Global, regional, and national mortality burden attributable to air pollution from landscape fires: a health impact assessment study

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Summary

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

Methods **We calculated country-specific population-weighted average daily and annual LFS fine particulate matter ($PM_{2·5}$) and surface ozone (O_3) during 2000–19 from a validated dataset. We obtained the relative risks (RRs) for both short-term and long-term impact 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 across 59 countries or territories. The long-term RRs were obtained from published meta-analyses of cohort studies on all-source $PM_{2·5}$ and O_3. Annual mortality, population, and socio-demographic data for each country or 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 using standard algorithms.**

Findings **Globally, 1·53 million all-cause deaths per year (95% empirical confidence interval [eCI] 1·24–1·82) were attributable to LFS air pollution during 2000–19, including 0·45 million (0·32–0·57) cardiovascular deaths and 0·22 million respiratory deaths (0·08–0·35). LFS $PM_{2·5}$ and O_3 contributed to 77·6% and 22·4% of the total attributable deaths, respectively. Over 90% of all attributable deaths were in low-income and middle-income countries, particularly in sub-Saharan Africa (606 769 deaths per year), southeast Asia (206 817 deaths), south Asia (170 762 deaths), and east Asia (147 291 deaths). The global cardiovascular attributable deaths saw an average 1·67% increase per year (p_{trend}<0·001), although the trends for all-cause and respiratory attributable deaths were not statistically significant. The five countries with the largest all-cause attributable deaths were China, the Democratic Republic of the Congo, India, Indonesia, and Nigeria, although the order changed in the second decade. The leading countries with the greatest attributable mortality rates (AMRs) 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 AMRs. Increasing cardiovascular AMR was also observed in southeast Asia, south Asia, and east Asia. In 2019, the AMRs in low-income countries remained four times those in high-income countries, though this had reduced from nine times in 2000. AMRs negatively correlated with a country-specific socio-demographic index (Spearman correlation coefficients *r* around –0·60).**

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 impact and the associated environmental injustice in a warming climate.**

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Introduction

Landscape fires include fires in any natural and cultural landscapes (eg, forest, shrub, grass, pastures, agricultural lands, and peri-urban areas), including both wildfires (uncontrolled or unplanned fires in wildland vegetation) and human-planned fires (eg, prescribed burns or agricultural fires).[1] Landscape fires pose an increasing threat to both the environment and public health, intensified by climate change.[1,2] The flames and heat from landscape fires can kill people near the fire areas, with 221 direct deaths reported globally in 2018.[3] However, the health risks from landscape fires are much greater, as landscape fire-sourced (LFS) air pollution (particularly fine particulate matter with a diameter of

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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" on May 20, 2024. We included all available research articles in English or Chinese that evaluated the mortality burden from landscape fire-sourced (LFS) air pollution from database inception to date of search. Most existing studies only assessed the mortality burden attributable to LFS air pollution in high income and upper-middle income countries or regions, eg, Europe, the USA, Canada, Australia, Brazil, and China. We found only three studies assessing the global total all-cause mortality burden (ranging from 135 180 to 677 745 deaths per year in these studies) attributable to LFS particulate matter with a diameter of 2·5 μm or less ($PM_{2·5}$), with little information about the spatiotemporal variations of the burden. Furthermore, little was known about the mortality burden attributable to LFS ozone (O_3) and the global cause-specific (eg, cardiovascular and respiratory deaths) attributable mortality burdens.

Added value of this study

To the best of our knowledge, this is the largest and most comprehensive study of the global, regional, and national mortality burdens attributable to LFS air pollution (including both $PM_{2·5}$ and O_3). We used recent advances in this field—first, global daily LFS $PM_{2·5}$ and O_3 data, which have higher accuracy than raw chemical transport model outputs after being calibrated and validated against air quality station observations; and second, the best available evidence on exposure–response relationships. The exposure–response relationships for long-term mortality impact were from the latest published meta-analyses of cohort studies, and exposure–response relationships for short-term mortality impacts were 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 the period 2000 to 2019. Sub-Saharan Africa had the largest burden, accounting for nearly 40% of global total all-cause and respiratory attributable deaths. Southeast Asia, east Asia and eastern Europe bore the largest cardiovascular attributable deaths. Over 90% of attributable deaths were in low-income and middle-income countries, with highest burdens in China, India, the Democratic Republic of the Congo, Indonesia, and Nigeria. We observed an increasing trend in global cardiovascular attributable deaths, although the trends for all-cause and respiratory attributable deaths were not statistically significant. Central sub-Saharan Africa had the highest all-cause and respiratory attributable mortality rates (AMRs), while eastern Europe saw the highest cardiovascular AMRs. AMRs in low-income countries were over four times higher than in high-income countries, and country-specific AMRs 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 attributable cardiovascular deaths. As wildfires are increasingly frequent and severe in a warming climate, urgent action is required to address such substantial impact on climate-related mortality and associated environmental injustice

2·5 μm or less [$PM_{2·5}$] and ozone [O_3]) often travels hundreds and even thousands of kilometres away from the source and affects much larger populations than the flames and heat do.[2,4] At least 90% of global landscape fire emissions of $PM_{2·5}$ were likely contributed by wildfires, and this proportion could increase with climate change (appendix pp 18–19).

Numerous studies have documented both long-term (ie, years following exposure)[5,6] and short-term (ie, within a few days of exposure)[7,8] effects 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 were 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 due to increases in both global population and LFS $PM_{2·5}$ from 2000 to 2019.[9] 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 climate mitigation and adaptation actions.

Despite some regional estimates for Europe,[10,11] the USA,[12,13] Canada,[14] Australia,[15–18] Brazil,[19,20] and China,[21] only three studies estimated the global all-cause mortality burden from LFS air pollution during 1997–2006,[22] 2016–19,[23] and 2010–19,[24] 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 (eg, cardiorespiratory) mortality burdens. The two recent global studies used LFS $PM_{2·5}$ data from chemical transport model simulations, without calibrations against real observations at air quality stations, which have much lower accuracy than the calibrated estimates.[23,24] Additionally, existing studies[10–24] only considered either short-term or long-term impacts on mortality of LFS $PM_{2·5}$, which do not overlap (appendix pp 19–21). Few studies have considered both simultaneously.[22] No study has assessed the global

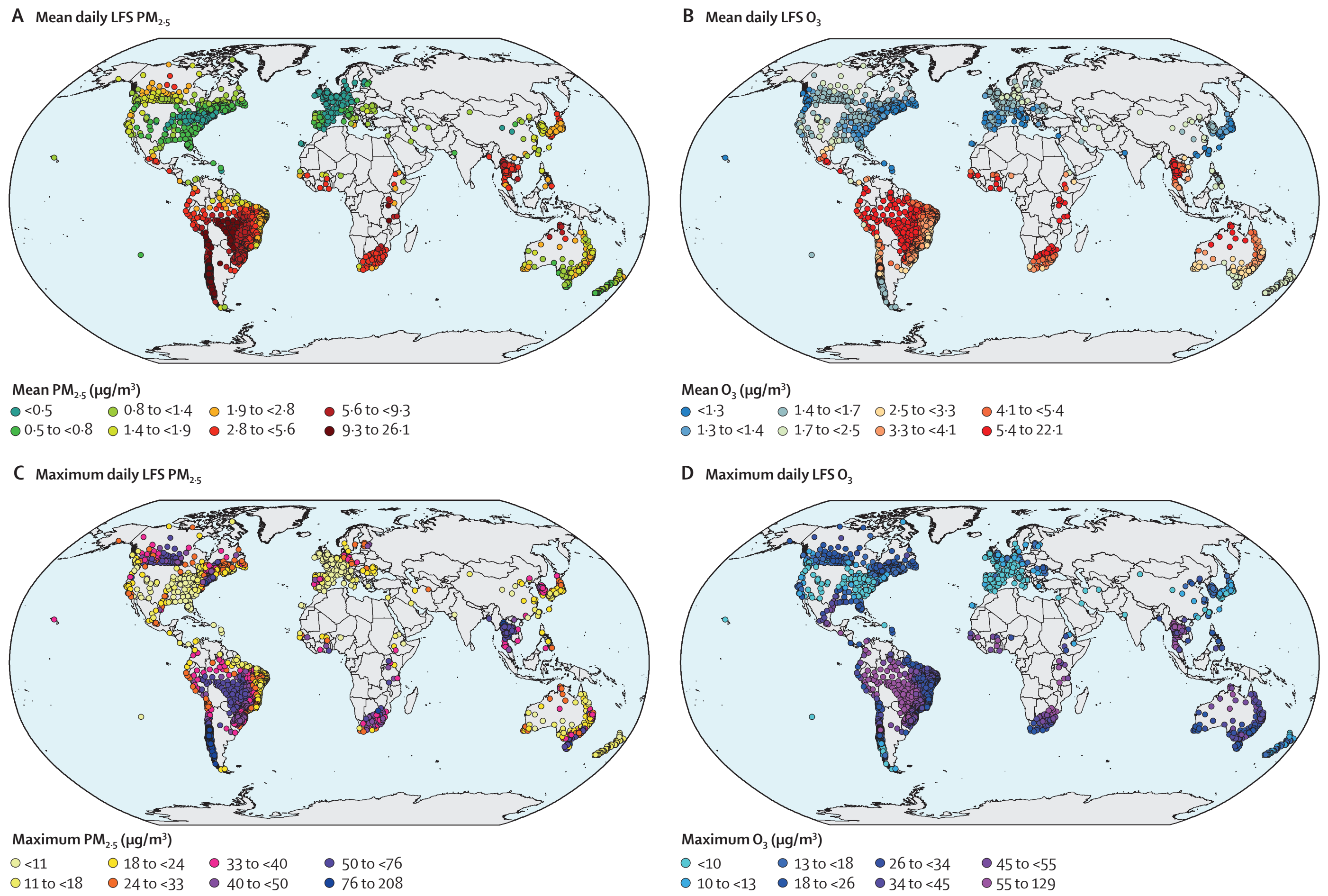

Figure 1: **Distribution of the 2267 communities used for time-series analyses and their mean (A,B) and maximum (C,D) daily LFS $PM_{2.5}$ and O_3 during the community-specific study periods**
LFS=landscape fire-sourced. $PM_{2.5}$=fine particulate matter with a diameter of 2·5 μm or less. O_3=ozone.

mortality burden from LFS O_3 that is also associated with significant mortality risks.[7] Most existing studies only estimated the all-cause mortality burden,[10–24] 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,[9] and multicountry exposure–response relationships,[7,8] we aimed to address those research gaps and perform an accurate and comprehensive estimation of the global mortality burdens attributable to LFS air pollution (both $PM_{2.5}$ and O_3) over two consecutive decades (2000–19), including their spatial and temporal variations and socioeconomic disparities.

Methods

Study design and data collection

This study is reported following the STROBE Statement (appendix pp 27–29). The study was approved by Monash University Human Research Ethics Committee (approval number 27582).

For mortality and socio-demographic data, we collected daily all-cause (or non-external cause), cardiovascular, and respiratory death count data from 2267 communities (appendix p 30) in 59 countries or territories across six continents (figure 1, appendix pp 30–32). These 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.[9]

We collected annual all-cause, cardiovascular and respiratory mortality data, and annual Socio-Demographic Index (SDI) and population data for each of 204 countries and territories during 2000–19 from the Global Burden of Diseases Study 2019 (GBD 2019).[25–27] These countries and territories were classified as four income groups (low income, lower-middle income, upper-middle income, and high income), and seven GBD super regions that can be further divided into 21 GBD regions.[26]

For exposure data, we estimated LFS daily average $PM_{2.5}$ and daily maximum 8 h average surface O_3 (henceforth daily LFS $PM_{2.5}$ and daily LFS O_3,

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See Online for appendix

For the **GEOS-Chem v.12·0.0** see https://zenodo.org/records/1343547

For the **Global Fire Emissions Database** see https://www.geo.vu.nl/~gwerf/GFED/GFED4/

respectively) at a 0·25°×0·25° (about 28 km×28 km at the equator) spatial resolution from Jan 1, 2000, to Dec 31, 2019, across the globe using machine learning and chemical transport models (GEOS-Chem v.12·0.0, with the Global Fire Emissions Database v.4.1s as our fire emission inventory). Details of the estimation process and validations against monitoring station observations, large wildfire events, and an independent data source (Child and colleagues)[28] have been published previously.[9] 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. After calibration, the R^2 in ten-fold spatial cross-validations against station observations improved from 0·48 to 0·89 for daily $PM_{2·5}$ and from 0·47 to 0·80 for daily O_3; the agreements of our daily LFS $PM_{2·5}$ with the smoke $PM_{2·5}$ estimated by Childs et al,[28] represented by Pearson correlation coefficients, improved from 0·48 to 0·88. Furthermore, our estimated daily $PM_{2·5}$ 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 (overall R^2 0·64 and 0·78 for $PM_{2·5}$ and O_3, respectively).

For each of the 2267 communities we calculated population-weighted average daily LFS $PM_{2·5}$, LFS O_3, ambient temperature, and relative humidity. We also calculated population-weighted average LFS $PM_{2·5}$ and O_3 at both daily and yearly timescales for each country or territory. Additional details of data collection are provided in the appendix (pp 4–7).

Statistical analyses

We quantified the exposure–response relationships for the short-term mortality impacts of LFS $PM_{2·5}$ and O_3 using a two-stage time-series analytical framework,[7,8] detailed in the appendix (pp 7–12). Briefly, 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 $PM_{2·5}$ or LFS O_3 separately, using single-pollutant models, and adjusting for temperature, relative humidity, long-term trends, seasonal variations, day of the week, and public holiday.

In the second stage, we pooled the community-specific effect estimates for all communities, using a random-effect meta-analysis with maximum likelihood estimation.[29] Our analyses showed that exposure–response relationships for the short-term mortality impacts of LFS $PM_{2·5}$ and O_3 were linear (appendix p 33). Both the interaction effects between LFS $PM_{2·5}$ and O_3 (appendix p 33), and the residual confounding of our main models (appendix p 34) were not statistically significant. The final global short-term exposure–response relationships were presented as cumulative relative risks (RRs) with 95% CIs of all-cause deaths (or cardiovascular or respiratory deaths) over 0–2 days following exposure to each 10 μg/m³ increase in daily LFS $PM_{2·5}$ (or LFS O_3; appendix p 34), and the country-specific or territory-specific effect estimates were presented (appendix pp 35–37).

These overall effect estimates of LFS $PM_{2·5}$ and O_3 were generally higher than those of all-source and non-fire $PM_{2·5}$ and O_3 (appendix pp 10–11, 37–38), and they did not change significantly in non-fire adjustment models (appendix pp 11–12, 39–41) and the two-pollutant models (appendix pp 12–13, 42–43).

Due to the scant 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,[30,31] the exposure–response 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.[5,6] These exposure–response relationships were expressed linearly, as supported by the majority of cohort studies included in the systematic reviews.[5,6] They were presented as pooled RRs (95% CI) of all-cause, cardiovascular, and respiratory mortality for each 10 μg/m³ in annual average $PM_{2·5}$ and O_3, estimated by random-effect meta-analyses of 15 to 25 cohort studies (appendix p 44). In the systematic review for $PM_{2·5}$, the pooled RR did not change (but the 95% CI became wider) when only pooling cohort studies with adjustment for O_3.[5] In the systematic review for O_3, over half of the included cohort studies already adjusted for $PM_{2·5}$, and there was no significant difference between pooled RRs with or without adjustment for $PM_{2·5}$.[6] Therefore, it is reasonable to consider our estimated long-term mortality burden attributable to $PM_{2·5}$ and O_3 as distinct and non-overlapping.

To estimate mortality burden 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:

$$AD_{iy} = AD\_short\_PM_{iy} + AD\_short\_O3_{iy} + AD\_long\_PM_{iy} + AD\_long\_O3_{iy}$$

$$AD\_long\_PM_{iy} = \sum_{t=1}^{day_y} \frac{death_{iy}}{day_y} \times (1 - RR_{short\_PM}^{-(PWC\_PM_{iyt} \div 10)})$$

$$AD\_long\_O3_{iy} = \sum_{t=1}^{day_y} \frac{death_{iy}}{day_y} \times (1 - RR_{short\_O3}^{-(PWC\_O3_{iyt} \div 10)})$$

$$AD\_long\_PM_{iy} = \sum Death_{iy} \times (1 - RR_{long\_PM}^{-(PWC\_PM_{iy} \div 10)})$$

$$AD\_long\_O3_{iy} = \sum Death_{iy} \times (1 - RR_{long\_O3}^{-(PWC\_O3_{iy} \div 10)})$$

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 estimate (appendix pp 34, 44). $Day_{\_y}$ was the number of days (ie, 365 or 366) in year y. $Death_{\_iy}$ was the annual number of all-cause deaths from GBD 2019 in country or territory i in year y. In equations (2) and (3), we assumed the daily death number was the average daily deaths due to unavailability of country-specific daily death data. $PWC\_PM_{\_iyt}$ and $PWC\_O3_{\_iyt}$ 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. $PWC\_PM_{\_iy}$ and $PWC\_O3_{\_iy}$ were population-weighted average annual LFS $PM_{2·5}$ and O_3, respectively.

To quantify uncertainty (95% empirical CIs [95% eCIs]) of the attributable death estimates, we used a Monte-Carlo simulation for 1000 iterations, assuming normal distributions of the annual death counts and log(RR) (ie, β values in the appendix pp 34, 44). The country-year-specific attributable fractions and attributable mortality rates (AMRs), along with their 95% eCIs, were then calculated by dividing attributable death and its 95% eCI with annual deaths and population size, respectively.

The same equations and processes were used to calculate attributable deaths, attributable fractions, and AMRs for cardiovascular and respiratory deaths. We conducted three sensitivity analyses by using alternative exposure–response relationships in the mortality burden assessment (appendix pp 13–16), including using short-term exposure–response relationships from the two-pollutant models and non-fire adjustment models (appendix p 13), and using hypothetical long-term exposure–response relationships assuming enhanced long-term mortality impacts of LFS $PM_{2·5}$ and O_3 compared with all-source $PM_{2·5}$ and O_3 (appendix pp 13, 45). We also tested the potential bias caused by using average daily deaths in the short-term mortality burden assessment based on time-series data of 2267 communities (appendix p 14).

In descriptive analyses we presented the estimated mortality burdens at the global scale, and by GBD super regions, GBD regions, country or territory, and income and socio-demographic index groups. The long-term trends of each metric (attributable deaths, attributable fractions, and AMR) and their contributors (population, mortality rates, and LFS $PM_{2·5}$ and O_3) were tested using linear regressions, with the log-transformed annual metrics during 2000–19 as the dependent variable and year as the only predictor. GBD 2019 mortality data included 204 countries and territories. Three island countries or territories (the Marshall Islands, Tokelau, and Tuvalu, total population 70 050 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. Associations of country-level or territory-level AMR with socio-demographic index were quantified as Spearman correlation coefficients.

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 statistically significant.

Role of the funding source

The funders of the study did not play any role in the data collection, analyses, interpretation, writing of the manuscript, and the decision to submit for publication.

Results

Globally, 1·53 million all-cause deaths (95% eCI 1·24–1·82), 0·45 million cardiovascular deaths (0·32–0·57), and 0·22 million respiratory deaths (0·08–0·35) per year were attributable to LFS air pollution during 2000–19 (table). These deaths attributable to LFS air pollution represented 2·90% (95% eCI 2·35–3·44), 2·80% (2·04–3·56), and 3·48% (1·35–5·56) of global annual all-cause, cardiovascular and respiratory deaths, respectively (appendix pp 46–47). The corresponding annual average AMRs per 100 000 residents were 22·08 (95% eCI 17·88–26·24), 6·43 (4·67–8·17) and 3·12 (1·21–4·97) for all-cause, cardiovascular and respiratory deaths, respectively (appendix pp 48–49).

Among the 1·53 million all-cause attributable deaths per year, LFS $PM_{2·5}$ and O_3 contributed to 77·6% and 22·4% of the total attributable deaths, respectively; 66·2% and 7·2% were caused by the long-term mortality impacts of LFS $PM_{2·5}$ and O_3, respectively; and 11·4% and 15·2% were caused by the short-term mortality impacts of LFS $PM_{2·5}$ and O_3, respectively (appendix p 50); these proportions remained stable over the two decades (appendix p 51).

Cardiovascular attributable deaths saw an increasing trend over the two decades, with a 1·67% increase per year ($p_{trend}<0·001$), driven by the rising global population, cardiovascular mortality rates, and LFS $PM_{2·5}$ (appendix pp 52–53). However, all-cause deaths and respiratory attributable deaths did not show significant trends, because the all-cause and respiratory mortality rates decreased, thus cancelling the contribution of the increasing global population and LFS $PM_{2·5}$.

There were spatiotemporal variations in the attributable mortality burden. Among the seven GBD super regions, sub-Saharan Africa had the largest all-cause and respiratory attributable deaths (almost 40% of the global total), while the super region of southeast Asia, east Asia, and Oceania had the largest cardiovascular attributable deaths (approximately a third of the global total; figure 2A–C). Among the 21 GBD regions, eastern sub-Saharan Africa had the largest all-cause attributable deaths (212 968 attributable deaths per year), followed by southeast Asia (206 817) and central sub-Saharan Africa (173 838; table, figure 2D). Southeast Asia had the largest cardiovascular attributable deaths (78 132 attributable deaths per year), followed by east Asia (70 570) and eastern Europe (51 324; figure 2E). The region with the largest respiratory attributable deaths was south Asia (33 218 attributable deaths per

	All-cause death		Cardiovascular death		Respiratory death	
	Annual AD (95% eCI)	Change per year (%)	Annual AD (95% eCI)	Change per year (%)	Annual AD (95% eCI)	Change per year (%)
Global	1 532 540* (1 240 832–1 821 326)	–0·08%	446 093 (324 251–567 224)	1·67%†	216 318 (84 080–345 251)	–0·17%
GBD super regions and regions†						
Central Europe, eastern Europe, and central Asia ‡	99 118 (80 511–117 543)	–1·28%§	68 490 (49 895–86 950)	–1·36%§	5821 (2223–9367)	–1·92%¶
Central Asia||	12 821 (10 399–15 229)	–0·11%	7921 (5767–10 062)	–0·10%	1274 (482–2056)	–1·23%
Central Europe||	14 410 (11 721–17 083)	0·23%	9245 (6736–11 745)	–0·09%	922 (376–1464)	0·27%
Eastern Europe||	71 886 (58 392–85 231)	–1·84%§	51 324 (37 392–65 143)	–1·82%§	3626 (1365–5847)	–2·78%†
GBD high-income‡	132 867 (108 253–157 160)	0·59%	49 919 (36 365–63 392)	–0·07%	18 376 (7076–29 381)	1·15%¶
Australasia||	3811 (3110–4506)	0·41%	1532 (1115–1949)	–0·94%	408 (166–647)	1·09%
High-income Asia–Pacific||	36 668 (29 764–43 489)	0·05%	12 380 (8976–15 760)	–0·64%	5355 (1926–8717)	0·56%
High-income North America||	27 738 (22 605–32 818)	3·14%†	11 246 (8190–14 304)	2·24%¶	3470 (1397–5533)	3·60%†
Southern Latin America||	39 766 (32 378–47 022)	–0·85%¶	14 461 (10 567–18 281)	–1·45%†	6418 (2343–10 278)	0·23%
Western Europe||	24 883 (20 396–29 325)	0·94%	10 300 (7516–13 097)	0·15%	2725 (1244–4206)	1·47%§
Latin America and the Caribbean‡	121 562 (98 785–144 161)	1·31%¶	36 622 (26 677–46 508)	1·57%¶	16 327 (6503–25 905)	1·41%¶
Andean Latin America||	19 123 (15 397–22 814)	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||	40 014 (32 537–47 446)	2·95%†	11 025 (8031–14 013)	3·84%†	4574 (1903–7204)	2·58%†
Tropical Latin America||	58 883 (47 991–69 680)	0·09%	20 045 (14 630–25 410)	0·02%	7860 (3071–12 527)	0·81%
North Africa and the Middle East‡	43 805 (35 252–52 330)	1·77%†	19 661 (14 223–25 102)	3·07%†	4569 (1706–7419)	0·48%
South Asia‡	170 762 (138 286–203 074)	1·23%§	48 218 (34 998–61 402)	3·70%†	33 218 (12 452–53 794)	1·57%¶
Southeast Asia, east Asia, and Oceania‡	357 656 (289 162–425 598)	1·70%§	149 629 (108 801–190 220)	3·17%†	56 395 (21 524–90 566)	0·12%
East Asia||	147 291 (119 142–175 297)	0·86%	70 570 (51 299–89 812)	2·22%§	26 524 (10 356–42 558)	–1·59%§
Oceania||	3548 (2818–4274)	2·71%†	927 (666–1190)	3·85%†	867 (318–1402)	1·98%†
Southeast Asia||	206 817 (167 202–246 028)	2·30%§	78 132 (56 836–99 218)	4·03%†	29 005 (10 850–46 605)	1·63%
Sub-Saharan Africa‡	606 769 (490 583–721 460)	–1·88%†	73 553 (53 292–93 651)	1·07%†	81 612 (32 596–128 819)	–1·65%†
Central sub-Saharan Africa||	173 838 (140 725–206 342)	–1·42%†	22 709 (16 516–28 786)	1·65%†	23 911 (9279–37 581)	–1·73%†
Eastern sub-Saharan Africa||	212 968 (172 243–253 155)	–2·49%†	24 630 (17 864–31 332)	1·34%†	26 418 (10 362–41 900)	–1·97%†
Southern sub-Saharan Africa||	52 599 (42 423–62 685)	–3·90%†	7501 (5458–9526)	–1·36%§	5776 (2261–9177)	–2·50%†
Western sub-Saharan Africa||	167 364 (135 192–199 279)	–0·99%¶	18 713 (13 454–24 006)	0·97%¶	25 507 (10 694–40 161)	–1·08%†
World Bank income groups*						
Low income	374 059 (302 325–444 791)	–1·52%†	49 507 (35 891–62 990)	1·64%†	51 637 (20 208–81 816)	–1·24%†
Lower-middle income	602 901 (487 629–717 179)	0·29%	163 592 (118 761–208 174)	3·11%†	90 785 (35 107–145 251)	0·18%
Upper-middle income	438 116 (355 185–520 369)	0·34%	187 754 (136 663–238 551)	0·72%	59 393 (23 073–95 017)	–0·17%
High income	117 462 (95 692–138 986)	1·08%§	45 239 (32 935–57 508)	0·42%	14 502 (5692–23 166)	1·49%¶
Institute for Health Metrics and Evaluation SDI levels						
Low SDI	653 002 (527 665–776 824)	–1·60%†	94 920 (68 730–120 924)	1·40%†	93 198 (36 638–147 819)	–1·52%†
Low-middle SDI	433 391 (351 184–514 971)	1·79%†	146 092 (106 255–185 687)	3·54%†	64 257 (24 670–103 105)	1·78%†
Middle SDI	252 461 (204 387–300 157)	0·50%	104 651 (76 125–133 048)	1·59%§	40 592 (15 659–65 080)	–0·61%
High-middle SDI	108 806 (88 436–128 947)	–0·94%	68 858 (50 168–87 404)	–1·27%§	7128 (2718–11 432)	–0·94%§
High SDI	84 880 (69 160–100 427)	1·24%§	31 571 (22 972–40 162)	0·52%	11 143 (4395–17 814)	1·68%¶

AD=attributable deaths. eCI=empirical confidence interval. SDI=Socio-Demographic Index. *Two island countries (Cook Islands and Niue, with an estimated two attributable deaths per year) were not classified as any one of the World Bank income groups, thus they were excluded in the analyses by income group. †p_{trend} <0·001. ‡GBD super regions. §p_{trend} <0·05. ¶p_{trend} <0·01. ||GBD regions.

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

year), followed by southeast Asia (29 005), and east Asia (26 524; figure 2F).

For all-cause attributable deaths, eastern Europe, southern Latin America, and all the four sub-Saharan African regions all showed a decreasing trend (range –3·90% to –0·85% per year, $p_{trend}<0·05$). The regions and super regions of high-income North America, Andean and central Latin America, north Africa and the Middle East, south Asia, Oceania, and southeast Asia saw significant increasing trends (range 1·23% to 3·14% per year; all $p_{trend}<0·05$). The trends for cardiovascular and respiratory attributable deaths were generally consistent with the trends of all-cause attributable deaths, with only three notable differences. First, all sub-Saharan African regions except for southern sub-Saharan Africa saw increasing trends of cardiovascular attributable deaths (range 0·97% [p<0·01] to 1·65% [p<0·001] per year in western to central sub-Saharan Africa); second, east Asia saw an increasing trend of cardiovascular attributable deaths (2·22% per year, p<0·05) versus decreasing respiratory attributable deaths (–1·59% per year, p<0·05), despite a non-significant trend of all-cause attributable deaths; and third, in southeast Asia, the increasing trend of cardiovascular attributable deaths was much more significant and larger than the trend for all-cause attributable deaths (4·03% [p<0·001] *vs* 2·30% [p<0·05] per year), while the trend of respiratory attributable deaths was non-significant.

The notable increases of all-cause, cardiovascular, and respiratory attributable deaths from 2013 to 2014 were mainly driven by substantial increases in LFS $PM_{2·5}$ and O_3, particularly in Asian regions, eastern Europe, and northern South America (appendix pp 54–56). This can be explained by the 2014–16 El Niño event, which has been the strongest El Niño event since 1950.[32] El Niño

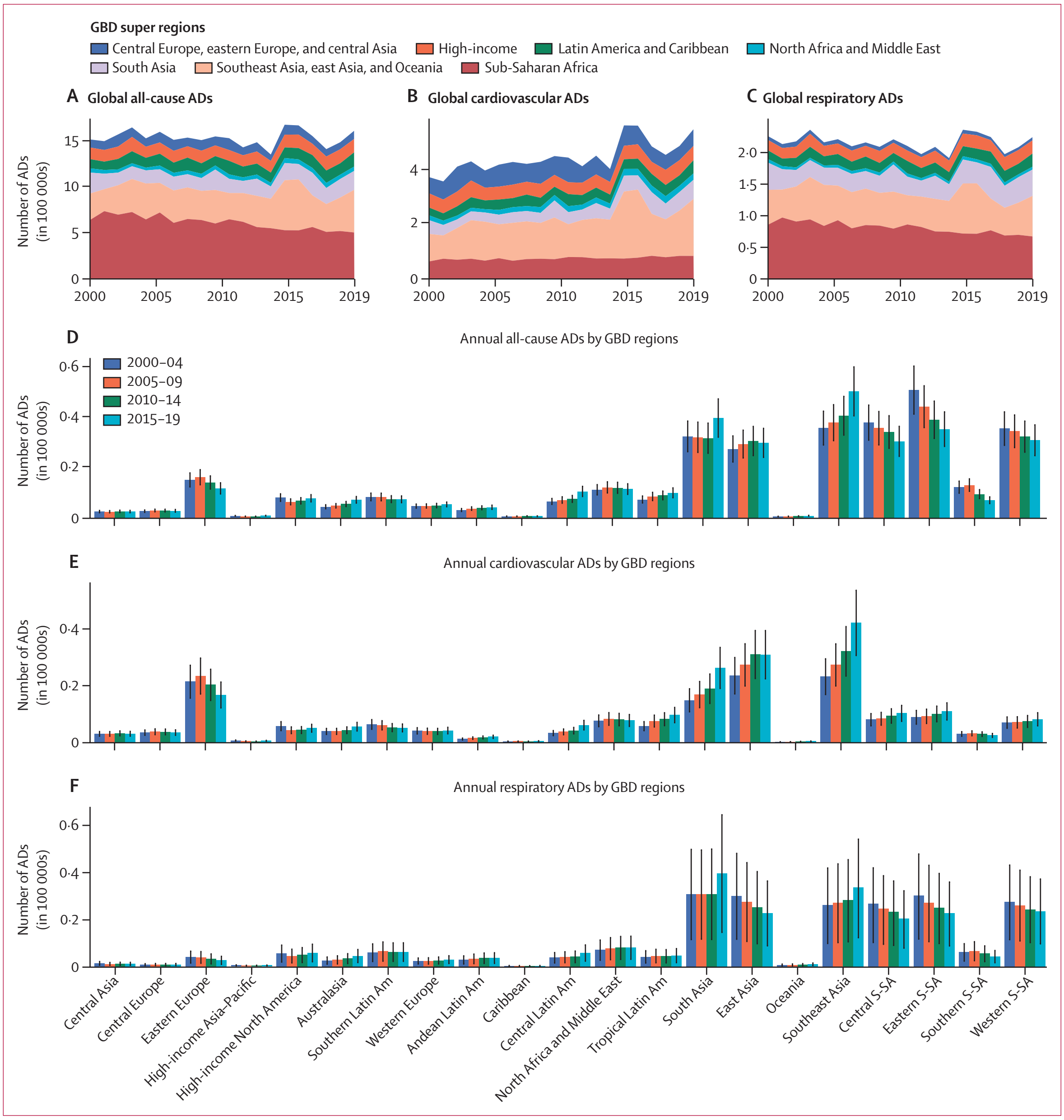

Figure 2: **Global and regional trends of annual ADs attributable to exposure to landscape fire-sourced air pollution from 2000 to 2019**
In panels A–C, the scale for the number of ADs changes by panel. Error bars in panels D–F represent the 95% empirical confidence intervals. ADs=annual deaths. GBD=Global Burden of Diseases study. Latin Am=Latin America not including the Caribbean. S-SA=sub-Saharan Africa.

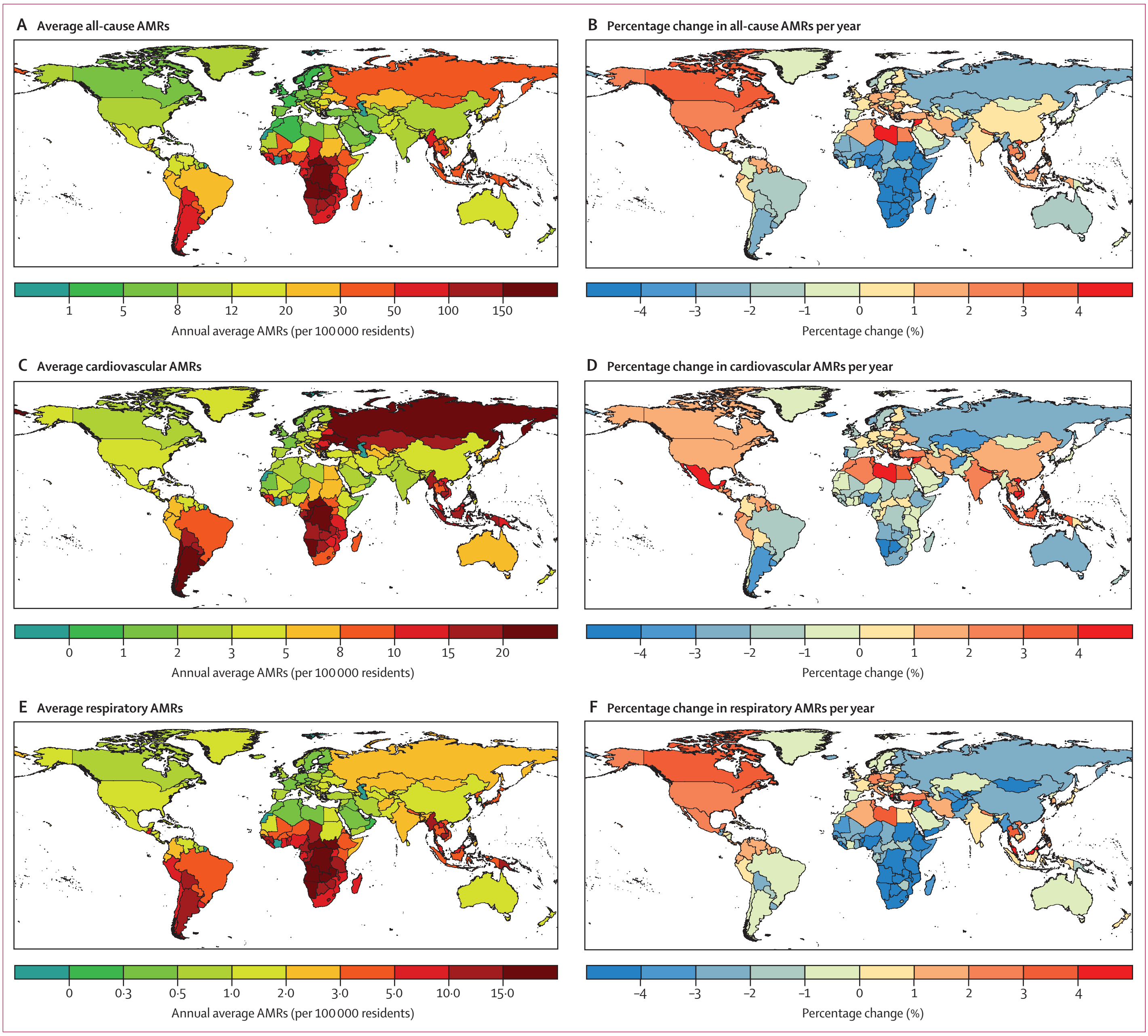

Figure 3: **Annual average AMRs attributable to fire-sourced air pollution and corresponding trends for 201 countries and territories from 2000 to 2019**
All-cause AMRs (A) and percentage change (B). Cardiovascular AMRs (C) and percentage change (D). Respiratory AMRs (E) and percentage change (F). For each country or territory, percentage change per year was estimated based on a linear regression model considering a Gaussian distribution on the log scale. AMRs=attributable mortality rates.

events can increase wildfires significantly in areas mentioned above by inducing more extreme hot and dry weather.[33]

Central sub-Saharan Africa had the highest all-cause AMR, followed by southern and eastern sub-Saharan Africa, and southern Latin America (figure 3A, appendix pp 46–49). The highest respiratory AMRs were also seen in central Sub-Saharan Africa, followed by southern Latin America and some countries in southeast Asia and Oceania. However, the highest cardiovascular AMR was in eastern Europe, followed by southern Latin America and some countries in central sub-Saharan Africa and southeast Asia. These highest-AMR regions also had the highest LFS $PM_{2·5}$ and O_3 exposure over 2000 to 2019 (appendix p 57). Although they generally showed decreasing trends of AMR from 2000 to 2019, they remained high-AMR regions during 2010–19.

North America, central America, and countries surrounding the Mediterranean showed increasing trends of all-cause, cardiovascular, and respiratory

Figure 4: **Annual ADs and AMRs attributable to landscape fire-sourced air pollution from 2000 to 2019 by World Bank income group**
The shaded area in panels D–F represents the 95% empirical confidence interval of the AMR estimates. ADs=attributable deaths. AMRs=attributable mortality rates. LMIC=low-income and middle-income countries.

AMRs. Most countries in southeast Asia and south Asia were characterised by increasing cardiovascular AMRs, but non-significant trends of respiratory AMRs. Most countries in east Asia saw increasing cardiovascular AMRs but decreasing respiratory AMRs (figure 3B, D, F).

There were also global socioeconomic disparities in attributable mortality burdens. Overall, approximately 90% of global all-cause, cardiovascular, and respiratory attributable deaths were in World Bank low-income and middle-income countries (LMICs) during 2000–19 (1415 076 [92·3%] of 1532 540, 400 853 [89·9%] of 446 093, and 201 815 [93·3%] of 216 318, respectively; table, figure 4A–C). The proportions of all-cause and respiratory attributable deaths in LMICs showed decreasing trends over the two decades but remained over 90% in 2019 (figure 4G). In contrast, the proportions of cardiovascular attributable deaths in LMICs increased from 87·8% in 2000 to 90·7% in 2019. The attributable fractions and AMRs generally decreased, although not linearly, with the increase in income groups over 2000–19 (figure 4D–F, appendix pp 48–49). Overall, the all-cause, cardiovascular, and respiratory AMRs in low-income countries were 6·2 times, 2·1 times, and 7·0 times those in high-income countries, respectively. The low-income versus high-income countries ratios for all-cause and respiratory AMRs declined substantially over 2000–19 but remained approximately four times by 2019, while the cardiovascular AMRs in low-income countries stayed around two times as high as those in high-income countries over the two decades (figure 4H, appendix p 49).

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

A Annual attributable deaths

Leading countries 2000–09	Attributable deaths (95% eCI)
1 China	136 288 (110 539–161 957)
2 Democratic Republic of the Congo	128 409 (104 503–151 675)
3 India	117 781 (95 618–139 855)
4 Indonesia	84 443 (68 570–100 181)
5 Nigeria	82 151 (66 659–97 416)
6 Russia	62 182 (50 540–73 687)
7 Brazil	56 063 (45 709–66 325)
8 Tanzania	41 746 (33 865–49 472)
9 Angola	37 550 (30 508–44 439)
10 South Africa	33 752 (27 269–40 191)
13 Japan	30 521 (24 757–36 210)
24 Viet Nam	18 562 (14 987–22 094)

Leading countries 2010–19	Attributable deaths (95% eCI)	Change per year (%)
1 China	145 692 (117 669–173 525)	0·9
2 India	137 711 (111 527–163 756)	1·7*
3 Democratic Republic of the Congo	113 242 (91 474–134 727)	–1·4†
4 Indonesia	106 069 (85 788–126 097)	2·5
5 Nigeria	70 104 (56 571–83 568)	–1·5†
6 Brazil	56 428 (46 002–66 770)	0·1
7 Russia	50 104 (40 661–59 441)	–2·3‡
8 Tanzania	33 832 (27 357–40 232)	–2·1†
9 Japan	30 306 (24 593–35 953)	–0·1
10 Viet Nam	29 782 (24 024–35 482)	4·6†
11 Angola	29 256% (23 529–34 917)	–2·4
17 South Africa	23 699% (19 232–28 127)	–3·2

B Annual attributable fractions, %

Leading countries 2000–09	Attributable fraction (95% eCI)
1 Democratic Republic of the Congo	18·66 (15·18–22·04)
2 Angola	18·58 (15·10–21·99)
3 Zambia	17·14 (13·93–20·28)
4 Central African Republic	15·93 (12·81–19·01)
5 Namibia	14·96 (12·09–17·79)
6 Congo (Brazzaville)	14·94 (12·11–17·76)
7 Burundi	13·80 (11·19–16·36)
8 Rwanda	12·81 (10·41–15·16)
9 Chile	12·65 (10·31–14·94)
10 Bolivia	12·03 (9·74–14·28)
14 South Sudan	10·58 (8·49–12·66)
15 Gabon	10·52 (8·49–12·55)

Leading countries 2010–19	Attributable fraction (95% eCI)	Change per year (%)
1 Democratic Republic of the Congo	18·40 (14·86–21·89)	–0·3%
2 Central African Republic	16·95 (13·50–20·35)	0·5%
3 Congo (Brazzaville)	15·93 (12·77–19·06)	0·5%*
4 Angola	15·61 (12·56–18·64)	–1·7%†
5 Zambia	13·65 (11·03–16·22)	–2·3†
6 Burundi	13·00 (10·37–15·62)	–0·8%‡
7 Rwanda	12·23 (9·88–14·56)	–0·7%
8 Gabon	11·44 (9·20–13·68)	0·6%*
9 South Sudan	11·31 (9·04–13·56)	0·6%
10 Chile	11·27 (9·18–13·32)	–0·9%‡
11 Bolivia	11·15 (8·96–13·32)	–0·7%
13 Namibia	10·54 (8·45–12·62)	–3·7%†

C Annual AMRs per 100 000

Leading countries 2000–09	AMR (95% eCI)
1 Central African Republic	283·19 (227·77–338·03)
2 Zambia	240·25 (195·22–284·21)
3 Democratic Republic of the Congo	219·59 (178·71–259·38)
4 Angola	212·16 (172·37–251·09)
5 Burundi	187·93 (152·40–222·86)
6 Namibia	180·35 (145·78–214·46)
7 Malawi	169·54 (137·38–201·22)
8 Zimbabwe	166·64 (133·62–199·32)
9 Congo (Brazzaville)	159·98 (129·61–190·16)
10 Botswana	156·00 (124·36–187·34)
14 South Sudan	109·68 (87·97–131·26)
17 Gabon	99·36 (80·18–118·51)

Leading countries 2010–19	AMR (95% eCI)	Change per year (%)
1 Central African Republic	249·72 (198·89–299·90)	–1·4%†
2 Democratic Republic of the Congo	145·25 (117·33–172·81)	–4·2%†
3 Congo (Brazzaville)	121·13 (97·11–144·93)	–2·9%†
4 Angola	112·92 (90·81–134·77)	–6·0%†
5 Zambia	108·52 (87·75–129·02)	–7·5%†
6 Burundi	105·08 (83·78–126·19)	–5·9%†
7 South Sudan	99·71 (79·69–119·59)	–1·1%*
8 Namibia	88·68 (71·06–106·13)	–6·8%†
9 Zimbabwe	87·56 (70·75–104·18)	–6·0%†
10 Gabon	83·99 (67·50–100·43)	–1·8%†
11 Malawi	81·36% (65·78–96·75)	–6·9†
23 Botswana	65·47% (52·05–78·79)	–8·8†

***Figure 5:* Top ten countries or territories with greatest total all-cause deaths (A), fractions of all-cause deaths (B), and AMRs (C) attributable to landscape fire-sourced air pollution during the first and second decades of 2000–19**

AMRs=all-cause mortality rates. *p_{trend}<0·05. †p_{trend}<0·001. ‡p_{trend} <0·01.

The socioeconomic disparities were further characterised by negative correlations between country-specific or territory-specific AMRs and SDI (appendix p 58). The correlations with SDI were stronger for all-cause and respiratory AMRs (Spearman correlation coefficients *r* around 0·60 and 0·65, respectively) than for cardiovascular AMRs (*r*=0·33). The disparities in all-cause and respiratory AMRs by SDI slightly narrowed from 2000–09 to 2010–19, as evidenced by the slightly flattened slopes and decreased *r*.

The five countries with the largest all-cause attributable deaths were China, the Democratic Republic of the Congo, India, Indonesia, and Nigeria. This list stayed the same from the 2000–09 period to the 2010–19 period, despite changes in order (ie, India replaced the Democratic Republic of the Congo as having the second highest burden; figure 5A). In 2000–19, the top ten countries with highest attributable deaths accounted for over half (773 270 [50·9%] of 15 194 383) of the global total attributable deaths per year during the decade. Japan was the only high-income country in this top ten list. India and Viet Nam experienced significant increases in attributable deaths (1.7% [p_{trend}<0.05] and 4.6% [p_{trend}<0.001] per year over 2000–19, respectively). In contrast, the Democratic Republic of the Congo, Nigeria, Russia, Tanzania, Angola, and South Africa all had statistically significant decreases in attributable deaths (–1·4% to –3·2% per year).

The top ten countries in attributable fractions were dominated by sub-Saharan African countries with only two exceptions (Chile and Bolivia, both in South America; figure 5B). In those countries, over 10% of the deaths were attributable to LFS air pollution. The highest attributable fraction was in the Democratic Republic of the Congo (>18% in both 2000–09 and 2010–19).

The countries with the highest AMRs were all in sub-Saharan Africa (figure 5C), although all ten had statistically significant decreases in AMRs (–1·1% to –8·8% per year, all p_{trend}<0.001 except for South Sudan [p_{trend}<0.05]). The highest AMR was observed in the Central African Republic (249·72 per 100 000 [95% eCI 198·89–299·90]). Of the countries with highest all-cause attributable deaths, attributable fractions, and AMRs, all were LMICs with the exception of Japan and Chile.

The countries with the highest cardiovascular and respiratory attributable fractions, and AMRs, shared similar positions to those for all-cause deaths (appendix pp 59–60). However, there were several notable differences in the lists for attributable deaths and AMRs. Compared with the top ten countries with the largest all-cause attributable deaths, Argentina and Myanmar replaced Russia and Viet Nam for the largest burden of respiratory attributable deaths, and the USA and Ukraine replaced Tanzania and Nigeria for the largest burden of cardiovascular attributable deaths. Cardiovascular attributable deaths in the USA saw a notable increase (2·2% per year, p_{trend}<0·01). China, Viet Nam, India, and Indonesia also saw substantial and significant increases (1·7% to 5·2% per year; all p_{trend}<0·05) in cardiovascular attributable deaths. The countries with the highest respiratory AMRs were still all Sub-Saharan African countries. However, countries in eastern Europe (Russia, Ukraine, and Bulgaria), South America (Argentina, Chile, and Uruguay) and southeast Asia (Cambodia) entered the top ten countries for cardiovascular AMRs. Cambodia had a substantial increase in cardiovascular AMR from 2000–19 (4·5% per year, p_{trend}<0·001).

The main drivers of the long-term trends of attributable deaths vary by country (appendix p 61). For example, the increasing trends of all-cause, cardiovascular, and respiratory attributable deaths in North American and north African countries were mainly driven by increasing LFS $PM_{2·5}$, while the increasing trends of cardiovascular attributable deaths in sub-Saharan Africa were predominantly driven by population growth (despite decreasing mortality rates and LFS air pollution).

As detailed the appendix (pp 13–15) our results are robust against three sensitivity analyses, evidenced by the largely overlapping 95% eCIs and unchanged overall trends of the attributable deaths estimates (appendix pp 62–63). Compared with our main analyses, the estimated global attributable deaths decreased slightly in the first sensitivity analysis (global annual all-cause attributable deaths 1·50 million per year [95% eCI 1·19–1·81]) and second sensitivity analysis (1·44 million per year [1·14–1·74]), but increased in the third sensitivity analysis (1·85 million per year [1·40–2·29]). However, the spatial and temporal variations of the attributable death estimates across the 201 included countries and territories did not change in these sensitivity analyses (appendix pp 64–66).

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 provides insights into the distribution and temporal trends of mortality attributable to LFS. The mortality burden was not evenly distributed; sub-Saharan Africa had the largest global total all-cause and respiratory attributable deaths, bearing almost 40% of the total burden. Southeast Asia, east Asia, and eastern Europe bore the largest cardiovascular attributable deaths. Overall, there was an increasing trend in global cardiovascular attributable deaths, mainly driven by increasing trends in sub-Saharan Africa, east Asia, south Asia, southeast Asia, and the USA. Central sub-Saharan Africa had the highest all-cause and respiratory AMRs, while eastern Europe saw the highest cardiovascular AMR. While these regions with high AMRs showed a decreasing trend in mortality rates over the two decades, they still had high AMRs in 2019. Mediterranean countries and north and central America showed increasing trends of all-cause, cardiovascular, and respiratory AMRs. Southeast Asia, south Asia, and east Asia also saw increasing cardiovascular AMRs. Over 90% of the attributable deaths occurred in LMICs, including the five leading countries (China, India, Democratic Republic of the Congo, Indonesia, and Nigeria). Despite trends narrowing over the two decades, socioeconomic disparity in the mortality burden remained substantial.

Overall, despite international variations, our data suggest that LFS air pollution is an increasing risk factor for global mortality burden, particularly for cardiovascular deaths. This increase will probably continue over the next decades, as robust studies suggest that climate change will keep increasing the frequency and intensity of wildfires.[1,2,4]

The health impact of increasing LFS air pollution could be mitigated through implementing effective and evidence-based fire management, and careful planning and design of natural and urban landscapes.[4] Immediate climate actions to limit the magnitude of climate change are also crucial. A modelling study suggests that from 60% to 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 temperature, respectively.[34] Unfortunately, as discussed in detail before,[1,2] the existing interventions and strategies (eg, 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 impact 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, cost-effective, and equitable 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 allocation 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 injustice (ie, those who suffer the most are often those who bear the least responsibility for climate change)[35] and suggests that climate change can exacerbate global health inequality, at least in part through LFS air pollution. Financial and technological support from high-income countries to lower-income countries is needed to help vulnerable countries deal with the health impact of LFS air pollution.

Our study has several strengths compared with previous studies.[10–24] By quantifying global, regional, and national attributable mortality burdens over two decades, including all-cause and cause-specific burdens, short-term and long-term burdens, and LFS $PM_{2\cdot5}$ and O_3, our study is much more comprehensive and informative than previous studies, which were mostly regional, or only focused on global total all-cause mortality burden from LFS $PM_{2\cdot5}$. We have also made major advances in both exposure assessment and exposure–mortality relationships.

Our study does have limitations. We did not account for other LFS air pollutants or consider the potential synergistic impacts of LFS $PM_{2\cdot5}$ and O_3 on long-term mortality, both of which tend to cause underestimation of the attributable deaths (although without changing the spatial or temporal variations of our estimates). Using average daily death counts in calculating short-term attributable deaths and assuming long-term mortality impacts of LFS $PM_{2\cdot5}$ and O_3 the same as all-source $PM_{2\cdot5}$ and O_3 could also result in underestimation (appendix pp 67–68). Other limitations can lead to uncertainties in our attributable deaths estimates, including the uncertainties in LFS air pollution and GBD mortality data, the exposure–response relationships derived from available data not covering many countries (eg, sub-Saharan African and eastern European countries), and the within-country variations that are unaccounted for. Further investigations are warranted to address those limitations and improve mortality burden assessment for LFS air pollution.

In conclusion, LFS air pollution induces 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.

For **Github** see https://github.com/Rongbin553/wildfire_death

For **Multi-Country Multi-City Collaborative Research Network** see https://mccstudy.lshtm.ac.uk/ linked to multi-country multi-city collaborative research network

For the **GBD 2019 data** see https://vizhub.healthdata.org/gbd-results/

Contributors

YG and AG set up the collaborative network. RX, YG, SL, and GC designed the study and statistical methods. RX took the lead in the statistical analyses, drafting of the manuscript, and interpretation of the results. TY contributed to visualisation. XY contributed to exposure assessment. YG, SL, RX, TY, and WH accessed and verified the data. All authors contributed to interpreting the results and revising the manuscript, and were responsible for the decision to submit the manuscript for publication.

Declaration of interests

MJA holds investigator-initiated grants from Pfizer, Boehringer-Ingelheim, GlaxoSmithKline, and Sanofi for unrelated research, and has received a speaker's fee from GlaxoSmithKline. All other authors declare no competing interests.

Data sharing

Estimates of attributable deaths, attributable fractions, and attributable mortality rates for global, regional (Global Burden of Disease [GBD] 2019 super regions and GBD regions), socio-demographic index, and income groups for the 201 included countries and territories in each year during 2000 to 2019, as well as the relative risks for short-term and long-term mortality impacts are available on GitHub. Daily mortality data for 2267 communities were under a data sharing agreement with the Multi-Country Multi-City Collaborative Research Network and cannot be made publicly available. Annual mortality and socio-demographic data from GBD 2019 are publicly available. Researchers can email yuming.guo@monash.edu or 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.

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