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Impacts of implementing Healthy Building guidelines for daily $PM_{2.5}$ limit on premature deaths and economic losses in urban China: A population-based modeling study

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ABSTRACT

Given a large fraction of people's exposure to urban $PM_{2.5}$ occur indoors, reducing indoor $PM_{2.5}$ levels may offer a more feasible and immediate way to save substantial lives and economic losses attributable to $PM_{2.5}$ exposure. We aimed to estimate the premature mortality and economic loss reductions associated with achieving the newly established Chinese indoor air guideline and a few hypothetical indoor $PM_{2.5}$ guideline values. We used outdoor $PM_{2.5}$ concentrations from 1497 monitoring sites in 339 Chinese cities in 2015, coupled with a steady-state mass balance model, to estimate indoor concentrations of outdoor-infiltrated $PM_{2.5}$. Using province-specific time-activity patterns for urban residents, we estimated outdoor and indoor exposures to $PM_{2.5}$ of outdoor origin. We then proceeded to use localized census-based concentration-response models and the value of statistical life estimates to calculate premature deaths and economic losses attributable to $PM_{2.5}$ exposure across urban China. Finally, we estimated potentially avoidable mortality and corresponding economic losses by meeting the current 24-hour based guideline and various hypothetical indoor limits for $PM_{2.5}$. In 2015 in urban areas of mainland China, the city-specific annual mean outdoor and indoor $PM_{2.5}$ concentrations ranged 9–108 μg/m^3 and 5–56 μg/m^3, respectively. Indoor exposures contributed 62%–91% daily and 68%–83% annually to the total time-weighted exposures. The potential reductions in total deaths and economic losses for the scenario in which daily indoor concentrations met the current guideline of 75 μg/m^3, 37.5 μg/m^3, and 25 μg/m^3 were 16.9 (95% CI: 0.7–62.1) thousand, 87.7 (95% CI: 9.7–197.7) thousand, and 165.5 (95% CI: 30.8–304.0) thousand, respectively. The corresponding reductions in economic losses were 5.7 (95% CI: 0.2–34.8) billion, 29.4 (95% CI: 2.4–109.6) billion, and 55.2 (95% CI: 7.7–168.0) billion US Dollars, respectively. Deaths and economic losses would be reduced exponentially within the range of 0–75 μg/m^3 for hypothetical indoor $PM_{2.5}$ limits. The findings demonstrate the effectiveness of reducing indoor concentrations of outdoor-originated $PM_{2.5}$ in saving substantial lives and economic losses in China. The analysis provides quantitative evidence to support the implementation of an indoor air quality guideline or standard for $PM_{2.5}$.

1. Introduction

The ongoing COVID-19 pandemic, which caused more than 1.2 million deaths globally as of November 5, 2020 (Johns Hopkins University 2020), has generated much attention to the current and future health-related policies. One of China's most important health-related policies, the Healthy China 2030 Plan, released by the State Council of China in 2016, highlights the goals of reducing premature mortality and promoting air quality and many challenges (Tan et al. 2017). The challenge from severe ambient air pollution was further elucidated in

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the Healthy Cities movement, which aims at achieving the ambitious goals of the Healthy China 2030 Plan (Yang et al. 2018). Numerous studies have shown that both short-term and long-term exposures to ambient $PM_{2.5}$ have been associated with premature mortality (Burnett et al. 2014; Chen et al. 2017; Englert 2004; Pope III 2007; Yin et al. 2017). Among these studies, Burnett et al. (2014) developed an integrated exposure–response (IER) model for long-term exposure effects by integrating available risk information from studies of ambient air pollution, secondhand tobacco smoke, household solid cooking fuel, and active smoking. Based on Global Burden of Disease estimates using the IER model, ambient $PM_{2.5}$ was responsible for 0.8 million premature deaths in China in 2015, mainly from stroke, ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lung cancer (LC), and acute lower respiratory infection (ALRI) (Institute for Health Metrics and Evaluation 2020). A recent study established a nonlinear short-term-effect model for the Chinese population, and estimated a total of 0.17 million additional deaths from short-term $PM_{2.5}$ exposure throughout China in 2015 (Li et al. 2019). On the other hand, early evidence has shown that a small increase in long-term exposure to $PM_{2.5}$ may lead to a large increase in the COVID-19 death rate (Liang et al. 2020; Wu et al. 2020).

Ambient $PM_{2.5}$ reductions are vitally important but take time — it may take years, even decades, to meet the ambient air quality guidelines (AQG) for highly-polluted regions in China (Xiang et al. 2019a). Outdoor $PM_{2.5}$ enters the indoor environment through infiltration and ventilation. The total exposure to outdoor-origin $PM_{2.5}$ is the sum of outdoor and indoor exposure. Based on a previous study, indoor exposures accounted for 66–87% of total exposure to $PM_{2.5}$ of outdoor origin and contributed up to 81% of the premature deaths attributable to ambient $PM_{2.5}$ in urban China in 2015 (Xiang et al. 2019a). With available technologies, it is feasible to reduce indoor $PM_{2.5}$ levels and, consequently, reduce total exposures.

Indoor AQGs, known as Healthy Building standards/guidelines in certain countries, are designed to reduce indoor $PM_{2.5}$ exposure by limiting daily- and yearly mean indoor concentrations. In China, the indoor AQGs include Assessment Standard for Healthy Building (ASHB) established by the Architectural Society of China in 2017 (Architectural Society of China 2017), ASHB Exposure Draft (ASHB-ED) established by the Ministry of Housing and Urban-Rural Development of China in 2018 (Ministry of Housing and Urban-Rural Development of China 2018), and Indoor Air Quality Standard Exposure Draft (IAQS-ED) established by the State Administration for Market Regulation of China and the China National Standardization Management Committee in 2020 (State Administration for Market Regulation of China and China National Standardization Management Committee 2020). Xiang et al. estimated premature adult deaths attributable to $PM_{2.5}$ across urban China in 2015 and the corresponding mortality reductions achievable by meeting different indoor AQGs for annual mean $PM_{2.5}$ (Xiang et al. 2019a). Lacking Chinese census-based concentration–response (C-R) models, they used an IER model, primarily based on estimates from smoking on the upper end and the US/European cohort studies on the lower end (Burnett et al. 2014). However, some recent Chinese census-based cohort studies show that the hazard ratio (HR) estimates from these cohorts were consistently higher than IER predictions (Li et al. 2018; Xue et al. 2019; Yin et al. 2017). Hence, a new analysis based on the Chinese census-based C-R models can provide more accurate estimates.

Like ambient AQGs for $PM_{2.5,}$ indoor AQGs have a long-term limit as an annual average and a short-term limit as a 24-hour average. To our knowledge, no studies have quantitatively evaluated the health and economic benefits of daily $PM_{2.5}$ indoor AQGs. Here, the present study aims to: 1) estimate the premature deaths in China for urban population $\geq$ 25 years of age and the corresponding economic losses attributable to indoor exposures to outdoor-infiltrated $PM_{2.5}$ using localized census-based C-R models; 2) estimate potentially avoidable mortality and corresponding economic losses associated with meeting the daily AQGs in the ASHB, ASHB-ED, and IAQS-ED, as well as more stringent hypothetical guideline limits. The analysis in the present study contributes to a better estimate of indoor $PM_{2.5}$-attributable deaths and economic losses and, consequently, provides a basis for policy formulation and to support the implementation of indoor $PM_{2.5}$ guidelines.

2. Methods

2.1. Study overview

An overview of the model is shown in Fig. 1. The input parameters are detailly described in Appendix pp 3–4. We estimated city-specific daily $PM_{2.5}$ infiltration factors, indoor concentrations, exposure concentrations, disease-specific relative risks, premature deaths, and associated economic losses attributable to $PM_{2.5}$ from outdoor origins under the baseline scenario. We further estimated premature deaths and associated economic losses under reduction scenarios in which daily indoor $PM_{2.5}$ concentrations met potential indoor AQGs. The method enabled us to estimate the reductions in deaths and economic losses by meeting various indoor AQGs for daily $PM_{2.5}$ limits.

2.2. Exposure estimates

Since approximately 99% of Chinese housing is naturally ventilated (Zhiyan Consulting Group), natural ventilation without any air cleaning intervention was considered in the baseline scenario. We used a previously validated steady-state mass balance model (Xiang et al. 2019a), as shown in Equation (1), to estimate the season-specific infiltration factor (F_{inf}), or indoor/outdoor ratio of $PM_{2.5}$ in the absence of indoor sources, for 339 cities located in 31 mainland Chinese provinces (see major cities in each province in Appendix pp 9–10).

$$F_{inf} = \frac{AER_{open} \times p_{open}}{AER_{open} + k} \times \frac{t_{open}}{t_{open} + t_{closed}} + \frac{AER_{closed} \times p_{closed}}{AER_{closed} + k} \times \frac{t_{closed}}{t_{open} + t_{closed}} \tag{1}$$

where AER_{open} and AER_{closed}, p_{open} and p_{closed}, t_{open} and t_{closed} are air exchange rates (AERs), $PM_{2.5}$ penetration factors, and seasonal amount of time when windows are open or closed, respectively; k is the rate constant for $PM_{2.5}$ deposition to indoor surfaces.

Although there are indoor sources of $PM_{2.5}$, the dominant sources of $PM_{2.5}$ in most indoor environments are from the outdoor air in present-day Chinese cities (Wang et al. 2016; Zhu et al. 2015). Thus, only outdoor-origin $PM_{2.5}$ was considered in the present analysis. Daily mean concentrations for indoor $PM_{2.5}$ of outdoor origins (Equation (2)), C_{in}, for each city were calculated by multiplying the infiltration factor, F_{inf}, and daily mean outdoor $PM_{2.5}$ concentrations, C_{out}. Outdoor $PM_{2.5}$ concentrations for the 339 cities located in 31 mainland Chinese provinces were obtained from 1497 public fixed-site monitoring stations.

$$C_{in} = F_{inf} \times C_{out} \tag{2}$$

Daily personal $PM_{2.5}$ exposure concentration (C_{exp}) is the sum of time-weighted outdoor and indoor $PM_{2.5}$ concentrations (Equation (3)). t_{in} and t_{out} are a province-specific fraction of time indoors and outdoors for each season for urban adults over 18 years old, respectively.

$$C_{exp} = C_{in} \times \frac{t_{in}}{t_{in} + t_{out}} + C_{out} \times \frac{t_{out}}{t_{in} + t_{out}} \tag{3}$$

Exposure factor, f_{exp}, is the factor that relates exposure concentrations to outdoor concentrations when there is no filtration of outdoor $PM_{2.5}$. It can be calculated using Equation (4). This approach is discussed in greater detail elsewhere (Xiang et al. 2019a).

$$f_{exp} = \frac{C_{exp}}{C_{out}} \tag{4}$$

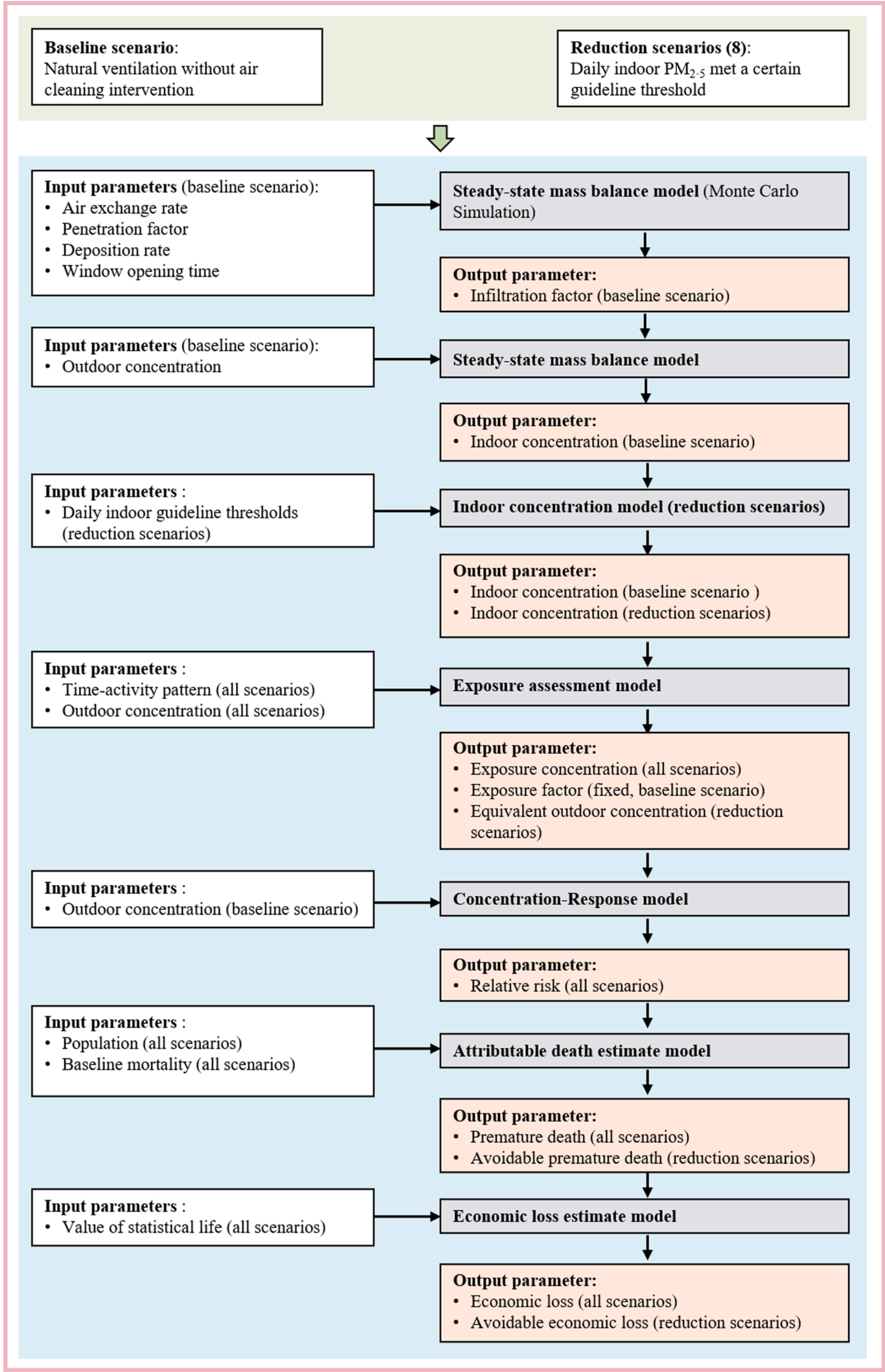

Fig. 1. Model schematic.

2.3. *Premature deaths attributable to short- and long-term $PM_{2.5}$ exposure*

The premature deaths attributable to short- and long-term exposure to $PM_{2.5}$ were estimated based on Equation (5), which was used in many previous studies (Lelieveld et al. 2013; Xiang et al. 2019a; Xiang et al. 2019b).

$$\Delta Mort = Population \times y_0 \times \frac{RR - 1}{RR} \tag{5}$$

where $\Delta Mort$ is premature deaths for a specific disease attributable to $PM_{2.5}$ exposure; *Population* is the total urban population $\geq$ 25 years of age; y_0 is the baseline mortality rate for a specific disease for population $\geq$ 25 years of age; RR is relative risk for a specific disease attributable to total $PM_{2.5}$ exposure, and the expression $(RR - 1)/RR$ is a factor that represents the fraction of deaths for a specific disease attributable to $PM_{2.5}$ exposure.

RR was estimated based on a commonly-used C-R model (Equation (6)) (Xiang et al. 2019b).

$$RR = \begin{cases} 1, C_{out} \leq LCC \\ exp(\beta(C_{out} - LCC)), C_{out} > LCC \end{cases} \tag{6}$$

where β is the effect estimate, and LCC is the low-concentration cutoff, below which the effect estimate (β) has not been evaluated.

Both short- and long-term exposure effects were considered in our calculations. The short-term exposure effect estimate was derived from a nationwide time-series analysis in 272 representative Chinese cities from 2013 to 2015, in which the health endpoints were stroke, IHD, and COPD (Chen et al. 2017). Using the short-term-effect model, we calculated daily mortality associated with daily $PM_{2.5}$ concentration and then multiplied the daily death count by 365 to get the annual mortality. The long-term exposure effect estimate was derived from a prospective cohort study following 189,793 participants from 1990 to 2006 from 45 areas in China, in which the health endpoints were stroke, IHD, COPD, and LC (Yin et al. 2017). All attributable deaths from each health endpoint were summed up as the total deaths attributable to short- or long-term $PM_{2.5}$ exposure.

2.4. Economic losses of $PM_{2.5}$-attributable premature deaths

The $PM_{2.5}$-attributable premature deaths are monetized using the value of statistical life (VSL) estimates (Jin and Zhang 2018). VSL is the marginal rate of substitution between income and micro mortality risk reduction. It is obtained by aggregating individuals' willingness to pay for mortality risk reductions over the affected population. With the city-specific VSL and $PM_{2.5}$-attributable premature deaths, the economic losses (EL) of premature deaths for each city can be calculated as Equation (7).

$$EL = VSL \times \Delta Mort \quad (7)$$

2.5. Benefits by meeting various daily indoor $PM_{2.5}$ standards/guidelines

Sustaining compliance with daily indoor $PM_{2.5}$ guidelines in a whole year can reduce both short- and long-term exposure. Deaths and corresponding economic losses that can be avoided by reaching an AQG limit were evaluated if daily mean indoor $PM_{2.5}$ concentrations across China for each day in 2015 did not exceed eight different standard or guideline values. These are 75 μg/m^3 (IAQS-ED) (State Administration for Market Regulation of China and China National Standardization Management Committee 2020), 37.5 μg/m^3 (ASHB/ASHB-ED) (Architectural Society of China 2017; Ministry of Housing and Urban-Rural Development of China 2018), 25 μg/m^3 (ambient and indoor AQG of World Health Organization [WHO]) (World Health Organization 2006), and five other hypothetical guidelines (30, 15, 10, 5, and 0 μg/m^3). For a given city, premature deaths and economic losses were calculated by assuming that the daily mean indoor concentrations in 2015 never exceeded the guideline value. In cities with daily mean indoor $PM_{2.5}$ concentrations above a specific guideline, indoor concentrations were reduced to the target concentration; in cities below the guideline, indoor concentrations remained unchanged. The equivalent outdoor concentration under a certain reduction scenario was calculated based on the exposure concentration under this scenario and the exposure factor under the baseline scenario (see Appendix pp 4–5 for more details). For each scenario, the cause-specific baseline mortality rates, population, and age structure remained unchanged. For each city, the differences of the $PM_{2.5}$-attributable deaths and economic losses between the baseline and reduction scenarios were taken as the avoidable premature deaths and economic losses that might be achieved by attaining a given indoor guideline value, respectively. In the particular case of hypothetically reducing daily indoor $PM_{2.5}$ concentrations to 0 μg/m^3, the calculated avoidable premature deaths and corresponding economic losses were assumed to equal the premature deaths and corresponding economic losses attributable to either short- or long-term indoor exposure to $PM_{2.5}$.

Based on the short-term exposure effects, daily avoidable deaths and economic losses were calculated for each day in 2015 and summed into annual avoidable short-term-exposure-attributable deaths and economic losses. The daily avoidable short-term-exposure-attributable deaths and economic losses reflect the benefits of short-term (i.e., two-day herein) indoor air filtration, regardless of the indoor $PM_{2.5}$ levels on other days. In contrast, the annual avoidable long-term-exposure-attributable deaths were calculated based on the long-term exposure effects, reflecting the benefits of long-term (i.e., annual herein) indoor air purification.

2.6. Uncertainty analyses

Monte Carlo simulations were used to estimate the distribution of the $PM_{2.5}$ infiltration factor for each province in each of the four seasons. In total, 5000 draws were performed from the distribution of each parameter and calculated the province-specific F_{inf}'s for each season. The uncertainties of effect estimates (β) and VSL were also incorporated to estimate relative risks (RRs), associated deaths, and economic losses. More details for the Monte Carlo simulations and uncertainty analyses are presented in Appendix p 5.

All calculations were made using R (Version 3.30) embedded in RStudio (Version 1.1.456). In the *Results* section and Figs. A2–A6 (Appendix pp 38–42), specific estimates are presented for 339 cities (adjusted for each city's urban population over 25 years of age). For each province, summed estimates are presented for its major cities (Table A2–A10, Appendix pp 11–34).

3. Results

3.1. Exposure

Table 1 summarizes the descriptive statistics of exposure data in the analysis. The average of annual mean outdoor $PM_{2.5}$ concentrations in the 339 cities was 48 μg/m^3 (range, 9–108 μg/m^3), with 252 cities exceeding 35 μg/m^3 (ambient AQG of China) and 338 cities exceeding 10 μg/m^3 (ambient AQG of WHO). Daily mean outdoor $PM_{2.5}$ ranged from 1 to 876 μg/m^3 in the 339 cities, among which 324 cities have an average of 61 days (range, 1–228 days) exceeding 75 μg/m^3 (ambient AQG of China) and 339 cities have an average of 257 days (range, 2–363 days) exceeding 25 μg/m^3 (ambient AQG of WHO). Daily infiltration factors (F_{inf}) ranged from 0.4 (95% confidence interval [CI], 0.2–0.7) to 0.8 (95% CI, 0.5–1.0), with an average of 0.6 (95% CI, 0.3–0.9), consistent with the values reported in previous studies (Wang et al. 2015; Xiang et al. 2017; Xu et al. 2017). The average of annual mean indoor $PM_{2.5}$ of outdoor origin concentrations in the 339 cities was 28 (95% CI, 14–43) μg/m^3 (ranging from 5 (95% CI, 2–8) to 56 (95% CI, 25–90) μg/m^3), with 72 cities exceeding 35 μg/m^3 (ASHB) and 197 cities exceeding 25 μg/m^3 (ASHB-ED). Daily mean indoor $PM_{2.5}$ of outdoor origin ranged from 0 (95% CI: 0–1) to 458 (95% CI, 211–759) μg/m^3 in the 339 cities, among which 329 cities have an average of 84 days (range, 1–268 days) exceeding 37.5 μg/m^3 (ASHB and ASHB-ED) and 334 cities have an average of 164 days (range, 1–332 days) exceeding 25 μg/m^3 (indoor AQG of WHO). Annual mean exposure to $PM_{2.5}$ ranged from 5 (95% CI: 3–8) to 63 (95% CI: 37–92) μg/m^3, with an average of 30 (95%CI: 18–43) μg/m^3; while the maximum daily mean exposure concentration was 529 (95%CI: 324–779) μg/m^3. Of the total time-weighted exposure, indoor exposures accounted for 62%–91% daily and 68%–83% annually.

3.2. Premature deaths and economic losses attributable to $PM_{2.5}$ exposure

Fig. 2 shows the total premature deaths and associated economic losses attributable to short- and long-term total and indoor exposure of outdoor origin $PM_{2.5}$ in urban areas of mainland China in 2015. In total, 20.0 (95% CI: 12.1–28.0) thousand (7.2 per 100000; urban population $\geq$ 25 years of age, the same below) and 672.7 (95% CI: 569.2–754.2) thousand (241.2 per 100000) premature deaths were attributable to short- and long-term exposure to $PM_{2.5}$ of outdoor origin, respectively

Table 1
Descriptive summary of daily and annual mean (95% confidence interval) of outdoor, indoor, time-weighted exposure $PM_{2.5}$ concentrations, and infiltration factors in urban areas of 339 Chinese cities in 2015.

Variable	Scale	Min	P25	P50	Mean	P75	Max
Outdoor (μg/m^3)	Daily	1	23	37	48	60	876
	Annual	9	35	47	48	57	108
Infiltration factor	Daily	0.42 (0.16–0.67)	0.52 (0.24–0.9)	0.61 (0.31–0.95)	0.61 (0.31–0.91)	0.68 (0.36–0.96)	0.81 (0.52–0.98)
	Annual	0.50 (0.22–0.78)	0.53 (0.25–0.88)	0.60 (0.3–0.95)	0.61 (0.31–0.91)	0.66 (0.34–0.96)	0.79 (0.48–0.97)
Indoor (μg/m^3)	Daily	0 (0–1)	14 (7–21)	23 (11–34)	28 (14–43)	36 (18–54)	458 (211–759)
	Annual	5 (2–8)	21 (10–31)	27 (13–41)	28 (14–43)	34 (17–51)	56 (25–90)
Exposure (μg/m^3)	Daily	0 (0–1)	15 (9–21)	24 (15–34)	30 (18–43)	39 (23–55)	529 (324–779)
	Annual	5 (3–8)	22 (13–32)	29 (17–41)	30 (18–43)	36 (21–51)	63 (37–92)
Time-weighted indoor/total Exposure fraction (%)	Daily	62 (46–71)	76 (62–83)	81 (68–86)	80 (66–86)	84 (72–88)	91 (80–94)
	Annual	68 (50–77)	76 (62–83)	81 (69–86)	80 (66–86)	84 (72–88)	86 (76–90)

Definition of abbreviations: P25 = the 25th percentile; P50 = the 50th percentile; P75 = the 75th percentile

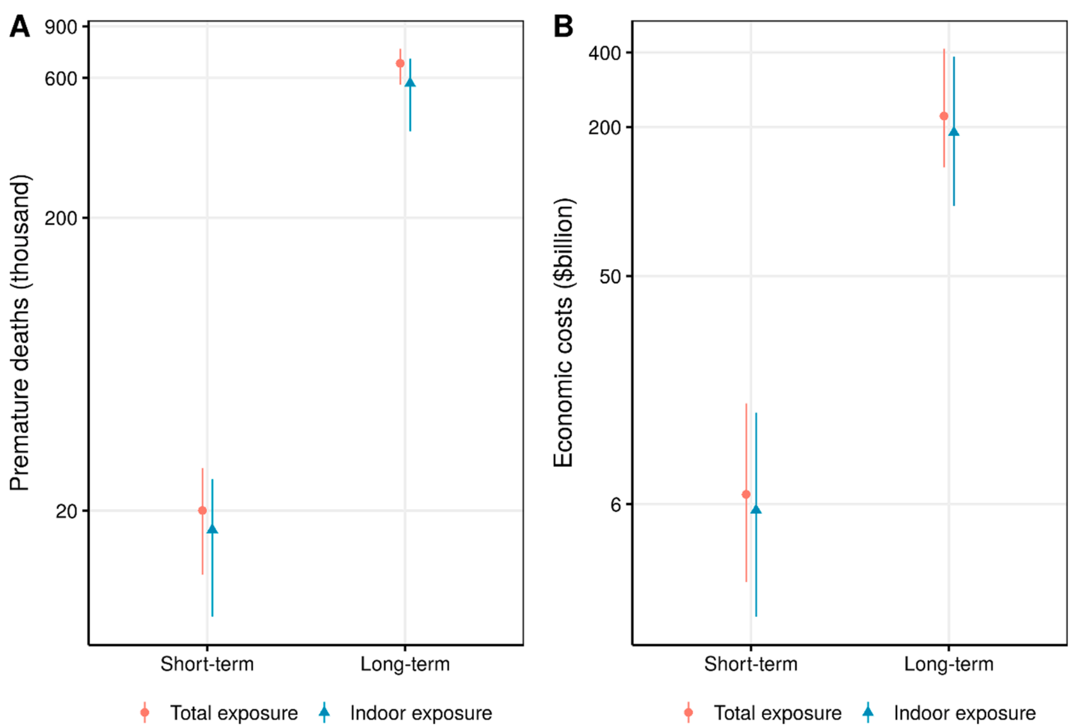

Fig. 2. In urban areas of mainland China in 2015, (A) total premature deaths and (B) associated economic losses attributable to short- and long-term total and indoor $PM_{2.5}$ exposure of outdoor origin. The scale of the y-axis is log2 transformed.

(Fig. 2A). The latter is approximately 33 times larger than the former, reflecting that the long-term exposure effect accounts for the majority of the total $PM_{2.5}$-attributable premature mortality in a year. The outdoor $PM_{2.5}$-associated deaths attributable to short- and long-term effects were divided into deaths due to time-weighted outdoor exposure and indoor exposure based on the approach described above. Results show that the premature deaths attributable to the short- and long-term indoor exposure alone were 17.2 (95% CI: 8.7–25.6) thousand (6.2 per 100000) and 575.3 (95% CI: 394.6–697.8) thousand (206.3 per 100000), accounting for approximately 86.1% and 85.5% of the total mortality attributable to short- and long-term $PM_{2.5}$ exposure from outdoor origins, respectively. These numbers illustrate the strikingly large potential for reducing premature deaths by reducing indoor $PM_{2.5}$ of outdoor origins. Fig. 2B shows the corresponding economic losses for the four scenarios mentioned above. In total, 6.6 (95% CI: 2.9–15.3) billion (7.2 per capita; urban population $\geq$ 25 years of age, the same below) and 221.4 (95% CI: 137.3–413.8) billion (241.2 per capita) US Dollar losses were attributable to short- and long-term total exposure to $PM_{2.5}$ of outdoor origin. Among those economic losses attributable to total exposure, 5.7 (95% CI: 2.1–14.0) billion (6.2 per capita) and 190.1 (95% CI: 95.9–384.0) billion (206.3 per capita) US Dollar losses were attributable to indoor exposure to $PM_{2.5}$ of outdoor origin.

Cause-specific results for each province are shown in Tables A2–A9 (Appendix pp 11–28). Generally, IHD and stroke were the causes that led to the most deaths and economic losses attributable to acute and chronic exposure, respectively. Compared with respiratory causes (COPD and LC), cardiovascular causes (IHD and stroke) resulted in more deaths and economic losses attributable to $PM_{2.5}$ exposure-with ratios of 3.1 and 2.4 on average for short- and long-term exposure, respectively, on the national scale.

Figs. 3–4 shows the city-specific annual premature deaths (per 100000) and associated economic losses (per capita) attributable to short- and long-term total and indoor exposure of outdoor origin $PM_{2.5}$ in urban areas of mainland China in 2015. The highest values of $PM_{2.5}$-attributable deaths and economic losses were mostly found in central and central-northern China, including Henan Province, Shandong Province, and the Beijing-Tianjin-Hebei region. For instance, 264 and 209 deaths (per 100000) in Beijing were attributable to long-term total

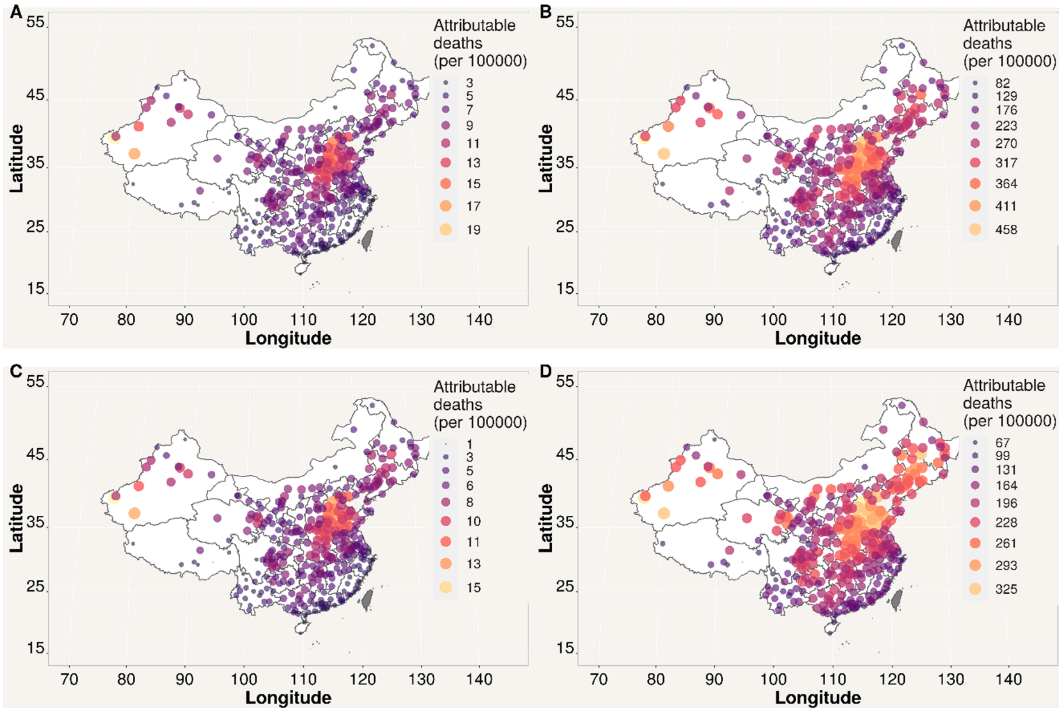

Fig. 3. Map of urban areas in mainland China showing in 2015: mean of premature deaths (per 100000) attributable to outdoor-originated (A) short-term total $PM_{2.5}$ exposure, (B) long-term total $PM_{2.5}$ exposure, (C) short-term indoor $PM_{2.5}$ exposure, (D) long-term indoor $PM_{2.5}$ exposure.

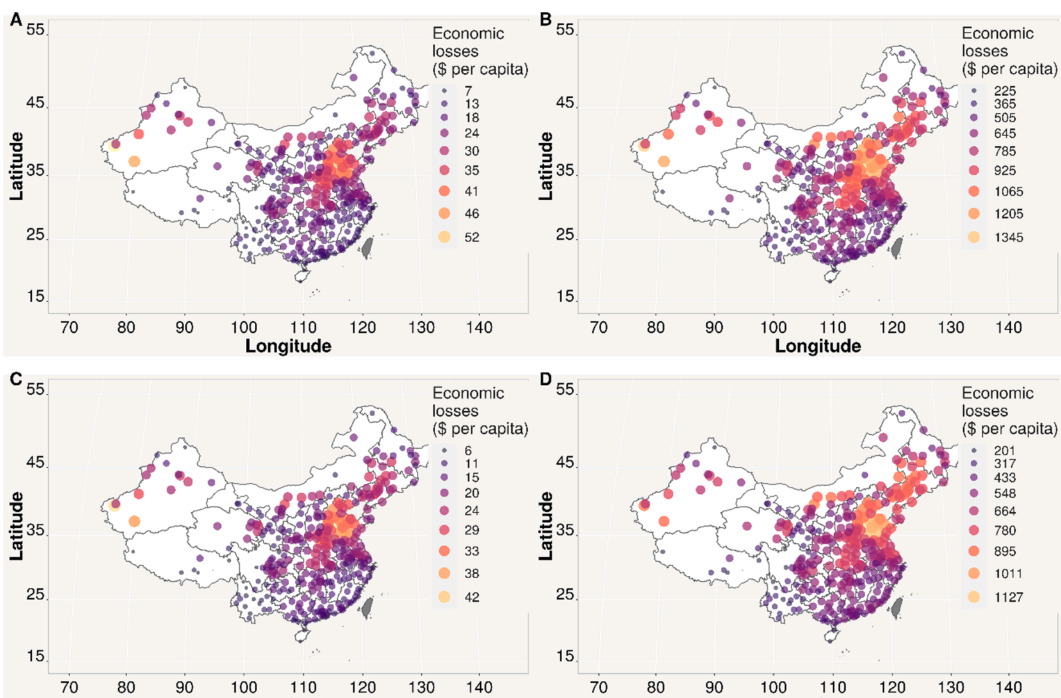

Fig. 4. Map of urban areas in mainland China showing in 2015: mean of economic losses ($ per capita) attributable to outdoor-originated (A) short-term total $PM_{2.5}$ exposure, (B) long-term total $PM_{2.5}$ exposure, (C) short-term indoor $PM_{2.5}$ exposure, (D) long-term indoor $PM_{2.5}$ exposure.

and indoor $PM_{2.5}$ exposure, respectively. The corresponding economic losses (per capita) were 1182 and 936 US Dollars, respectively.

3.3. Benefits by meeting various daily indoor $PM_{2.5}$ limits

Table A10 (Appendix p 29) shows the province-specific annual mean indoor $PM_{2.5}$ concentrations by sustaining compliance of different daily indoor $PM_{2.5}$ limits in 2015. Significant reductions were found in indoor yearly $PM_{2.5}$ levels by meeting a daily indoor $PM_{2.5}$ limit. For example, sustaining a limit of 37.5 μg/m^3 would reduce the annual mean indoor $PM_{2.5}$ levels from 42 (95% CI: 20–67) μg/m^3 to 26 (95% CI: 18–30) μg/m^3 in Beijing.

Table 2 summarizes the estimated total avoidable deaths and economic losses attributable to short- and long-term $PM_{2.5}$ exposure effects by meeting different limits for daily indoor $PM_{2.5}$. The reductions in total deaths attributable to short- and long-term $PM_{2.5}$ exposure effects for the scenario in which daily indoor concentrations in urban mainland China met the limit of 75 μg/m^3 (IAQS-ED) were 0.7 (95% CI: 0–3.3) thousand and 16.9 (95% CI: 0.7–62.1) thousand, respectively, and the corresponding reductions in economic losses were 0.2 (95% CI: 0–1.8) billion and 5.7 (95% CI: 0.2–34.8) billion US Dollars, respectively. For the scenario where daily indoor $PM_{2.5}$ concentrations met a limit of 37.5 μg/m^3 (ASHB and ASHB-ED), 87.7 (95% CI: 9.7–197.7) thousand deaths and 29.4 (95% CI: 2.4–109.6) billion US Dollars could potentially be avoided attributable to long-term $PM_{2.5}$ exposure effects, which are approximately five times of those in the 75-μg/m^3 scenario. When the daily indoor $PM_{2.5}$ met the AQG of WHO (25 μg/m^3), the potentially avoidable deaths and economic losses attributable to long-term $PM_{2.5}$ exposure effect were 165.5 (95% CI: 30.8–304.0) thousand and 55.2 (95% CI: 7.7–168.0) billion US Dollars, respectively, which are approximately twice of those in the 37.5-μg/m^3 scenario. The proportions of the avoidable deaths and economic losses to the total $PM_{2.5}$-attributed deaths and economic losses in the 75-μg/m^3, 37.5-μg/m^3, and 25-μg/m^3 scenarios were approximately 3%, 15%, and 28%, respectively. Province-specific results are shown in Table A11 (Appendix pp 30–35).

Fig. 5 presents nonlinear fits (mean and 95% CI) of reduced premature deaths and economic losses versus daily mean indoor $PM_{2.5}$ limits based on the data in Table 2. The exponential equations that describe the relationship show that the benefits achieved from per unit indoor $PM_{2.5}$ decrease would increase at an accelerating rate as stricter standards/guidelines are adopted for daily indoor $PM_{2.5}$ concentrations. Also, the differences between the short-term-effect and long-term-effect benefits would increase as stricter standards/guidelines are adopted.

Table 2
Mean (95% confidence interval) of annual total avoidable deaths and economic losses attributable to short- and long-term $PM_{2.5}$ exposure effects by meeting different indoor air quality guidelines for daily indoor $PM_{2.5}$ limit.

	Avoidable deaths (thousand)		Avoidable economic losses ($billion)	
	Short-term effect [a]	Long-term effect [b]	Short-term effect [a]	Long-term effect [b]
75 μg/m^3 (IAQS-ED)	0.7 (0.0–3.3)	16.9 (0.7–62.1)	0.2 (0.0–1.8)	5.7 (0.2–34.8)
37.5 μg/m^3 (ASHB/ ASHB-ED)	3.4 (0.3–9.3)	87.7 (9.7–197.7)	1.1 (0.1–5.1)	29.4 (2.4–109.6)
30 μg/m^3	4.8 (0.5–11.6)	127.8 (19.1–255.5)	1.6 (0.1–6.4)	42.7 (4.8–141.4)
25 μg/m^3 (WHO)	6.1 (0.9–13.4)	165.5 (30.8–304)	2.0 (0.2–7.3)	55.2 (7.7–168)
15 μg/m^3	9.6 (2.3–17.7)	279.5 (87.3–431.2)	3.2 (0.6–9.7)	92.8 (21.5–237.9)
10 μg/m^3	11.9 (3.8–20.3)	361.6 (149.5–511.7)	3.9 (0.9–11.1)	119.9 (36.7–282)
5 μg/m^3	14.5 (5.9–23.0)	461.9 (251.1–602.1)	4.8 (1.4–12.6)	152.9 (61.3–331.5)
0 μg/m^3	17.2 (8.7–25.6)	575.3 (394.6–697.8)	5.7 (2.1–14.0)	190.1 (95.9–384.0)

Definition of abbreviations: IAQS-ED = Indoor Air Quality Standard Exposure Draft; ASHB = Assessment Standard for Healthy Building; ASHB-ED = Assessment Standard for Healthy Building Exposure Draft; WHO = World Health Organization.

[a] Annual sum of daily avoidable short-term-exposure-attributable deaths and economic losses, which were calculated based on the short-term concentration–response model.

[b] Calculated based on long-term concentration–response model.

This fitted model provides a convenient way to evaluate the benefits of formulating indoor air guidelines based on different daily indoor $PM_{2.5}$ limits.

4. Discussion

Previous studies have estimated outdoor $PM_{2.5}$-attributable premature deaths in China and the potential reductions in $PM_{2.5}$-attributable deaths by realizing various outdoor air quality guidelines (Huang et al. 2017; Liu et al. 2016; Xie et al. 2016). Two studies have estimated indoor $PM_{2.5}$-attributable premature deaths in the US (Azimi and Stephens 2020; Zhao et al. 2015). Additionally, a study has evaluated the incremental mortality rate attributable to each 10 μg/m^3 increase in indoor $PM_{2.5}$ of outdoor origin in several countries/regions (Ji and Zhao 2015). Moreover, our previous analysis has estimated premature adult deaths attributable to long-term exposure to indoor $PM_{2.5}$ of outdoor origin across urban China, and the corresponding mortality reductions achievable by meeting different indoor AQGs for annual mean $PM_{2.5}$ (Xiang et al. 2019a). However, the present study is the first to estimate premature deaths and economic losses attributable to indoor exposures to outdoor-infiltrated $PM_{2.5}$ in urban mainland China using localized census-based C-R models. It is also the first to estimate the potential reduction in deaths and economic losses from reducing indoor exposures to meet various daily guideline values of indoor $PM_{2.5}$. The findings show the dominant contribution of indoor exposure to premature mortality and economic losses attributable to outdoor-originated $PM_{2.5}$. The findings also demonstrate the substantial benefits of reducing the daily indoor $PM_{2.5}$ levels to meet various indoor guideline values.

Based on our calculations using the localized census-based C-R models, the estimated premature deaths attributable to long-term outdoor-originated $PM_{2.5}$ exposure are approximately 70% higher than those estimated based on the IER functions (Xiang et al. 2019a). This finding is consistent with previous studies (Li et al. 2018; Xue et al. 2019; Yin et al. 2017). IER function is a useful tool in GBD estimates; however, the localized census-based C-R models can provide more accurate estimates of the burden of disease in China. The merits of using localized census-based C-R models are discussed in greater detail elsewhere (Li et al. 2018; Xue et al. 2019; Yin et al. 2017). Nevertheless, the C-R models established from the existing Chinese cohorts may not fully represent all adult population in China. Future larger-scale cohorts should result in more accurate estimates, using an approach analogous to that applied in this study.

As mentioned in the Results section, premature deaths and economic losses attributable to short-term $PM_{2.5}$ exposure effects accounted for approximately 3% of those attributable to long-term exposure effects. Although another study utilizing a splined C-R model shows a potential larger acute-to-chronic ratio (Li et al. 2019), the fact remains that short-term-exposure-attributable deaths only represent a small proportion of long-term-exposure-attributable deaths. It highlights the importance of long-term indoor $PM_{2.5}$ purification, in contrast to purification on limited highly polluted days. People tend to use an indoor air purifier in extreme air pollution scenarios, e.g., sandstorm, haze, wildfire, and smoke. However, this study demonstrates the importance and significant benefits of sustained long-term indoor air purification. For example, based on our calculations, approximately 49.8 thousand (148 per 100000) premature deaths and 17.8 billion (528 per capita) US Dollar economic losses were attributable to total ambient $PM_{2.5}$ exposure in urban Guangdong Province, where the annual mean ambient and indoor $PM_{2.5}$ level were 32 and 24 μg/m^3, respectively (lower than the ambient AQG of China and indoor AQG of ASHB, respectively). If the daily mean indoor $PM_{2.5}$ levels met the limit of 15 μg/m^3, 18.1 thousand deaths and 6.5 billion US Dollar economic losses could potentially be avoided.

Both daily and annual indoor $PM_{2.5}$ guidelines provide valuable guidance for determining indoor air quality policies. However, the two guidelines are not independent of each other. Once a yearly guideline is

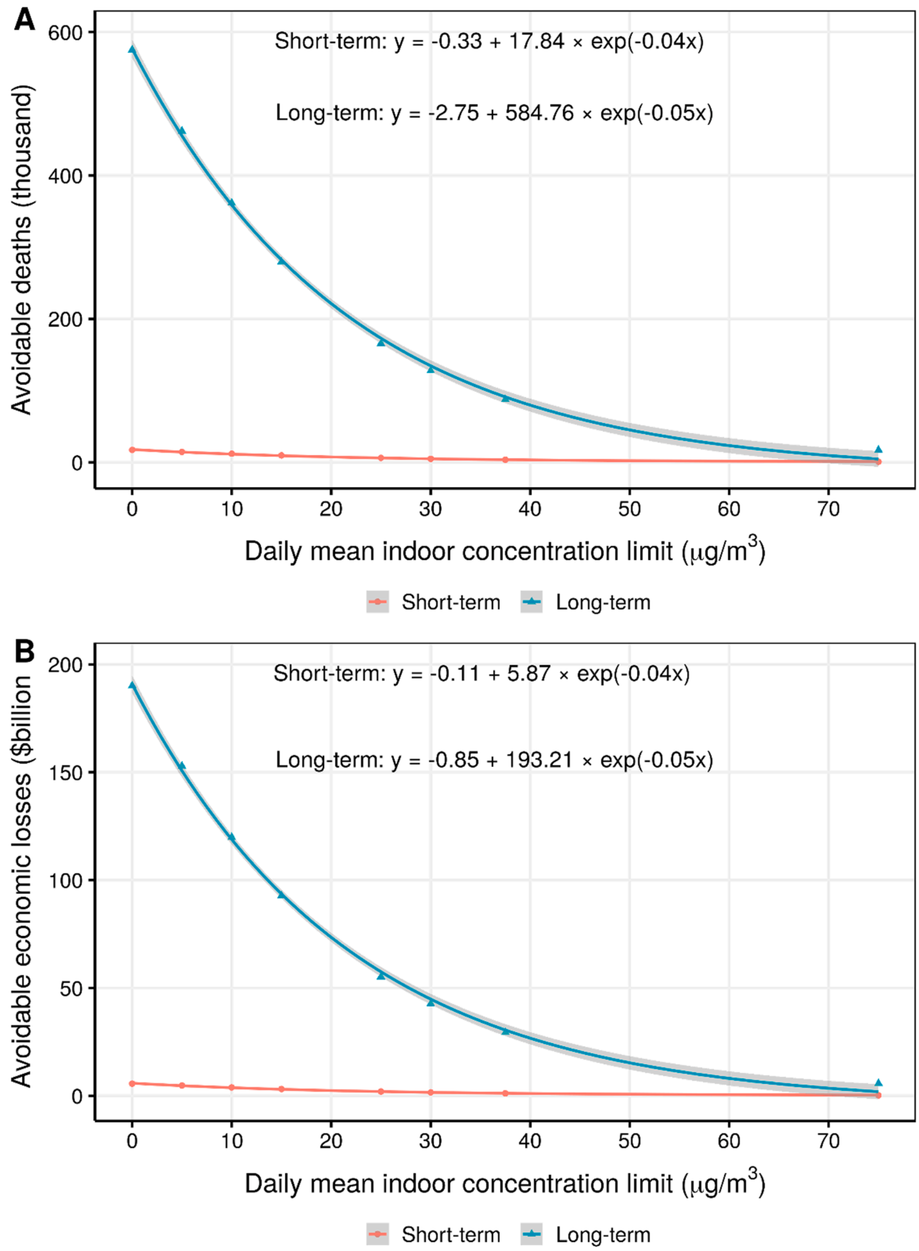

Fig. 5. Nonlinear fits of mean total avoidable (A) premature deaths and (B) economic losses attributable to short- and long-term $PM_{2.5}$ exposure effects in urban mainland China predicted to be achieved by meeting different indoor air quality guidelines for $PM_{2.5}$ daily limits.

set, the corresponding daily guideline can be determined, and vice versa. Given that it is more operable to control daily means/24-hour moving averages than annual means in the real-world settings, daily guidelines for indoor $PM_{2.5}$ might be taken as the primary indicator in indoor air quality guidelines. Indoor $PM_{2.5}$ levels in residences and workplaces can be readily reduced using portable air purifiers or mechanical ventilation systems that include high-efficiency particulate air (HEPA) filters. With HEPA filtration, typical indoor/outdoor (I/O) ratios for $PM_{2.5}$ (of outdoor origin) are in the range of 0.01–0.2 (Cui et al. 2018; Day et al. 2017). Given that the maximum daily mean outdoor $PM_{2.5}$ concentrations have generally been less than 500 μg/m^3 in China since 2018, it is feasible to control daily mean indoor $PM_{2.5}$ levels under 25 μg/m^3 (see more details in Appendix p 6). However, most existing portable air purifiers or mechanical ventilation systems can probably not control the indoor $PM_{2.5}$ at a certain level, e.g., 37.5 μg/m^3. In most cases, the indoor $PM_{2.5}$ level tends to be lower than the set value for such air cleaning technologies. Thus, if the intervention measure of meeting the standards is to use effective air cleaners/mechanical ventilation systems, the reductions in premature deaths and economic losses estimated in this study were conservative. Additionally, using such air cleaning technologies will reduce indoor ultrafine particles (UFPs; particles with aerodynamic diameters no larger than 100 nm) (Azimi et al. 2014; Cui et al. 2018; Xiang et al. 2016). UFPs have been associated with adverse human cardiorespiratory health effects (Olsen et al. 2014; Soppa et al. 2014) and caused heritable mutations in an animal model (Somers et al. 2004). As the analysis in the study does not account for UFPs, the net benefits of meeting a specific indoor $PM_{2.5}$ guideline can be underestimated. Future studies will benefit from taking both $PM_{2.5}$ and UFPs into account.

More stringent guidelines will contribute to larger reductions in $PM_{2.5}$-attributable deaths and economic losses, but will also be more costly to achieve. As an attempt to balance the health benefit with the cost of reducing indoor $PM_{2.5}$, 5–18 "special days" in each year, when daily indoor $PM_{2.5}$ levels are allowed to exceed the suggested guideline, were introduced in the ASHB and ASHB-ED (Architectural Society of

China 2017; Ministry of Housing and Urban-Rural Development of China 2018). The impacts of such "special days" on premature deaths and economic losses, and the compatibility between daily and annual guidelines with and without "special days" were further discussed in Appendix p 7. The analysis presented in this paper provides insights regarding a critical component of this overall process of determining a guideline — what is the anticipated reduction in premature mortality and economic losses, city-by-city as well as for cities within a given province, that might be achieved by attaining a given daily indoor $PM_{2.5}$ guideline. A discussion of benefits versus costs would provide a full picture of the determination of optimal guidelines. However, several studies have argued that more efficient filtration is cost-effective in selected scenarios (Fisk and Chan 2017; Montgomery et al. 2015).

This study has several limitations. First, indoor air quality guidelines generally refer to total indoor $PM_{2.5}$ levels, with no distinction regarding the sources. This study, focusing on indoor exposure to $PM_{2.5}$ of outdoor origin, tends to underestimate the benefits of meeting a certain daily guideline. It is currently challenging to estimate indoor $PM_{2.5}$ of indoor origin in urban China due to the lack of data. With growing interests in utilizing low-cost sensors for long-term indoor monitoring, we anticipate more indoor-originated $PM_{2.5}$ data to become available. Although indoor sources tend to have a large heterogeneity across households and buildings, future analyses considering indoor-originated $PM_{2.5}$ in the same approach used in the present study are warranted to generate estimates associated with total $PM_{2.5}$ exposure. Second, we have treated outdoor and indoor $PM_{2.5}$ of outdoor origin as equally toxic without accounting for the changes in $PM_{2.5}$ chemical compositions during the infiltrating process. However, studies suggest that some major $PM_{2.5}$ components, such as nitrates and ammonium, showed a sink effect and lower infiltration factor during winter due to their volatility (Zauli-Sajani et al. 2018). On the other hand, as the penetration factor is size-dependent, the finer fractions of $PM_{2.5}$, e.g., ultrafine particles, have smaller penetration factors due to Brownian diffusion (Chen and Zhao 2011). The differences in compositions between outdoor and indoor $PM_{2.5}$ of outdoor origin can lead to different toxicity and, thus, different effect estimates (β). Third, the indoor $PM_{2.5}$ levels were estimated based on steady-state assumptions in this study, which could lead to bias compared to a dynamic method that takes transient effects into account. Based on a previous case study leveraging the data for a residence in Beijing, the relative differences of indoor $PM_{2.5}$ levels using the steady-state method compared with the dynamic method were 15% at daily mean metric and 11% at annual mean metric (Sun et al. 2019), which is acceptable for a large-scale modeling study. Fourth, this study utilized the ground-level $PM_{2.5}$ monitoring network to evaluate total and indoor $PM_{2.5}$ exposure in urban areas. Since the monitoring network is almost non-existent in small towns and villages, it disabled us to extend the analyses for rural areas of China. Future studies would benefit from more monitors in both urban and rural areas of China. Fifth, due to data constraints, some parameters, e.g., baseline mortality, used in the models were not city-specific, and population data were adjusted based on the 2010 *National Population Census*. Finally, the results in this study are based on the 2015 outdoor $PM_{2.5}$ concentration data of 339 cities. Further investigation is required to determine what kind of outdoor $PM_{2.5}$ data (e.g., the past year or the mean values of the past three years) should be used as the baseline for the present and future Healthy Building guidelines/standards. The overall outdoor air quality in urban China has been improving in recent years, indicating that the current indoor guidelines can be met more easily. Therefore, a more stringent guideline can be designed based on the models derived from this study.

Despite these limitations, the fact remains that substantial deaths and economic losses could be avoided by reducing daily indoor $PM_{2.5}$ levels from outdoor origins. It is more feasible to achieve an indoor $PM_{2.5}$ limit, as opposed to a similar limit for outdoor air, because there are more immediately available methods (e.g., central- or room-based air filtration) to reduce indoor $PM_{2.5}$ concentrations effectively. The present study provides quantitative health and economic benefit data to support the design and implementation of daily indoor $PM_{2.5}$ guidelines using urban China as a case study. The results are expected to facilitate formulating present and future indoor air quality policies. Given that ambient $PM_{2.5}$ concentrations in Chinese cities and many places in the world will not meet health-associated standards in a short time, it is imperative to determine a near-term strategy to minimize the adverse effects of $PM_{2.5}$ on health and the economy.

5. Conclusion

This study reveals that indoor exposures contributed to 86% of the total premature deaths and economic losses attributable to outdoor-originated $PM_{2.5}$ in urban China in 2015. Exponential models were established to estimate the reduction in deaths and economic losses when daily mean indoor $PM_{2.5}$ levels met a certain limit within 0–75 μg/m^3. For instance, nearly 90 thousand premature deaths and 30 billion US Dollar economic loss could potentially be avoided by meeting the indoor AQG of 37.5 μg/m^3 as a daily limit. Such analysis should facilitate the implementation and compliance check of the newly established indoor AQGs in China. The analysis framework and findings are applicable globally, especially when outdoor $PM_{2.5}$ concentrations are elevated, such as during a wildfire episode.

CRediT authorship contribution statement

Jianbang Xiang: Conceptualization, Methodology, Software, Data curation, Formal analysis, Supervision, Writing - original draft, Writing - review & editing. **Edmund Seto:** Writing - review & editing. **Jinhan Mo:** Writing - review & editing. **Junfeng (Jim) Zhang:** Conceptualization, Supervision, Writing - review & editing. **Yinping Zhang:** Funding acquisition, Conceptualization, Supervision, Writing - review & editing.

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.envint.2020.106342.

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