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Global, regional, and national mortality burden attributable to air pollution from landscape fires

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Abstract:	Background Landscape fire-sourced (LFS) air pollution is an increasing public health concern under climate change. However, little is known about the global, regional, and national mortality burden attributable to it. Methods We calculated country-specific population-weighted average daily and annual LFS fine particulate matter (PM2.5) and surface ozone (O3) during 2000-2019 from a validated dataset. We obtained the relative risks (RRs) for both short-term and long-term impacts of LFS PM2.5 and O3 on all-cause, cardiovascular and respiratory mortality. The short-term RRs were pooled from community-specific standard time-series regressions in 2267 communities from 59 countries/territories. The long-term RRs were obtained from published meta-analyses of cohort studies. Annual mortality, population and sociodemographic data for each country/territory were extracted from the Global Burden of Diseases Study 2019. These data were used to estimate country-specific annual deaths attributable to LFS air pollution with standard algorithms. Findings Globally, 1.53 (95% empirical confidence interval [eCI]: 1.24-1.82) million all-cause deaths per year were attributable to LFS air pollution during 2000-2019, including 0.45 (95% eCI: 0.32-0.58) million cardiovascular deaths and 0.22 (95% eCI: 0.08-0.35) million respiratory deaths. LFS PM2.5 and O3 contributed to 77.6% and 22.4% of the total attributable deaths [AD], respectively. Over 90% of AD were in low- and middle-income countries, particularly in Sub-Saharan Africa (0.61 million per year), Southeast Asia (0.21 million), South Asia (0.17 million), and East Asia (0.15 million). The global cardiovascular AD saw an average 1.67% increase per year (p for trend <0.001). The top five countries in AD were China, India, DR Congo, Indonesia, and Nigeria. The leading countries with the greatest attributable mortality rates [AMR] were all in Sub-Saharan Africa, despite decreasing trends from 2000 to 2019. North and Central America, and countries surrounding the Mediterranean showed increasing trends of all-cause, cardiovascular and respiratory AMR. Increasing cardiovascular AMR was also observed in Southeast, South and East Asia. The AMR in low-income countries remained 4-fold of those in high-income countries in 2019, decreasing from 9-fold in 2000. AMR negatively correlated with a country-specific sociodemographic index (r = -0.6). Interpretation LFS air pollution induced a substantial global mortality burden, with notable geographical and socioeconomic disparities. Urgent actions are required to address such substantial health impacts and the associated environmental injustice in a warming climate.

Global, regional, and national mortality burden attributable to air pollution from landscape fires

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Research in context

Evidence before this study

We searched Medline, Web of Science and Google Scholar using terms for landscape fires ("landscape fires", "wildfires", "bushfires", "wildland fires", "forest fires") and terms for "mortality" and "death" in May 2024. We included all available research articles that evaluated the mortality burden from landscape fire-sourced (LFS) air pollution. Most existing studies only the assessed mortality burden attributable to LFS air pollution in certain countries or regions, e.g., Europe, US, Canada, Australia, Brazil, and China. We only found three studies assessing the global total all-cause mortality burden (ranged from 135,180 to 677,745 deaths per year in these studies) attributable to LFS particulate matter with a diameter of 2.5μm or less ($PM_{2.5}$), with little information about the spatiotemporal variations of the burden. These global studies used LFS $PM_{2.5}$ estimated by chemical transport models (CTM) without calibration against real observations of air quality stations; and the also used exposure-response (E-R) relationships derived from early epidemiological studies with unreasonable assumptions and limited global representativeness. Furthermore, little is known about the mortality burden attributable to LFS ozone (O_3) and the global cause-specific (e.g., cardiovascular and respiratory deaths) attributable mortality burdens.

Added value of this study

To our best knowledge, this is by far the largest and most comprehensive study of the global, regional and national mortality burden attributable to LFS air pollution (including both $PM_{2.5}$ and O_3). We utilized the recent advances in this field, including: 1) global daily LFS $PM_{2.5}$ and O_3 data that showed much higher accuracy than raw CTM outputs after calibration and validation against air quality station observations; and 2) the best available evidence on the E-R relationships. The E-R relationships for long-term mortality impacts were from the latest published meta-analyses of cohort studies, and E-R relationships for short-term mortality impacts from meta-analyses of time-series analyses of 2267 communities in 59 countries or territories. We found a substantial global mortality burden attributable to LFS air pollution, including 1.53 million all-cause deaths (77.6% and 22.4% from LFS $PM_{2.5}$ and O_3, respectively), 0.45 million cardiovascular deaths, and 0.22 million respiratory deaths per year during 2000-2019. Sub-Saharan Africa had the largest burden, accounting for nearly 40% of global total all-cause and respiratory attributable deaths (AD). Southeast Asia, East Asia and Eastern Europe bore the largest cardiovascular AD. Over 90% of AD were in low- and middle-income countries led by China, India, Congo, Indonesia, and Nigeria. We observed an increasing trend in global cardiovascular AD, although the trends for all-cause and respiratory AD were not statistically significant. Central Sub-Saharan Africa had the highest all-cause and respiratory attributable mortality rates (AMR), while Eastern Europe saw the highest cardiovascular AMR. AMR in low-income countries were over 4-fold of high-income countries and country-specific AMR negatively correlated with a socio-demographic index.

Implications of all the available evidence

A substantial global mortality burden can be attributed to LFS air pollution, and there were notable geographical and socioeconomic disparities in the burdens, as well as an alarming increasing trend of the attributable cardiovascular deaths. As wildfires are increasingly frequent and severe in a warming climate, urgent actions are required to address such substantial health impacts and the associated environmental injustice.

Abstract

Background Landscape fire-sourced (LFS) air pollution is an increasing public health concern under climate change. However, little is known about the global, regional, and national mortality burden attributable to it.

Methods We calculated country-specific population-weighted average daily and annual LFS fine particulate matter ($PM_{2.5}$) and surface ozone (O_3) during 2000-2019 from a validated dataset. We obtained the relative risks (RRs) for both short-term and long-term impacts of LFS $PM_{2.5}$ and O_3 on all-cause, cardiovascular and respiratory mortality. The short-term RRs were pooled from community-specific standard time-series regressions in 2267 communities from 59 countries/territories. The long-term RRs were obtained from published meta-analyses of cohort studies. Annual mortality, population and sociodemographic data for each country/territory were extracted from the Global Burden of Diseases Study 2019. These data were used to estimate country-specific annual deaths attributable to LFS air pollution with standard algorithms.

Findings Globally, 1.53 (95% empirical confidence interval [eCI]: 1.24-1.82) million all-cause deaths per year were attributable to LFS air pollution during 2000-2019, including 0.45 (95% eCI: 0.32-0.58) million cardiovascular deaths and 0.22 (95% eCI: 0.08-0.35) million respiratory deaths. LFS $PM_{2.5}$ and O_3 contributed to 77.6% and 22.4% of the total attributable deaths [AD], respectively. Over 90% of AD were in low- and middle-income countries, particularly in Sub-Saharan Africa (0.61 million per year), Southeast Asia (0.21 million), South Asia (0.17 million), and East Asia (0.15 million). The global cardiovascular AD saw an average 1.67% increase per year (p for trend <0.001), although the trends for all-cause and respiratory AD were not statistically significant. The top five countries in AD were China, India, DR Congo, Indonesia, and Nigeria. The leading countries with the greatest attributable mortality rates [AMR] were all in Sub-Saharan Africa, despite decreasing trends from 2000 to 2019. North and Central America, and countries surrounding the Mediterranean showed increasing trends of all-cause, cardiovascular and respiratory AMR. Increasing cardiovascular AMR was also observed in Southeast, South and East Asia. The AMR in low-income countries remained 4-fold of those in high-income countries in 2019, decreasing from 9-fold in 2000. AMR negatively correlated with a country-specific sociodemographic index ($r = -0.6$).

Interpretation LFS air pollution induced a substantial global mortality burden, with notable geographical and socioeconomic disparities. Urgent actions are required to address such substantial health impacts and the associated environmental injustice in a warming climate.

Introduction

Landscape fires include fires in any natural and cultural landscapes (e.g., forest, shrub, grass, pastures, agricultural lands, and peri-urban areas), including both wildfires (uncontrolled or unplanned fires in wildland vegetation) and human-planned fires (e.g., prescribed burns, agricultural fires).[1] Landscape fires are an increasing environmental and health threat fuelled by climate change.[1-5] Recent data showed that 72% of countries had increased human exposure to landscape fires in 2017–20 compared with 2001–04.[6] Landscape fire flames and heat can kill people near the fire areas, with 221 direct deaths reported globally in 2018.[7] However, the actual health risks from landscape fires are much greater, as landscape fire-sourced (LFS) air pollution (particularly fine particulate matter with a diameter of 2.5μm or less [$PM_{2.5}$] and ozone [O_3]) often travel hundreds and even thousands of kilometres away and affect much larger populations than flames and heat do.[5,8]

Numerous studies have documented both long-term (i.e., years following exposure) [9,10] and short-term (i.e., few days following exposure) [11,12] impacts of exposure to $PM_{2.5}$ and O_3 on all-cause, cardiovascular, and respiratory mortality. A recent study showed that each year, 2.18 billion people worldwide are exposed to substantial LFS air pollution defined by high concentrations of $PM_{2.5}$ and O_3, and the global population exposure to this hazard increased from 2000 to 2019.[13] Therefore, it is expected that LFS air pollution can induce a considerable mortality burden. Mapping and tracking this burden are essential for monitoring and managing the health impacts of LFS air pollution, for more targeted prevention and intervention, and for supporting actions for climate mitigation.

Despite some regional estimates for Europe,[14,15] the US,[16,17] Canada,[18] Australia,[19-22] Brazil,[23,24] and China[25], only three studies that estimated the global all-cause mortality burden from

LFS air pollution during 1997-2006, [26] 2016-2019,[27] and 2010-2019,[28] respectively. However, these global studies mainly reported the global total mortality burden from LFS $PM_{2.5}$, with little information on the spatiotemporal trends of the burden, and they did not evaluate cause-specific (e.g., cardiorespiratory) mortality burdens. All three global studies used LFS $PM_{2.5}$ data from chemical transport model simulations without limited calibrations against real observations at air quality stations. The accuracy of uncalibrated LFS $PM_{2.5}$ are much lower than the calibrated estimates according to recent studies.[13,29] In addition, these existing regional and global studies[17-31] examining the mortality burden only considered either short-term or long-term mortality impacts (independent with each other[30]) of LFS $PM_{2.5}$, while few studies have considered both simultaneously [26]. No study has till date to the best of our knowledge has assessed the global mortality burden from LFS O_3 that also associated with significant mortality risks.[11] Most existing studies only estimated the all-cause mortality burden[17-31], while little is known about the cardiovascular and respiratory mortality burden attributable to LFS air pollution.

With recent advances in both accurate global LFS air pollution data (calibrated against air quality stations)[13] and multi-country exposure-response (E-R) relationship estimates,[11,12] we aimed to address those research gaps and perform an accurate and comprehensive estimation of the global mortality burden attributable to LFS air pollution (both $PM_{2.5}$ and O_3) in recent two decades (2000-2019). We also aimed to evaluate the long-term trends, and geographical and socioeconomic disparities in the estimated mortality burdens.

Methods

Data collection

Mortality data

We collected daily all-cause (or non-external cause), cardiovascular, and respiratory death count data from 2267 communities from 59 countries or territories. Those communities were widely distributed across six continents. The 59 countries and territories included 72.4% of the global total population, as well as 63.8% of the global population exposed to substantial LFS air pollution in 2019.[13] As detailed in the Supplementary Material, the sources of the daily death count data included Multi-Country Multi-City (MCC) Collaborative Research Network database, [11,12] Australian Cause of Death Unit Record File, New Zealand Mortality Collection, Brazil Mortality Information System, Vital Statistics Deaths Database of Statistics Canada, Chilean Ministry of Health Epidemiology Department, and International Network for the Demographic Evaluation of Populations and their Health (INDEPTH) Network database.

We collected annual all-cause, cardiovascular and respiratory mortality data for each of 204 countries and territories during 2000-2019 from the Global Burden of Diseases Study 2019 (GBD2019).[31,32] The GBD 2019 directly provided estimates of cardiovascular deaths as a whole, but this was not the case for respiratory deaths. In this study, we calculated the respiratory deaths by summing up the deaths from chronic respiratory diseases and lower and upper respiratory infections as defined in GBD 2019.[31,32]

Exposure data

We estimated LFS daily average $PM_{2.5}$ and daily maximum 8-hour average surface O_3 (daily LFS $PM_{2.5}$ and daily LFS O_3, respectively hereafter) at a 0.25° × 0.25° (about 28km×28km at the equator) spatial resolution from 1/1/2000 to 31/12/2019 across the globe using machine learning and chemical transport models. Details of the estimation and validation of the estimates were provided in the previous published study.[13] Briefly, the estimated daily LFS

$PM_{2.5}$ and O_3, which have been calibrated against monitoring station observations using machine learning models, showed much higher accuracy than the daily LFS $PM_{2.5}$ and O_3 based purely on chemical transport models. Furthermore, our estimated daily LFS $PM_{2.5}$ and O_3 also showed good agreement with $PM_{2.5}$ and O_3 measured by monitoring stations during ten selected large wildfire events (assumed to be mainly contributed by wildfire emission) in Australia, the US, Chile, Portugal and South Africa. Finally, our daily LFS $PM_{2.5}$ estimates also showed good agreement with the smoke $PM_{2.5}$ estimates by Childs et al. ($r = 0.85$) in the contiguous US based on an independent validated approach.[33]

We calculated daily mean (according to location-specific local time zone) ambient temperature and relative humidity from hourly data obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) at a 0.25° × 0.25° spatial resolution, as described previously.[13]

We obtained annual population counts from 2000 to 2019 for each 1km×1km grid from the WorldPop project.[34] These population data were then aggregated to 0.25° × 0.25° spatial resolution to match the daily LFS air pollution and weather data.

For each of the 2267 communities with daily death data, we calculated population-weighted average daily LFS $PM_{2.5}$, LFS O_3, ambient temperature, and relative humidity by averaging the exposure of all 0.25° × 0.25° grids within the community boundaries, weighted by grid-specific population counts multiplying by the proportions (0-100%) of the grid's area size intersecting with the community. Following the same approach, we also calculated population-weighted average LFS $PM_{2.5}$ and O_3 at both daily and yearly time scales for each country or territory.

Sociodemographic data

Country- or territory-specific annual Socio-Demographic Index (SDI) and population data were sourced from GBD 2019.[32] The SDI is an integrated index of country-specific social and economic development that combines information on the economy, education, and fertility rate.[32] The included countries and territories were classified as 6 GBD super regions, and then 21 GBD regions following the geographical hierarchy of GBD 2019.[31] We also classified countries or territories as low-income, lower-middle income, upper-middle income, and high-income countries according to World Bank 2019 criteria.[35]

Statistical analyses

E-R relationships between LFS air pollution and mortality

We quantified the E-R relationships for the short-term mortality impacts of LFS $PM_{2.5}$ and O_3 following a widely used two-stage time-series analytical framework. [11,12,36,37] In the first stage, quasi-Poisson regressions with a distributed lag model were used to estimate the community-specific associations between daily deaths and daily LFS $PM_{2.5}$ and O_3 with the equation below:

$$\text{Log}\ (Y_{it}) = \alpha + \text{cb}(\text{LFS\_AP}_{it}) + \text{ns}(\text{date}_{it}, \text{df} = 7 \times \text{Years}_i) + \text{ns}(\text{Tmean\_lag07}_{it}, \text{df} = 4) + \text{ns}(\text{RH\_lag07}_{it}, \text{df} = 4) + \text{DOW}_{it} + \delta\text{Holiday}_{it} + \varepsilon_{it} \quad (1)$$

where Y_{it} represented the daily death counts (all-cause deaths, or cardiovascular deaths, or respiratory deaths) in community i on day t. α was the intercept; γ and δ were coefficients; ε_{it} was the residual error. $\text{ns}(\text{date}_{it}, \text{df} = 7 \times \text{Years}_i)$ meant that the date was modelled as a nature cubic spline with 7 degrees of freedom (df) per year (Years_i was the number years of death data for community i), to adjust for long-term trends and seasonal variations. Similarly, we modelled the 8-day (lag07, current day and previous 7 days) moving average of daily mean temperature (Tmean_lag07_{it}) and daily mean relative humidity (RH_lag07_{it}) using a natural cubic spline with 4 df to adjust for their potential non-linear impacts on mortality.[12] DOW_{it} referred to categorical day of week (Monday to Sunday) to adjust for death variations within a week. Holiday_{it} was a binary variable (public holiday or not) to adjust for potential impacts of public holidays on deaths.

$\text{cb}(\text{LFS\_AP}_{it})$ was a two-dimensional (exposure-response dimension and lag-response dimension) cross-basis function to model the lagged associations of daily mean LFS $PM_{2.5}$ (or LFS O_3) with death outcomes. According to our preliminary analyses and previous study,[12] the impacts of daily LFS $PM_{2.5}$ and O_3 on daily death were generally linear and lasted to up to 2 days following exposure. Therefore, we used a linear function for the exposure-response dimension, and an unconstrained function at the lag-response dimension along $0-2$ lag days.[36] The E-R relationships or effect estimates were then presented as cumulative relative risks (RR) with 95% confidence intervals [CI] of all-cause deaths (or cardiovascular and respiratory deaths) over lag0-2 days following exposure to each 10 μg/m^3 increases in daily LFS $PM_{2.5}$ (or daily LFS O_3).

In the second stage, we pooled the community-specific effect estimates for all communities, using a random-effect meta-analysis with maximum likelihood estimation.[38] This provided a global average estimation of RRs (95% CI) for short-term mortality impacts of LFS air pollution, as summarized in **Table S2**.

Due to the limited availability of evidence on the long-term mortality impacts of LFS $PM_{2.5}$ and O_3, particularly in regions with high LFS air pollution,[39,40] the E-R relationships for the long-term mortality impacts of LFS air pollution were sourced from the most recent systematic reviews on long-term mortality impacts of all-source $PM_{2.5}$ and O_3.[9,10] We assumed that long-term mortality impacts of LFS $PM_{2.5}$ and O_3 were the same as those of all-source $PM_{2.5}$ and O_3, respectively. These E-R relationships were expressed as linear as supported by most studies included in the systematic reviews.[9,10] **Table S3** summarizes the RRs of all-cause, cardiovascular, and respiratory mortality for each 10 μg/m^3 in annual average $PM_{2.5}$ and O_3, including the number of cohorts on which the meta-analyses were based. For example, the RR (95%CI) of all-cause mortality for each 10 μg/m^3 in annual average $PM_{2.5}$ was 1.08 (1.06, 1.09), which was estimated by a meta-analysis of 25 cohort studies.

Mortality burden estimation

For each country or territory in each year from 2000 to 2019, the annual all-cause deaths attributable to LFS air pollution were calculated using the following equations:

$$\mathrm{AD_{iy}} = \mathrm{AD\_short\_PM_{iy}} + \mathrm{AD\_short\_O3_{iy}} + \mathrm{AD\_long\_PM_{iy}} + \mathrm{AD\_long\_O3_{iy}} \quad (2)$$

$$\mathrm{AD\_short\_PM_{iy}} = \sum_{t=1}^{\mathrm{Day_y}} \frac{\mathrm{Death_{iy}}}{\mathrm{Day_y}} \times \left(1 - \mathrm{RR_{short\_PM}^{-(PWC\_PM_{iyt} \div 10)}}\right) \quad (3)$$

$$\mathrm{AD\_short\_O3_{iy}} = \sum_{t=1}^{\mathrm{Day_y}} \frac{\mathrm{Death_{iy}}}{\mathrm{Day_y}} \times \left(1 - \mathrm{RR_{short\_O3}^{-(PWC\_O3_{iyt} \div 10)}}\right) \quad (4)$$

$$\mathrm{AD\_long\_PM_{iy}} = \mathrm{Death_{iy}} \times \left(1 - \mathrm{RR_{long\_PM}^{-(PWC\_PM_{iy} \div 10)}}\right) \quad (5)$$

$$\mathrm{AD\_long\_O3_{iy}} = \mathrm{Death_{iy}} \times \left(1 - \mathrm{RR_{long\_O3}^{-(PWC\_O3_{iy} \div 10)}}\right) \quad (6)$$

Here, the total attributable deaths in country or territory i in year y consisted of four parts, including deaths from short-term mortality impacts of LFS $PM_{2.5}$ (AD_short_PM) and O_3 (AD_short_O3), and deaths from long-term mortality impacts of LFS $PM_{2.5}$ (AD_long_PM) and O_3 (AD_long_O3). Each part has its own RR estimates as provided in Table S3. $\mathrm{Day_y}$ was the number of days (i.e., 365 or 366) in year y, $\mathrm{Death_{iy}}$ the annual number of all-cause deaths from GBD 2019 in country or territory i in year y. In equations (3) and (4), we assumed the daily death number was the average daily deaths (i.e., $\frac{\mathrm{Death}_{iy}}{\mathrm{Day}_y}$) due to unavailability of country-specific daily death data. $\mathrm{PWC\_PM}_{iyt}$ and $\mathrm{PWC\_O3}_{iyt}$ were population-weighted average daily LFS $PM_{2.5}$ and O_3 in country or territory i on day t (1 to Day_y) in year y, respectively. $\mathrm{PWC\_PM}_{iy}$ and $\mathrm{PWC\_O3}_{iy}$ were population-weighted average annual LFS $PM_{2.5}$ and O_3, respectively.

Monte-Carlo simulations (1000 samples) assuming normal distributions of the annual death counts and log(RR) (i.e., Beta values in Table S2-S3) were used to quantify the uncertainty, i.e., 95% empirical confidence intervals [eCI] of the AD estimates. The country-year-specific attributable fractions (AF) and attributable mortality rates (AMR), along with their 95% eCI, were then calculated by dividing AD and its 95% eCI with annual deaths and population size, respectively.

The same equations and processes were used to calculate AD, AF and AMR for cardiovascular and respiratory deaths, simply replacing the all-cause death and RR data with data specific to cardiovascular or respiratory deaths.

Descriptive analyses of attributable mortality burdens

All descriptive analyses of the estimated mortality burdens were performed at the global scale, and by GBD super regions, GBD regions, and country or territory, and World Bank income group, for each year from 2000 to 2019. The long-term trends of each metric (AD, AF, AMR) were tested using linear regressions assuming a Gaussian distribution of the metric on a log scale, with the log-transformed annual metrics during 2000-2019 as the dependent variable and year (numeric) as the only predictor. GBD 2019 mortality data included 204 countries and territories, but three island countries or territories (Marshall Islands, Tokelau, and Tuvalu, with a total population of 70050 in 2019, accounting for 0.0009% of the global total) were not covered by the LFS air pollution data due to their small land size. Consequently, our mortality burden analyses included 201 countries and territories.

All data analyses were performed using R software (version 4.0.2), and maps were drawn using ArcGIS desktop (version 10.1). A two-sided P-value < 0.05 was considered as statistically significant.

Results

Global total attributable mortality burden and the overall trends

Globally, 1.53 (95% eCI: 1.24, 1.82) million all-cause deaths, 0.45 (95% eCI: 0.32, 0.58) million cardiovascular, and 0.22 (95% eCI: 0.08, 0.35) million respiratory deaths per year were attributable to LFS air pollution during 2000-2019 (**Table 1**). These ADs represented 2.90% (95%eCI: 2.35%, 3.44%), 2.80% (95%eCI: 2.04%, 3.56%), and 3.48% (95%eCI: 1.35, 5.56) of global annual all-cause, cardiovascular and respiratory deaths, respectively (**Table S4**). The corresponding annual average AMRs (95eCI%) were 22.08 (17.88, 26.24), 6.43 (4.67, 8.17) and 3.12 (1.21, 4.97) per 100,000 residents for all-cause, cardiovascular and respiratory deaths, respectively (**Table S5**).

Among the 1.53 million all-cause AD per year, 66.2% and 7.2% were caused by the long-term mortality impacts of LFS $PM_{2.5}$ and O_3, respectively; 11.4% and 15.2% were caused by the short-term mortality impacts of LFS $PM_{2.5}$ and O_3, respectively (**Table S6)**; these proportions remained stable over the two decades (**Figure S2**).

Cardiovascular AD saw an increasing trend from 2000 to 2019 (increase by 1.67% per year, *P* for trend<0.001), while all-cause and respiratory AD did not show significant trends.

Spatiotemporal variations in attributable mortality burden

Among the six GBD super regions, Sub-Saharan Africa had the largest all-cause and respiratory AD (nearly 40% of the global total), while Southeast Asia, East Asia, and Oceania had the largest cardiovascular AD (a third of the global total) (**Figure 1A-C**). Among the 21 GBD regions, Eastern Sub-Saharan Africa had the largest all-cause AD (212,968 AD per year), followed by Southeast Asia (206,817) and Central Sub-Saharan Africa (173,838) (**Figure 1D**). The largest cardiovascular AD was in Southeast Asia (78,132 AD per year), then in East Asia (70570) and Eastern Europe (51 thousand) (**Figure 1E**). The region with the largest respiratory AD was South Asia (33,218 AD per year), followed by Southeast Asia (29,005), and East Asia (26,524) (**Figure 1F**).

For all-cause AD, Eastern Europe, Southern Latin America, and Sub-Saharan African regions showed decreasing trends (all P for trends < 0.05, change per year: -3.90% to -0.85%), while many other regions (including High-income North America, Andean and Central Latin America, North Africa and Middle East, South Asia, Oceania, Southeast Asia) saw significant increasing trends. The trends for cardiovascular and respiratory AD were generally consistent with the trends of all-cause AD across those GBD regions, with only three notable differences: 1) all Sub-Saharan African regions except for Southern Sub-

Saharan Africa saw increasing trends of cardiovascular AD; 2) East Asia saw increasing trend of cardiovascular AD (+2.22% per year) while decreasing respiratory AD (-1.59% per year), despite a non-significant (*P* for trend >0.05) trend of all-cause AD; 3) in Southeast Asia, the increasing trend of cardiovascular AD was much more substantial than the trend for all-cause AD (+4.03% versus +2.30% per year), while the trend of respiratory AD was non-significant.

Central Sub-Saharan Africa had the highest all-cause AMR, followed by Southern and Eastern Sub-Saharan Africa, and Southern Latin America (**Tables S4-S5, Figure 2**). The highest respiratory AMR was also seen in Central Sub-Saharan Africa, followed by Southern Latin America and Oceania. However, the highest cardiovascular AMR was in Eastern Europe, then in Southern Latin America and Southeast Asia.

These high-AMR regions generally showed decreasing trends of AMR from 2000 to 2019. Countries in North and Central America, and those surrounding the Mediterranean showed increasing trends of all-cause, cardiovascular and respiratory AMR. Most counties in Southeast Asia and South Asia were characterised by increasing cardiovascular AMR, but non-significant trends of respiratory AMR. Most counties in East Asia saw increasing cardiovascular AMR but decreasing respiratory AMR.

Global socioeconomic disparities in attributable mortality burden

Overall, 92.3%, 89.9% and 93.2% of global all-cause, cardiovascular and respiratory AD, respectively, were in low- and middle-income countries (LMICs) during 2000-2019 (**Table 1, Figure 3A-C**). The proportions of all-cause and respiratory AD in LMICs showed decreasing trends over the two decades but remained more than 90% in 2019 (**Figure 3G**). In contrast, the proportions of cardiovascular AD in LMICs increased from 87.8% in 2000 to 90.7% in 2019. The AF and AMR decreased with the increase in income groups, and such disparities were consistently observed from 2000 to 2019 (**Table S4-S5, Figure 3D-F**). Overall, the all-cause, cardiovascular and respiratory AMR in low-income countries were 6.2-, 2.1- and 7.0-fold of those in high-income countries, respectively. Due to the notable decreasing trends of all-cause and respiratory AMR (decreased by 3.97% and 3.70% per year, *P* for trends<0.001, **Table S5**) in low-income countries, the ratio of all-cause and respiratory AMR in low- versus high-income countries declined substantially over 2000-2019 but remained about 4-fold (**Figure 3H**). The ratio of cardiovascular AMR in low- versus high-income countries remained stable around 2-fold over the two decades.

The socioeconomic disparities were further characterised by negative correlations between country- or territory-specific AMR and SDI (**Figure 4**). The correlations with SDI were stronger for all-cause and respiratory AMR (Pearson correlation coefficients *r* around 0.60 and 0.65, respectively) than for cardiovascular AMR (*r*=0.33). The disparities of all-cause and respiratory AMR by SDI slightly narrowed from 2000-09 to 2010-19 as evidenced by the slightly flattened slopes of the trend lines for AMR against SDI, and the decreased *r*.

Leading countries in attributable mortality burden

The top five countries with the greatest all-cause AD were China, Democratic Republic of the Congo (DR Congo), India, Indonesia, and Nigeria. This list stayed the same from 2000-09 to 2010-19 despite changes in order (i.e., India replaced DR Congo as the second) (**Figure 5A**). In 2000-19, the top 10 countries with greatest AD accounted for over half (50.9%) of the global total AD. Japan was the only high-income country in this top 10 list. India and

Vietnam experienced statistically significant increases in AD (increased by 1.7% and 4.6% per year over 2000-2019, *P* for trends<0.05). In contrast, DR Congo, Nigeria, Russia, Tanzania, Angola and South Africa experienced statistically significant AD decreases (by 1.4% to 3.2% per year).

The leading (top 10) countries in AF were dominated by Sub-Saharan African countries with only two exceptions (Chile and Bolivia in South America) (**Figure 5B**). In those countries, over 10% of the deaths were attributable to LFS air pollution. The highest AF was in DR Congo, which was 18.7% (95% eCI: 15.2-22.0%) in 2000-09 and 18.4% (95% eCI: 14.9-21.9%) in 2010-19.

The leading countries in AMR were all Sub-Saharan African countries (**Figure 5C**), despite all experiencing statistically significant decreases in AMR (by 1.1% to 8.8% per year, all *P* for trends < 0.05). The highest AMR was observed in the Central African Republic, where 283 (95% eCI: 228-338) and 250 (95% eCI: 199-300) deaths per 100,000 residents per year were attributable to LFS air pollution in 2000-09 and 2010-19, respectively. All leading countries in all-cause AD, AF and AMR were LMICs except for Japan and Chile.

The leading countries in cardiovascular (**Figure S3**) and respiratory (**Figure S4**) AD, AF and AMR shared similar positions than for all-cause deaths. However, there were also several notable differences in the lists for AD and AMR. Compared with the top 10 countries with the greatest all-cause AD, Argentina and Myanmar replaced Russia and Vietnam as the top 10 countries with the greatest respiratory AD. The US and Ukraine replaced Tanzania and Nigeria as the top 10 countries with the greatest cardiovascular AD. Specifically, the cardiovascular AD in the US was 9160 (95%eCI: 6679-11644) per year in 2000-09 (ranked 10th), and this rose to 11430 (95%eCI: 8317-14545) per year in 2010-19 (ranked 8th) after a 2.2% increase (*P* for trend<0.01) per year. Vietnam, India, and Indonesia also experienced substantial increases (4.2-5.2% per year) in cardiovascular AD over the past two decades.

The leading countries with the highest respiratory AMR were still all Sub-Saharan African countries. However, countries in Eastern Europe (Russia, Ukraine, Bulgaria), South America (Argentina, Chile, Uruguay) and Southeast Asia (Cambodia) entered the top 10 list for cardiovascular AMR. Cambodia had a substantial increase in cardiovascular AMR from 2000-2019 (4.5% increase per year, *P* for trend < 0.001).

Discussion

This study highlights the substantial global mortality burden attributable to LFS air pollution, including 1.53 million all-cause deaths, 0.45 million cardiovascular deaths, and 0.22 million respiratory deaths per year. Our comprehensive global assessment also generated many other key insights:

- The mortality burden was not evenly distributed; for example, Sub-Saharan Africa had the largest and nearly 40% of the global total all-cause and respiratory AD, but Southeast Asia, East Asia, and Eastern Europe bore the largest cardiovascular AD.
- There was an increasing trend of the global cardiovascular AD, mainly driven by increasing trends in Sub-Saharan Africa, East Asia, South Asia, and Southeast Asia and North America, represented by countries like DR Congo, China, India, Indonesia, and US, respectively.
- Central Sub-Saharan Africa had the highest all-cause and respiratory AMR, while Eastern Europe saw the highest cardiovascular AMR.
- These high-AMR regions showed decreasing trends of AMR. However, North and Central America, and Mediterranean countries showed increasing trends of all-cause, cardiovascular and respiratory AMR. Increasing cardiovascular AMR was also found in Southeast Asia and South Asia and East Asia.
- Over 90% of the AD in LMICs, including the five leading countries: China, India, DR Congo, Indonesia, and Nigeria.
- Despite a narrowing trend over the two decades, the socioeconomic disparity in the mortality burden remained substantial, as evidenced by the over 4-fold AMR in low- compared with high-income countries and the negative correlations between AMR and country-specific SDI.

The trend of AD was determined by three components: LFS air pollution exposure level (both daily and annual exposures), population size, and baseline mortality rates. Firstly, a previous study reported an increasing trend of global average population exposure to LFS $PM_{2.5}$ from 2000 to 2019, although no trend was observed for global LFS O_3.[13] This trend was also consistent with the previously reported increasing trends of global human exposure to wildfires since 2000 [6,7] which are related to anthropogenic climate change.[2,8] The present study found that LFS $PM_{2.5}$ contributed to 77.6%, 81.2%, and 74.0% of global total all-cause, cardiovascular, and respiratory AD, respectively (Table S6), thus the increasing LFS $PM_{2.5}$ was a driver of the global increasing AD trend. Secondly, the global population size increased substantially from 6.15 billion in 2000 to 7.73 billion in 2019,[32] another driver of the global increasing AD trend.

Finally, in terms of baseline mortality rates, the GBD 2019 reported increasing trends of cardiovascular mortality rates, while decreasing all-cause and respiratory mortality rates from 2000 to 2019.[31,32] This is the main reason why the present study found an increasing global total cardiovascular AD, while the trends for global total all-cause and respiratory AD were non-significant. However, the non-significant trends of all-cause and respiratory AD can also be interpretated as that increasing LFS air pollution attenuated the global progress made in reducing all-cause and respiratory mortality to some extent. [31,32] Overall, our data suggested that LFS air pollution was an increasing risk factor of global mortality burden, particularly for cardiovascular deaths. This worrying increasing trend is likely to continue in the next decades, as robust studies suggest that climate change will keep increasing wildfire frequency and intensity in the future.[5,41-43]

The health impacts of increasing LFS air pollution could be mitigated through effective evidence-based fire management, planning and design of natural and urban landscapes.[5] Immediate climate actions to limit the magnitude of climate change are also critical. A modelling study suggests that over 60% or 80% of the increase in wildfire exposure by 2100 could be avoided if the global mean temperature increase could be limited to 2.0˚C or 1.5˚C above pre-industrial, respectively. [43] The 1.5°C target remains reachable if the world could take an additional 28 gigatons of carbon dioxide equivalent (~50% of current emission levels) off annual emissions by 2030. [44] Unfortunately, as discussed in detail before,[1,8] the existing interventions and strategies (e.g., relocation, staying indoors, using air purifiers with effective filters, and wearing N95 or P100 face masks) that individuals can take to mitigate the adverse health impacts of wildfire-related air pollution are often not accessible to people of low socioeconomic status. Therefore, investment in health protection measures is required to help those people and communities affected by LFS air pollution, and more studies are also needed to identify, develop and evaluate innovative and cost-effective strategies.

Our analyses identified some regions and countries with particularly high mortality burdens attributable to LFS air pollution. This information is important for efficient resource allocations to implement better-targeted prevention and interventions in future. Notably, we observed a consistent socioeconomic disparity in the attributable mortality burden. This adds to the argument for climate or environmental injustice (i.e., people who suffer the most are those who bear the least responsibility for climate change [45]) and suggests that climate change is exacerbating global health inequality, partly through LFS air pollution. Financial and technological support from high-income to developing countries is needed to help vulnerable countries deal with the health impacts of LFS air pollution.

The present study has several strengths compared with previous studies on the mortality burden of LFS air pollution.[14-23,26-28] First, rather than only accounting for the total mortality burdens from LFS $PM_{2.5}$, our study also accounted for cause-specific mortality burdens and those from LFS O_3. We found that the spatiotemporal patterns of cardiovascular mortality burden attributable to LFS air pollution were quite different from the all-cause and respiratory attributable burdens, and LFS O_3 was responsible for 22.4% of the total AD (0.34 million deaths per year). Furthermore, we have provided global, regional and national estimates of attributable mortality burdens for each year over 2000-2019, which is much more comprehensive and informative than previous studies focusing on certain regions or countries [14-23] or the global total.[26-28]

Our estimated mortality burdens from LFS $PM_{2.5}$ (about 1.19 million deaths per year) were much higher than previous global studies focusing on total mortality burden from LFS $PM_{2.5}$.[26-28] Johnston et al estimated that 339,000 deaths per year were attributable to LFS $PM_{2.5}$ globally from 1997 to 2006.[26] A more recent study, applying the same exposure-response (E-R) relationship, estimated 677,745 deaths per year attributable to LFS $PM_{2.5}$ during 2016-2019.[27] Notably, the E-R relationship used in these two studies were from early epidemiological studies covering only three locations, and two of them relied on a strong assumption (i.e., 75% of all particles <10 μm were also <2.5 μm, because these two locations only assessed PM_{10} rather than $PM_{2.5}$ exposure) not supported by PM observations during wildfire events.[46] The third global study used the methods and E-R relationships of the GBD 2019 to estimate the long-term mortality burden from LFS $PM_{2.5}$ in 2010-2019 (135,180 attributable deaths per year) and in different future climate change scenarios.[28] The GBD method has the advantage of quantifying diseases-specific burden, but it can significantly underestimate the total mortality burden of $PM_{2.5}$ as it sums attributable mortality burden from several selected diseases (chronic obstructive pulmonary disease, lung cancer, ischemic heart disease, stroke, lower respiratory tract infection, and type 2 diabetes) while excluding other diseases related to $PM_{2.5}$ exposure.[47]

Compared to previous global studies, [26-28] we have made major advances in both exposure assessment and exposure-mortality relationships, which can explain our difference in estimates. For exposure assessment, our LFS $PM_{2.5}$ and O_3 from chemical transport simulations have been calibrated against observations from thousands of air quality stations across the world using a machine learning approach, while previous global studies used the chemical transport simulations without calibration. As shown in our previous validation studies, the calibration approach could improve the accuracy of the exposure estimates substantially (e.g., R^2 against station observed daily $PM_{2.5}$ improved from 0.48 to 0.89 after calibration).

E-R relationships for long-term mortality impacts were sourced from the latest published meta-analyses of cohort studies worldwide,[9,10] representing the best available evidence for global assessment. The E-R relationships for short-term mortality impacts were from meta-analyses from time-series analyses of 2267 communities in 59 countries or territories worldwide, which is also by far the most global representative evidence. This is superior to two previous global studies[26,27] (another global study did not account for short-term mortality burden[28]) which used evidence based on analyses from only 3 locations. This has also improved from our previously published analyses based on 749 communities worldwide[11,12] by adding much more daily mortality data from communities in Sub-Saharan Africa, South Asia, Southeast Asia, South America, and Oceania where LFS air pollution was high.

However, several limitations should be acknowledged. We did not quantify the mortality burdens attributable to other LFS air pollutants (e.g., carbon monoxide [1,8]), due to the unavailability of data. Therefore, the total mortality burden attributable to LFS air pollution should be higher than our estimates. We also did not assess the morbidity (e.g., hospital admissions, emergency department visits) burden of LFS air pollution.[8] Further investigations are warranted to fill the data and evidence gaps to give more comprehensive estimates of diseases burdens from LFS air pollution. As discussed before,[13] there were some uncertainties in estimating LFS $PM_{2.5}$ and O_3 (e.g., chemical transport model simulations, machine learning model predictions), and we could not incorporate these uncertainties in our mortality burden estimates. The mortality data from the GBD 2019 also has some limitations, such as relying on model estimates in countries with no death registrations, and uncertainties in disease classifications, which have been discussed in detail before.[31,32] These limitations of GBD 2019 will be continuously improved in future rounds of GBD, and thus, our estimates could also be updated and improved in the future.

Our estimates of the long-term mortality burdens relied on the assumption that the long-term mortality impacts of LFS $PM_{2.5}$ and O_3 are the same as all-source $PM_{2.5}$ and O_3, respectively. This was due to the limited evidence on long-term mortality impacts of LFS $PM_{2.5}$ and O_3, particularly in regions with high LFS air pollution.[39,40] However, this assumption may not hold true, given the differences in chemical components, toxicity, accompanying exposures (e.g., high ambient temperatures often come together with wildfires), and exposure patterns (acute high exposure versus chronic moderate or low exposure) between LFS and other-sourced (e.g., traffic, industry, household) air pollution. Generally, existing evidence on chemical components and toxicity of LFS $PM_{2.5}$ suggests that the LFS $PM_{2.5}$ tends to have stronger mortality impacts than all-source $PM_{2.5}$, and high temperatures accompanying wildfires also tend to exacerbate the mortality impacts of $PM_{2.5}$ and O_3.[1,8] However, more epidemiological studies are warranted to address the evidence gap on the long-term mortality impacts of LFS $PM_{2.5}$ and O_3,[1] which will improve our mortality burden estimates in future.

In conclusion, LFS air pollution induced a substantial global mortality burden, with notable geographical and socioeconomic disparities. In a warming climate with increasing wildfires, urgent climate mitigation and adaptation actions are warranted to address the substantial health impacts of LFS air pollution and the associated environmental injustice.

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Conflicts of Interests

Michael Abramson holds investigator initiated grants from Pfizer, Boehringer-Ingelheim, GlaxoSmithKline and Sanofi for unrelated research. He also received a speaker's fee from GSK. The other authors declare no competing interests.

Ethics Committee Approval

The project was approved by Monash University Human Research Ethics Committee (reference number 27582).

Data and Code Availability

Estimates of AD, AF and AMR for global, regional (GBD super regions and GBD regions), SDI and income groups, and 201 countries and territories in each year during 2000-2019, as well as the relative risks for short-term and long-term mortality impacts were shared on https://github.com/Rongbin553/wildfire_death. Daily mortality data for 2267 communities were under a data sharing agreement (http://mccstudy.lshtm.ac.uk/) and cannot be made publicly available. Annual mortality and sociodemographic data from GBD 2019 were publicly available (https://vizhub.healthdata.org/gbd-results/). Researchers can contact the corresponding authors (Yuming Guo, yuming.guo@monash.edu; and Shanshan Li, shanshan.li@monash.edu) for information on accessing the analytical codes, GEOS-Chem simulation outputs, estimated LFS air pollution data, and restricted daily mortality data.

Author contributions

YG, AG, MH, and BA set up the collaborative network. RX, YG, SL, GC designed the study and statistical methods. RX took the lead in statistical analyses, manuscript drafting, and results interpreting. TY contributed visualisation. YX contributed to exposure assessment, All authors contributed to interpreting the results, revising the manuscript, and approved the submission of the manuscript for publication.

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Table 1. Global annual average deaths attributable to landscape fire air pollution by GBD super regions, regions, World Bank income groups, and SDI levels

Subgroup	All-cause death: Annual AD (95%CI)	All-cause death: Change per year (%)	Cardiovascular death: Annual AD (95%CI)	Cardiovascular death: Change per year (%)	Respiratory death: Annual AD (95%CI)	Respiratory death: Change per year (%)
Global	1532540 (1240832, 1821326)	-0.08	446093 (324251, 567224)	1.67***	216318 (84080, 345251)	-0.17
GBD super regions and regions						
Central Europe, Eastern Europe, and Central Asia	99118 (80511, 117543)	-1.28*	68490 (49895, 86950)	-1.36*	5821 (2223, 9367)	-1.92**
Central Asia	12821 (10399, 15229)	-0.11	7921 (5767, 10062)	-0.10	1274 (482, 2056)	-1.23
Central Europe	14410 (11721, 17083)	0.23	9245 (6736, 11745)	-0.09	922 (376, 1464)	0.27
Eastern Europe	71886 (58392, 85231)	-1.84*	51324 (37392, 65143)	-1.82*	3626 (1365, 5847)	-2.78***
High-income	132867 (108253, 157160)	0.59	49919 (36365, 63392)	-0.07	18376 (7076, 29381)	1.15**
Australasia	3811 (3110, 4506)	0.41	1532 (1115, 1949)	-0.94	408 (166, 647)	1.09
High-income Asia Pacific	36668 (29764, 43489)	0.05	12380 (8976, 15760)	-0.64	5355 (1926, 8717)	0.56
High-income North America	27738 (22605, 32818)	3.14***	11246 (8190, 14304)	2.24**	3470 (1397, 5533)	3.60***
Southern Latin America	39766 (32378, 47022)	-0.85**	14461 (10567, 18281)	-1.45***	6418 (2343, 10278)	0.23
Western Europe	24883 (20396, 29325)	0.94	10300 (7516, 13097)	0.15	2725 (1244, 4206)	1.47*
Latin America and Caribbean	121562 (98785, 144161)	1.31**	36622 (26677, 46508)	1.57**	16327 (6503, 25905)	1.41**
Andean Latin America	19123 (15397, 22814)	1.80**	4307 (3114, 5495)	3.04***	3512 (1377, 5566)	1.43*
Caribbean	3542 (2861, 4221)	0.10	1245 (902, 1590)	0.92	380 (152, 608)	-0.28
Central Latin America	40014 (32537, 47446)	2.95***	11025 (8031, 14013)	3.84***	4574 (1903, 7204)	2.58***
Tropical Latin America	58883 (47991, 69680)	0.09	20045 (14630, 25410)	0.02	7860 (3071, 12527)	0.81
North Africa and Middle East	43805 (35252, 52330)	1.77***	19661 (14223, 25102)	3.07***	4569 (1706, 7419)	0.48
South Asia	170762 (138286, 203074)	1.23*	48218 (34998, 61402)	3.70***	33218 (12452, 53794)	1.57**
Southeast Asia, East Asia, and Oceania	357656 (289162, 425598)	1.70*	149629 (108801, 190220)	3.17***	56395 (21524, 90566)	0.12
East Asia	147291 (119142, 175297)	0.86	70570 (51299, 89812)	2.22*	26524 (10356, 42558)	-1.59*
Oceania	3548 (2818, 4274)	2.71***	927 (666, 1190)	3.85***	867 (318, 1402)	1.98***
Southeast Asia	206817 (167202, 246028)	2.30*	78132 (56836, 99218)	4.03***	29005 (10850, 46605)	1.63
Sub-Saharan Africa	606769 (490583, 721460)	-1.88***	73553 (53292, 93651)	1.07***	81612 (32596, 128819)	-1.65***
Central Sub-Saharan Africa	173838 (140725, 206342)	-1.42***	22709 (16516, 28786)	1.65***	23911 (9279, 37581)	-1.73***

Eastern Sub-Saharan Africa	212968 (172243, 253155)	-2.49***	24630 (17864, 31332)	1.34***	26418 (10362, 41900)	-1.97***
Southern Sub-Saharan Africa	52599 (42423, 62685)	-3.90***	7501 (5458, 9526)	-1.36*	5776 (2261, 9177)	-2.50***
Western Sub-Saharan Africa	167364 (135192, 199279)	-0.99**	18713 (13454, 24006)	0.97**	25507 (10694, 40161)	-1.08***
World Bank Income groups						
Low Income	374059 (302325, 444791)	-1.52***	49507 (35891, 62990)	1.64***	51637 (20208, 81816)	-1.24***
Lower Middle Income	602901 (487629, 717179)	0.29	163592 (118761, 208174)	3.11***	90785 (35107, 145251)	0.18
Upper Middle Income	438116 (355185, 520369)	0.34	187754 (136663, 238551)	0.72	59393 (23073, 95017)	-0.17
High Income	117462 (95692, 138986)	1.08*	45239 (32935, 57508)	0.42	14502 (5692, 23166)	1.49**
SDI levels						
Low SDI	653002 (527665, 776824)	-1.60***	94920 (68730, 120924)	1.40***	93198 (36638, 147819)	-1.52***
Low-middle SDI	433391 (351184, 514971)	1.79***	146092 (106255, 185687)	3.54***	64257 (24670, 103105)	1.78***
Middle SDI	252461 (204387, 300157)	0.50	104651 (76125, 133048)	1.59*	40592 (15659, 65080)	-0.61
High-middle SDI	108806 (88436, 128947)	-0.94	68858 (50168, 87404)	-1.27*	7128 (2718, 11432)	-0.94*
High SDI	84880 (69160, 100427)	1.24*	31571 (22972, 40162)	0.52	11143 (4395, 17814)	1.68**

Notes: AD, attributable deaths; SDI, socio-demographic index. CI, confidence interval. From row 3 to 28, those in bold text were **GBD super regions**, and those in plain text were GBD regions. * *P* for trend < 0.05; ** *P* for trend < 0.01; *** *P* for trend < 0.001

Figure 1. Global and regional trends of annual deaths, fractions of deaths, and mortality rates attributable to exposure to LSF $PM_{2.5}$ from 2000 to 2019.

Notes: error bars in panels D-F represent the 95% empirical confidence intervals. AD, attributable deaths; GBD, Global Burden of Diseases study. SSA, Sub-Saharan Africa.

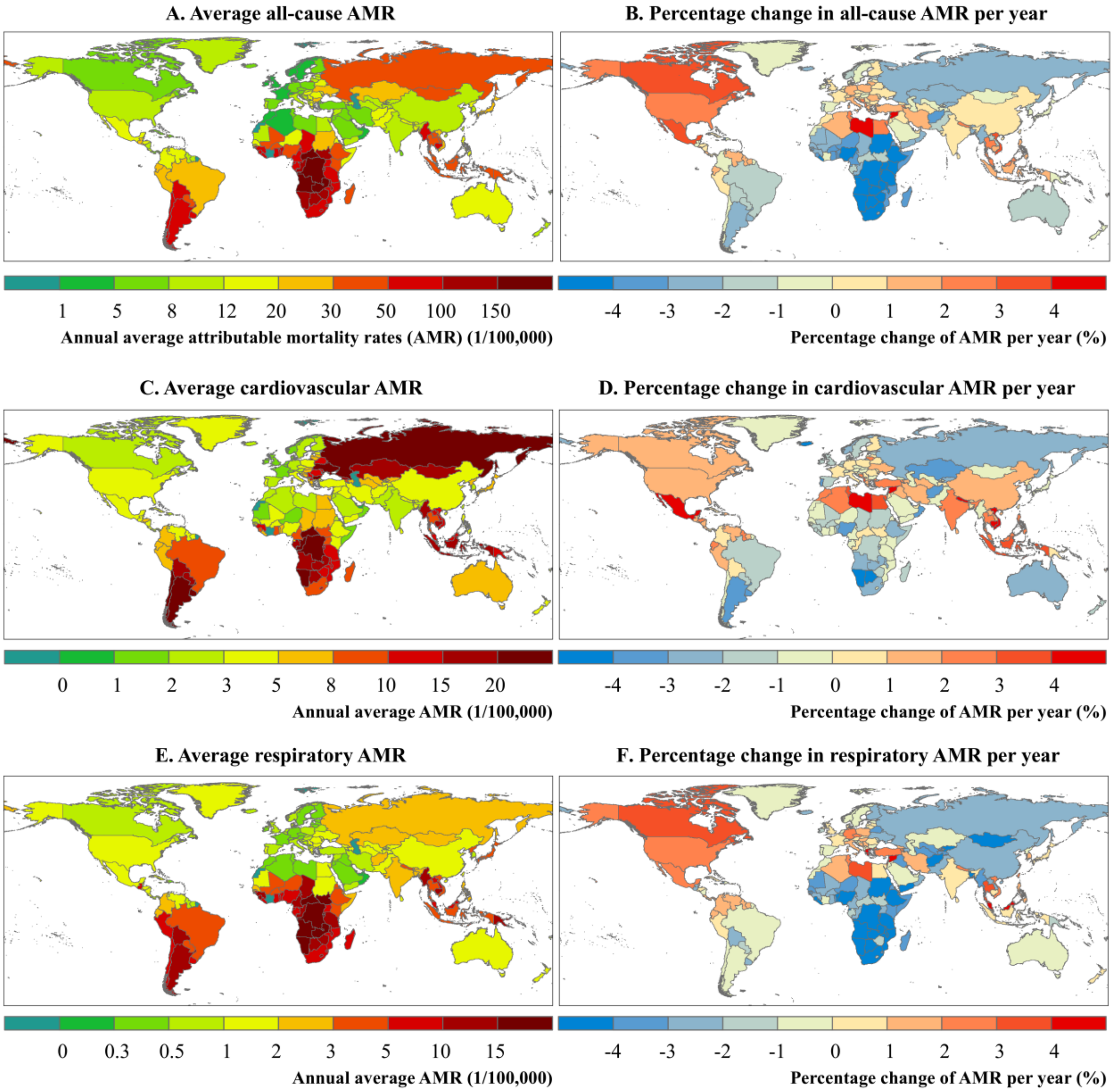

Figure 2. Annual average all-cause (a), cardiovascular (c) and respiratory (e) mortality rates attributable to fire-sourced air pollution and their corresponding trends (b, d, f) for 201 countries and territories from 2000 to 2019.

Notes: For each country or territory, percentage change per year was estimated based on a linear regression model considering a Gaussian distribution of attributable mortality rates (AMR) on the log scale.

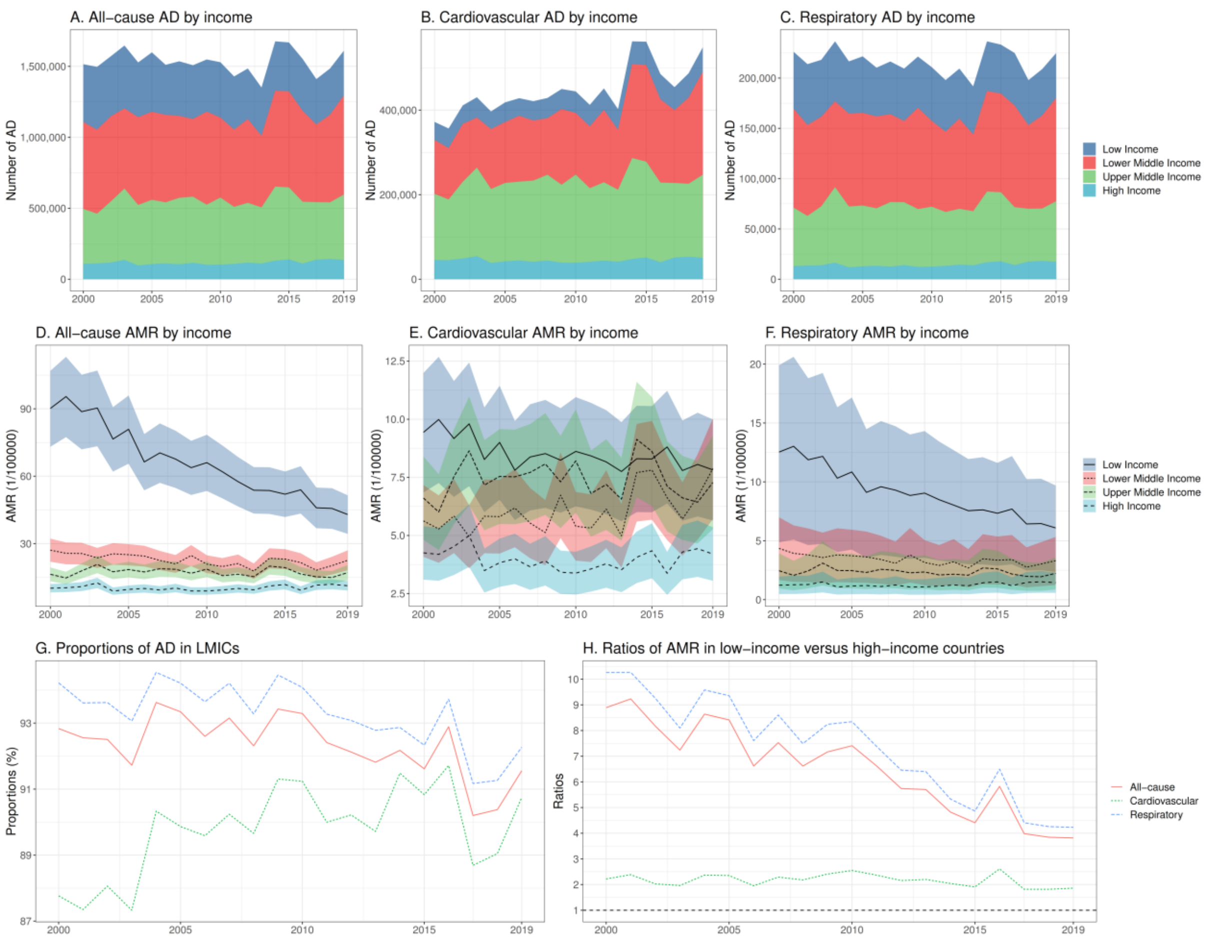

Figure 3. Annual deaths, mortality rates attributable to landscape fire-sourced air pollution from 2000 to 2019, by World Bank income groups.
Notes: AD, attributable deaths; AMR, attributable mortality rates; LMIC, low- and middle-income countries. The shaded area in panels D-F represented the 95% empirical confidence interval of the AMR estimates.

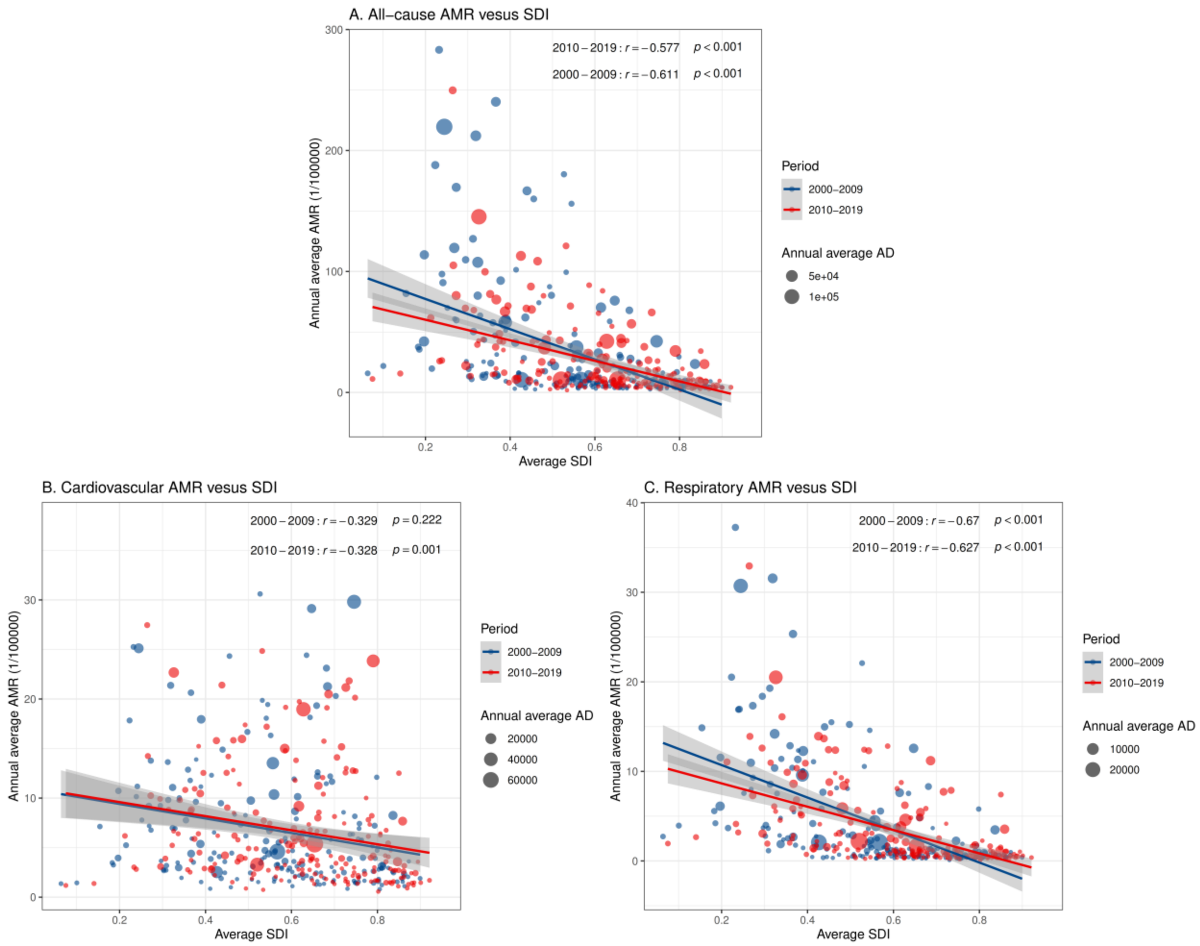

Figure 4. Associations of country- or territory-level attributable mortality rates (AMR) with socio-demographic index (SDI) by period.

Notes: each dot represents one country or territory. r refers to Spearman correlation coefficient.

Low income | Lower middle income | Upper middle income | High income

A. Annual attributables deaths (AD)

Leading countries 2000-09	AD (95% eCI)	Leading countries 2010-19	AD (95% eCI)	Change per year (%)
1 China	136288 (110539, 161957)	1 China	145692 (117669, 173525)	0.9
2 Democratic Republic of the Congo	128409 (104503, 151675)	2 India	137711 (111527, 163756)	1.7*
3 India	117781 (95618, 139855)	3 Democratic Republic of the Congo	113242 (91474, 134727)	-1.4***
4 Indonesia	84443 (68570, 100181)	4 Indonesia	06069 (85788, 126097)	2.5
5 Nigeria	82151 (66659, 97416)	5 Nigeria	70104 (56571, 83568)	-1.5***
6 Russian Federation	62182 (50540, 73687)	6 Brazil	56428 (46002, 66770)	0.1
7 Brazil	56063 (45709, 66325)	7 Russian Federation	50104 (40661, 59441)	-2.3**
8 United Republic of Tanzania	41746 (33865, 49472)	8 United Republic of Tanzania	33832 (27357, 40232)	-2.1***
9 Angola	37550 (30508, 44439)	9 Japan	30306 (24593, 35953)	-0.1
10 South Africa	33752 (27269, 40191)	10 Viet Nam	29782 (24024, 35482)	4.6***
13 Japan	30521 (24757, 36210)	11 Angola	29256 (23529, 34917)	-2.4***
24 Viet Nam	18562 (14987, 22094)	17 South Africa	23699 (19232, 28127)	-3.2***

B. Annual attributable fractions (AF), %

Leading countries 2000-09	AF (95% eCI)	Leading countries 2010-19	AF (95% eCI)	Change per year (%)
1 Democratic Republic of the Congo	18.66 (15.18, 22.04)	1 Democratic Republic of the Congo	18.40 (14.86, 21.89)	-0.3
2 Angola	18.58 (15.10, 21.99)	2 Central African Republic	16.95 (13.50, 20.35)	0.5
3 Zambia	17.14 (13.93, 20.28)	3 Congo	15.93 (12.77, 19.06)	0.5*
4 Central African Republic	15.93 (12.81, 19.01)	4 Angola	15.61 (12.56, 18.64)	-1.7***
5 Namibia	14.96 (12.09, 17.79)	5 Zambia	13.65 (11.03, 16.22)	-2.3***
6 Congo	14.94 (12.11, 17.76)	6 Burundi	13.00 (10.37, 15.62)	-0.8**
7 Burundi	13.80 (11.19, 16.36)	7 Rwanda	12.23 (9.88, 14.56)	-0.7
8 Rwanda	12.81 (10.41, 15.16)	8 Gabon	11.44 (9.20, 13.68)	0.6*
9 Chile	12.65 (10.31, 14.94)	9 South Sudan	11.31 (9.04, 13.56)	0.6
10 Bolivia (Plurinational State of)	12.03 (9.74, 14.28)	10 Chile	11.27 (9.18, 13.32)	-0.9**
14 South Sudan	10.58 (8.49, 12.66)	11 Bolivia (Plurinational State of)	11.15 (8.96, 13.32)	-0.7
15 Gabon	10.52 (8.49, 12.55)	13 Namibia	10.54 (8.45, 12.62)	-3.7***

C. Annual attributable mortality rates (AMR), 1/100000

Leading countries 2000-09	AMR (95% eCI)	Leading countries 2010-19	AMR (95% eCI)	Change per year (%)
1 Central African Republic	283.19 (227.77, 338.03)	1 Central African Republic	249.72 (198.89, 299.90)	-1.4***
2 Zambia	240.25 (195.22, 284.21)	2 Democratic Republic of the Congo	145.25 (117.33, 172.81)	-4.2***
3 Democratic Republic of the Congo	219.59 (178.71, 259.38)	3 Congo	121.13 (97.11, 144.93)	-2.9***
4 Angola	212.16 (172.37, 251.09)	4 Angola	112.92 (90.81, 134.77)	-6.0***
5 Burundi	187.93 (152.40, 222.86)	5 Zambia	108.52 (87.75, 129.02)	-7.5***
6 Namibia	180.35 (145.78, 214.46)	6 Burundi	105.08 (83.78, 126.19)	-5.9***
7 Malawi	169.54 (137.38, 201.22)	7 South Sudan	99.71 (79.69, 119.59)	-1.1*
8 Zimbabwe	166.64 (133.62, 199.32)	8 Namibia	88.68 (71.06, 106.13)	-6.8***
9 Congo	159.98 (129.61, 190.16)	9 Zimbabwe	87.56 (70.75, 104.18)	-6.0***
10 Botswana	156.00 (124.36, 187.34)	10 Gabon	83.99 (67.50, 100.43)	-1.8***
14 South Sudan	109.68 (87.97, 131.26)	11 Malawi	81.36 (65.78, 96.75)	-6.9***
17 Gabon	99.36 (80.18, 118.51)	23 Botswana	65.47 (52.05, 78.79)	-8.8***

Figure 5. Top 10 countries or territories with greatest total all-cause deaths, fractions of all-cause deaths, and all-cause mortality rates attributable to landscape fire-sourced air pollution during the first and second decades of 2000-2019.

Notes: * indicates the P for long-term trend < 0.05; ** P <0.01; *** P<0.001.

Figure 1


A. Global all−cause attributable deaths (AD)
B. Global cardiovascular AD
C. Global respiratory AD
Number of AD
0
500,000
1,000,000
1,500,000
200,000
400,000
50,000
100,000
150,000
200,000
2000
2005
2010
2015
2019
GBD super regions
Central Europe, Eastern Europe, and Central Asia
High−income
Latin America and Caribbean
North Africa and Middle East
South Asia
Southeast Asia, East Asia, and Oceania
Sub−Saharan Africa
D. Annual all−cause AD by GBD regions
E. Annual cardiovascular AD by GBD regions
F. Annual respiratory AD by GBD regions
2000−2004
2005−2009
2010−2014
2015−2019
100,000
200,000
300,000
50,000
20,000
40,000
60,000
Central Asia
Central Europe
Eastern Europe
Australasia
High−income Asia Pacific
High−income North America
Southern Latin America
Western Europe
Andean Latin America
Caribbean
Central Latin America
Tropical Latin America
North Africa and Middle East
South Asia
East Asia
Oceania
Southeast Asia
Central SSA
Eastern SSA
Southern SSA
Western SSA

Figure 2

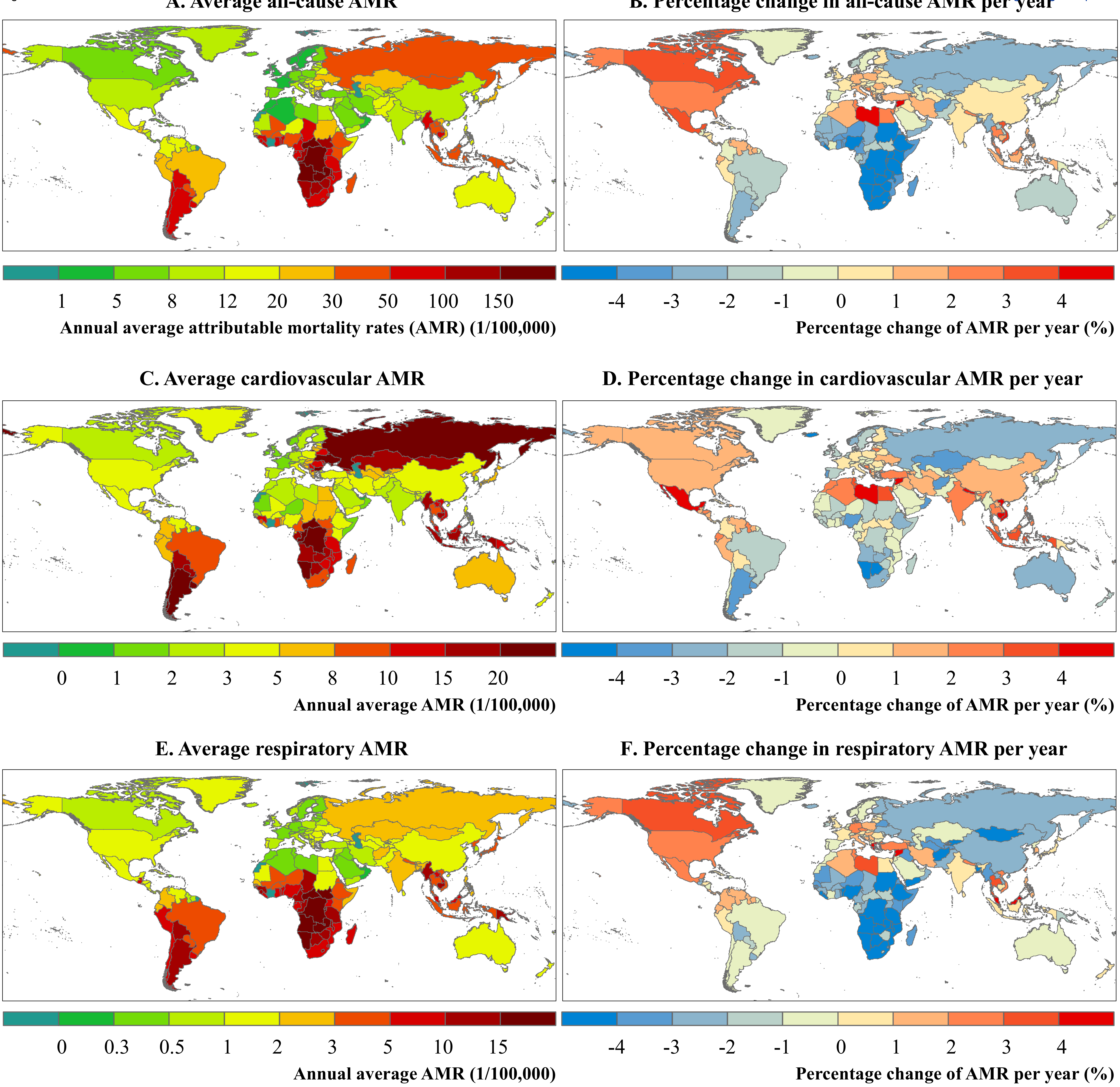
A. Average all-cause AMR
B. Percentage change in all-cause AMR per year
1 5 8 12 20 30 50 100 150
Annual average attributable mortality rates (AMR) (1/100,000)
-4 -3 -2 -1 0 1 2 3 4
Percentage change of AMR per year (%)
C. Average cardiovascular AMR
D. Percentage change in cardiovascular AMR per year
0 1 2 3 5 8 10 15 20
Annual average AMR (1/100,000)
-4 -3 -2 -1 0 1 2 3 4
Percentage change of AMR per year (%)
E. Average respiratory AMR
F. Percentage change in respiratory AMR per year
0 0.3 0.5 1 2 3 5 10 15
Annual average AMR (1/100,000)
-4 -3 -2 -1 0 1 2 3 4
Percentage change of AMR per year (%)

Figure 3

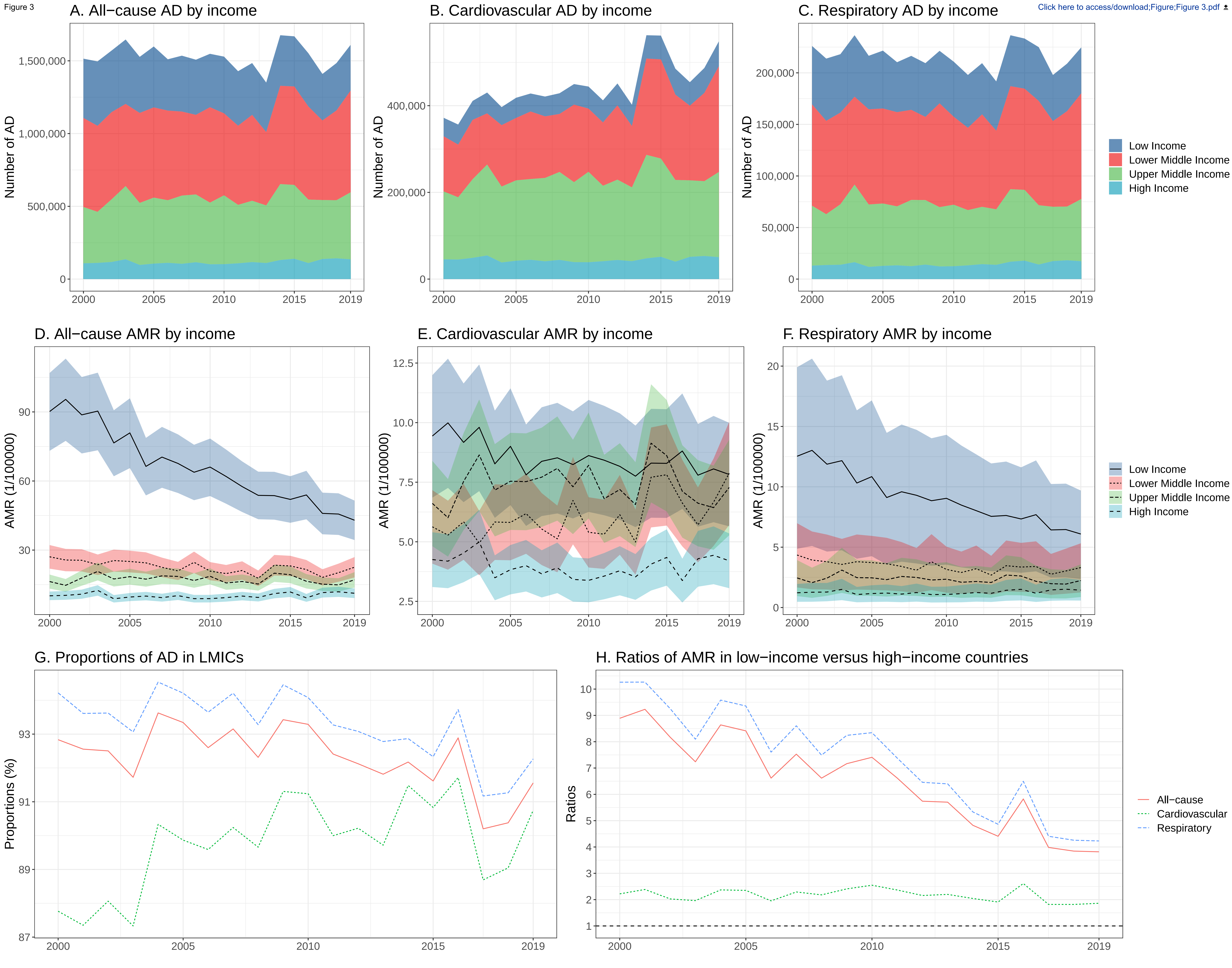
A. All−cause AD by income
B. Cardiovascular AD by income
C. Respiratory AD by income
Number of AD
Low Income
Lower Middle Income
Upper Middle Income
High Income
D. All−cause AMR by income
E. Cardiovascular AMR by income
F. Respiratory AMR by income
AMR (1/100000)
G. Proportions of AD in LMICs
Proportions (%)
H. Ratios of AMR in low−income versus high−income countries
Ratios
All−cause
Cardiovascular
Respiratory

Figure 4

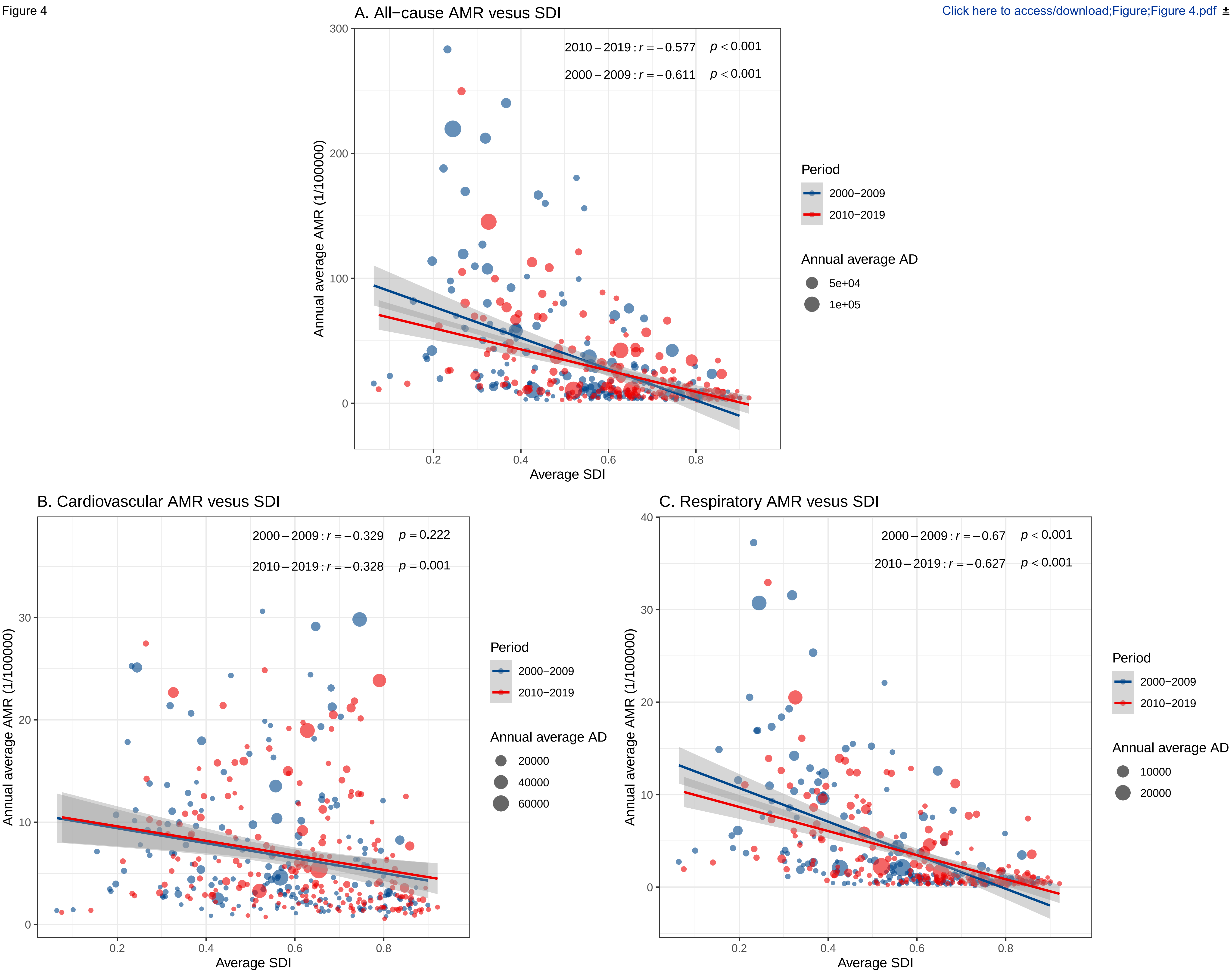
A. All−cause AMR vesus SDI
$2010-2019: r = -0.577 \quad p < 0.001$
$2000-2009: r = -0.611 \quad p < 0.001$
Annual average AMR (1/100000)
Average SDI
Period
2000−2009
2010−2019
Annual average AD
5e+04
1e+05
B. Cardiovascular AMR vesus SDI
$2000-2009: r = -0.329 \quad p = 0.222$
$2010-2019: r = -0.328 \quad p = 0.001$
Annual average AMR (1/100000)
Average SDI
Period
2000−2009
2010−2019
Annual average AD
20000
40000
60000
C. Respiratory AMR vesus SDI
$2000-2009: r = -0.67 \quad p < 0.001$
$2010-2019: r = -0.627 \quad p < 0.001$
Annual average AMR (1/100000)
Average SDI
Period
2000−2009
2010−2019
Annual average AD
10000
20000

Figure 5

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Low income | Lower middle income | Upper middle income | High income

A. Annual attributables deaths (AD)

Leading countries 2000-09	AD (95% eCI)	Leading countries 2010-19	AD (95% eCI)	Change per year (%)
1 China	136288 (110539, 161957)	1 China	145692 (117669, 173525)	0.9
2 Democratic Republic of the Congo	128409 (104503, 151675)	2 India	137711 (111527, 163756)	1.7*
3 India	117781 (95618, 139855)	3 Democratic Republic of the Congo	113242 (91474, 134727)	-1.4***
4 Indonesia	84443 (68570, 100181)	4 Indonesia	106069 (85788, 126097)	2.5
5 Nigeria	82151 (66659, 97416)	5 Nigeria	70104 (56571, 83568)	-1.5***
6 Russian Federation	62182 (50540, 73687)	6 Brazil	56428 (46002, 66770)	0.1
7 Brazil	56063 (45709, 66325)	7 Russian Federation	50104 (40661, 59441)	-2.3**
8 United Republic of Tanzania	41746 (33865, 49472)	8 United Republic of Tanzania	33832 (27357, 40232)	-2.1***
9 Angola	37550 (30508, 44439)	9 Japan	30306 (24593, 35953)	-0.1
10 South Africa	33752 (27269, 40191)	10 Viet Nam	29782 (24024, 35482)	4.6***
13 Japan	30521 (24757, 36210)	11 Angola	29256 (23529, 34917)	-2.4***
24 Viet Nam	18562 (14987, 22094)	17 South Africa	23699 (19232, 28127)	-3.2***

B. Annual attributable fractions (AF), %

Leading countries 2000-09	AF (95% eCI)	Leading countries 2010-19	AF (95% eCI)	Change per year (%)
1 Democratic Republic of the Congo	18.66 (15.18, 22.04)	1 Democratic Republic of the Congo	18.40 (14.86, 21.89)	-0.3
2 Angola	18.58 (15.10, 21.99)	2 Central African Republic	16.95 (13.50, 20.35)	0.5
3 Zambia	17.14 (13.93, 20.28)	3 Congo	15.93 (12.77, 19.06)	0.5*
4 Central African Republic	15.93 (12.81, 19.01)	4 Angola	15.61 (12.56, 18.64)	-1.7***
5 Namibia	14.96 (12.09, 17.79)	5 Zambia	13.65 (11.03, 16.22)	-2.3***
6 Congo	14.94 (12.11, 17.76)	6 Burundi	13.00 (10.37, 15.62)	-0.8**
7 Burundi	13.80 (11.19, 16.36)	7 Rwanda	12.23 (9.88, 14.56)	-0.7
8 Rwanda	12.81 (10.41, 15.16)	8 Gabon	11.44 (9.20, 13.68)	0.6*
9 Chile	12.65 (10.31, 14.94)	9 South Sudan	11.31 (9.04, 13.56)	0.6
10 Bolivia (Plurinational State of)	12.03 (9.74, 14.28)	10 Chile	11.27 (9.18, 13.32)	-0.9**
14 South Sudan	10.58 (8.49, 12.66)	11 Bolivia (Plurinational State of)	11.15 (8.96, 13.32)	-0.7
15 Gabon	10.52 (8.49, 12.55)	13 Namibia	10.54 (8.45, 12.62)	-3.7***

C. Annual attributable mortality rates (AMR), 1/100000

Leading countries 2000-09	AMR (95% eCI)	Leading countries 2010-19	AMR (95% eCI)	Change per year (%)
1 Central African Republic	283.19 (227.77, 338.03)	1 Central African Republic	249.72 (198.89, 299.90)	-1.4***
2 Zambia	240.25 (195.22, 284.21)	2 Democratic Republic of the Congo	145.25 (117.33, 172.81)	-4.2***
3 Democratic Republic of the Congo	219.59 (178.71, 259.38)	3 Congo	121.13 (97.11, 144.93)	-2.9***
4 Angola	212.16 (172.37, 251.09)	4 Angola	112.92 (90.81, 134.77)	-6.0***
5 Burundi	187.93 (152.40, 222.86)	5 Zambia	108.52 (87.75, 129.02)	-7.5***
6 Namibia	180.35 (145.78, 214.46)	6 Burundi	105.08 (83.78, 126.19)	-5.9***
7 Malawi	169.54 (137.38, 201.22)	7 South Sudan	99.71 (79.69, 119.59)	-1.1*
8 Zimbabwe	166.64 (133.62, 199.32)	8 Namibia	88.68 (71.06, 106.13)	-6.8***
9 Congo	159.98 (129.61, 190.16)	9 Zimbabwe	87.56 (70.75, 104.18)	-6.0***
10 Botswana	156.00 (124.36, 187.34)	10 Gabon	83.99 (67.50, 100.43)	-1.8***
14 South Sudan	109.68 (87.97, 131.26)	11 Malawi	81.36 (65.78, 96.75)	-6.9***
17 Gabon	99.36 (80.18, 118.51)	23 Botswana	65.47 (52.05, 78.79)	-8.8***