Mapping landscape fire-sourced air pollution-related mortality across 2288 local communities in Australia: a nationwide health impact assessment

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Summary

Background Landscape fire-sourced (LFS) air pollution has been linked to increased mortality, which is especially concerning in fire-prone regions such as Australia. However, there is little evidence on how this increased mortality and associated economic burden might vary by region in Australia or on the factors driving such regional differences. To address this gap, we aimed to estimate the community-level mortality burden and economic loss from LFS air pollution and examine the socioeconomic factors contributing to regional health disparities across 2288 communities in Australia.

Methods We obtained individual death records and community characteristics from the Australian Bureau of Statistics, together with community-level population-weighted average daily and annual estimates of LFS fine particulate matter ($PM_{2.5}$) and surface ozone (O_3) during 2009–19 from a validated dataset. We used two-stage time series analyses to derive relative risks for the short-term mortality risks of LFS $PM_{2·5}$ and O_3. By integrating recent evidence on long-term mortality impacts of all-source $PM_{2·5}$ and O_3, we calculated the total LFS air pollution-related mortality burden (including both short-term and long-term burdens) and economic loss for each of the 2288 communities (statistical area level 2) in Australia. Mortality burden was expressed as attributable deaths, attributable fractions, and attributable mortality rates. Economic loss was quantified with the value of statistical life approach on the basis of willingness-to-pay estimates.

Findings Between 2016 and 2019, LFS air pollution was responsible for 22 809 (95% CI 19 276–26 435) all-cause deaths in Australia, valued at AU$138·41 billion (95% CI 116·97–160·41). Communities in the Northern Territory had the highest LFS air pollution-related excess mortality rate, at 33·97 (95% CI 29·12–39·20) per 100 000 residents per year, followed by communities in New South Wales and Queensland, whereas Southern Australia had the lowest burden, at 12·25 (10·64–14·04) deaths per 100 000 residents per year. Notably, mortality burdens were greater in communities with higher proportions of Indigenous Australian residents or residents of lower socioeconomic status and in communities situated in rural locations.

Interpretation This study provides a comprehensive analysis of the mortality burden and economic loss associated with LFS air pollution, highlighting a clear socioeconomic inequality in health burdens across Australian communities. The results—presented as community-level mortality burden maps—could inform the development of targeted public health interventions and climate policies at both local and national levels.

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Introduction

Landscape fires, encompassing both wildfires and human-planned fires, such as those used for agricultural purposes, have emerged as a growing public health concern in recent years. Wildfire is becoming more frequent, fuelled by climate change.[1] Landscape fires not only potentially pose a direct threat to individuals living nearby but also generate air pollution, which is recognised as a considerable public health risk, including to people living far from the fire source. Recent global studies suggest that, per 1 μg/m^3 increase in pollution, the health risks associated with landscape fire-sourced (LFS) air pollution might be substantially higher than those associated with non-LFS air pollution.[1,2] In the context of climate change, a comprehensive assessment of LFS air pollution-related health risks is becoming urgent and important.

Our recent research has given an overview of the global and national mortality burden attributable to LFS air pollution in the last 20 years.[2–4] We estimated that 1·53 million all-cause deaths annually were attributable to LFS air pollution during 2000–19, of which 90% were in low-income and middle-income countries.[2] However,

Research in context

Evidence before this study

Landscape fires have become an increasingly important public health concern, particularly in wildfire-prone regions such as Australia, where climate change has intensified their frequency, severity, and duration. Previous studies have established a consistent association between landscape fire-sourced (LFS) air pollution, particularly fine particulate matter ($PM_{2\cdot5}$) and ozone (O_3), and increased mortality. To assess the existing evidence, we conducted a comprehensive search of Google Scholar and PubMed for studies published in English from database inception to Feb 3, 2025, using combinations of terms related to wildfires ("landscape fires" OR "wildfires" OR "bushfires" OR "wildland fires" OR "forest fires") and health outcomes ("mortality" OR "death"). Our search showed that few studies have comprehensively assessed the mortality burden associated with LFS air pollution, including the short-term and long-term impacts of LFS $PM_{2\cdot5}$ and O_3. Although a recent global evaluation estimated wildfire-related mortality at national, regional, and global scales, no studies have provided community-level estimates of mortality burden or the associated economic costs.

Added value of this study

This study provides detailed estimates of the mortality burden attributable to wildfire-related air pollution ($PM_{2\cdot5}$ and O_3) at the community level in Australia, offering a more granular understanding of the health risks associated with wildfires compared with recent studies. By focusing on community-level data, this research fills an important gap in the literature, enabling a detailed examination of how wildfire impacts vary across different regions and populations. Furthermore, this study is unique in its comprehensive assessment of the economic burden associated with wildfire-related mortality, providing valuable insights into the financial implications of these events. Importantly, the identification of modifying factors, such as socioeconomic status and ethnicity, enhances our understanding of the social determinants of health vulnerability and provides crucial information for targeted interventions and policies.

Implications of all the available evidence

The findings of this study have important implications for public health policy and disaster preparedness. By providing community-level estimates of mortality burden and economic losses, this research could inform the allocation of resources and development of interventions tailored to specific regions and populations. The identification of socioeconomic and ethnic disparities in vulnerability to wildfire-related health impacts underscores the need for equity-focused policies to mitigate the disproportionate burden on marginalised communities. These insights could also guide climate change adaptation strategies and support efforts to reduce the toll of future wildfires on both health and the economy.

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detailed subnational information on the mortality burden from LFS air pollution is also essential to develop context-specific responses. Due to decreasing rainfall and rising extreme temperatures, there has been a substantial increase in the frequency and intensity of landscape fires in Australia over the past four decades.[5] Furthermore, the country's vast land area contributes to considerable regional variability in wildfire characteristics and their associated impacts. Although previous investigations provided a country-level estimate for the mortality burden of LFS air pollution, community-level estimates would be useful to inform community-targeted interventions. Additionally, factors driving socioeconomic disparities in the mortality burden attributable to LFS air pollution have not yet been identified, and the economic cost of this burden remains unclear. Further exploration of cause-specific risks is possible through the use of detailed individual-level death records.

See Online for appendix

To fill these research gaps, we conducted a nationwide study to identify risk patterns across major causes of death and quantify the mortality burden and economic loss attributable to LFS air pollution across each community in Australia. By using individual death records and community characteristics from 2016 census information, we aimed to identify small-scale risk patterns and community-level risk factors across the whole of Australia.

Methods

Mortality data and community-level factors

Individual mortality data geocoded at the statistical area level 2 (SA2; appendix p 3) between Jan 1, 2009 and Dec 31, 2019, were obtained from the Australian Coordinating Registry and Australian Bureau of Statistics. The original records included date of death; sex; age; primary cause of death coded according to the ICD-10, Australian Modification; and SA2 in which the deceased person resided. Detailed information about mortality data and inclusion criteria can be found in the appendix (p 3). SA2s can be aggregated into larger SA3 areas.

We collected community-level data from the 2016 census, including the Index of Relative Socio-economic Advantage and Disadvantage (IRSAD; a lower score indicates greater disadvantage), proportion of Indigenous Australian residents, proportion with bachelor's degrees, and urban–rural classification. All 2288 SA2s were grouped in quintiles for each factor. Population size was used to calculate a standardised mortality burden index. For cause-specific analysis, we examined associations with cardiovascular diseases (ICD-10-AM I00–I99), respiratory diseases (ICD-10-AM J00–J99), and cancer (ICD-10-AM C00–D48), as they are major causes of death. Due to changes in SA2 boundaries, mortality burden analysis was restricted to the period from 2016 to 2019, whereas risk assessment was based on the full dataset from 2009 to 2019 for those SA3 areas with unchanged boundaries.

Exposure data

We obtained daily averages of particulate matter ($PM_{2·5}$) and ozone (O_3) concentrations at 0·25° × 0·25° (~28 km × 28 km) spatial resolution for the period spanning Jan 1, 2009, to Dec 31, 2019, using a combination of machine learning and chemical transport models (GEOS-Chem version 12.0.0). Details of estimation process, validations, and data sources were published previously.[6,7] Briefly, in ten-fold spatial cross-validations against station observations, R^2 was 0·89 for daily $PM_{2·5}$ and 0·80 for daily O_3 (the workflow for estimating all-source and LFS air pollution can be found in the appendix [pp 4–5]). We calculated the population-weighted daily mean LFS $PM_{2·5}$ and O_3 for each SA2 and SA3 in Australia. We also calculated population-weighted daily mean temperatures and relative humidity from hourly data from the European Centre for Medium-Range Weather Forecasts Reanalysis version 5.[8] Relative humidity was calculated with the temperature and dew point temperature.[9]

Statistical analysis

We used a standard two-stage analytical framework to quantify the exposure–response relationships for the short-term mortality impacts of LFS $PM_{2·5}$ and O_3, following previous protocols.[2] In the first stage, a quasi-Poisson regression with distributed lag linear model was used to estimate SA3-specific associations between daily deaths and daily LFS $PM_{2·5}$ and O_3, separately, from 2009 to 2019. We adjusted for 8-day (lag07) moving average temperature and humidity using natural cubic splines with three degrees of freedom to control for weather confounding. Long-term trends and seasonality were modelled with a natural cubic spline with seven degrees of freedom per year. Day of the week and holidays were adjusted as categorical variables to account for variations in the numbers of deaths on specific days of the week and the potential impacts of public holidays. A cross-basis function was used to fit the main exposure (LFS $PM_{2·5}$ or O_3) to model the associations of both the exposure–response and lag–response (ie, how long it takes the exposure to affect health) with death. In our preliminary analysis, the impacts of daily LFS $PM_{2·5}$ and O_3 on mortality were generally linear and persisted for up to 2 days following exposure (appendix pp 6–7), consistent with our previous global analysis.[2] Thus, we adopted a linear function for the exposure–response dimension and a strata function (equating to the moving average lag model) for the lag–response dimension over lag 0–2 days.[10,11] Details of model parameter settings can be found in the appendix (pp 6–9). Finally, we obtained parameters for both cumulative exposure–response associations and lag–response associations for each SA3.[12]

In the second stage, we pooled the SA3-specific exposure–response parameters, using a random-effect meta-analysis to estimate the exposure–response relationships for Australia overall as well as individual Australian states.[13] No additional predictors were included in the meta-regression model. The short-term associations for LFS $PM_{2·5}$ and O_3 are presented as cumulative relative risks (RRs) with 95% CIs of all-cause death over lag 0–2 days following exposure to each 10 μg/m^3 increase in daily LFS $PM_{2·5}$ or O_3. Unlike conventional RR, cumulative RR captures total impacts over the lag period. To explore effect modification by age, sex, and causes of death, we conducted stratified analyses by substituting all-cause death counts with group-specific death counts in the first-stage model to estimate the corresponding RRs.

As the risk estimates directly influence the burden estimates, we conducted multiple sensitivity analyses to test the robustness of our main results by (1) changing the degrees of freedom (two or four) of meteorology factors; (2) changing the lag period (14 days or 21 days) of meteorology factors; (3) removing relative humidity; (4) changing the degrees of freedom (six, eight, nine, or ten) for the long-term trend and seasonality; (5) additionally adjusting for non-fire air pollutants; and (6) additionally adjusting for another LFS air pollutant (eg, adding LFS O_3 when extracting LFS $PM_{2·5}$ in the main model).

In the extended stage, we calculated the total mortality burden and economic loss attributable to LFS $PM_{2·5}$ and O_3 for each SA2 from 2016 to 2019. The comprehensive mortality burden assessment encompassed both short-term (acute) and long-term (chronic) impacts, accounting for the health effects of immediate exposure (lag 0–2 days) to LFS air pollution and cumulative annual exposure to LFS pollutants. We calculated the total burden as the sum of both short-term and long-term attributable deaths following the established protocols from our previous study.[2] Specifically, the two-stage pooled cumulative RR was used to generate the short-term attributable deaths, and the calibrated RRs (appendix pp 11–13), originally derived from the most recent systematic reviews on the long-term effects on mortality of all-source $PM_{2·5}$ and O_3, were used to estimate the long-term attributable deaths.[14,15] Monte-Carlo simulations (1000 samples), assuming a normal distribution of estimated effect, were used to quantify uncertainty for both short-term and long-term LFS attributable deaths.[2,16] Attributable fractions and attributable mortality rates (AMRs) were calculated on the basis of attributable deaths.[2] After calculating the total mortality burden of LFS air pollution, we estimated the value of statistical life (VSL) by applying the willingness-to-pay approach,[17,18] using the values provided by the Organisation for Economic Co-operation and Development (appendix [pp 19–20]).[19] The total attributable mortality burden and related economic loss were calculated using the following equations:

	Communities	Total deaths	Age, years	Male deaths	Female deaths	LFS $PM_{2\cdot5}$, μg/m^3	LFS O_3, μg/m^3	All-source $PM_{2\cdot5}$, μg/m^3	All-source O_3, μg/m^3
New South Wales	576	215 583	77·7 (16·3)	111 151 (51·6%)	104 432 (48·4%)	3·1 (7·3)	4·5 (7·5)	9·9 (7·3)	67·2 (19·2)
Victoria	462	159 974	77·9 (16·4)	81 223 (50·8%)	78 751 (49·2%)	1·6 (2·9)	2·7 (3·4)	8·6 (3·7)	60·7 (16·2)
Queensland	528	124 053	76·0 (17·4)	65 977 (53·2%)	58 076 (46·8%)	2·4 (4·2)	4·6 (6·4)	8·3 (4·7)	65·4 (15·0)
South Australia	172	54 905	78·2 (16·0)	27 963 (50·9%)	26 942 (49·1%)	0·7 (1·2)	2·5 (2·2)	8·0 (2·4)	64·0 (13·6)
Western Australia	252	58 836	75·8 (17·8)	31 204 (53·0%)	27 632 (47·0%)	2·1 (2·4)	4·2 (5·4)	9·8 (3·2)	68·4 (13·3)
Tasmania	99	18 239	76·9 (15·7)	9359 (51·3%)	8880 (48·7%)	1·2 (3·6)	2·6 (3·5)	6·2 (6·4)	54·4 (9·0)
Northern Territory	68	4276	61·8 (21·5)	2506 (58·6%)	1770 (41·4%)	4·5 (5·1)	9·5 (7·9)	10·7 (6·4)	64·8 (18·6)
Australian Capital Territory	131	8334	76·8 (17·7)	4186 (50·2%)	4148 (49·8%)	3·2 (10·3)	4·3 (8·0)	9·6 (12·5)	67·3 (17·8)
Australia	2288	644 200	77·2 (16·8)	333 569 (51·8%)	310 631 (48·2%)	2·3 (5·2)	4·0 (6·1)	9·0 (5·9)	64·7 (16·6)

Data are n, mean (SD), or n (%). LFS=landscape fire sourced.

Table 1: **Descriptive statistics for mortality and environmental variables across 2288 communities in Australia, by state and overall, from 2016 to 2019**

$$AD = AD_{short\_PM2\cdot5} + AD_{short\_O3} + AD_{long\_PM2\cdot5} + AD_{long\_O3}$$

$$AF = \frac{AD}{\text{number of deaths}} \times 100\%$$

$$AMR = \frac{AD}{\text{population}} \times 100\,000$$

$$Total\_VSL_t = AD \times VSL_t$$

Here, AD, denoting attributable deaths, is the sum of the long-term and short-term mortality impacts of LFS $PM_{2\cdot5}$ and O_3; AF is the attributable fractions of deaths related to LFS air pollution; AMR is the excess mortality rate after accounting for demographic differences in each community; VSL_t is the value of one statistical life in year t; and $Total\_VSL_t$ is the total aggregated value of preventing all statistical deaths in year *t*.

All analyses were done with R software (version 4.3.0), with the dlnm and mixmeta packages. A two-sided p value <0·05 was considered statistically significant.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

This study analysed 644 200 deaths across 2288 SA2 communities between 2016 and 2019. Table 1 shows the descriptive statistics for mortality data and both LFS-related and all-source air pollution across Australia's eight states and territories, as well as across Australia as a whole. LFS $PM_{2\cdot5}$ and O_3 concentrations varied substantially between regions, with the Northern Territory recording the highest average daily concentrations of LFS $PM_{2\cdot5}$ (4·5 μg/m^3 [SD 5·1]) and O_3 (9·5 μg/m^3 [7·9]). In contrast, South Australia had the lowest concentrations of LFS $PM_{2\cdot5}$ (0·7 μg/m^3 [1·2]) and LFS O_3 (2·5 μg/m^3 [2·2]). Although concentrations of LFS O_3 were generally higher than those of LFS $PM_{2\cdot5}$ across all states, both were highest in fire-prone areas such as the Northern Territory, Western Australia, and eastern New South Wales. On average, LFS $PM_{2\cdot5}$ accounted for a notable proportion of all-source $PM_{2\cdot5}$ in regions such as the Northern Territory (4·5 μg/m^3 [42·0%] of 10·7 μg/m^3) and New South Wales (3·1 μg/m^3 [31·3%] of 9·9 μg/m^3). The northernmost regions of the Northern Territory and Western Australia had the highest levels of exposure to LFS $PM_{2\cdot5}$ and O_3 in Australia during 2016–19. The eastern part of New South Wales followed closely, ranking second-highest in LFS $PM_{2\cdot5}$ exposure, whereas South Australia had the lowest concentrations of both LFS pollutants (appendix p 21).

Generally, the short-term impacts of LFS $PM_{2\cdot5}$ or O_3 on mortality appeared immediately and lasted for 2 days (appendix pp 7–8). Across Australia, increases of 10 μg/m^3 in the mean daily concentrations of LFS $PM_{2\cdot5}$ and O_3 during lag 0–2 days were associated with increases of 1·4% (95% CI 0·5–2·2) and 1·7% (1·0–2·4), respectively, in daily all-cause mortality. Sensitivity analyses did not alter our primary findings (appendix p 22). Notably, when additional non-fire pollutants were incorporated into the model, the RRs associated with LFS $PM_{2\cdot5}$ showed modest changes, whereas the RRs associated with LFS O_3 decreased slightly. Furthermore, a two-pollutant model showed a decrease in risk for LFS $PM_{2\cdot5}$, although its 95% CI remained within our primary estimate (appendix p 22). No significant temporal changes were observed in the effect estimates of mortality per 10 μg/m^3 increase in LFS $PM_{2\cdot5}$ or O_3 (appendix p 10).

We did not observe significant effect modifications by age, sex, socioeconomic status, or region for either LFS $PM_{2\cdot5}$ or O_3 exposure (appendix p 26). Both LFS $PM_{2\cdot5}$ and O_3 appeared to have greater RRs for respiratory mortality than for cardiovascular mortality or cancer-related mortality. Specifically, per 10 μg/m^3 increase in LFS $PM_{2\cdot5}$, the RRs were 1·05 (95% CI 1·02–1·08) for respiratory mortality, 1·01 (0·99–1·03) for cardiovascular mortality, and 1·01 (0·99–1·02) for cancer-related mortality; per 10 μg/m^3

	Attributable deaths, n (95% CI)	Attributable fractions, % (95% CI)	Attributable mortality rates, deaths per 100 000 residents per year (95% CI)	Value of statistical life, AU$ billion (95% CI)*
New South Wales	10 030 (8413–11 668)	4·65% (3·90–5·41)	33·58 (28·16–39·06)	60·86 (51·05–70·80)
Victoria	3948 (3336–4594)	2·47% (2·09–2·87)	16·67 (14·09–19·40)	23·96 (20·25–27·88)
Queensland	4948 (4197–5705)	3·99% (3·38–4·60)	26·37 (22·37–30·41)	30·02 (25·47–34·62)
South Australia	820 (712–940)	1·49% (1·30–1·71)	12·25 (10·64–14·04)	4·98 (4·33–5·71)
Western Australia	1996 (1699–2305)	3·39% (2·89–3·92)	20·22 (17·21–23·34)	12·11 (10·31–13·99)
Tasmania	376 (321–435)	2·06% (1·76–2·38)	18·49 (15·76–21·37)	2·28 (1·94–2·64)
Northern Territory	307 (264–355)	7·19% (6·16–8·30)	33·97 (29·12–39·20)	1·87 (1·60–2·16)
Australian Capital Territory	383 (320–448)	4·60% (3·84–5·37)	24·15 (20·15–28·21)	2·33 (1·94–2·72)
Australia	22 809 (19 276–26 435)	3·54% (2·99–4·10)	24·42 (20·64–28·30)	138·41 (116·97–160·41)

*2015 values.

Table 2: **Attributable deaths, fractions, mortality rates, and value of statistical life attributable to landscape fire-sourced air pollution in Australia, by state and overall, from 2016 to 2019**

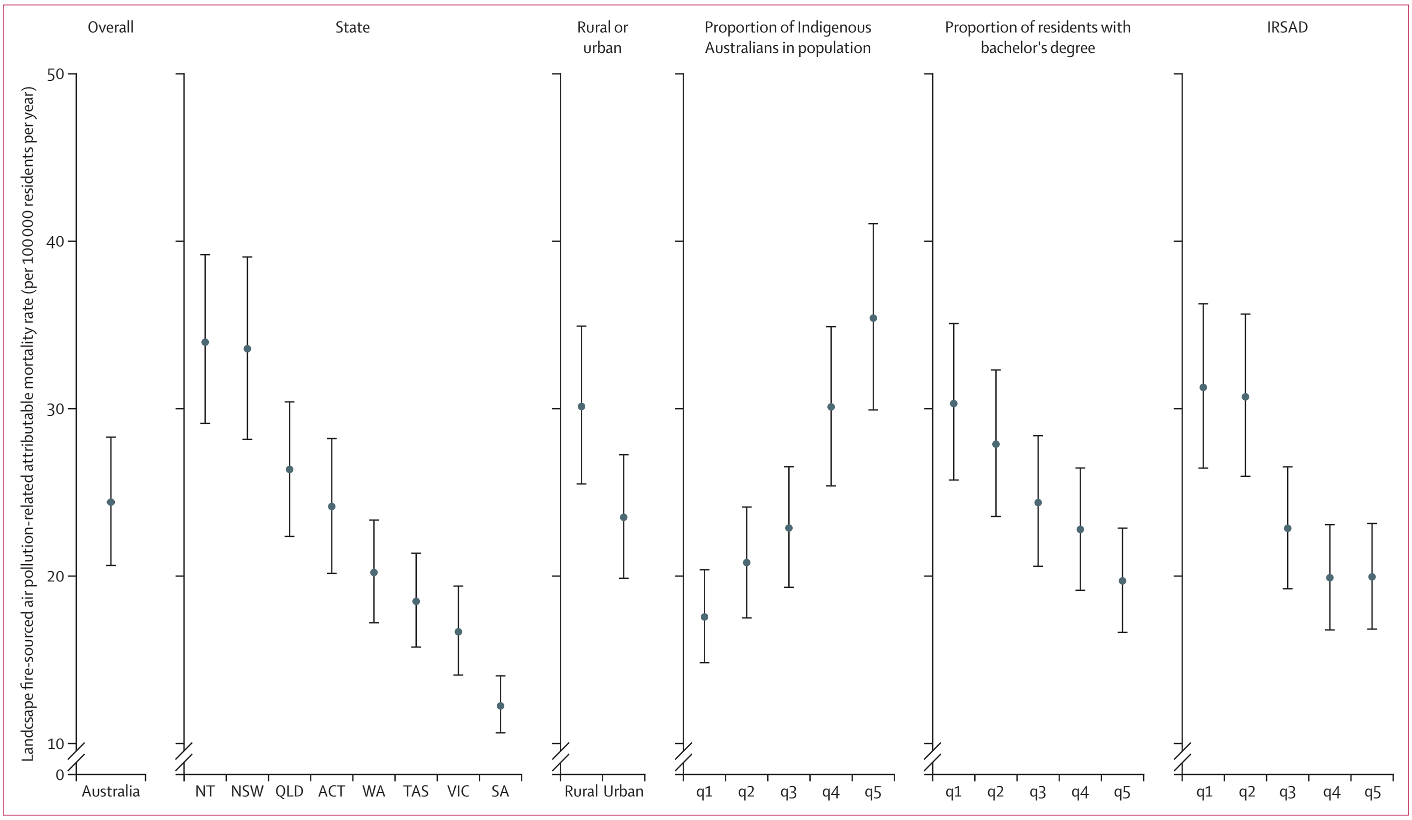

Figure 1: **Landscape fire-sourced air pollution-related attributable mortality rates in Australia**
Attributable mortality rates were stratified by state, rural or urban classification, and quintiles for proportion of Indigenous Australians in the population, proportion of residents with a bachelor's degree, and IRSAD score (for which the lowest quintile represents those with the highest level of deprivation). Whiskers indicate 95% CIs. q1 is equivalent to the lowest (≤20th) quintile; q2 is equivalent to the 20th–40th quintile; q3 is equivalent to the 40th–60th quintile; q4 is equivalent to the 60th–80th quintile; and q5 is equivalent to the highest (80th–100th) quintile. ACT=Australian Capital Territory. IRSAD=Index of Relative Socio-economic Advantage and Disadvantage. NSW=New South Wales. NT=Northern Territory. QLD=Queensland. SA=South Australia. TAS=Tasmania. VIC=Victoria. WA=Western Australia.

increase in LFS O_3, the RRs were 1·05 (1·02–1·08), 1.01 (1·00–1·03), and 1·00 (0·99–1·01), respectively. There was little evidence to suggest a significant cumulative relative risk for cancer-related mortality from either pollutant, although an increase in RR was observed at lag 0 (appendix pp 8–9). In addition, associations between LFS air pollution and mortality were stronger for chronic than for acute outcomes (appendix pp 16–18).

Nationally, 22 809 (95% CI 19 276–26 435) all-cause attributable deaths were attributable to LFS air pollution,

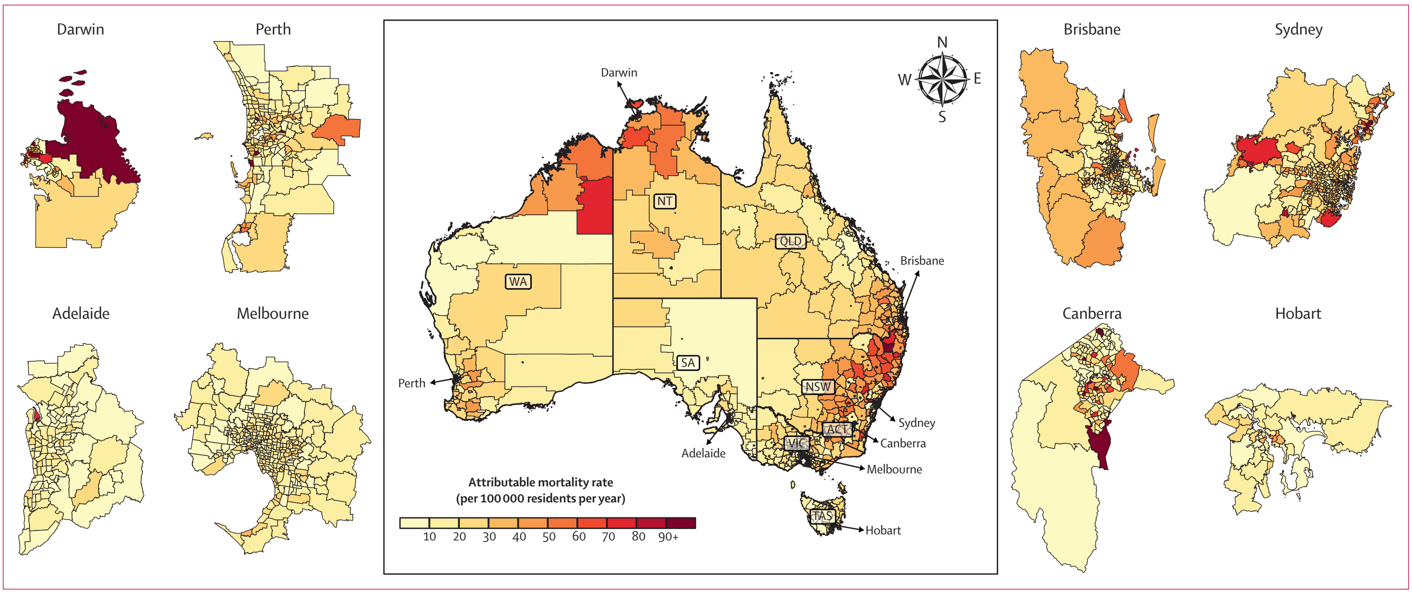

Figure 2: **Geographical distribution of landscape fire-sourced air pollution related-attributable mortality rates across 2288 communities in Australia**
ACT=Australian Capital Territory. NSW=New South Wales. NT=Northern Territory. QLD=Queensland. SA=South Australia. TAS=Tasmania. VIC=Victoria. WA=Western Australia.

accounting for 3·54% (95% CI 2·99–4·10) of all-cause deaths during 2016–19. The corresponding AMR was 24·42 (95% CI 20·64–28·30) per 100 000 residents per year for all-cause deaths, and there was an economic burden of AU $138·41 billion (95% CI 116·97–160·41) across the whole of Australia (table 2). Among total deaths attributable to LFS air pollution, 62·4% (59·6–64·7) and 8·4% (7·1–10·2) were caused by the long-term and short-term impacts, respectively, of LFS $PM_{2\cdot5}$ on mortality, whereas 11·6% (8·8–13·3) and 17·7% (14·8–21·5) were caused by the long-term and short-term impacts, respectively, of LFS O_3 on mortality (appendix p 27).

Compared with the other seven states in Australia, New South Wales had the largest number of all-cause attributable deaths (10 030 [44·0%, 95% CI 43·6–44·1] of the Australian total), followed by Queensland (4948 [21·7%, 21·6–21·7]) and Victoria (3295 [17·3%, 17·3–17·4]; table 2). Notably, despite having the lowest number of attributable deaths (307 [95% CI 264–355]) due to LFS air pollution compared with the other Australian states, Northern Territory had the highest all-cause attributable fraction, at 7·19% (95% CI 6·16–8·30).

Figure 1 shows AMRs across Australia, by state, rural or urban classification, proportion of Indigenous Australian residents, proportion of residents with a bachelor's degree, and IRSAD score (numerical data are in the appendix [p 23]). LFS air pollution-related AMR was lowest in South Australia (12·25 [95% CI 10·64–14·04] deaths per 100 000 residents per year) and highest in Northern Territory (33·97 deaths [29·12-39·20] per 100 000 person-years). AMR was higher in areas with a higher proportion of Indigenous Australian residents, a lower proportion of individuals with a bachelor's degree, and greater socioeconomic deprivation (as indicated by lower IRSAD score). The AMR associated with LFS air pollution was higher in rural areas than in urban areas.

Figure 2 shows the spatial distribution of LFS air pollution-related AMR in Australia. Overall AMR distribution was concordant with the spatial distribution of LFS air pollution (appendix p 21), with the highest AMRs in the Northern Territory and eastern New South Wales regions. For capital cities across each state, the highest AMRs were identified in Darwin, Sydney, Brisbane, and Canberra (in descending order). Conversely, Adelaide, Melbourne, and Hobart appeared to have relatively lower AMRs associated with LFS air pollution.

Figure 3 presents the yearly attributable deaths, attributable fractions, AMRs, and VSL associated with LFS air pollution of each state from 2016 to 2019. In general, these parameters increased at a steady rate year on year in New South Wales, Victoria, Queensland, Northern Territory, and Australia Capital Territory, as well as in Australia as a whole. However, all states experienced a substantial rise in LFS air pollution burden in 2019, resulting in a two-fold increase in attributable deaths compared with those estimated in 2016 across Australia (appendix pp 24–25).

Discussion

To our knowledge, this study is the first to evaluate the mortality burden and extent of economic loss related to LFS air pollution across 2288 SA2 communities in Australia. We captured 22 809 all-cause deaths attributable to LFS air pollution, equating to $138·41 billion lost from 2016 to 2019. Our assessment showed that this mortality burden was not evenly distributed among communities. Communities in New South Wales and Queensland shared

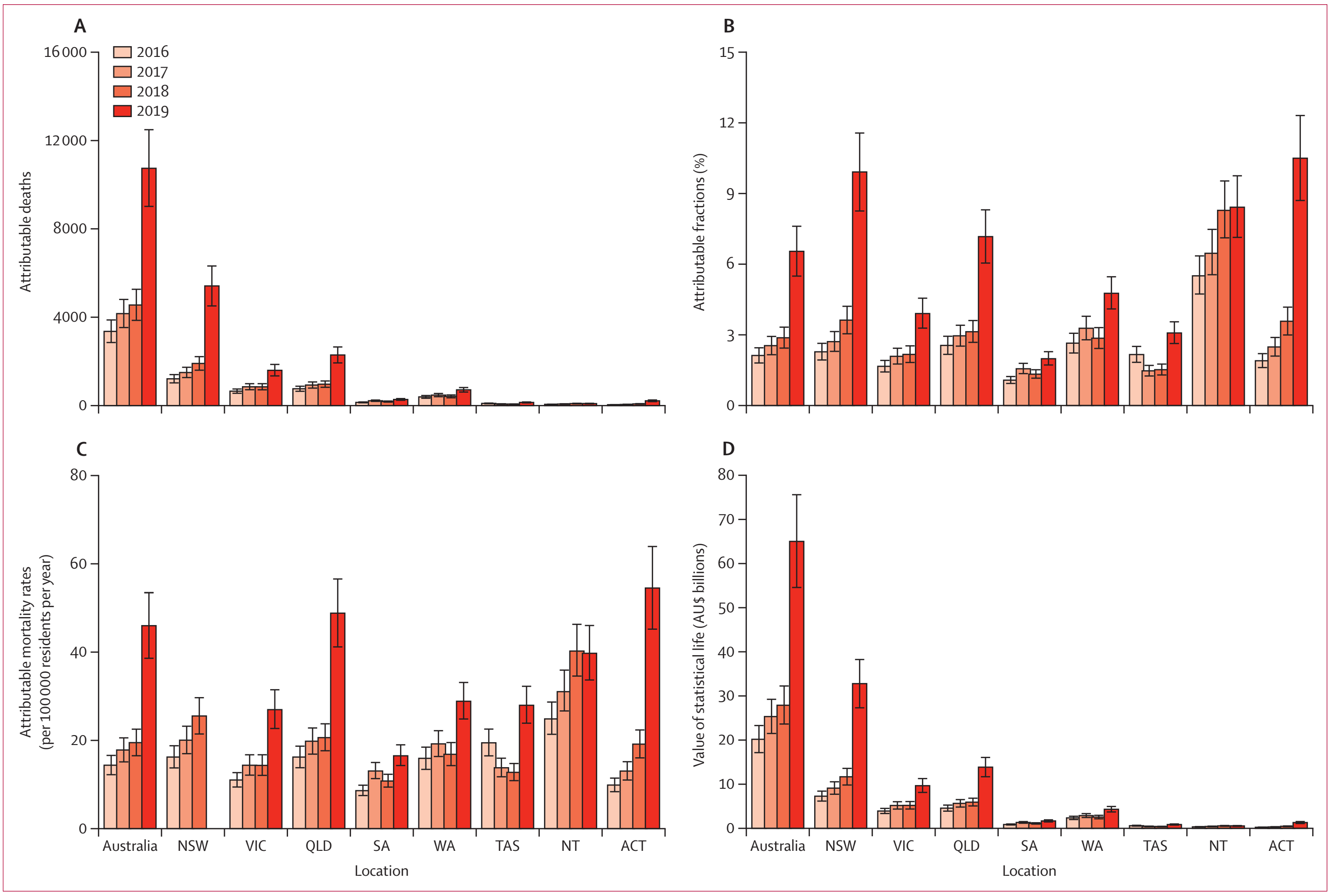

***Figure 3*: Estimated attributable deaths (A), attributable fractions (B), attributable mortality rates (C), and associated economic losses (D) across individual states and Australia overall, from 2016 to 2019**

ACT=Australian Capital Territory. NSW=New South Wales. NT=Northern Territory. QLD=Queensland. SA=South Australia. TAS=Tasmania. VIC=Victoria. WA=Western Australia.

the largest mortality burden, together totalling 65·7% of all-cause attributable deaths, whereas communities in the northernmost part of the Northern Territory had the highest attributable fraction of deaths related to LFS air pollution. Annual increases in attributable deaths, attributable fractions, AMRs, and VSL were observed in most communities, with a notable escalation in 2019 due to the extensive landscape fires that swept across Australia.

Due to changes in SA2 boundaries, we only assessed LSF-related mortality burden and economic losses from 2016 to 2019. Although our assessments for short-term risk associations were based on data from 2009 to 19, there was no evidence that the risks estimated from different periods varied significantly.

LFS air pollution can have widespread impacts on human health through multiple pathways, including direct toxicity of LFS $PM_{2\cdot5}$,[20] oxidate stress and inflammatory reactions,[21] immune dysregulation,[20] genotoxicity and mutations,[22] and skin allergies.[23] Although numerous studies have examined the health effects of individual components of LFS air pollution, comprehensive toxicology studies on the LFS air pollution mixture remain scarce.[24] Our analysis showed a disparity in mortality risks associated with LFS air pollution, with an elevated risk of respiratory deaths compared with cardiovascular deaths and cancer deaths. Previous studies have documented long-term associations between landscape fire exposure and cancer incidence.[25] The association observed for lag day 0 with cancer mortality suggests that even brief exposure to LFS air pollution might accelerate disease progression and reduce survival, possibly via inflammation or oxidative stress. Stronger associations for LFS air pollution with chronic outcomes than with acute outcomes support this finding, although the absence of cumulative risk might reflect a harvest effect.[26] Further investigation in large-scale epidemiological studies is warranted to validate these findings and to identify whether acute or chronic outcomes are more vulnerable to LFS air pollution in terms of both mortality and morbidity.

The results of our study are consistent with previous country-level estimates in a global study of LFS-related mortality burden.[2] Although Australia's AMR associated with LFS-related air pollution was lower than the global average in 2016, it increased steadily from 2016 to 2019, rising to nearly twice the global average by 2019. Despite this increasing trend, there have been few attempts to comprehensively address the health burden and related economic loss linked to LFS air pollution within Australia, one of the largest countries in the world. We have addressed this gap by identifying community-level differences in mortality burden and economic loss attributable to LFS air pollution. Current assessments of the economic burden primarily capture the direct effect on mortality. However, LFS air pollution might also reduce labour productivity and dampen consumer activity by impairing workers' health and restricting access to affected areas.

After adjusting for demographic differences, we found that the health impacts of LFS air pollution were disproportionately greater in rural areas, communities with higher proportions of Indigenous residents, those with fewer individuals holding bachelor's degrees, and areas of lower socioeconomic status. These findings align with broader patterns of environmental injustice observed in previous studies from Canada and the USA, which show that marginalised populations are exposed to higher concentrations of air pollution.[27,28] Factors such as reliance on natural resources and inadequate health-care access might heighten the vulnerability of these groups to the effects of LFS air pollution.[29]

Australia is one of the most fire-prone continents. Although landscape fires are part of natural cycles, their intensity is influenced by climate trends, weather patterns, and land management. LFS air pollution disproportionately affects socioeconomically vulnerable communities, and these impacts could worsen as climate change intensifies fire conditions.[1] Our analyses showed consistent yearly increases in LFS air pollution-related AMRs in Australia, according with global analysis.[2] Moreover, estimates of LFS air pollution-related AMR for 2019 were more than tripled compared with those for 2016, largely due to the prolonged impact of wildfires in Australia, causing both large effects on health and increased economic loss.

This study has several strengths compared with previous studies.[2–4] Notably, we were able to quantify mortality burden and economic loss for each community in Australia. The resulting high-resolution mortality burden maps provide valuable insights for policy makers, enabling the development of targeted public health interventions tailored to local needs. These community-level estimates allow for increased precision in resource allocation and risk communication strategies, which are essential for building resilience in the most affected areas. Furthermore, our findings indicate that there are considerable health inequities, with communities that have a high proportion of residents with lower socioeconomic status or a high proportion of Indigenous residents bearing a disproportionate burden. These insights underscore the need for equity-focused policies and could guide broader strategies to address climate change-related health risks at both local and national levels.

This study also has some limitations. Uncertainties in exposure assessment remain, and the use of location-level exposure as a proxy for individual exposure might not be able to effectively capture extreme exposure risks, potentially underestimating associated risks. Additionally, other LFS air pollutants (eg, polycyclic aromatic hydrocarbons and volatile organic compounds) were not considered in our main model due to data limitations. We estimated the long-term impact of LFS air pollution by calibrating the long-term effects of all-source air pollution. However, further refinement in methods to assess the long-term impact of LFS-related air pollutants is necessary to enhance the accuracy of future estimations of health burdens. The estimated economic losses did not account for age-related variations; thus, future assessment is needed if age-adjusted VSL becomes available. Furthermore, LFS events are strongly associated with extreme heat episodes. Although our primary analysis accounted for temperature effects,[2] future studies should investigate the possible interaction of temperature and LFS-related air pollutant exposure with respect to mortality. Due to some changes in SA2 boundaries in 2016, we could only evaluate the health burden from 2016 to 2019. However, these results are sufficient to enable policy makers to make community-specific interventions on the basis of our assessments.

In conclusion, this study provides a comprehensive assessment of LFS air pollution-related mortality burden and related economic loss across 2288 communities in Australia from 2016 to 2019. Our findings highlight substantial sociodemographic disparities in LFS air pollution-related mortality burden among communities with more Indigenous residents, lower education levels, lower socioeconomic status, and in rural settings, providing crucial information for the development and implementation of targeted public health policies to address the localised needs at the community level.

Contributors

YG, SL, and RX designed the study. ZX conducted the statistical analysis and took the lead in drafting the manuscript and interpreting the results. YG, SL, RX, and ZX accessed and verified data. All authors contributed to data provision, interpretation of the results, and manuscript revision. All authors had full access to all study data and shared final responsibility for the decision to submit the manuscript for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Estimates of attributable deaths, attributable fractions, attributable mortality rates, and value of statistical life for Australia overall and its states and communities from 2016 to 2019 are available on GitHub (https://github.com/zhihu3456/AUS_LFSair_mortality_burden). An online app developed with Shiny to display community-level estimates can be accessed at https://qr5g6g-zhihu-xu.shinyapps.io/LFSairShiny/. Daily mortality data for 2288 communities in Australia cannot be made publicly available according to a data sharing agreement. Researchers can email yuming.guo@monash.edu for information on accessing the analytical codes, GEOS-Chem simulation outputs, and estimated LFS air pollution data.

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