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Supporting Information

Supplementary materials

This appendix was part of the submitted manuscript and has been peer reviewed.
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Appendix to: Robinson DL, Horsley JA, Johnston FH, Morgan GG. The effects on mortality and the associated financial costs of wood heater pollution in a regional Australian city. *Med J Aust* 2021; doi: 10.5694/mja2.51199.

Supplementary introductory material

1. $PM_{2.5}$: the most hazardous air pollutant

Particles less than 2.5 millionths of a metre aerodynamic diameter ($PM_{2.5}$) are generally considered the most hazardous air pollutants. For example, the European Environment Agency attributed 492,600 premature deaths in 2018 to air pollution: 85% to $PM_{2.5}$, 11% to NO_2, and 4% to ozone exposure.[1] The *Lancet* 2019 Global Burden of Disease study attributed 4.51 million deaths worldwide to ambient air pollution: 92% to $PM_{2.5}$ and 8% to ozone.[2]

The NSW government draft Clean Air Strategy (March 2021) states that: "*Fine particles ($PM_{2.5}$) have the largest health impacts across New South Wales*"[3] and, for the 5.6 million residents of Sydney–Newcastle–Wollongong and the surrounding area (the Greater Sydney Metropolitan Region, GSMR), wood heaters account for an estimated 42% of anthropogenic $PM_{2.5}$ exposure (compared with 23% from industry, 19% from road transport and 7% from power stations). In Sydney, wood is the main heating source for only 4.4% of households, but Clean Air Strategy modelling attributes 46% of anthropogenic $PM_{2.5}$ exposure to wood heater pollution.[3]

The 42% of anthropogenic population-weighted $PM_{2.5}$ exposure in the GSMR attributed to wood heaters in models based on the 2013 emissions inventory suggests an increasing contribution from wood heating. Results published in 2019–20, based on the 2008 emissions inventory, were: 24–31% for wood heaters, 17–19% for road vehicles, and 11–17% for power stations.[4,5] Increasing exposure suggests increasing costs. The Clean Air Strategy population-weighted wood heater $PM_{2.5}$ exposure estimate (0.96 $\mu g/m^3$) for the GSMR is almost double the estimate of 0.49 $\mu g/m^3$ from the study published in 2020, in which an estimated 180,000 additional years of life (with present monetary value of about $8 billion) would be gained if wood heater pollution was reduced to zero.[4]

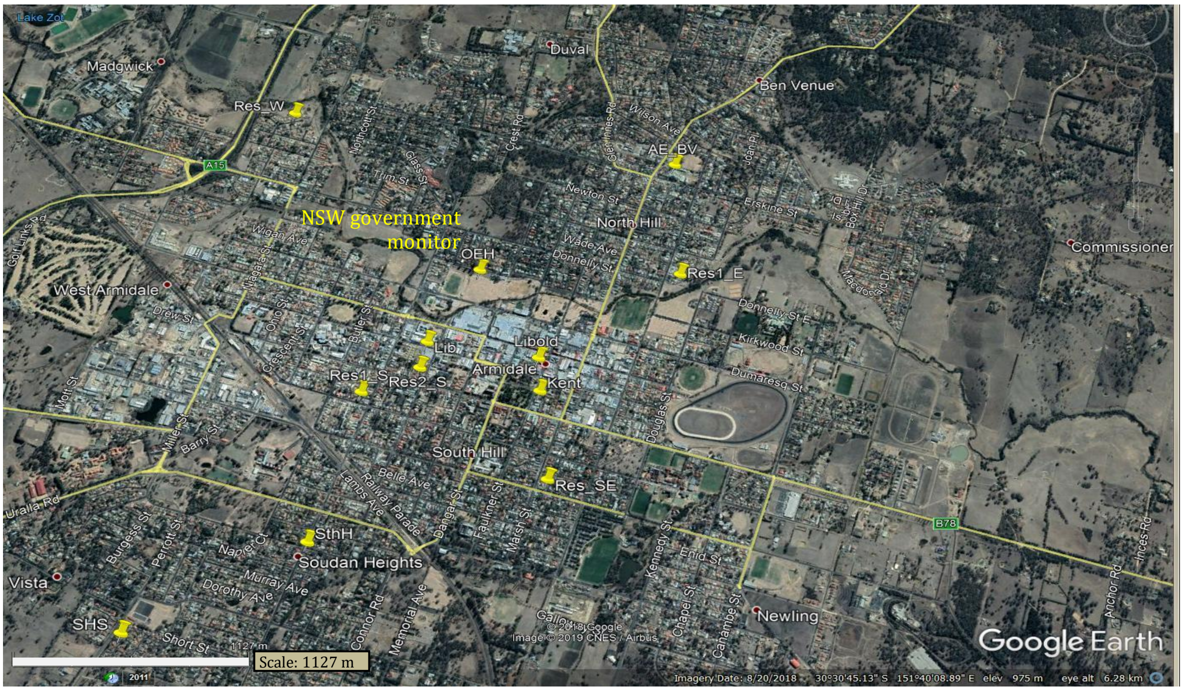
2. $PM_{2.5}$ monitoring in Armidale

A NSW government air pollution monitoring station was installed in Armidale in April 2018. Previously, the local council measured $PM_{2.5}$ using a DustTrak monitor (TSI) calibrated for wood smoke, using procedures developed for the Tasmanian BLANKET network.[6] In May and June 2018, 11 low-cost PurpleAir monitors (calibrated using NSW $PM_{2.5}$ data to provide measurements comparable with those of more expensive equipment[6]) were placed throughout the town to supplement NSW government and council data and to assess spatial variation in $PM_{2.5}$ caused by domestic wood heating (the major source of air pollution in Armidale)[6] (Figure 1).

Air pollution in Armidale exceeded the national daily $PM_{2.5}$ standard (25 $\mu g/m^3$)[7] on 32 days in 2018 (Figure 2); all 32 exceedance days were attributed to the non-exceptional event of winter wood heater pollution.[7] Liverpool had the next highest number of exceedance days in NSW in 2018, with eight exceedances that were attributed to hazard reduction burns and bushfires.[7]

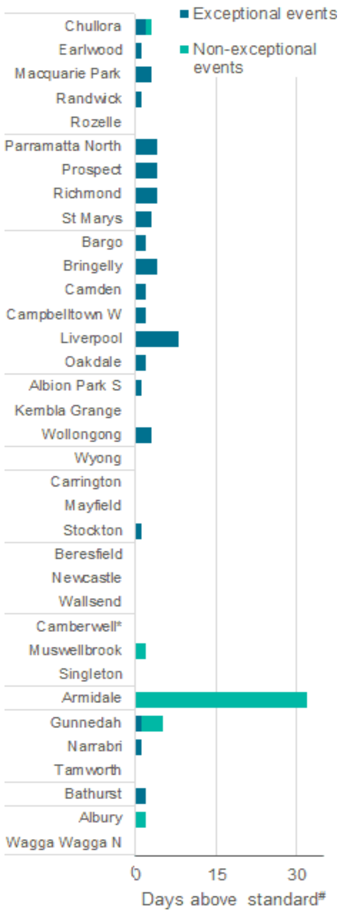
Historical DustTrak and PurpleAir measurements for Armidale for other years were similar to 2018.[6] PurpleAir data suggest that some residential areas of Armidale have substantially more $PM_{2.5}$ pollution than the official monitoring site; one PurpleAir location recorded 63 days on which pollution exceeded the $PM_{2.5}$ standard.[6]

Figure 1. Locations of the NSW government air pollution monitoring site and the PurpleAir monitors*



* We did not use data from the Res_W monitor because it appeared to be faulty.

Figure 2. NSW daily $PM_{2.5}$ monitoring: days on which levels exceeded the national standard of 25 $\mu g/m^3$, 2018[7,*]



* This diagram from the NSW Annual Air Quality Statement, 2018, is reproduced with permission of the NSW Department of Planning, Industry and Environment.

Supplementary methods

3. $PM_{2.5}$ exposure in Armidale

Daily mean $PM_{2.5}$ data from NSW government and PurpleAir monitors were used to assess population exposure during the period 1 May 2018 to 30 April 2019. During the initial, calibration period (1 May to 8 June 2018), measurements from two sites were available. Additional low cost monitors were then deployed throughout the city and measurements interpolated on a 0.001 degree grid across the Armidale Statistical Area 2 (SA2)[8] using autovariogram kriging. From January 2019, background monitoring continued at the original two sites. As autovariogram kriging requires at least three operational sites, the mean value from the two sites was used during the calibration period and during the final four months of background measurements. All results were averaged by Australian Bureau of Statistics mesh blocks[9] and aggregated to daily mean population-weighted $PM_{2.5}$ ($DPWP_{25}$) in the Armidale SA2 area, using 2016 mesh block usual resident population.[9] The data analyses were conducted in R 4.0.2.

4. Current mortality rate in Armidale

During 2012–2018, the annual number of deaths in the Armidale SA2 ranged between 160 and 187.[10] The mean standardised mortality rate of 6.0 deaths per 1000 population during this period was about 8% higher than for the whole of NSW.[10] Mean mortality rates by age and sex for NSW in 2018[11] were therefore considered conservative estimates of mortality in Armidale at current $PM_{2.5}$ levels.

5. Excess mortality associated with wood heater $PM_{2.5}$ pollution

Long term mortality attributed to wood heater $PM_{2.5}$ was estimated using similar methods to Borchers-Arriagada and colleagues.[12] We expressed wood heater $PM_{2.5}$ exposure during the 164-day wood heater pollution period as annual mean wood heater $PM_{2.5}$ population exposure (AWPE) (cf. Table 1).

The increased risk (IR) was calculated for each age group using the Global Exposure Mortality Model (GEMM) risk function as IR = GEMM(AWPE, age group) (reference 13, Table S2, non-communicable diseases (NCD) + lower respiratory infections (LRI), with Chinese male cohort).

We then estimated the effect on mortality associated with AWPE, by sex and 5-year age group, based on the Armidale population for each group and mean NSW mortality rates by sex and age group:

> Deaths averted if wood heater pollution is zero = $(1 - 1/IR) \times$ population $\times$ mortality rate

Alternative risk functions were also considered, including HRAPIE (Health Risks of Air Pollution in Europe[14]), in which there is no increase in risk with pollution exposure for people under 30 years of age (i.e. IR = 1), and $IR = 1.062^{AWPE/10}$ for all other age groups. Annual excess mortality by sex and age group was used to calculate years of life lost (YLL) and reduced life expectancy from both GEMM and HRAPIE.[15]

We also conducted a very conservative analysis in which we applied a short term exposure risk function to daily wood smoke-related $PM_{2.5}$ exposure above background (DWPE), to calculate a daily risk function, $IR = 1.0123^{DWPE/10}$ and the expected reductions in daily deaths[14] for each day of the 164-day wood heater pollution season. This approach estimates the numbers of deaths attributable to wood heater-related $PM_{2.5}$ pollution in Armidale, assuming that all premature deaths occur within a few days of exposure.

6. Economic cost of lives and years of life lost

The economic cost of the long term mortality burden was estimated using a Value of Statistical Life Year (VSLY) of \$213,000 (2019 value) for the first lost year of life, subsequently discounted by 3% per year, as recommended in 2019 by the Office of Best Practice Regulation.[16]

Supplementary results

7. Deaths, years of life lost and economic cost, lost life expectancy

The period of elevated $PM_{2.5}$ from wood heaters was judged to be 1 May – 11 Oct 2018 (wood heater pollution period; mean $DPWP_{25}$, 18.76 µg/m³ *v* 3.14 µg/m³ for the background period; Table 1). There was some elevated pollution during the background period caused by bushfires (14–31 Jan 2019) or dust storms (22–23 Nov, 2–3 Dec 2018, 13 Feb, 11–15 Mar 2019), as well as elevated pollution from a dust storm on one day during the wood heater pollution period (1 Sept 2018). Given their larger particle size, dust storms have only a minor impact on $PM_{2.5}$ measurements. In contrast, the 14–31 Jan 2019 bushfires increased the monthly mean $PM_{2.5}$ at the NSW government station to 6.90 µg/m³ (February: 1.45 µg/m³; March: 1.11 µg/m³; April 2019: 0.94 µg/m³), suggesting that 3.14 µg/m³ was probably an overestimate of the background concentration.

On wood heater pollution days, daily population-weighted $PM_{2.5}$ wood smoke exposure was defined as the amount by which $DPWP_{2.5}$ exceeded the mean daily population-weighted $PM_{2.5}$ exposure during the background period. This resulted in a 164-day (1 May – 11 Oct 2018) mean of 15.64 µg/m³, equivalent to a mean annual $PM_{2.5}$ value of 7.03 µg/m³ from wood smoke $PM_{2.5}$ (Table 1).

Table 1. $PM_{2.5}$ measurements (µg/m³) for Armidale, by season (wood heater pollution, background), days exceeding the national air quality $PM_{2.5}$ standard (25 µg/m³), and estimated seasonal and annual mean wood heater $PM_{2.5}$ exposure

Measurement location	Wood heating 1 May – 11 Oct	Background (12 Oct – 30 Apr)	Days exceeding air quality standard	Wood heater $PM_{2.5}$ exposure: Seasonal (164 days)	Annual (365 days)
Population-weighted city mean	18.76	3.14	46	15.64	7.03
NSW government monitor*	16.38	2.62	32	13.77	6.19
South Armidale†	24.64	3.22	63	21.47	9.65

* Measured by tapered element oscillating microbalance (TEOM).
† South Armidale residential area (Res1_S), monitored almost continuously by PurpleAir since mid-2017.

Compared with no wood heater pollution, the GEMM analysis indicated that long term exposure to wood heater $PM_{2.5}$ in Armidale was associated with an additional 14 (95% CI, 12–17) premature deaths per year, equivalent to 210 (95% CI, 172–249) years of life lost annually. We also estimated that long term exposure to mean $PM_{2.5}$ at the concentrations measured in Armidale leads to 364 (95% CI, 297–432) days of lost life expectancy at birth. The estimated annual cost of the YLL is \$32.8 million (95% CI, \$27.0–38.5 million). The number of wood stoves is believed to have declined slightly, from an estimated 3500 in use in Armidale in the late 1990s[17] to about 3000 today (approximately 40% of households). The estimated cost is therefore \$10,930 (95% CI, \$9004–12,822) per wood heater per year (Table 2).

Estimates using the HRAPIE risk function were substantially lower, $4928 per wood-heater per year (Table 2). The short term exposure risk function produced the lowest estimate of extra deaths: 1.4 (95% CI, 0.5–2.3) premature deaths per year.

The Armidale Council DustTrak measurements for 2010–2017 and calibrated PurpleAir and NSW government data indicate that the 2018 $PM_{2.5}$ exposure data were fairly typical, if slightly lower than in 2017.[6] Estimated health costs in 2018 are therefore representative of what can be expected in future, in the absence of effective policies to reduce wood heater pollution.

Table 2. Estimated number of premature deaths, years of life lost and associated economic cost, and loss of life expectancy attributable to domestic wood heater pollution in Armidale (with 95% confidence intervals), 1 May 2018 – 30 April 2019, by sex

Method	Premature deaths (per year)	Years of life lost (YLL)		Lost life expectancy at birth (days)
		Number	Economic cost ($ million, 2019)	
Global Exposure Mortality Model[13]				
All people	14.2 (11.7–16.6)	210.3 (171.7–248.9)	32.8 (27.0–38.5)	364 (297–432)
Males	6.7 (5.5–7.9)	107.3 (87.7–127.0)	16.5 (13.6–19.4)	379 (309–449)
Females	7.5 (6.2–8.8)	102.9 (84.0–121.9)	16.3 (13.4–19.1)	351 (285–416)
Health Risks of Air Pollution in Europe[14]				
All people	6.7 (4.4–8.9)	90.4 (58.9–120.1)	14.8 (9.7–19.5)	162 (105–216)
Males	3.1 (2.0–4.1)	45.2 (29.5–60.0)	7.3 (4.8–9.6)	166 (108–221)
Females	3.6 (2.4–4.7)	45.2 (29.4–60.0)	7.5 (4.9–9.9)	158 (103–210)

Supplement to the discussion

8. The Launceston wood smoke reduction program

Launceston's Wood Heater Replacement Program reduced wintertime PM_{10} pollution in June–August 2001–07 by an estimated 16.6 µg/m³ (compared with June–August, 1994–2000) and generated substantial health benefits, including 28% and 20% reductions in wintertime respiratory and cardiovascular disease deaths respectively, and a 11.4% reduction in annual all-cause mortality among males.[18] The program cost about $2 million. During the intervention period, Launceston's urban centre/locality had a population of about 70,000; the estimated cost of the intervention per resident was therefore about $29, or about $5 per year for the 6 year post-intervention period. For June–August 2018 (a shorter period than the 1 May – 11 October shown in Table 1), the mean population-weighted city wide wood smoke exposure in Armidale was 19.3 µg/m³, suggesting that eliminating wood heater-pollution in Armidale would achieve similar or greater benefits per capita than achieved by the Launceston program.

In Launceston, the National $PM_{2.5}$ daily standard was exceeded 10 times at the EPA Tasmania reference station in 2018, 16 in 2017, 9 in 2016, 12 in 2015, 11 in 2014, 12 in 2013, 6 in 2011, 11 in 2010, and 12 in 2009,[19] indicating that progress reducing pollution halted once external funding ceased and new heaters started to be installed.

9. Other benefits of reduced wood heater pollution

For simplicity, the estimates in our study were based on the exposure risk function for premature death. Other adverse health outcomes of air pollution listed in the Global Burden of Diseases include: premature birth, decreased birthweight, stroke, neurodegenerative diseases, diabetes, deep venous thrombosis, cardiovascular and lung diseases.[20] Fine particles ($PM_{2.5}$) enter lung alveoli; ultrafine particles ($PM_{0.1}$) pass through the alveolar–capillary membrane, readily enter cells, and carried via the bloodstream to almost all cells in the body.[21] Ultrafine particles are a substantial component of wood heater pollution; their size distribution peaks at 0.1–0.2 µm.[22] Studies specifically linking adverse health effects to wood heater pollution include a 7% increased risk in New Zealand of non-accidental hospital emergency presentations in children under three for each additional wood heater per hectare,[23] and a 55% increase in dementia for each 1 µg/m^3 increase in wood heater $PM_{2.5}$ pollution in Sweden.[24] In Tasmania, $PM_{2.5}$ pollution is mainly associated with winter wood heaters; hospital admissions for heart failure increased by 29% per 10 µg/m^3 $PM_{2.5}$ increase (one-day lag) above 4 µg/m^3.[25] In Armidale, visits to GPs for respiratory complaints were significantly associated with wood heater pollution, with estimated daily cost in 2007 of $1,666.[26]

The links between $PM_{2.5}$ pollution and increased risk of COVID-19[27] could also be a concern, especially if vaccines reduce the severity of disease but do not prevent transmission, leaving communities open to some risk of infection.

10. Policy implications

A 2017 study found that wood heater pollution caused $8 billion in health costs in Victoria over 10 years.[28] A similar study for NSW in 2011 reported estimated health costs over 20 years of $8 billion, which could be reduced by 75% by not allowing new heaters to be installed and requiring existing units to be removed when houses are sold.[29]

The major contribution of wood heaters to $PM_{2.5}$ exposure in Australia was also highlighted by several recent comprehensive modelling and economic studies, including a 35-author peer-reviewed 'Clean Air Plan for Sydney' that recommended considering legislation that "*works towards eliminating the use of wood-heaters in urban areas*".[30]

In 2011, the estimated annual average health cost per wood heater in Australian capital cities was $3,863.[31] A recent estimate for Tasmania, including rural areas, was $4232 per wood heater per year.[12] Real-life emissions depend critically on how the heater is operated; really bad operation can produce up to 100 times as much smoke as using it really well.[32] With measured real life emissions of new wood heaters only marginally lower than for older models, even after extensive education programs on correct operation,[33] the 40,000 to 50,000 new wood heaters sold each year in Australia[34] are expected to increase air pollution-related costs in Australia by $160 million every year.

Modern, efficient reverse cycle heater-air conditioners move the sun's warmth from outside to inside homes; they are now the cheapest and most environmentally friendly heating option, with substantially lower running costs than buying firewood. Some years ago, the Christchurch Clean Heat Project replaced wood heating in 1973 households with heater–air conditioners (and improved insulation when needed); the average increase in electricity use was just 1%. Households that removed open fires used less electricity, the amount saved offsetting the 8–10% increase in households that replaced free-standing wood heaters.[35] Efficient units can deliver 5 kW of heat for each kW of electricity used (of which 4 kW is derived from air heated by the sun, so that 80% of the heat delivered is from a renewable source) and have convenient thermostatic controls.

Wood smoke pollution from the unprecedented bushfires in eastern Australia was responsible for an estimated 417 excess deaths during 1 Oct 2019 – 10 Feb 2020.[36] Knowledge of the harms of bushfire smoke could increase community awareness of the harms of wood heater pollution and the need to switch to affordable, non-polluting heating. To be effective, the call by the Victorian AMA for a wood heater buyback scheme[37] needs widespread support, including not permitting new wood-heaters, and information and education programs to help affected parties make an informed choice. Useful resources include short videos by the WHO and UNICEF about how $PM_{2.5}$ pollution affects our bodies and brains.[38,39] Also needed is an acknowledgement that families affected by other people's wood heater pollution have a right to clean air.

Similar to the $25,000 COVID-19 recovery grant for new homes or renovations over $150,000, subsidies to replace wood heater with non-polluting heating (in conjunction with upgraded insulation, when necessary) would be an excellent way to stimulate economic recovery from COVID-19. It could provide additional employment, improve health, reduce heating costs for households that buy firewood and help slow global warming.

11. Choice of exposure risk function

Estimates of the cost of air pollution are highly sensitive to the choice of exposure risk function. The HRAPIE meta-analysis, published in 2013, relied on 11 studies of $PM_{2.5}$ and mortality.[14] Subsequent meta-analyses considered many more published results, including GEMM, published in 2018, which used 41 cohorts from 16 countries.[13] Another meta-analysis published in 2018 considered 53 studies with 135 estimates of the relationship between $PM_{2.5}$ and mortality. The best estimate of the exposure risk function according to the authors of the 53-study meta-analysis was more than twice the HRAPIE estimate.[40]

Recent studies controlling for confounders such as area level socio-economic status, and studies with more accurate estimates of exposure (eg. using space-time exposure models or fixed monitors at postcode level) generally produced higher estimates of increased mortality per unit increase in $PM_{2.5}$,[40] as expected, because of downward bias when the independent variable — $PM_{2.5}$ exposure — is subject to measurement error.[6] Consequently, more recent exposure risk function estimates, such as GEMM, derived from many more studies, including some with more accurate estimates of exposure, are likely to provide better and more robust estimates of the impact of pollution than HRAPIE.

The only recent analysis of Australian long term data (for Queensland, 1998–2013) was based on satellite-averaged $PM_{2.5}$ measurements by postcode. The exposure range (1.6 to 9.0 $\mu g/m^3$) was lower than the Armidale population-weighted background plus wood heater $PM_{2.5}$ exposure of 3.14 + 7.03 = 10.17 $\mu g/m^3$ (Table 1); the exposure risk function for the Queensland study (a 2.0% increase in non-accidental mortality per unit increase in annual $PM_{2.5}$ exposure)[41] was higher than the GEMM exposure risk function in this exposure range.

Many cities and towns in New Zealand have patterns of wood heater pollution similar to those of Armidale; for example, winter PM pollution in Christchurch (90% attributed to wood heating[42]) is much higher than at other times of year,[43] and 76% of annual $PM_{2.5}$ exposure is attributed to domestic sources.[44] Overall, wood heaters account for 56% of anthropogenic $PM_{2.5}$ in New Zealand; a study of long term PM exposure and mortality reported a higher exposure risk function than HRAPIE,[45] again suggesting that estimates based on long term exposure models (such as GEMM or HRAPIE) more accurately reflect the impact of wood heater pollution than those of short term exposure models.

Investigations of mortality in Christchurch during 1988–1999 using distributed lag models led to similar conclusions: "*the combined effect on daily mortality of up to 40 preceding days'* *exposure may be much greater (on average 13–23% increase in mortality per 10 μg/m³ increase of PM10) than the single-day effect".*[42]

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