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A comparative study of the disease burden attributable to $PM_{2.5}$ in China, Japan and South Korea from 1990 to 2017

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ABSTRACT

Background: Exposure to fine particulate matter ($PM_{2.5}$) is one of the leading contributors to disease burden. However, little is known about the spatial and temporal trends of the disease burden attributable to $PM_{2.5}$ in the three major economies in East Asia. We aimed to estimate the patterns and temporal variations of the disease burden attributable to $PM_{2.5}$ in China, Japan, and South Korea from 1990 to 2017.

Methods: We obtained data on disease burden attributable to $PM_{2.5}$ from the Global Burden of Disease Study (GBD) 2017. We retrieved the numbers and age-standardized mortality rate (ASMR) and disability-adjusted life years (DALYs) rate (ASDR) of disease attributable to $PM_{2.5}$ by age, sex, socio-demographic index (SDI), and country. We used percentage change and estimated annual percentage change (EAPC) to assess the trends of ASMR and ASDR attributable to $PM_{2.5}$ between 1990 and 2017. We further calculated the contribution of population growth, population aging, and changes in mortality or DALYs rate to the net changes in total deaths and DALYs associated with $PM_{2.5}$.

Results: We found considerable differences in the disease burden attributable to $PM_{2.5}$ in China, Japan, and South Korea. In 2017, the ASMR and ASDR of disease attributable to $PM_{2.5}$ in China were 49.37 (95% UI: 41.18, 57.5) per 100,000 population and 1065.9 (95% UI: 891.28, 1237.38) per 100,000 population, respectively, which was about four times higher than that of Japan and twice higher than that of South Korea. Regardless of country, the ASMR and ASDR were more pronounced among elders and males. From 1990 to 2017, the declines in ASMR and ASDR were more pronounced in Japan and South Korea than in China. The changes in $PM_{2.5}$ associated total deaths and DALYs between 1990 and 2017 were the combined effects of population aging, population growth, and changes in mortality or DALY rate, resulting in a net increase in total deaths and DALYs in China but little changes in Japan and South Korea.

Conclusions: $PM_{2.5}$ still contributed to significant disease burdens in 2017, although age-standardized disease burden has declined from 1990 to 2017. There has been an increasing trend in total deaths and DALYs in China, which was primarily driven by population aging.

1. Introduction

Ambient air pollution is recognized as one of the main risk factors for morbidity and mortality (Collaborators, 2019b; India State-Level Disease Burden Initiative Air Pollution, 2019; Xie et al., 2015). The WHO estimates that 91% of the world's population lives in places where the air quality exceeds the limits of the WHO guidelines (WHO, 2016). Each year, ambient air pollution claims about 4.2 million lives, mainly due to cardiorespiratory diseases.

Fine particulate matter is defined as particles that are 2.5 μm or less in diameter ($PM_{2.5}$), which can be inhalable into the lungs and induce adverse health effects (Pope et al., 2009; Qiu et al., 2017, 2018). The main target of $PM_{2.5}$ is the cardiovascular system (Rajagopalan et al., 2018). $PM_{2.5}$ penetrates deep into the lower respiratory tract, escapes

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the host defense, and alveolar clearance mechanisms. It may reach the bloodstream and organs through transport across biofilms. Besides, the large surface of $PM_{2.5}$ promotes the adsorption of organic substances, heavy metals, and other toxic substances. It provides space for the generation of oxygen free radicals in the lungs and blood (Brauer et al., 2016; Dockery and Stone, 2007; India State-Level Disease Burden Initiative Air Pollution, 2019; Mannucci et al., 2019; Simkhovich et al., 2008).

China, Japan, and South Korea are the three major economies in East Asia, with total economic volume exceeding one-fifth of the world. These three countries have similar genetic backgrounds and cultures; however, they are at different stages of social and economic development. Japan and South Korea are ahead of China in industrialization and urbanization. As the world's largest developing country, China's industrial and transportation emissions, as well as air pollution from natural phenomena, have been rising since 1990 (Huang et al., 2017), South Korea is also facing severe air pollution problems, while Japan's situation is much better (Bloom et al., 2018; Hwang et al., 2014; North et al., 2019; Pawankar et al., 2020).

There is a lack of comprehensive comparative studies on the health burden associated with ambient air pollution among the three countries. Knowing this information could be useful for taking priority actions to prevent the disease burden attributable to air pollution and providing a scientific reference for air pollution management.

Accordingly, we sought to estimate the disease burden attributable to $PM_{2.5}$ in east Asia and to examine its temporal variations between 1990 and 2017. We used the Global Burden of Disease Study (GBD) 2017, which is an ongoing global effort to measure death and disability in 195 countries and territories worldwide.

2. Material and methods

2.1. Study data

We obtained data used in this study from the GBD 2017 through the Global Health Data Exchange query tool (Global Burden of Disease Collaborative Network, 2018). Annual rates of age-standardized and age-specific disability-adjusted life years (DALYs) and deaths of diseases attributable to $PM_{2.5}$ were extracted by age and sex from 1990 to 2017 for China, Japan, and South Korea. We collected the summary exposure value (SEV) of $PM_{2.5}$, which is a measure of a population's exposure to a risk factor (Collaborator, 2017). The value of SEV ranges from 0 to 100, with a value of 0 indicating no excess risk for a population exists, and a value of 100 indicating that the total population is at the highest level of that risk. We also extracted the socio-demographic index (SDI) of the three countries, SDI is a composite indicator of development status strongly correlated with health outcomes. It is the geometric mean of 0–1 index of total fertility rate under the age of 25, mean education for those aged 15 and older, and lag distributed income per capita (Collaborators, 2018a, 2018b).

The methods of the GBD for the estimations of the disease burden attributable to $PM_{2.5}$ have been detailed elsewhere (Cohen et al., 2017; Collaborator, 2017, 2019a; India State-Level Disease Burden Initiative Air Pollution, 2019). DALYs were calculated as the sum of years lost due to premature death (YLLs) and years lived with disability (YLDs), deaths were defined as the number of deaths occurring in a population during a specific period.

2.2. Ambient air pollution assessment

GBD defined ambient air pollution exposure as the population-weighted annual average mass concentration ($\mu g/m^3$) of $PM_{2.5}$ per cubic meter of air. The data came from multiple sources, including satellite observations of atmospheric aerosols, ground monitoring data, chemical transport model simulations, population estimates, and land-use data (Cohen et al., 2017; India State-Level Disease Burden Initiative Air Pollution, 2019). GBD calibrated satellite measurements to ground measurements using the Data Integration Model for Air Quality (DIMAQ) (Shaddick et al., 2018). The satellite-based estimates of $PM_{2.5}$ were at $0.1° \times 0.1°$ resolution and combine aerosol optical depth retrievals from multiple satellites and land use information. The ground measurements were from the WHO Global Ambient Air Quality Database, including specific PM concentration measurements by 9960 ground monitors from 108 countries. For each $0.1° \times 0.1°$grid cell, GEOS-Chem chemical transport model was used to simulate the sum of particulate sulfate, nitrate, ammonium and organic carbon, as well as the compositional concentrations of mineral dust, combined with elevation and the distance to the nearest urban land surface (Ma et al., 2014; Shaddick et al., 2018).

The joint theoretical minimum risk exposure level for household and ambient particulate matter pollution was a uniform distribution between 2.4 and 5.9 $\mu g/m^3$, with burden attributed proportionally between household and particulate matter pollution based on the source of $PM_{2.5}$ exposure above theoretical minimum risk exposure level.

2.3. Statistical analysis

Differences in population age structures may lead to the heterogeneity in disease burden quantified by death and DALYs. We selected the age-standardized rate of mortality and DALYs to eliminate the influence of population structure differences. We used percentage change and estimated annual percentage change (EAPC) to assess the trends of the age-standardized mortality rate (ASMR) and age-standardized DALYs rate (ASDR). GBD calculated the percentage change based on the point estimates of the age-standardized rate (Collaborators, 2019b). EAPC is a measure of the trend of age-standardized rates (ASR) over a time interval, it can be obtained from a log-linear model: $\ln(ASR)=\beta_0+\beta_1 X+\varepsilon$, where X was the calendar year and EAPC was calculated as $(\exp(\beta_1) - 1) \times 100$ (Hankey et al., 2000). The ASR was considered to be increased if the lower boundary of its 95% UIs was higher than zero. In contrast, if the higher boundary of its 95% UIs was lower than zero, then there was a decreasing trend for ASR. Otherwise, the ASR was considered to be stable.

Pearson correlation coefficient was used to evaluate the correlation between SDI and ASR, and the expected relation between SDI and ASR between 1990 and 2017 for three countries were fitted a generalized additive model with a Loess smoother.

Additionally, we used a recently proposed decomposition algorithm (Cheng et al., 2020) to calculate the percentage contribution of changes of each of the three factors, population growth, population ageing, and mortality change, to the net change in total deaths and DALYs attributable to $PM_{2.5}$ between 1990 and 2017 for the three countries. All statistics were performed using the R software (version 3.5.3, R core team). A 2-sided p-value less than 0.05 was considered as statistically significant.

3. Results

3.1. Trends of $PM_{2.5}$ SEV

Globally, the age standardized SEV of $PM_{2.5}$ increased from 28.45 (95% UI: 22.23, 36.60) in 1990 to 40.62 (95% UI: 32.30, 51.53) in 2011, and then leveled off to 40.18 (95% UI: 32.49, 50.87) in 2017 (Fig. S1). The changing trend in the SEV of $PM_{2.5}$ in China was consistent with that in the world, but the rate was much higher than the global level. SEV of $PM_{2.5}$ in China increased from 29.19 (95% UI: 22.05, 38.88) in 1990 to 59.27 (95% UI: 47.23,75.07) in 2011 and began to decline slowly after 2011. In addition, males had slightly higher SEV of $PM_{2.5}$ than females, both globally and in China. The SEV of $PM_{2.5}$ was relatively stable in Japan and South Korea, with the SEV values of 29.18 (95% UI: 20.92, 42.03) and 48.12(95% UI: 32.99, 67.15) in 2017, respectively, and have been declined since 2010. Besides, the SEV of $PM_{2.5}$ were at the same

Table 1
The age-standardized DALYs rate of disease attributable to $PM_{2.5}$ in 1990 and 2017, and its percentage change and estimated annual percentage change by location, by sex, from 1990 to 2017.

Location	Gender	ASDR (1990)	ASDR (2017)	Percentage change (95% UI), 1990–2017	EAPC (95% CI)
Global	Both	1287.52 (1080.36–1493.88)	1064.92 (913.91–1213.48)	−17.29% (−24.61 to −8.84)[a]	−0.78 (−0.84 to −0.71)[a]
	Male	1559.01 (1309.55–1814.69)	1316.76 (1126.6–1498.05)	−15.54% (−22.36 to −7.77)[a]	−0.68 (−0.76 to −0.60)[a]
	Female	1050.05 (869.11–1232.33)	836.36 (702.84–954.02)	−20.35% (−28.64 to −11.17)[a]	−0.94 (−1.00 to −0.88)[a]
China	Both	1404.21 (1088.72–1690.37)	1065.90 (891.28–1237.38)	−24.09% (−33.16 to −12.54)[a]	−1.08 (−1.22 to −0.93)[a]
	Male	1663.58 (1290.93–2025.30)	1364.39 (1155.29–1577.82)	−17.99% (−27.78 to −5.58)[a]	−0.77 (−0.92 to −0.61)[a]
	Female	1171.94 (898.31–1413.39)	779.94 (640.41–914.42)	−33.45% (−42.64 to −20.95)[a]	−1.59 (−1.74 to −1.45)[a]
Japan	Both	478.33 (402.34–562.48)	264.79 (211.52–320.75)	−44.64% (−48.98 to −40.21)[a]	−2.09 (−2.19 to −1.98)[a]
	Male	666.76 (562.35–778.79)	372.42 (300.68–450.39)	−44.14% (−48.18 to −39.95)[a]	−2.04 (−2.17 to −1.91)[a]
	Female	331.08 (277.93–389.29)	171.21 (131.73–210.98)	−48.29% (−53.42 to −43.08)[a]	−2.39 (−2.52 to −2.27)[a]
South Korea	Both	1209.18 (1026.49–1386.26)	503.04 (402.45–604.20)	−58.40% (−66.77 to −50.41)[a]	−2.99 (−3.08 to −2.89)[a]
	Male	1662.20 (1420.48–1906.41)	702.70 (560.17–839.47)	−57.72% (−65.96 to −49.52)[a]	−2.77 (−2.91 to −2.63)[a]
	Female	880.19 (743.75–1020.39)	343.60 (266.24–419.09)	−60.96% (−68.81 to −52.90)[a]	−3.45 (−3.53 to −3.37)[a]

EAPC = estimated annual percentage change; UI = uncertainty interval; CI = confidence interval;
[a] Changes that are statistically significant.

level for both sexes, which were different from global and China.

3.2. Disease burden attributable to $PM_{2.5}$

Globally, in 2017, the global ASMR and ASDR of disease attributable to $PM_{2.5}$ were 38.15 (95% UI: 32.5, 43.68) per 100,000 population and 1064.92 (95% UI: 913.91, 1213.48) per 100,000 population, respectively, decreased by 12.65% (95% UI: 17.72, 7.22) and 17.29% (95% UI: 24.61, 8.84) respectively (Tables 1 and 2) compared with 1990, and changed by an average −0.58% (95% CI: −0.67%, −0.49%) per year for deaths and −0.78% (95% CI: −0.84%, −0.71%) per year for DALYs from 1990 to 2017.

We found considerable heterogeneity in the disease burden attributable to $PM_{2.5}$ across China, Japan, and South Korea. In 2017, the ASMR and ASDR of disease attributable to $PM_{2.5}$ in China were 49.37 (95% UI, 41.18, 57.5) per 100,000 population and 1065.9 (95% UI: 891.28, 1237.38) per 100,000 population respectively, which was about four times that of Japan and twice that of South Korea. Although the ASMR and ASDR of disease attributable to $PM_{2.5}$ in all the three countries decreased from 1990 to 2017, the decline in China was much smaller than that in Japan and South Korea. The EAPC of ASMR in China [− 0.46 (95% CI: −0.65, −0.26)] was about one-sixth of that of Japan and one-seventh of that of South Korea, while the EAPC of ASDR in China [−1.08 (95% CI: −1.22, −0.93)] was about one half of that of Japan and one-third of that of South Korea.

3.3. Correlation of disease burden attributable to $PM_{2.5}$ and SDI

We found a significant and strong negative correlation between SDI and the expected ADMR and ASDR of disease attributable to $PM_{2.5}$ regardless of sex and country (Fig. 1). China had slightly higher ASMR of disease attributable to $PM_{2.5}$ than expected based on SDI for most of the years between 1990 and 2017. The global ASMR of disease attributable to $PM_{2.5}$ for both male and female was a bit lower than expected, based on their SDI values.

3.4. Disease burden attributable to $PM_{2.5}$ by sex and age

In terms of sex, the ASMR and ASDR of disease attributable to $PM_{2.5}$ were significantly higher in males than in females, regardless of the country (Tables 1 and 2, Fig. 1, Fig. 2). We observed a considerable difference of male to female ratio of the ASMR and ASDR of disease attributable to $PM_{2.5}$ (Fig. S2). Japan had the highest male to female ratio of the ASMR and ASDR of disease attributable to $PM_{2.5}$, followed by South Korea. However, both were higher than the global level, and the male to female ratios of the ASMR of disease attributable to $PM_{2.5}$ had been increasing since 1990 and began to decline after 2010. In China, the male to female ratio of the disease burden attributable to $PM_{2.5}$ was close to the world and relatively stable, while the ratio of male to female ASDR had an apparent increasing trend from 1990 to 2017.

Fig. 3 shows age-specific rates of mortality and DALYs attributable to $PM_{2.5}$ in 1990 and 2017 in China, Japan, and South Korea. The rates of deaths attributable to $PM_{2.5}$ increased sharply after 60 years of age, regardless of period or sex. In 2017, the rate of deaths attributable to $PM_{2.5}$ of the 95+ group was more than 50 times that of the 55–59-year-old group in China. Whereas DALYs rates attributable to $PM_{2.5}$ sharply increased after 40 years old, increased to the highest value about 85–89 or 90–94 years-old group, after which they became stable or even slightly decreased.

3.5. Disease burden of $PM_{2.5}$ by causes

In GBD 2017, seven diseases could be attributable to $PM_{2.5}$, including stroke, ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), tracheal, bronchus, and lung cancer, liver cancer, stomach cancer, and Alzheimer's disease and other dementias (Fig. 4). Globally, in 2017, IHD, stroke, and COPD were the three leading causes of death attributable to $PM_{2.5}$. All of them showed a downward trend in the ASMR from 1990 to 2017. Besides, the ASMRs of the diseases attributable to $PM_{2.5}$ in males were higher than that in females.

Unlike the global situation, from 1990 to 2017, in China, of the deaths attributable to $PM_{2.5}$, COPD fell in rank from the first to third, and stroke and IHD rose to the top two. In 2017, the ASMRs of stroke and COPD attributable to $PM_{2.5}$ in China were higher than the global level, and the ASMR of IHD was similar to the global level. The ASMR of COPD attributable to $PM_{2.5}$ had a dramatic downward trend. In contrast, the ASMR of IHD attributable to $PM_{2.5}$ had increased significantly. Similarly, consistent with the global situation, males had a significantly higher ASMR of disease attributable to $PM_{2.5}$ than that of females.

The situation in Japan was very different from that of the world and China. The level of the causes of death attributable to $PM_{2.5}$ was much lower than that in China and the world. In 2017, the ASMRs of major diseases attributable to $PM_{2.5}$ in Japan were only one third to one half of that of China. From 1990–2017, all the leading diseases had a significant downward trend. In 2017, the top three diseases of death attributable to $PM_{2.5}$ for Japanese males were IHD, stroke and Alzheimer's disease and other dementias. For Japanese females, the ASMR of Alzheimer's disease and other dementias attributable to $PM_{2.5}$ was even higher than that of stroke or IHD.

South Korea saw a significant decrease in the ASMR attributable to $PM_{2.5}$ from 1990 to 2017. In 2017, the ASMRs caused by stroke and IHD attributable to $PM_{2.5}$ were reduced to one-fifth and one-quarter compared with that of in 1990. In 2017, the ASMRs of diseases attributable to $PM_{2.5}$ were slightly higher than that of Japan.

The diseases DALYs attributed to $PM_{2.5}$ were slightly different from that of death (Fig. S3). The disease DALYs attributed to $PM_{2.5}$ were

Table 2
The age-standardized mortality rate of disease attributable to $PM_{2.5}$ in 1990 and 2017, and its percentage change and estimated annual percentage change by location, by sex, from 1990 to 2017.

Location	Gender	ASMR (1990)	ASMR (2017)	Percentage change (95% UI), 1990–2017	EAPC (95% CI)
Global	Both	43.68 (36.88–50.85)	38.15 (32.50–43.68)	−12.65% (−17.72 to −7.22)[a]	−0.58 (−0.67 to −0.49)[a]
	Male	56.79 (47.83–66.44)	49.89 (42.19–57.23)	−12.15% (−16.94 to −6.63)[a]	−0.53 (−0.63 to −0.43)[a]
	Female	33.50 (28.20–39.08)	28.39 (24.12–32.64)	−15.24% (−20.81 to −8.78)[a]	−0.73 (−0.80 to −0.65)[a]
China	Both	56.11 (43.06–67.54)	49.37 (41.18–57.50)	−12.01% (−22.11 to 1.37)	−0.46 (−0.65 to −0.26)[a]
	Male	71.50 (54.44–87.88)	64.59 (53.85–75.23)	−9.66% (−20.35 to 3.90)	−0.34 (−0.56 to −0.11)[a]
	Female	44.14 (33.64–54.04)	36.06 (29.55–42.51)	−18.30% (−29.48 to 0.53)	−0.74 (−0.91 to −0.57)[a]
Japan	Both	22.67 (19.21–26.58)	10.29 (8.33–12.53)	−54.59% (−58.16 to −51.04)[a]	−2.86 (−2.98 to −2.74)[a]
	Male	32.94 (27.62–39.00)	16.07 (12.80–19.65)	−51.20% (−55.05 to −47.29)[a]	−2.58 (−2.7 to −2.45)[a]
	Female	15.79 (13.42–18.49)	6.06 (4.92–7.37)	−61.63% (−64.61 to −58.29)[a]	−3.53 (−3.65 to −3.40)[a]
South Korea	Both	50.35 (42.74–57.90)	20.12 (16.48–23.86)	−60.03% (−67.49 to −51.55)[a]	−3.27 (−3.44 to −3.10)[a]
	Male	71.59 (61.14–82.36)	30.77 (24.8–37.15)	−57.03% (−65.68 to −47.65)[a]	−2.86 (−3.02 to −2.70)[a]
	Female	37.83 (31.91–43.72)	13.38 (10.83–15.89)	−64.63% (−71.55 to −56.69)[a]	−3.87 (−4.08 to −3.66)[a]

EAPC = estimated annual percentage change; UI = uncertainty interval; CI = confidence interval;
[a] Changes that are statistically significant.

stroke, IHD, COPD, liver cancer, diabetes mellitus, stomach cancer, tracheal, bronchus, and lung cancer. IHD, stroke, and COPD were the three leading diseases of DALYs attributable to $PM_{2.5}$ regardless of location and sex, and the trends of disease DALYs attributable to $PM_{2.5}$ were similar to that of death attributable to $PM_{2.5}$.

3.6. Effect of demography on the disease burden attributable to $PM_{2.5}$

Trends in total deaths and DALYs attributable to $PM_{2.5}$ reflect the influence not only of changing mortality and DALY rate but also of demography. We calculated the contribution of changes in population growth, population aging, and changes in mortality or DALY rate between 1990 and 2017 in global, China, Japan and South Korea according to the contributions of these three factors (Fig. 5).

All three countries had experienced a decline in mortality rate, but the magnitude of the decline varies considerably. China's female mortality rate declined slightly more than the global rate, while the mortality rate for Chinese males declined slightly less than the global rate. Both Japan and Korea experienced mortality declined significantly higher than the global level. However, the effects of mortality declines were offset by population aging and population growth, most notably in China, where the effects of population aging and population growth outweighed the effects of mortality declines, resulting in a net increase in total deaths and DALYs. In contrast, in Japan and South Korea, the effects of population aging and population growth were roughly equivalent to the effects of their declining mortality rates, resulting in little increases in total or disability. In Japan, it was mainly the effect of population aging with little contribution from population growth; while in South Korea it was the combined effect of population aging and population growth, similar to the case of China.

4. Discussion

In this study, we performed a comprehensive estimation of the patterns and temporal trends of disease mortality and DALYs attributable to $PM_{2.5}$ in China, Japan, and South Korea. In 2017, the ASRs of $PM_{2.5}$-attributable disease burden were much higher in China than those in Japan and South Korea, and males have a higher burden than females. The ASRs decreased significantly from 1990 to 2017 in all three countries. However, the downward trend was varying, Japan had the highest decrease, while China had the lowest decrease. Stroke, IHD, and COPD were the leading causes attributable to $PM_{2.5}$ in China and had much higher ASRs than that in Japan and South Korea. The total deaths and DALYs attributed to $PM_{2.5}$ were the combined effect of demographic changes and changes in mortality or DALY rates, resulting in a net increase in total deaths and DALYs in China and almost no increase in Japan and South Korea.

The causal relationship between $PM_{2.5}$ and human adverse health outcomes has been confirmed and strengthened by a large number of studies. Short-term (Chang et al., 2015; Faustini et al., 2015; Li et al., 2015) and long-term (Sun et al., 2005; Wang et al., 2020a) exposure to $PM_{2.5}$ were associated with an increased risk in respiratory and cardiovascular diseases. Due to a small size, $PM_{2.5}$ may probe into the respiratory tract into the lungs and deposited in the lung and cause local inflammation. Soluble components of $PM_{2.5}$ can enter the systemic circulation leading to increased systemic oxidative stress and inflammation, which further leads to the increase of mutagenicity/genotoxicity and inflammatory responses (Dockery and Stone, 2007; Feng et al., 2016; Shrey et al., 2011; Simkhovich et al., 2008). Children and the elderly are more susceptible to these effects and are, therefore, at risk of developing chronic health conditions, and people with existing ailments are more susceptible to disease progression (India State-Level Disease Burden Initiative Air Pollution, 2019).

The $PM_{2.5}$-attributable disease burden varied among the three countries, with more than 3-fold in ASMR and ASDR between China and Japan (Fig. 4 and Fig. S2). The trend of the ASRs of disease attributable to $PM_{2.5}$ was strongly negatively related to that of SDI of each country. As the largest developing country, China's $PM_{2.5}$ exposure value was much higher than Japan's and the world's average. Although China's $PM_{2.5}$ exposure value was relatively stable and even showed a downward trend after 2012, there was no fundamental improvement. As a result, China has the highest disease burden attributable to $PM_{2.5}$ among the three countries. While Japan is one of the world's most developed countries, and environmental governance ranks among the highest in the world, so disease burden attributed to $PM_{2.5}$ was far less than in China. South Korea's $PM_{2.5}$ exposure value was in the middle of China and Japan, so the disease burden attributed to $PM_{2.5}$ was also in the middle of China and Japan.

We observed an increasing trend in disease burden attributable to $PM_{2.5}$ with age. The rate of deaths and DALYs of causes attributable to $PM_{2.5}$ increased sharply with the increase of age, especially in the elderly over 80 years old. Because the elderly population has a higher proportion of chronic diseases, such as cardiovascular and cerebrovascular diseases, exposure to $PM_{2.5}$ has a superimposed adverse effect on health outcomes. The elderly is more susceptible to $PM_{2.5}$ than healthy adults. We also found that the DALYs rate attributable to $PM_{2.5}$ increased with age is less sharply than that of death. Since DALYs are the sum of YLL and YLD, and the 80 years old has reached or exceeded the life expectancy, the primary source of DALYs after 80 years old is YLD, so the rate of DALYs of the elderly group will even decline.

We found that the disease burden attributable to $PM_{2.5}$ was higher in males than in females, regardless of country. This was likely due to higher exposure to $PM_{2.5}$ among males than females, such as for global and China. It was also related that males have a higher all-cause

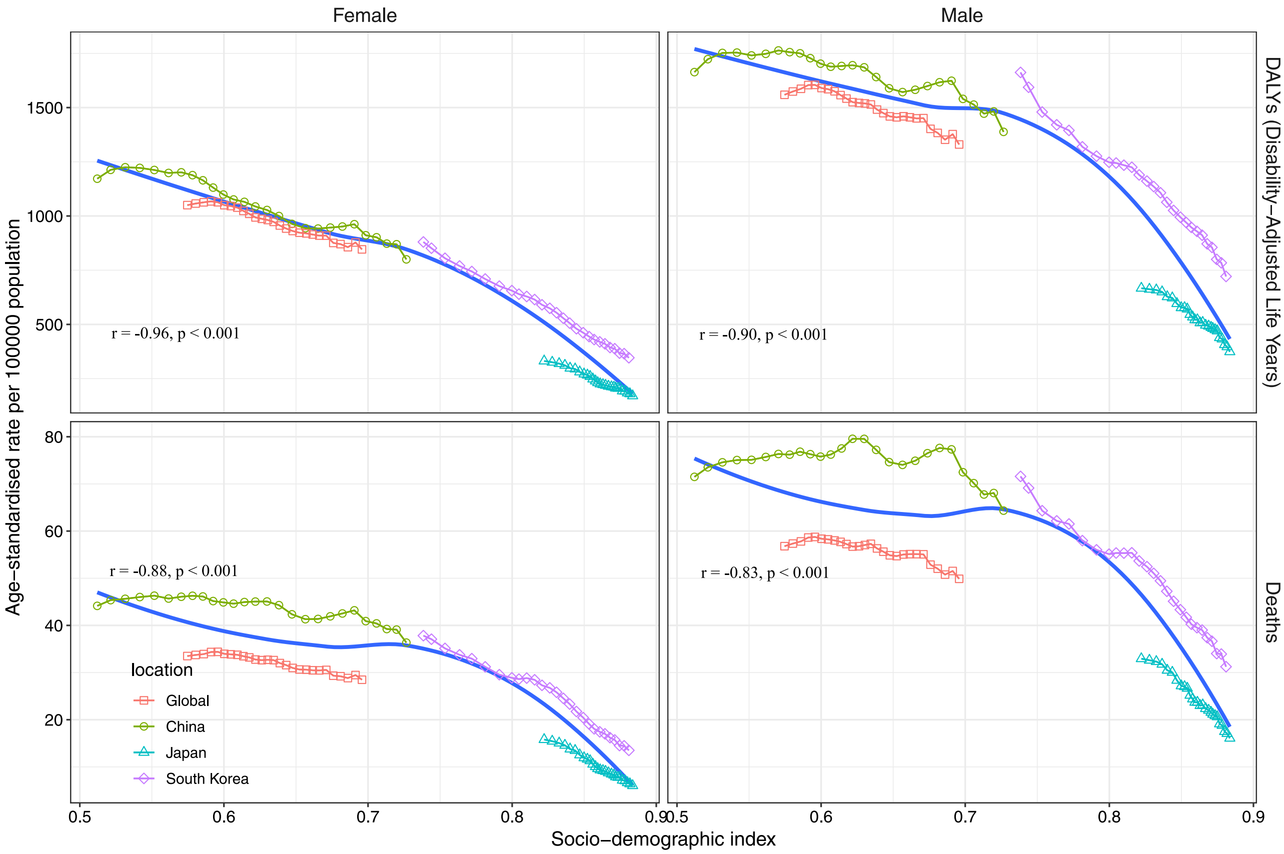

Fig. 1. Age-standardized rate of mortality and DALYs of disease attributable to $PM_{2.5}$ for Global, China, Japan, and South Korea, 1990–2017. The solid line shows expected values across the spectrum of the socio-demographic index. The Pearson correlation coefficient and its p-value were denoted.

mortality (Collaborators, 2019b).

The disease spectrums of deaths and DALYs attributable to $PM_{2.5}$ were significantly different among the three countries. The three primary diseases attributed to $PM_{2.5}$ were stroke, IHD, and COPD. Compared with South Korea, Japan, and the global level, China's situation was much worse. The disease burden attributed to $PM_{2.5}$ in South Korea and Japan was not only much smaller than that in China but also had a pronounced downward trend. On the contrary, in China, the age-standardized rates of IHD DALY and death were still increasing, and the decreasing trend of stroke was relatively slow. The age-standardized rates of COPD death and DALY had a significant downward trend in China, but compared with Japan and South Korea, the burden level was still very high. In developed countries, the leading cause of COPD was smoking, while in developing countries, $PM_{2.5}$ was another major cause of COPD (Feetham and van Dorn, 2017; López-Campos et al., 2016; Rabe and Watz, 2017). However, in China, both causes were much higher.

Our study found the remarkable contribution of population aging and population growth to the burden of diseases attributed to $PM_{2.5}$. China, Japan, and South Korea are all facing serious problems of population aging, so it is important to improve the prevention of age-related diseases such as stroke, coronary heart disease. It is also necessary for the governments to take measures to address the healthcare issues in an aging society due to population growth and ageing.

The evidence that air pollution damages health is irrefutable, and all three countries have taken legislative action to respond. Over the past decade, the governments of China, Japan, and South Korea had mandated lower emissions from vehicles and factories, promoted the use of clean fuels, increased support for clean energy, and strengthen the annual national air quality regulations (North et al., 2019). We can foresee that in the near future, the disease burden attributable to $PM_{2.5}$ in South Korea and Japan will continue to decrease or remain stable. In contrast, the disease burden attributable to $PM_{2.5}$ in China will remain high, because various regulations in China have not kept pace with its economic growth and the use of fossil fuels, even if there is a tendency to decrease. Besides, researches showed that even at very low levels (much lower than national standards) (Fann et al., 2012), $PM_{2.5}$ still posed a nontrivial risk to public health. Therefore, there is an urgent need for all three countries to continue adopting multiple approaches and regulations to air pollution management and promoting primary and secondary prevention for diseases, such as for stroke, IHD, and COPD.

Our study has some limitations. First, the accuracy and robustness of estimations largely depend on the quality and quantity of data used in the modeling. As mentioned earlier, GBD's data analysis framework cannot avoid data bias when estimating disease burden (Collaborator, 2017, 2019b). Second, GBD 2017 assumes that the toxicity of environmental $PM_{2.5}$ depends only on the concentration and not on the source (such as coal-burning or vehicular emissions) (Cohen et al., 2017). However, it has been shown that $PM_{2.5}$-related health effects are not adequately explained by $PM_{2.5}$ concentration alone (Huang et al., 2012). The composition of $PM_{2.5}$ differs significantly among China, Japan, and South Korea, with China having higher $PM_{2.5}$ emissions of fossil fuel combustion (Philip et al., 2014). So, the health effects of $PM_{2.5}$ should be examined by considering both its composition and concentration with appropriate weighting according to the hazard of $PM_{2.5}$ composition, such as increasing the weights of secondary components, combustion species and transition metals, which have been shown to be closely associated with health outcome (Huang et al., 2012). However, GBD implements the same data inclusion and standard methodological standards for all countries or territories, so these limitations should not affect the comparison of patterns and temporal trends of the disease burden attributable to $PM_{2.5}$ among countries.

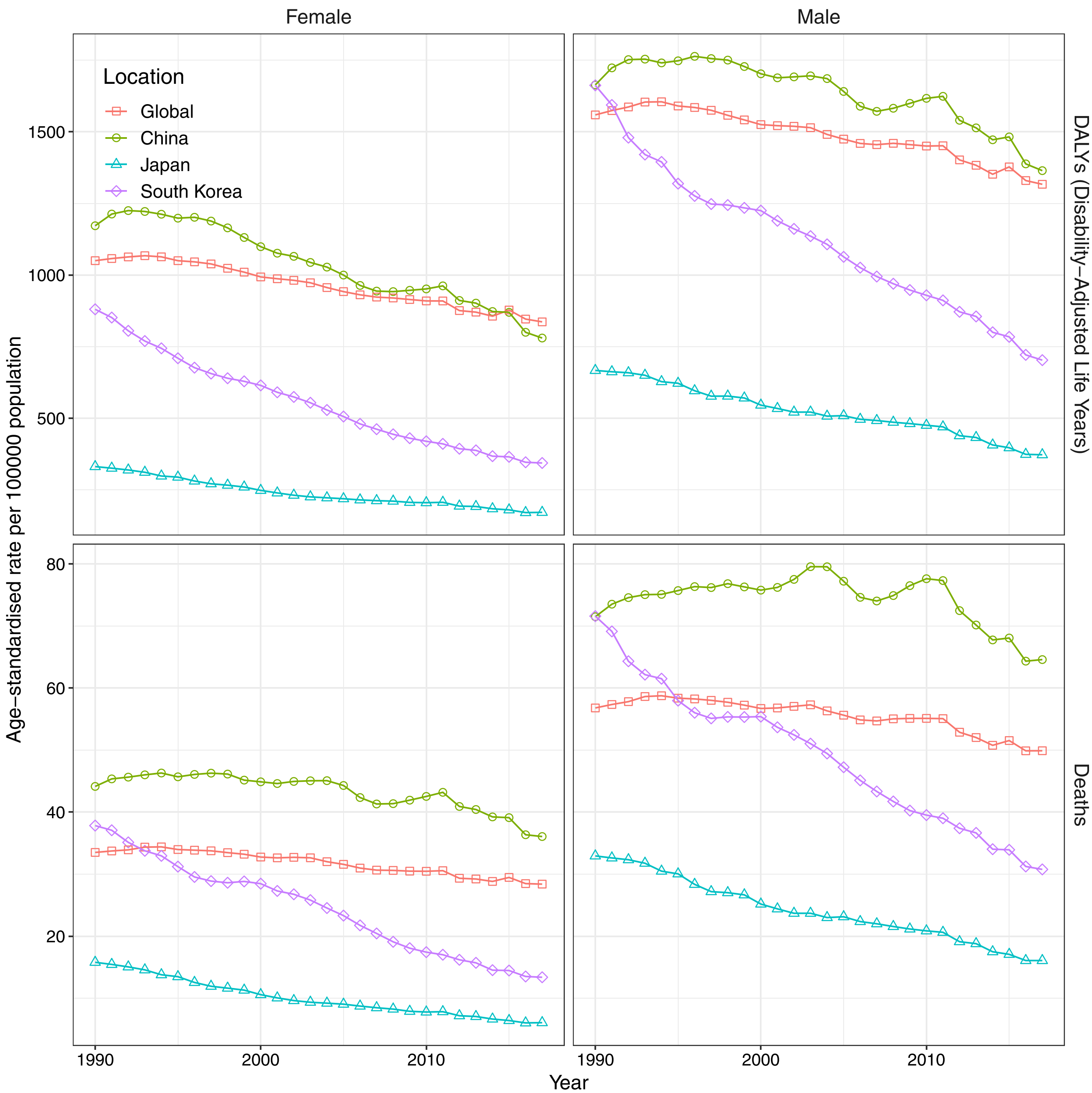

Fig. 2. The age-standardized rates of mortality and DALYs attributable to $PM_{2.5}$ from 1990 to 2017 for global, China, Japan, and South Korea.

5. Conclusion

In summary, our study assessed patterns and temporal trends of disease burden attributable to $PM_{2.5}$ in China, Japan, and South Korea. While the burden of disease attributable to $PM_{2.5}$ declined in all three countries from 1990 to 2017, the disease burden in China remains high. As very low levels of $PM_{2.5}$ still pose a considerable risk to public health, the three countries still need to continue to take a variety of approaches and regulations for air pollution management and promote primary and secondary prevention of stroke, IHD, COPD, and other diseases. Our findings will assist policymakers and government agencies to enact plans and policies for air management and disease prevention.

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Ethics approval

Ethics approval was not required as the data are public available.

CRediT authorship contribution statement

Jianqiang Du: Conceptualization, Writing - original draft, Methodology, Data analysis, Writing - review & editing. **Jianjun Yang:** Conceptualization, Writing - review & editing, Methodology, Data analysis. **Lina Wang:** Conceptualization, Writing - original draft, Methodology, Data analysis, Writing - review & editing. **Xiaoming Wu:** Conceptualization, Writing - review & editing. **Wangnan Cao:** Writing - review & editing. **Shengzhi Sun:** Conceptualization, Writing - original draft, Data curation, Investigation, Writing - review & editing.

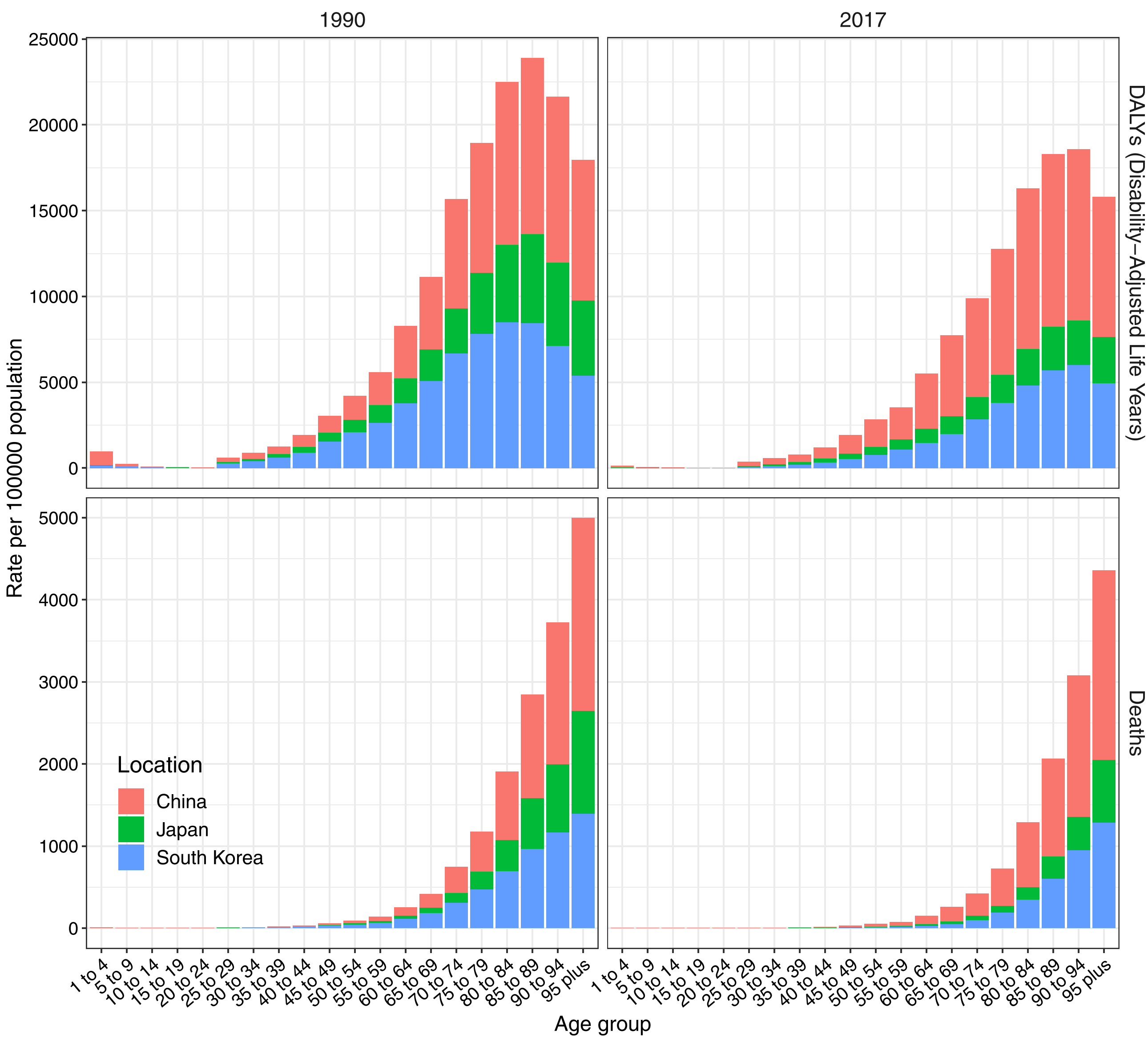

Fig. 3. Age-specific rates of mortality and DALYs attributable to $PM_{2.5}$ in 1990 and 2017 in China, Japan, and South Korea.

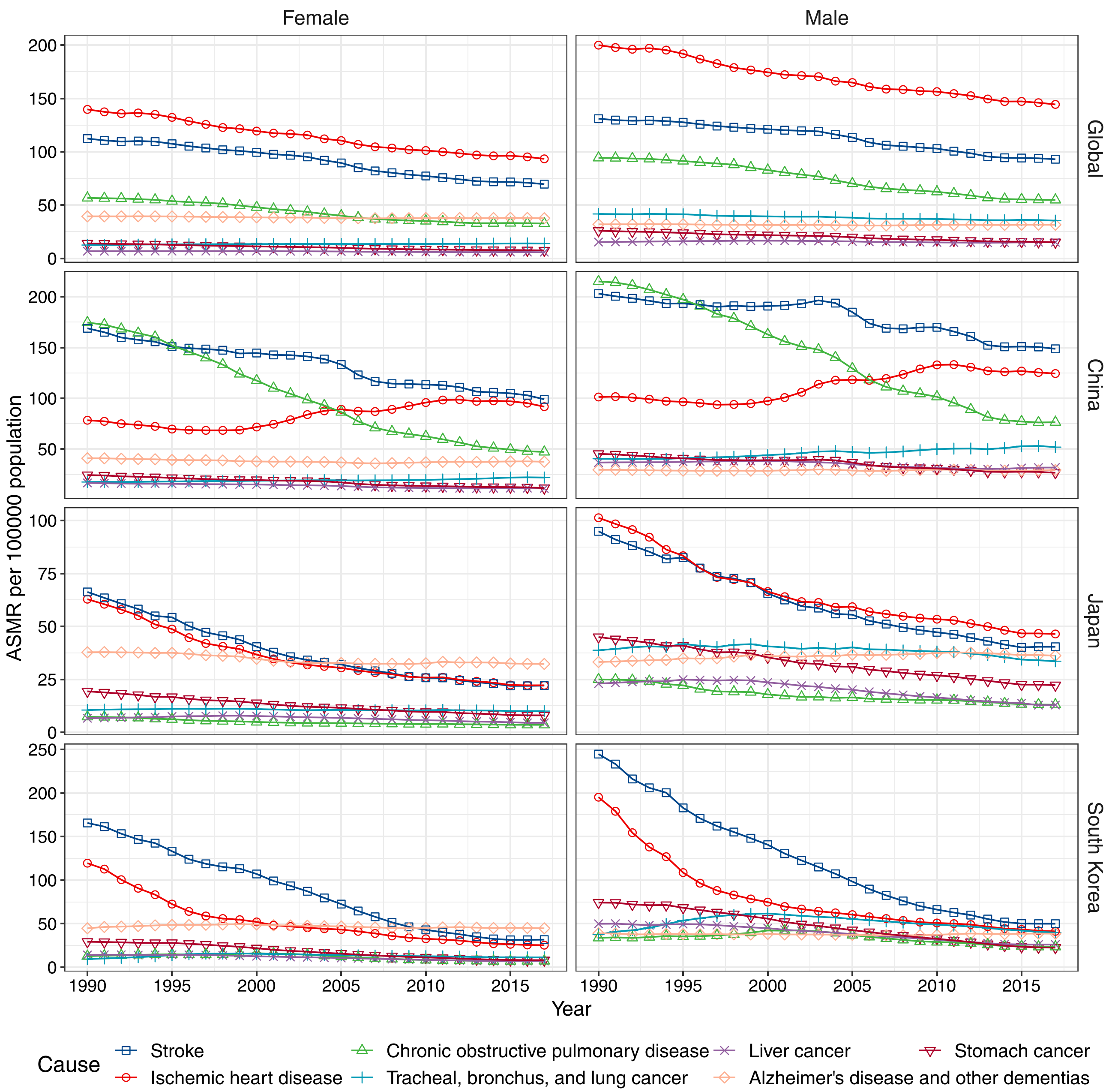

Fig. 4. The age-standardized mortality rates of causes attributable to $PM_{2.5}$ in China, Japan, and South Korea from 1990 to 2017.

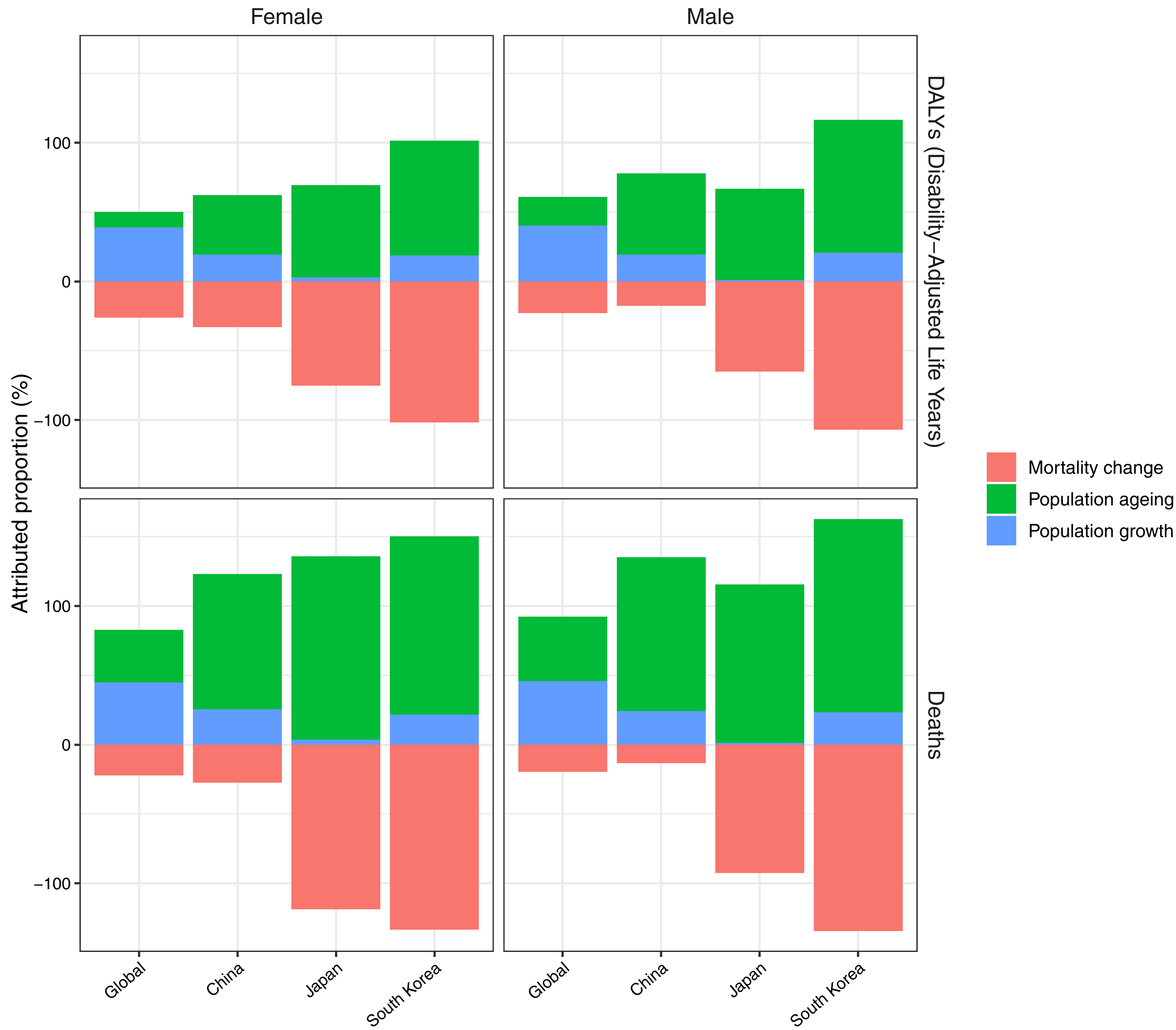

Fig. 5. Net changes of deaths and DALYs of disease attributable to $PM_{2.5}$ according to population-level determinants in global, China, Japan, and South Korea between 1990 and 2017.

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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2020.111856.

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