superlinear “reduction-benefit” relationship similar to that in national results (Supplementary Materials Fig. S1).

4. Discussions and policy implications

To better understand the potential health benefits of China's

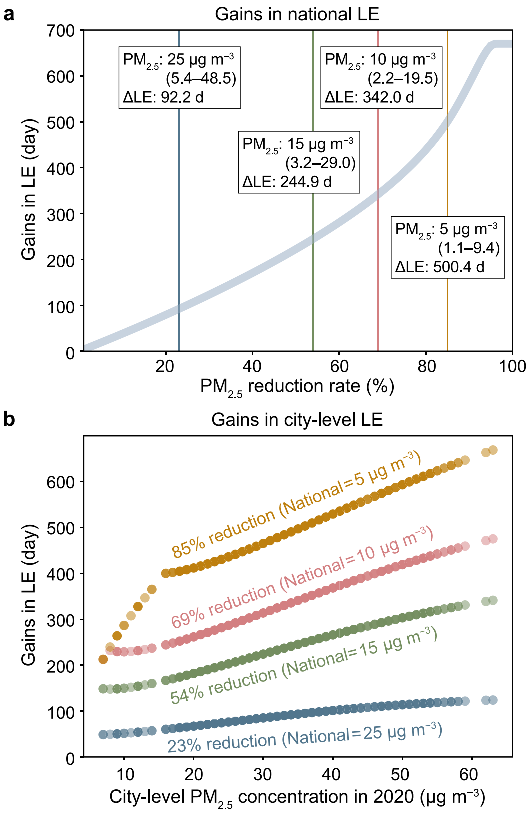

Fig. 3. Potential to increase life expectancy by reducing PM$_{2.5}$ concentrations. **a**, Potential gains in national mean life expectancy with the PM$_{2.5}$ concentration reduced by 1%–100%, with the interval of 1%, for all cities. **b**, Potential gains in life expectancy for each city with PM$_{2.5}$ concentrations reduced by 23%, 54%, 69%, and 85% from the 2020 levels, corresponding to cases with national annual mean PM$_{2.5}$ concentrations reaching the levels of 25, 15, 10, and 5 μg m^{-3}, respectively, which are the recommended interim targets 2–4 and AQG level for annual PM$_{2.5}$ by the WHO.

14th-FYP on air quality protection, this study estimates the potential impacts of achieving China's 2025 PM$_{2.5}$ air quality target on the country's life expectancy. The analysis based on the GEMM exposure-response model and the "risk-reduced" life table approach shows that with a 10% reduction in the national mean PM$_{2.5}$ with higher reductions over key regions achieved, the national mean life expectancy could be expected to increase by 42.5 days, and gains in life expectancy greater than 100 days could be expected in the current most polluting cities. The results suggest that achieving the air quality target could help to fulfill more than 10% of the "Healthy China" target in terms of life expectancy increment, which would be a notable contribution. In addition, given that the Chinese government generally outperforms in air quality protection compared with its plan, air quality improvements are likely to contribute to 18% of the "Healthy China" life expectancy increment task during the 14th-FYP period (i.e., in the *Outperform* scenario).

Our study is subject to several uncertainties and limitations. First, various factors would affect life expectancy, such as economic growth, improved health care, and improved air quality. This study aims to evaluate the impacts of clean air policies on life expectancy; therefore, impacts of other factors are not estimated. In total, with all factors considered, the national average life expectancy is expected to increase by one year from 2020 to 2025, which is the target set by the "Healthy China" mission [8]. Second, interactions between different factors might affect our estimates. Changes in demographic structure and baseline mortality incidence rate reflect the combined effects of all factors. In this study, we based our estimation on demographic information and baseline mortality incidence rate in 2019, which are the latest available results. Our sensitivity test shows that the estimated changes in life expectancy associated with improved PM$_{2.5}$ air quality from 2020 to 2025 would vary by less than 1% when demographic information and baseline mortality incidence rate vary from 2014 to 2019 (see Supplementary Materials Table S2). This result indicates that the interactions between different factors would have limited impacts on our estimates. Third, changes in population distribution, which could be induced by varying population migration and population growth rates in different regions, might also affect the estimated changes in life expectancy by affecting the PM$_{2.5}$ exposure of the population. Geng et al. (2021) show that, with the distribution of PM$_{2.5}$ pollution fixed at the 2017 levels, changes in population distribution from 2002 to 2017 would have contributed to 0.07 μg m^{-3} changes in China's national population-weighted annual mean PM$_{2.5}$ concentrations, which is neglectable [13]. The historical experiences imply that by 2025 the impacts of changes in population distribution would probably have limited impacts on the population-weighted annual mean PM$_{2.5}$ concentrations as well as the estimated change in PM$_{2.5}$-related life expectancy on the national scale. Forth, the potential impacts of changes in O$_3$ pollution are not considered in this study because the 14th-FYP Action Plan has not specified reduction targets for O$_3$ concentration. In the future, tailored control measures targeting both nitrogen oxides (NO$_x$) and volatile organic compound (VOC) emissions would be beneficial for controlling PM$_{2.5}$ and O$_3$ pollution simultaneously, and reductions in O$_3$ concentrations and the associated health burden could be expected.

By 2035 when the "Beautiful China" targets are preliminarily achieved, China's national annual mean PM$_{2.5}$ concentration would probably be lower than 25 μg m^{-3} (the WHO Interim target-2 for annual mean PM$_{2.5}$) [29,30]. Moreover, with the pledge to achieve carbon neutrality in 2060, China's fundamental reforms in its industrial, energy, and transportation structures, together with further clean air policies such as the deployment of advanced end-of-pipe controls, are likely to drive the country's annual mean PM$_{2.5}$ concentration reaches a level around 10 μg m^{-3}, i.e., the WHO Interim target-4 for annual mean PM$_{2.5}$ [29,31,32]. Assuming other factors are fixed, as shown in Fig. 3a, the improved PM$_{2.5}$ air quality by 2035 and 2060 would probably increase the country's mean life expectancy by about a quarter year and one year, respectively, showing tremendous health benefits that could not be neglected by policymakers.

The comparison between the *Policy* scenario and the *Average Reduction* scenario indicates that the current key-region-prioritized strategy may not substantially increase the health benefits, even though this strategy may help reduce the imbalances in regional PM$_{2.5}$ pollution levels. To test whether higher reductions over populous regions would help to increase the national mean health impacts, we design a hypothetical scenario, the *Population Prioritized* scenario. The new scenario adopts the setting of the reduction rates for key regions (i.e., 20% and 15%) from the *Policy* scenario but allocates higher reduction rates to cities with larger populations rather than cities in the key regions. In the new scenario, the number of cities with 20% and 15% reduction rates are the same as in the *Policy* scenario, and a new reduction rate for the remaining cities is estimated based on equation (1), with a 10% reduction in the national mean PM$_{2.5}$ concentration retained. In the *Population Prioritized* scenario, the national mean life expectancy is estimated to increase by 52.2 days, 22.8% higher than that in the *Policy* scenario. For comparison, the difference between the *Policy* scenario and the *Average Reduction* scenario is 10.6%. These results highlight that the strategies that prioritize the reductions in the average population exposure would lead to higher gains in national mean life expectancy. However, we do not mean to recommend applying a strategy that simply follows the *Population Prioritized* scenario. Instead, a well-designed strategy that synergistically balances health benefits, costs, and regional discrepancies would be preferred.

This study suggests that achieving China's 2025 air quality target would notably increase the life expectancy of China's citizens, which would contribute to the “Healthy China” mission regarding life expectancy increment. Furthermore, with the country's $PM_{2.5}$ concentration keep declining, the potential gains in life expectancy would keep increasing at an accelerated rate. Similar impacts would apply to most Chinese cities, regardless of polluting levels, indicating a non-regret choice for local authorities: continuously reducing $PM_{2.5}$ concentration to protect the public health of their citizens. A tailored air quality target allocation strategy that balances health benefits and cost, or even a step forward, a nationwide health-prioritized air quality management system, is highly recommended to maximize the public health benefits associated with air quality improvement in China.

Author contributions

Y.Z. and Y. L. designed the research. Y.Z., T.X, and H.Z. performed the research. Y.Z. and Y. L. interpreted data and wrote the paper with input from all co-authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2022.100203.

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