

Article

# Accurate, Low Cost PM<sub>2.5</sub> Measurements Demonstrate the Large Spatial Variation in Wood Smoke Pollution in Regional Australia and Improve Modeling and Estimates of Health Costs

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**Abstract:** The accuracy and utility of low-cost PM<sub>2.5</sub> sensors was evaluated for measuring spatial variation and modeling population exposure to PM<sub>2.5</sub> pollution from domestic wood-heating (DWH) in Armidale, a regional town in New South Wales (NSW), Australia, to obtain estimates of health costs and mortality. Eleven ‘PurpleAir’ (PA) monitors were deployed, including five located part of the time at the NSW government station (NSWGov) to derive calibration equations. Calibrated PA PM<sub>2.5</sub> were almost identical to the NSWGov tapered element oscillating microbalance (TEOM) and Armidale Regional Council’s 2017 DustTrak measurements. Spatial variation was substantial. National air quality standards were exceeded 32 times from May–August 2018 at NSWGov and 63 times in one residential area. Wood heater use by about 50% of households increased estimated annual PM<sub>2.5</sub> exposure by over eight micrograms per cubic meter, suggesting increased mortality of about 10% and health costs of thousands of dollars per wood heater per year. Accurate real-time community-based monitoring can improve estimates of exposure and avoid bias in estimating dose-response relationships. Efforts over the past decade to reduce wood smoke pollution proved ineffective, perhaps partly because some residents do not understand the health impacts or costs of wood-heating. Real-time Internet displays can increase awareness of DWH and bushfire pollution and encourage governments to develop effective policies to protect public health, as recommended by several recent studies in which wood smoke was identified as a major source of health-hazardous air pollution.

**Keywords:** wood smoke; low cost sensors; calibration; health costs; spatial variability; PM<sub>2.5</sub>

## 1. Introduction

Particulate matter  $\leq 2.5$   $\mu\text{m}$  in aerodynamic diameter (PM<sub>2.5</sub>) is considered the most health-hazardous air pollutant [1] that causes more deaths and illnesses than all other environmental exposures combined [2]. As shown in Table 1, domestic wood-heating (DWH) is now recognized as the largest single source of PM<sub>2.5</sub> in Australia, New Zealand and many cities and towns in other countries, despite, in many cases, only a small proportion of households using wood as the main form of heating. In Sydney, for example, only 4.4% of households use wood as main heating, but DWH accounts for over 50% of annual PM<sub>2.5</sub> emissions (Table 1). Estimated health costs often amount to thousands of dollars per heater per year (Table 1).

Accurate estimates of health costs and the exposure–response relationships used to derive those costs require accurate estimates of exposure. Otherwise the models can be subject to considerable bias [3] leading to inaccurate results. One difficulty is that DWH pollution has considerable spatial and temporal variation [4,5] and the locations of some current fixed monitors were chosen to measure

traffic pollution [6] and therefore provide inaccurate estimates of population exposure. Car-based night–time monitoring (using optical instruments calibrated by comparison with official government or other accredited PM<sub>2.5</sub> data) was used by some researchers to monitor spatial variation [4,7–9]. The alternative of accurate low-cost community monitors in fixed locations has several advantages, including continuous measurements that are readily available to the public in real time over the Internet and no need for researchers to be exposed to high levels of PM<sub>2.5</sub> pollution, often in excess of 100 µg/m<sup>3</sup>. Such monitors could also satisfy the need to monitor bushfire smoke and provide warnings in small towns for which standard equipment is prohibitively expensive. In June 2020, Asthma Australia called for improvements at a NSW parliamentary inquiry because lives are “at risk due to inadequate air quality monitoring” [10].

**Table 1.** Some studies showing domestic wood-heating (DWH) is a major source of particulate matter ≤2.5 µm in aerodynamic diameter (PM<sub>2.5</sub>) pollution that causes considerable health costs in several countries, states and regional or metropolitan areas.

Location	Contribution to PM <sub>2.5</sub> Pollution and Health Costs
Tasmania, Australia	Estimated health costs in Tasmania = A\$4232 per wood heater per year [11]; 43.4% of days were polluted with DWH smoke (mean PM <sub>2.5</sub> = 7.7 µg/m <sup>3</sup> ); 30.6% of days were polluted with landscape fire smoke (mean PM <sub>2.5</sub> = 4.2 µg/m <sup>3</sup> ); 26% of days were unpolluted (mean PM <sub>2.5</sub> = 1.4 µg/m <sup>3</sup> ) [11].
Victoria, Australia	Estimated health costs of DWH pollution in Victoria = A\$8 billion over 10 years [12]. For the Port Phillip air quality control region (PPAQR), the average wood heater was reported to burn 3.75 tonnes per year. The health cost was estimated at A\$180 per kg PM <sub>2.5</sub> emissions [12]. This implies that a brand new wood heater satisfying current requirements and real-life emissions of 6.5 g per kg wood burned (the best available estimate [13]) has estimated annual health costs in the PPAQR of 180 × 3.75 × 6.5 = A\$4388.
New South Wales (NSW), Australia	Estimated cumulative health costs = A\$8 billion, more than A\$21,000 for every wood heater in NSW [14].
New Zealand	In New Zealand (NZ), DWH accounts for 56% of the estimated health costs of man-made air pollution, equivalent to NZ\$4425 (about A\$4238) per wood heater per year [15,16].
European Union (EU)	Households are said to be the main source of fine particulate matter emissions in the EU because of DWH [6]. In the Île-de-France, Paris, 56% of total PM <sub>1</sub> emissions were attributed to DWH in the Airparif inventory. DWH was also identified as and the most important source of volatile organic compounds during the winter season (47%, compared to 22% from traffic) [17]. Although estimated health costs in Europe are lower than Australia and NZ (e.g., in Denmark 7650 kr, approximately A\$1700 per wood heater per year [18]), such costs are still likely to outweigh the benefits. Emissions from wood-heating are increasing [19], unlike other sources of PM <sub>2.5</sub> pollution. From 1998–2018 the UK’s wood-heating PM <sub>2.5</sub> emissions increased from 13,215 to 40,676 tonnes, representing 38% of all UK PM <sub>2.5</sub> emissions, 3.4 times the 11,983 tonnes of PM <sub>2.5</sub> emissions from all UK road transport [20], even though only 7.5% of the UK population use wood for some of their heating [21].
USA and Canada	Source apportionment studies in several Northwest US locations identified wood smoke as the dominant source of wintertime air pollution. In December–January, PM <sub>2.5</sub> averaged 22.4, 20.2, 16.0, 12.8 and 7.1 µg/m <sup>3</sup> , respectively, in Lakeview, Klamath Falls, Oakridge, Fairbanks and Portland, representing 93%, 86%, 91%, 52% and 58% of all measured PM <sub>2.5</sub> [22]. In five western Montana valley communities, wood smoke was identified as the major source (56–77%) of PM <sub>2.5</sub> pollution from November–February when PM <sub>2.5</sub> averaged 9–13.7 µg/m <sup>3</sup> [23]. Wood smoke was also found to contribute 74% of wintertime PM <sub>2.5</sub> in Golden, British Columbia [22].
Sydney Greater Metropolitan Region, Australia	The most recent inventory (for 2013) attributes 50.4% of Sydney’s man-made PM <sub>2.5</sub> emissions to domestic solid fuel heating [24]. In 2019, DWH was estimated to account for a population-weighted annual exposure (PWAE) of 0.75 µg/m <sup>3</sup> (31% of total PWAE to man-made PM <sub>2.5</sub> ) in the New South Wales Greater Metropolitan Region (NSW–GMR) [25]. An earlier estimate in 2017 was that DWH (used as main heating by only 4.4% of Sydney households) accounted for 0.49 µg/m <sup>3</sup> PWAE, 1400 years of life lost (100 premature deaths, i.e., 24% of pollution-related deaths in the NSW–GMR), compared to, e.g., 4.1% of PWAE for man-made PM <sub>2.5</sub> from petrol vehicle exhausts [26]. Pro-rating the more recent exposure estimate of 0.75 µg/m <sup>3</sup> [25] would imply that DWH is responsible for 153 premature deaths in the NSW–GMR or 2148 lost years of life annually.

Table 1. Cont.

Location	Contribution to PM <sub>2.5</sub> Pollution and Health Costs
Muswellbrook, (mining town) Hunter Valley, Australia	Muswellbrook is near to open-cut coal mines and power-stations generating enough electricity for 3.25 million homes. Only about 940 households in the urban area use wood-heating, but DWH was considered responsible for 62% of Muswellbrook's wintertime PM <sub>2.5</sub> [27].
Armidale, NSW, Australia	Substantial spatial variation in DWH pollution and estimated health costs of A\$4270 per wood heater per year [4].

Armidale, NSW, Australia has a population of about 24,000 with approximately 3000 households using wood-heating. Previous research into wood smoke pollution demonstrated the considerable spatial variation in night-time PM<sub>2.5</sub> measurements and that estimated health costs exceed A\$4000 per wood heater per year [4]. The current study aimed: (1) to review published information and identify the most accurate and useful low-cost PM<sub>2.5</sub> monitors, (2) assess their accuracy and utility to measure PM<sub>2.5</sub> pollution in an area affected by wood smoke and derive appropriate calibration equations using NSW government data (from the station installed in Armidale in April 2018) and compare results with the local council's DustTrak data and (3) build on previous research using the calibrated measurements to obtain updated estimates of spatial variation, population exposure, mortality and health costs, in Armidale, NSW. Consequences for policy development are also discussed.

## 2. Experiments and Data

### 2.1. Monitoring Equipment

#### 2.1.1. DustTrak

Armidale Regional Council (ARC) and predecessor (Armidale Dumaresq Council) operated a DustTrak 8520 for many years. Located on the roof of the Council Building, it was checked and calibrated for wood smoke using procedures developed for Tasmania's BLANKET network of 29 TSI DRX DustTraks [28] that provide real-time, highly accurate measurements of wood smoke without the substantial expenditure needed for reference or equivalent equipment available at the time (microbalances, air conditioned enclosures, power, maintenance [28,29]). ARC's DustTrak ceased operation in 2017 when it was considered to have reached the end of its useful life.

#### 2.1.2. TEOM and Nephelometer

In April 2018, the NSW government Office of Environment and Heritage (OEH) installed an air-quality monitoring station at Armidale's Harris Park football field, about one kilometer to the north of the Council Building (Figure 1). The NSW government station (NSWGov) is equipped with an Ecotech (Aurora 1000G) integrating nephelometer and a tapered element oscillating microbalance (TEOM 1405) with filter dynamics measurement system (FDMS). The FDMS directs particle-laden air to the microbalance for six min (to weigh the particles), then filtered air for six min (reference period)—a 12 min cycle repeated five times per hour. This system is used for aerosols affected by wood smoke because they contain volatile particles (e.g., creosotes) that can evaporate from the heated microbalance. The FDMS system therefore estimates and corrects for the weight of evaporating particles.



**Figure 1.** Measurement locations (yellow markers), site names (white text) and estimated average annual PM<sub>2.5</sub> exposure from wood smoke, Armidale, 2017–2018.

Because particles are weighed for only half the time, differences in pollution levels and evaporation during the reference and measurement periods can create inaccuracies, some of which can result in negative pollution readings at low PM<sub>2.5</sub> levels. Analyses of relationships between TEOM PM<sub>2.5</sub> and other collocated monitors should therefore consider discrepancies between TEOM PM<sub>2.5</sub> (based on weights for 50% of each hour) and monitors recording data for the entire hour. As well as PM<sub>2.5</sub> (generally recognized as the most health-hazardous air pollutant), PM<sub>10</sub> (to indicate the presence of any larger dust particles), temperature and humidity data were downloaded from the NSW government website as daily and hourly averages.

The very high correlations between daily average TEOM and nephelometer measurements ( $r = 0.98$ ) allowed a simple equation to be developed to accurately predict daily average PM<sub>2.5</sub> from daily average nephelometer measurements.

### 2.1.3. Low-Cost Monitors

California's South Coast Air Quality Management District's AQ-SPEC carried out field evaluations of 44 low to moderate cost PM<sub>2.5</sub> monitors by comparing them with two US Federal Equivalent Method (FEM) PM<sub>2.5</sub> instruments. A subset of 14 sensors with acceptable field performance were compared with PM<sub>2.5</sub> dust concentrations at the AQ-SPEC laboratory under controlled conditions in an environmental chamber alongside FEM instruments [30].

Of the 44 sensors tested, PurpleAir (PA-II) had the highest field correlations (0.95–0.99) with FEM instruments (a MetOne beta-attenuation monitor costing US\$20,000 and a GRIMM EDM 180 PM<sub>2.5</sub> optical particle counter costing US\$25,000). Excluding a faulty sensor in one PA unit (evident from unexpectedly low correlations between that PA unit's two sensors), field correlations between individual PA sensor's 1-h PM<sub>2.5</sub> and GRIMM measurements averaged 0.99, although the slopes of the relationships were less than unity [31–33]. Correlations with PM<sub>2.5</sub> dust concentrations in the lab test were equally high, but the slope was greater than unity [34]. Part of this study was therefore

to compare PA data with data from the official NSW government PM<sub>2.5</sub> measurements to derive calibration equations for wood smoke and ensure PA measurements were identical to what NSWGov equipment and the local council's DustTrak would measure.

Three PurpleAir (PA) units (Armidale\_1, 2 and 3, costing less than A\$300 each) were installed in July 2017. Two were installed in residential areas, one south of the CBD (Res1\_S) and another to the east of the CBD (Res1\_E). The third was collocated beside Armidale Regional Council's DustTrak monitor. In 2018, the units were deployed to various locations including periods of collocation with the NSWGov equipment. In 2018, additional PA-II units were purchased by Armidale Regional Council and deployed at various locations (Figure 1) including NSWGov.

Wood smoke is now recognized as the dominant source of wintertime PM<sub>2.5</sub> in many urban areas. Consequently, it is important to ensure calibrations are accurate and to measure in locations that cover the expected range of PM<sub>2.5</sub> pollution, so that information is available on spatial variation and to provide accurate estimates of population exposure. An added advantage of the PA system is that real time data can be displayed on maps that are freely available on the Internet and downloaded for further analysis. This system is now a popular choice with thousands of units installed worldwide, so it is important to have validated calibration equations for common pollutants such as wood smoke.

## 2.2. Checking and Calibrating Sensors

A total of 5 PA units were collocated on the roof of the NSWGov pollution station in Armidale (Figure S1) in 2018 for the periods shown in Table 2. One PA unit was also collocated with ARC's DustTrak monitor in 2017, as noted above. Two variables representing PM<sub>2.5</sub> (PM2.5\_CF\_ATM and PM2.5\_CF\_1) were downloaded from the PA website as 80-s averages and converted to hourly averages to match the NSW government data. Both variables were very highly correlated with TEOM and nephelometer (neph) measurements, but PM2.5\_CF\_1 (henceforth abbreviated to PA2.5C1) showed slightly closer correlations, so was used for this study. The very high correlations (averaging 0.99) between hourly PA2.5C1 and nephelometer data, observed over a 6 month period for ARC1, suggest that PA units can predict hourly neph coefficients with virtually no error. Calibration equations were therefore derived to convert PA2.5C1 to neph measurements, which were then converted to daily average TEOM PM<sub>2.5</sub>. The calibrations of PA units that had not been collocated at NSWGov were checked before deployment by operating them for a few days alongside PA ARC2, after its initial calibration period at NSWGov (Table 2).

**Table 2.** Relationships of hourly average PurpleAir (PA2.5C1<sup>1</sup>) with nephelometer (neph) measurements at the Armidale NSW government pollution station.

PA Monitor	Correlation with Neph	Regression Equation to Predict Neph		Dates When Collocated, Day/Month
		Slope	Intercept	
ARC1	0.99	0.023	0.03	31/5–23/12
ARC2	0.98	0.023	0.05	31/5–8/6, 8/7–17/12
Armidale_1	0.99	0.026	ns	8/6–14/6
Armidale_2	0.99	0.023	ns	10/5–8/6
Armidale_3	0.99	0.027	ns	9/5–8/6

<sup>1</sup> PA2.5C1 = 'PM2.5\_CF\_1\_μg/m<sup>3</sup>', downloaded as 80-s averages from the PurpleAir website.

## 3. Results

### 3.1. Calibration Equations

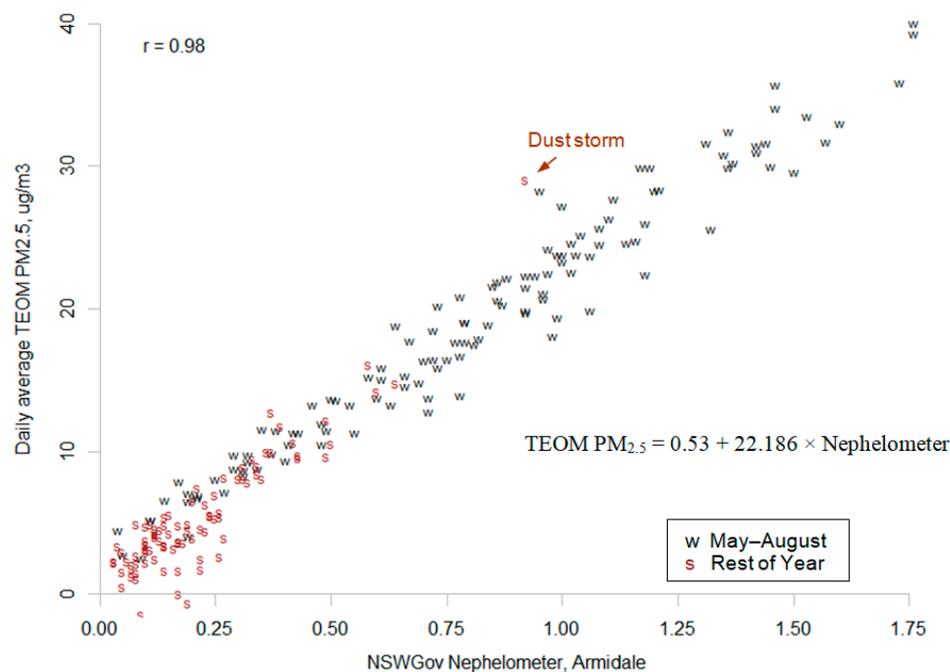
#### 3.1.1. TEOM PM<sub>2.5</sub> vs. Nephelometer

National Air Quality PM<sub>2.5</sub> standards are based on annual and daily averages, so the relationship between daily average TEOM and nephelometer readings was investigated. Use of daily averages avoids some of the inaccuracies of hourly TEOM measurements. At low PM<sub>2.5</sub> levels, some inaccuracies

were nonetheless evident in the validated data, including one day (17 November) with daily average TEOM of  $2.8 \mu\text{g}/\text{m}^3$  and 22 negative hourly readings.

Figure 2 shows the relationship between daily average TEOM and neph measurements in 2018 at the NSW government station by season (May–August, rest of the year). The high correlation ( $r = 0.98$ ) between daily average TEOM and neph data indicates the overall strength of the relationship (Figure 2), as does the fact that only a modest departure from the overall relationship was noted for a dust storm when  $\text{PM}_{10}$  averaged a very high  $158 \mu\text{g}/\text{m}^3$ , but  $\text{PM}_{2.5}$  was much lower at  $29 \mu\text{g}/\text{m}^3$ . Both linear and quadratic relationships were modeled, with and without a few days identified as being affected by dust storms. Excluding the days with dust storms increased the multiple  $R^2$  from 0.95 to 0.96. The multiple  $R^2$  from the quadratic relationship was also 0.96, so a simple linear relationship (excluding dust storm days) was considered adequate:

$$\text{TEOM} = 0.53 + 22.186 \times \text{neph} \quad (1)$$



**Figure 2.** Comparison of daily average  $\text{PM}_{2.5}$  and nephelometer measurements at the NSW government station, Armidale.

The average number of hours per day with negative TEOM readings was calculated to assess the accuracy of hourly data. For May to August 2018, the average was a low 0.8 h per day (presumably because most hourly averages were higher than the measurement error), increasing to 3.4, 6.4 and 10.6 h, respectively for September, October and November 2018. Interestingly, initial data (unvalidated, except perhaps for simple automatic checks, but available within a day of measurement) had more missing values and fewer negative readings, e.g., only 6.1 h per day of negative pollution in November.

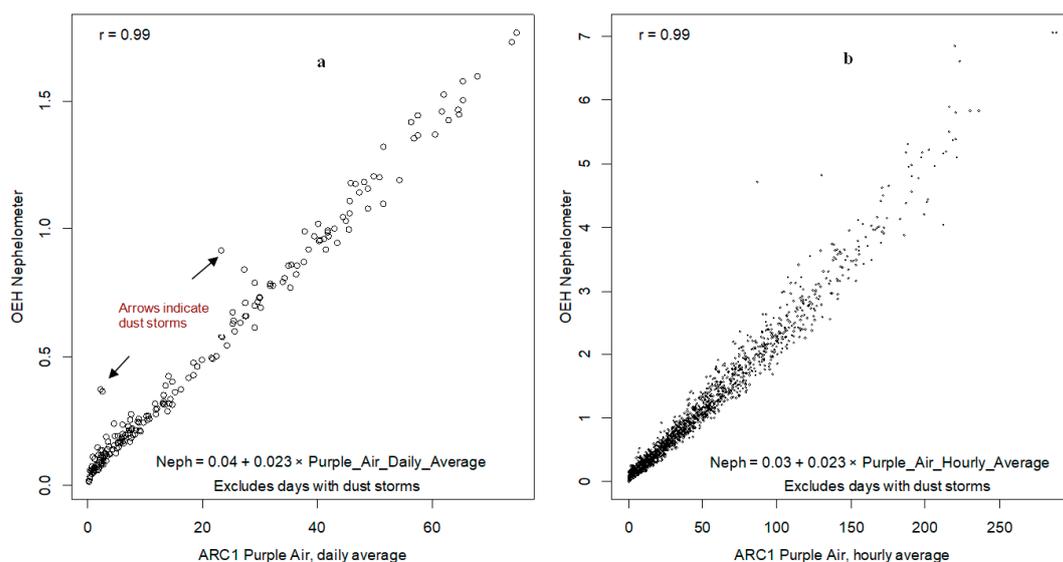
The effects of particle size and dust storms were examined by comparing daily  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  pollution. Three major outliers from the overall relationship (Figure S2) with very high  $\text{PM}_{10}$  (158, 95,  $102 \mu\text{g}/\text{m}^3$ ) but much lower  $\text{PM}_{2.5}$  (29, 12,  $13 \mu\text{g}/\text{m}^3$ ) corresponded to days when severe dust storms were reported [35,36]. Dust storms have larger particles, e.g., dry soil blown away by high winds, often in droughts, such as those commencing in NSW in 2017 and continuing in 2018 [37].

Excluding the 3 major outliers, the fitted equation was:  $\text{PM}_{10} = 4.6 + 1.05 \times \text{PM}_{2.5}$  ( $r = 0.91$ ), implying that approximately 95% of any increase in  $\text{PM}_{10}$  pollution above  $4.6 \mu\text{g}/\text{m}^3$  consisted of the much smaller and generally more health-hazardous  $\text{PM}_{2.5}$  particles, as would be expected when wood

smoke is the dominant source of PM<sub>2.5</sub>. The size distribution of wood smoke particles was shown to have a single peak between 0.1 µm and 0.2 µm [38].

### 3.1.2. PA vs. Nephelometer and TEOM

Relationships with neph measurements and periods when the 5 PA units were located at the NSW government station are shown in Table 2. Figure 3a,b show the very strong ( $r = 0.99$ ) relationships between daily and hourly average neph and PA ARC1 data, recorded continuously at NSWGov from 31 May to 23 December.



**Figure 3.** Comparison of daily (a) and hourly (b) nephelometer and ‘PurpleAir’ measurements (from PA ARC1, see Table 2) at the NSW government station, Armidale.

Three days of dust storms (1 September, 22–23 November) were noted to depart somewhat from the relationship on most other days. Hourly averages (Figure 3b) cover a much larger range, but the relationship with nephelometer readings was equally strong ( $r = 0.99$ ) and almost identical ( $\text{neph} = 0.023 \times \text{PA} + 0.03$  (hourly averages) or  $0.04$  (daily averages)), implying that relationships derived using hourly averages should provide accurate calibrations of PA units. The difference in intercepts for daily vs. hourly averages equates to  $0.25 \mu\text{g}/\text{m}^3$ —much smaller than some inaccuracies in TEOM readings, e.g.,  $-2.8 \mu\text{g}/\text{m}^3$  on 17 November.

Temperature and humidity measurements were examined to determine if there were any effects of fog and mist. The inlet stream to the nephelometer is heated to drive off water droplets [39] so it should not be affected by ambient temperature or humidity. Temperatures inside the PA housing are also somewhat higher, and humidity lower, than ambient, because of a small amount of heat is given off by the Wi-Fi unit. Neither ambient temperature nor humidity significantly affected the relationship between PA and nephelometer measurements. Similarly, there was no significant effect of temperature nor humidity measured inside the PA unit. This implies that there should be little concern, under the conditions in this study, about the ability of PA measurements to predict ambient PM<sub>2.5</sub> when there is mist or fog.

Hourly averages from all PA units were highly correlated with nephelometer measurements (average  $r = 0.99$ , Table 2). There was some minor variation in slopes; for ARC1 and ARC2, the intercepts were significantly different from zero (Table 2), but the differences were relatively small compared to the range of measurements—an intercept of  $0.03$  equals a PM<sub>2.5</sub> concentration of  $0.63 \mu\text{g}/\text{m}^3$ . These results provide confidence that PA units can provide accurate prediction of nephelometer readings—either

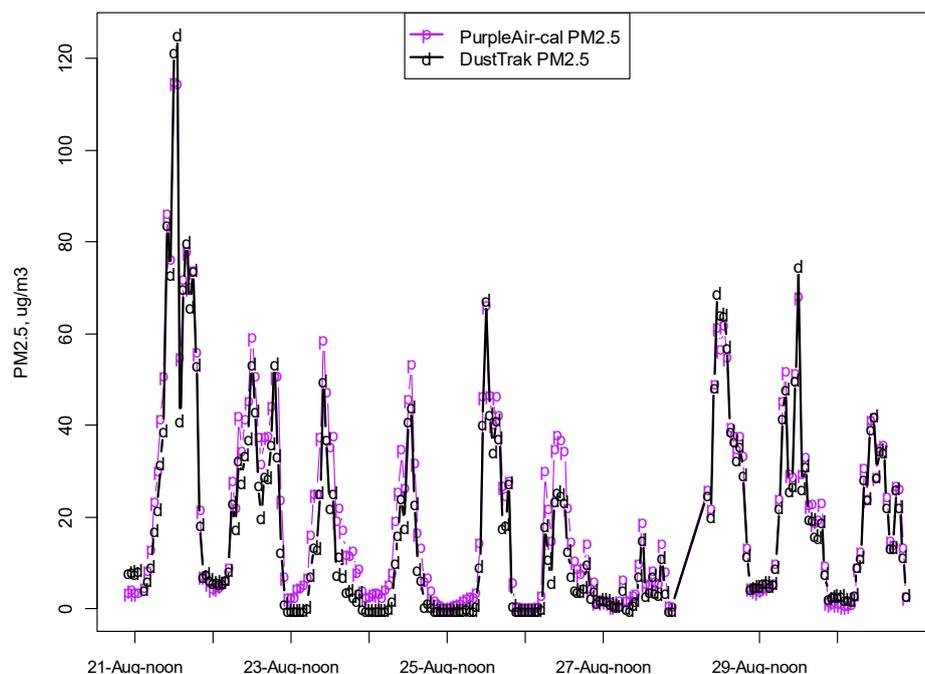
daily or hourly averages—which can then be converted to daily average  $PM_{2.5}$  using the slope of Equation (1).

To avoid any risk of overestimating the true amount of pollution from PA measurements, the intercept of 0.53 in Equation (1) was ignored, so that when PA measurements indicated a neph coefficient of zero, the estimated PA  $PM_{2.5}$  measurement was also zero. As shown in Figure A1 this resulted in some underestimation of TEOM  $PM_{2.5}$  measurements on low pollution days (e.g., 3 to 5 July). Predicted  $PM_{2.5}$  from neph measurements including the intercept in Equation (1) are also shown in Figure A1 for comparison. On most days, the two follow each other very closely, except for the effect of the intercept. Exceptions are days with dust storms when the nephelometer predicts substantially higher  $PM_{2.5}$  than PA units.

The average slope for the 5 PA units with the neph was 0.0246. Multiplying this by 22.186 (the slope of Equation (1) converting neph to TEOM measurements) generates a conversion factor of 0.55. Thus, for  $PM_{2.5}$  in a wood smoke-affected area, the value of  $0.55 \times PA_{2.5C1}$  provides a highly accurate estimate of  $PM_{2.5}$  almost identical to what would be measured by a TEOM at the same location. The PA website displays  $PM_{2.5}$  using various conversion factors, the default being  $PM_{2.5\_CF\_ATM}$  ( $PA_{2.5CA}$ ). Wood smoke  $PM_{2.5}$  could be added to the list. However,  $PA_{2.5CA}$  is equal to about two thirds  $PA_{2.5C1}$ , so the AQandU conversion ( $2.65 + 0.778 \times PA_{2.5CA}$ ) has a very similar slope to that derived here for wood smoke ( $0.55/0.67 = 0.82$ ) and could serve as a suitable alternative.

### 3.1.3. PA vs. DustTrak

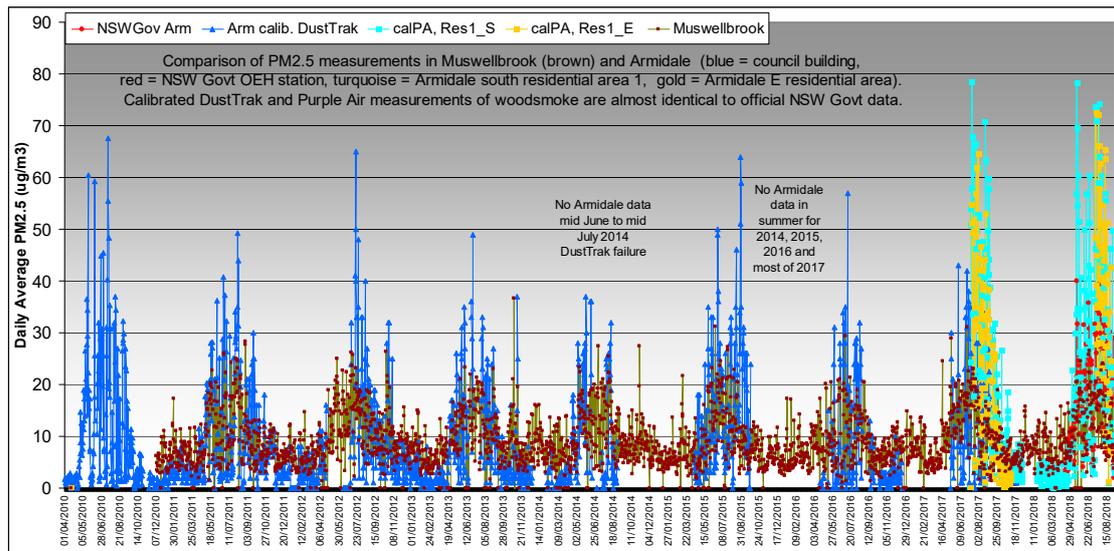
Comparison data were available only for 21 August to 1 September because of problems with power supplies and Internet communications. The calibration equation in Table 1 was used to convert PA Armidale\_3 measurements to what would have been recorded by the NSWGov TEOM. Figure 4 shows that the results are almost identical to published DustTrak  $PM_{2.5}$  measurements (using the calibration described above). Apart from a few occasions when the DustTrak records zero, but the PA has a slightly higher reading, the concordance is remarkable, suggesting that both calibrated DustTrak and PA units have almost identical measurements to what would be recorded by the NSWGov TEOM.



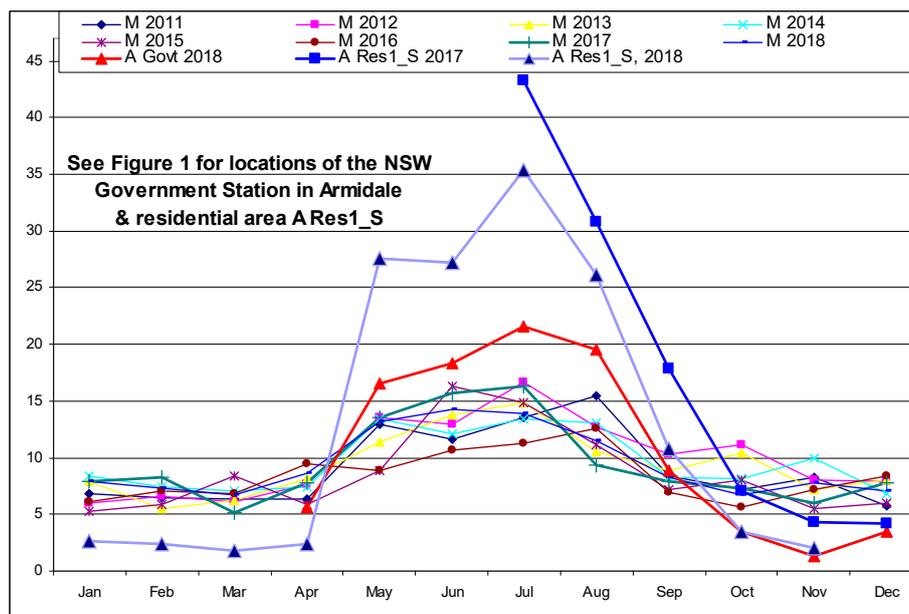
**Figure 4.** Comparison of calibrated PurpleAir  $PM_{2.5}$  and the Armidale Regional Council DustTrak measurements, 21 August to 1 September 2017.

### 3.2. Spatial and Temporal Variation

Figures 5 and 6 and Figure S3 compare Armidale’s PM<sub>2.5</sub> pollution (dominated by wood heater smoke) with other locations such as the Hunter Valley mining town of Muswellbrook, where other sources are often perceived to dominate, because of proximity to open-cut mines and power stations generating enough electricity for 3.25 million homes. The high wintertime peaks in Muswellbrook (Figure 5) and even higher peaks in Armidale, strongly support the chemical fingerprinting results that wood smoke is also the dominant source in Muswellbrook, accounting for 62% of wintertime PM<sub>2.5</sub> and 30% to 34% of annual PM<sub>2.5</sub> (about 3 µg/m<sup>3</sup>) [27].



**Figure 5.** Daily average PM<sub>2.5</sub>, 2010–2018, at the NSW government air pollution stations in Muswellbrook (brown) and Armidale (red), DustTrak PM<sub>2.5</sub> (blue, wood smoke calibration) at Armidale Regional Council building and calibrated PurpleAir PM<sub>2.5</sub> measurements (gold & cyan) at two locations in Armidale.



**Figure 6.** Monthly mean PM<sub>2.5</sub> measurements by year in (M) Muswellbrook and (A) Armidale at the NSW government stations and a residential area in Armidale in 2017 and 2018.

In Armidale, calibrated PurpleAir  $PM_{2.5}$  measurements in 2017 and 2018 show much higher  $PM_{2.5}$  pollution in some residential areas than the central business district or the NSWGov station, e.g., from May to August 2018, Res1\_S had 63 days exceeding the National Air Quality Standard of  $25 \mu\text{g}/\text{m}^3$  (and many more exceeding the stricter standard of  $20 \mu\text{g}/\text{m}^3$  to be introduced in 2025), compared to 32 reported exceedances at the NSWGov station, all attributed in the NSW Annual Air Quality Statement to wood-heating [40]. Figure S3 provides additional comparisons of daily average  $PM_{2.5}$  at two sites in central Sydney (Rozelle and Macquarie Park), the two Hunter Valley towns with NSWGov monitoring stations, together with TEOM and calibrated PA measurements at the Armidale NSWGov site and at Armidale residential areas Res1\_S and Res1\_E. The difference between TEOM and PA measurements is almost negligible compared with the much greater spatial variation, indicating that calibrated PA  $PM_{2.5}$  measurements are much more accurate than measurements from expensive equipment located a few hundred meters away.

Monthly averages (Figure 6) highlight Armidale's low  $PM_{2.5}$  outside the wood-heating season. The only data available from Jan to April 2018 were from Res1\_S, which averaged 1.7 to  $2.6 \mu\text{g}/\text{m}^3$   $PM_{2.5}$ . Monthly averages at Res1\_S increased more than 10-fold to 26 to  $35 \mu\text{g}/\text{m}^3$  for May to August when DWH were used (Table 3). In Muswellbrook,  $PM_{2.5}$  averaged  $13.2 \mu\text{g}/\text{m}^3$  from May to August 2018, nearly double the average of  $7.3 \mu\text{g}/\text{m}^3$  for January–March and October–December 2018.

### 3.3. Annual $PM_{2.5}$ Exposure

Table 3 shows monthly average  $PM_{2.5}$  pollution at the locations in Figure 1. To avoid potential biases, an estimation procedure was used if a site had less than 18 days of data that month. First, for sites with least 18 days of data the month, ratios were calculated of mean  $PM_{2.5}$  for each month to the site's mean for July and August. Means ratios for all sites: 8% (April), 90% (May), 89% (June) and 37% (September) were used to estimate monthly averages for sites with insufficient data that month. Means for 2017 were assumed to be 5% higher than measurements in 2018, in line with the 5% higher average  $PM_{2.5}$  in 2017 at the two sites that were measured in both years.

Armidale has no significant sources of  $PM_{2.5}$  pollution apart from the 3000 households using DWH and occasional bushfires or dust storms that normally happen at other times of year. Hence, for simplicity (apart from the intercept of 0.53 in Equation (1), assumed to be unrelated to wood smoke), all measured pollution from May to September was considered to originate from DWH, as was 75% of  $PM_{2.5}$  pollution in April and October. Although wood heaters are used in Armidale before April and after October, the contribution in other months was assumed to be zero.

The PA monitoring sites cover a wide range of locations, from central areas to the less polluted areas on South Hill, so the average of all sites was used as the best estimate of population exposure. One site (Res\_W, upwind of most sources of wood smoke pollution) appeared atypical. Its readings were at variance from all the other monitors on a few days when the entire city suffered high bushfire pollution, so it was omitted from the average.

**Table 3.** PM<sub>2.5</sub> measurements at various locations (shown in Figure 1) in Armidale (estimated values in red).

Month Location	April	May	June	July	August	September	October	November	December	Smoke <sup>1</sup> 2017	Smoke <sup>1</sup>
2017, Res1_S <sup>2</sup>	2.9	33.3	32.8	43.3	30.8	17.9	7.1	4.4		13.8	
2017, Res1_E	2.5	28.9	28.5	39.3	25.0	13.7	2.8	1.9		11.6	
<b>Mean</b>	<b>2.7</b>	<b>31.1</b>	<b>30.7</b>	<b>41.3</b>	<b>27.9</b>	<b>15.8</b>	<b>4.9</b>	<b>3.1</b>		<b>12.7</b>	
<b>2018</b>										<b>2018</b>	<b>2017–2018</b>
<b>NSWGov (TEOM)<sup>3</sup></b>	5.6	16.5	18.4	21.6	19.6	8.9	3.5	1.4	3.5	7.7	7.9
NSWGov (PA) <sup>2</sup>	5.0	18.1	17.5	20.8	18.9	7.3	3.4	2.6	2.3	7.4	7.6
Res1_S	2.4	27.6	27.2	35.4	26.1	10.8	3.4	2.0	2.6	11.0	12.4
Res2_S	2.3	27.1	26.8	34.1	26.2	10.6	3.7			10.8	11.1
Res_E	2.8	32.9	32.4	43.6	29.6	14.3	3.5	2.6	2.0	13.1	12.4
Kent	1.5	17.0	16.4	22.3	15.7	7.4	3.5	3.0	2.2	6.9	7.1
CBD (Libold)	1.3	15.3	14.8	19.3	14.8	6.6	3.5	2.9	2.1	6.2	6.4
Lib	1.7	20.0	22.1	24.8	19.8	9.2	3.8	2.5	2.2	8.3	8.6
E_BV	2.0	22.6	22.3	30.6	19.8	8.1	3.6			9.0	9.2
Res_SE	1.8	20.7	23.1	24.4	21.7	8.8	3.3	2.7	2.2	8.6	8.8
SthH	1.3	14.9	14.7	17.9	15.3	6.8	3.2	2.7	2.0	6.1	6.2
SHS	1.2	13.8	6.9	15.4	15.4	7.4	3.2	2.7	2.3	5.2	5.3
Res_W	0.8	8.7	7.7	12.8	6.7	4.9	3.5	2.5		3.7	3.8
<b>Overall mean<sup>4</sup></b>	<b>2.2</b>	<b>20.8</b>	<b>20.5</b>	<b>26.3</b>	<b>20.4</b>	<b>9.0</b>	<b>3.5</b>	<b>2.5</b>	<b>2.3</b>	<b>8.4</b>	<b>8.6</b>

<sup>1</sup> Annual wood heater smoke exposure calculated as 100% of pollution from May to September and 75% of that in April and October; means for 2017 were assumed to be 5% higher than in 2018 (see text). <sup>2</sup> Values for PA monitors exclude the intercept of 0.53. Red values show estimated PM<sub>2.5</sub> concentrations, calculated as 8% (April), 90% (May), 89% (June) and 37% (September) of the average for July and August—see text. <sup>3</sup> Annual average PM<sub>2.5</sub> pollution at the NSW government station April 2018 to March 2019 (all sources) = 10.8 µg/m<sup>3</sup>. <sup>4</sup> Overall mean excludes NSWGov PA measurements (the TEOM is used for this site) and Res\_W (possible faulty monitor or atypical location upwind of most sources of wood smoke pollution).

### 3.4. Estimating Health Effects

#### 3.4.1. Published Exposure–Response Relationships (ERR)

A comprehensive meta-analysis of 53 studies with 135 estimates of the increase in mortality from PM<sub>2.5</sub> exposure was published in 2018. Studies with more accurate estimates of exposure had larger estimates of increased mortality per unit (1 µg/m<sup>3</sup>) increase in PM<sub>2.5</sub> exposure (as expected, because of downward bias when the independent variable—PM<sub>2.5</sub> exposure—is subject to measurement error, see e.g., [3]). For those with the most accurate exposure assessments—using hybrid space time models and fixed monitors at zip code scale—estimates per unit PM<sub>2.5</sub> increase were, respectively, 1.61% (95% CI 1.18–2.04) and 1.67% (95% CI 0.85–2.49) at mean exposure of 10 µg/m<sup>3</sup> [41].

The largest study was of 61 million US Medicare beneficiaries (average age 70 years at study entry) over the years 2000–2012. It had 460 million person–years of follow-up (pyfu) and 22.5 million deaths, including 248 million pyfu and 11.9 million deaths at PM<sub>2.5</sub> exposure below 12 µg/m<sup>3</sup> [42]. The estimated ERR for exposure below 12 µg/m<sup>3</sup> was 1.36% increased mortality per unit increase in PM<sub>2.5</sub>, substantially higher than the overall estimated ERR of 0.73%.

Another comprehensive study published in 2018 used 41 cohorts in 16 countries to derive global exposure mortality models (GEMM) for PM<sub>2.5</sub> exposure and non-accidental mortality. GEMM hazard ratios were derived for overall mortality, lower respiratory infections (LRI), ischemic heart disease (IHD) chronic obstructive pulmonary disease (COPD) and lung cancer. The steepest ERR for overall mortality were at low PM<sub>2.5</sub> levels, where the increase was about 10% for increased exposure of 8 µg/m<sup>3</sup>; the increased risk for IHD and LRI per unit increase in PM<sub>2.5</sub> was about 2% [43].

An analysis of Australian data (Queensland) for 1998–2013 with relatively low PM<sub>2.5</sub> reported 2.0% increased non-accidental mortality per unit increase in annual PM<sub>2.5</sub> exposure [44]. This Australian study and the most recent studies and meta-analyses therefore suggest that the true increase in mortality from PM<sub>2.5</sub> exposure is higher than the 2013 World Health Organization review estimate of 0.62% increased mortality per unit increase in PM<sub>2.5</sub> exposure for people over 30 [45]. The lowest estimate from the comprehensive studies using improved PM<sub>2.5</sub> exposure data is the GEMM analysis—1.25% increased mortality per 1 µg/m<sup>3</sup> annual PM<sub>2.5</sub> increment at exposure of 10 µg/m<sup>3</sup>.

#### 3.4.2. ERR for Wood Heater and Biomass Smoke

Studies where wood smoke is a major component of the aerosol have similar (or even higher) ERR than the GEMM models. A Canadian study with mean PM<sub>2.5</sub> of 5.9 µg/m<sup>3</sup> reported 1.1% increased mortality per unit increase in annual PM<sub>2.5</sub> exposure, with effects extending down to 2 µg/m<sup>3</sup> and steeper ERR slopes at low PM<sub>2.5</sub> levels [46]. An earlier Canadian study with median PM<sub>2.5</sub> concentrations of 7.4 µg/m<sup>3</sup> reported similar results—an increase in annual PM<sub>2.5</sub> exposure of 1 µg/m<sup>3</sup> increased IHD deaths by 3% with 1% to 1.5% increases in all deaths [47]. Excluding open sources (largely from activities associated with construction and dust from paved and unpaved roads), emissions from home firewood burning are the largest source of PM<sub>2.5</sub> in Canada, representing 160 kt (53% of the 300 kt Canadian total in 2014 [48]).

Another Canadian study reported risk ratios for hospital admission due to myocardial infarction (MI). Overall, a 5 µg/m<sup>3</sup> increase in 3-day mean PM<sub>2.5</sub> was associated with 6% increased risk of MI among elderly subjects (≥65 years) [49], an order of magnitude greater than the World Health Organisation (WHO) estimate of 0.45% for increased cardiovascular hospital admissions per 5 µg/m<sup>3</sup> increase in daily PM<sub>2.5</sub> [45]. The difference could be partly due to stratification by age. In the Canadian study, 54% of all cases were 65 years or older; there was no significant effect of PM<sub>2.5</sub> pollution in younger patients. Importantly, during cold periods, the risk increased with increasing proportion of PM<sub>2.5</sub> from biomass combustion (highest tertile: 19%, mid: 8%, lowest: 4%) [49].

In Tasmania where air pollution is mainly associated with wood-burning for winter heating and from bushfires and planned burns at other times of year, a study of hospital admissions for heart failure

showed similar results—above a threshold of  $4 \mu\text{g}/\text{m}^3$ , the risk of hospital admission was estimated to increase by 14.5% for a  $5 \mu\text{g}/\text{m}^3$  increase in  $\text{PM}_{2.5}$  with 1 day time lag [50].

The ‘45 and up’ study in Sydney found a 5% increase in mortality per additional  $1 \mu\text{g}/\text{m}^3$  of  $\text{PM}_{2.5}$  exposure [51], but this was not statistically significant when marital status, physical activity, area level SES, and random location intercepts were added to the model. More data will therefore be required to shed light on the effect of confounders, given a recent study attributing 31% of man-made  $\text{PM}_{2.5}$  pollution to DWH in the metropolitan region [25]; areas with high levels of wood smoke such as Liverpool (in western Sydney) have lower SES.

The Sydney Particle Characterisation Study Report states: “The Mixed-Smoke-Auto contributions at Liverpool during the winter months were on average about  $5 \mu\text{g}/\text{m}^3$  higher than at Mascot, and this is anticipated to be due to wood smoke and biomass burning not associated with controlled burning or bushfire events” [52]. Liverpool’s additional  $5 \mu\text{g}/\text{m}^3$  winter  $\text{PM}_{2.5}$  from wood smoke therefore contributes  $1.25 \mu\text{g}/\text{m}^3$  to annual exposure, substantially more than the observed 25–75% range of  $\text{PM}_{2.5}$  exposure of 0.82 (4.10–4.92) in the ‘45 and up’ Sydney Study.

### 3.4.3. Increased Mortality from Armidale’s Wood Smoke

The above results suggest that the estimate from the GEMM model of 10% increased total mortality per  $8 \mu\text{g}/\text{m}^3$  increased  $\text{PM}_{2.5}$  exposure is likely to represent a plausible, perhaps conservative, estimate of increased mortality due to  $\text{PM}_{2.5}$  exposure from wood smoke. Armidale’s population averaged 24,027 from 2012–2018 with deaths averaging 170 per year [53]. Based on the GEMM model estimate (10% increased total mortality per  $8 \mu\text{g}/\text{m}^3$  increase in  $\text{PM}_{2.5}$  exposure [43]), the estimated increased exposure of  $8.4 \mu\text{g}/\text{m}^3$  from Armidale’s wood smoke in 2018 corresponds to 10.5% increased mortality—an average of 16.2 premature deaths per year. The estimated 2-year average of  $8.6 \mu\text{g}/\text{m}^3$  (Table 3) equates to 16.5 premature deaths per year or about 165 lost years of healthy life, assuming an average loss of 10 years of healthy life per premature death. Wood heater use is common throughout the wider statistical area of New England North West, so a substantial proportion of the 3.1 year gap in life expectancy between New England North West and Greater Sydney in 2013–2018 [54] could be due to wood smoke pollution.

## 4. Discussion

### 4.1. Additional Benefits of Low Cost Sensors—Bushfire Alerts, Actions, Exposure Measurements

Accurate, low-cost sensors have many benefits. They can measure exposure and spatial variation in  $\text{PM}_{2.5}$  pollution from DWH and bushfires and alert residents, especially susceptible groups, to unsafe levels of pollution. Official monitoring in NSW in areas affected by bushfires uses a small number of portable air quality monitoring pods that report measurements after a 1–2 h delay. By contrast, PA measurements can be displayed on the Internet in real time or averaged over 10 min to 1 week periods. Anyone concerned about pollution can check outdoor measurements at the nearest monitor and switch on high efficiency particle air (HEPA) filters before indoor  $\text{PM}_{2.5}$  builds up to dangerous levels, or open windows to ventilate homes or exercise outdoors when air quality is good.

Bushfire smoke can increase and decrease rapidly depending on the wind direction. Accurate low-cost monitors in every town and village could provide immediate warnings to supplement information from a small number of high-cost stations. This is important because research in Tasmania (where the main source of  $\text{PM}_{2.5}$  is DWH and landscape fires) shows that even a  $5 \mu\text{g}/\text{m}^3$  increase in the previous day’s  $\text{PM}_{2.5}$  concentration above a threshold of  $4 \mu\text{g}/\text{m}^3$ , increased hospital admissions for heart failure by 14.5% [50].

Low-cost sensors can also measure indoor pollution and demonstrate that  $\text{PM}_{2.5}$  pollution inside some older-style Australian houses is almost identical to outdoor pollution after a small time delay (Figure A2). In Tasmania, real-time  $\text{PM}_{2.5}$  measurements are available via a web interface from the 35 BLANKET monitors [55] and the ‘Air-Rater’ mobile phone app [56]. Low-cost sensors could extend

the utility of these systems, both in Tasmania and elsewhere. The Tasmanian EPA developed a prototype lower-cost 'babyBLANKET' station that showed much higher measurement (peaks up to  $600 \mu\text{g}/\text{m}^3$ ) outside a bedroom window, than in the street in front of the house (peaks up to  $200 \mu\text{g}/\text{m}^3$  [57]). PA sensors could serve a similar function at even lower cost.

#### 4.2. DWH Contributions to $\text{PM}_{2.5}$ Exposure and Health Costs

A previous study, using a vehicle to measure spatial variation of Armidale's wood smoke, led to a city-wide estimate of  $11.5 \mu\text{g}/\text{m}^3$  for annual wood smoke  $\text{PM}_{2.5}$  exposure. The estimated cost of premature deaths exceeded A\$4000 per wood heater per year, based on 0.7% increased mortality per  $1 \mu\text{g}/\text{m}^3$  increase in  $\text{PM}_{2.5}$  exposure [4]. The large spatial variation (e.g., a 4-fold increase in average night-time  $\text{PM}_{2.5}$ ) was attributed to topography, prevailing wind direction, the potential for smoke to drain downhill and local emissions; individual and groups of chimneys were noted to have a noticeable effect on local pollution [4].

The estimates for wood smoke  $\text{PM}_{2.5}$  exposure from this study ( $8.4 \mu\text{g}/\text{m}^3$  in 2018;  $8.6 \mu\text{g}/\text{m}^3$  for 2017–2018) suggest a slight improvement, although health costs—thousands of dollars per wood heater per year—remain substantial, as are estimated costs of DWH for the whole of Tasmania: A\$293 million annually or A\$4232 per wood heater per year [11]. The same study reported much smaller estimates of the health costs of bushfire and landscape fire smoke—4 deaths and 18 hospital admissions, compared to 65 deaths and 68 hospital admissions for wood heater pollution.

The health costs of wood-heating are substantial because emissions per heater are substantial. A petrol car emits about  $1 \text{ mg } \text{PM}_{2.5}$  per km, i.e.,  $1 \text{ g}$  per 1000 km. Measured real-life emissions of 35 wood heaters in New Zealand averaged  $6.5 \text{ g } \text{PM}_{2.5}$  per kg firewood burned, nearly 8 times worse than the average of the same models in the AS4013 test ( $0.85 \text{ g}/\text{kg}$ ), despite owners knowing their emissions were being measured and most likely operating their heaters as carefully as possible [13]. This suggests that carefully operated brand new heaters burning Sydney's average of 3.4 tons of firewood per year [58] would, on average, each emit  $22.1 \text{ kg } \text{PM}_{2.5}$  per year, as much as 2210 petrol cars each driving 10,000 in the NSW Greater Metropolitan Region.

An 18 month study of pollution from hazard-reduction burns and DWH in the Sydney suburb of Auburn in 2016 and 2017 concluded that: "the overall exposure to air toxins was greater from DWH due to their higher frequency and total duration" [59]. Average population  $\text{PM}_{2.5}$  exposure of  $0.75 \mu\text{g}/\text{m}^3$  from DWH in the NSW-GMR [25] represents the largest single-source of  $\text{PM}_{2.5}$ . Another study found the contribution from DWH in suburbs such as Liverpool is about  $5 \mu\text{g}/\text{m}^3$  more than eastern suburbs such as Mascot, implying substantial spatial variation [52]. Western Sydney's winter DWH average of  $5 \mu\text{g}/\text{m}^3$  is, however, only a quarter of Armidale's winter (June–August)  $\text{PM}_{2.5}$  average of  $20 \mu\text{g}/\text{m}^3$  (NSW Gov site) and a sixth of the  $30 \mu\text{g}/\text{m}^3$  in some residential areas.

#### 4.3. Policy Implications

##### Reducing Wood Smoke Pollution Reduces Mortality

Launceston's wood smoke reduction program encouraged residents to switch to nonpolluting heating. The result was 28% fewer deaths in winter from respiratory disease and 20% fewer cardiovascular disease deaths [60]. By contrast, encouraging residents to operate heaters correctly or replace old wood heaters with newer ones rarely achieved any significant reductions in  $\text{PM}_{2.5}$  pollution [61]. This perhaps explains Armidale's limited success despite the local council's estimates in 2013 that it spent more than A\$300,000 (excluding wages) in the previous 10 years on wood smoke abatement measures [62].

New policies should therefore prioritize the public interest and aim to achieve the greatest benefits for the resources that are available. A consultancy report for the NSW government in 2012 concluded that wood smoke pollution NSW was an A\$8 billion health problem—an average cost of over A\$21,000 per wood heater [14]. Not allowing new heaters and removing existing heaters

(e.g., when houses are sold) was estimated to reduce health costs by 75%—an estimated saving of A\$6 billion for a cost of perhaps A\$170 million, i.e., 35 times as many benefits as costs [14].

The main conclusion from the air quality study in Auburn, Sydney [59] was: “results suggest that policy-makers should place a greater focus on reducing wood smoke pollution in Sydney and on communicating the issue to the public.” Informed consumers would probably not want to spend thousands of dollars on new heaters that damage health, speed up global warming [63] and “give off six times as much pollution as a diesel truck” [64]. Despite advice by NSW Chief Medical Officer that wood-heating is “so detrimental to health she supports banning and phasing them out in built-up urban areas” [65], new wood heaters continue to be marketed as efficient and clean burning with company names such as ‘Clean Air Wood Heaters’ [66].

When cigarette smoke is breathed in, chemicals can enter to the bloodstream and reach every organ of the body, including our brains. Similarly, the chemicals in wood smoke also enter the bloodstream and are transported to every organ in the body and cause similar health problems—heart attacks and strokes, lung diseases, cancers and premature aging [67]. Recent research also links both wood smoke and PM<sub>2.5</sub> exposure to dementia, still births, cot deaths, reduced IQ when children start school and behavioral problems such as attention deficit [68]. In the USA, Italy, China and the Netherlands PM<sub>2.5</sub> exposure has also been linked to increased risk of Covid-19, e.g., if all Netherlands municipalities had 6.9 µg/m<sup>3</sup> PM<sub>2.5</sub> (the same as the least polluted municipality), there may have been 37% fewer Covid-19 cases, 45% fewer hospital admissions and 75% fewer deaths [69].

Wood smoke contains several known human carcinogens, including benzene, benzo[a] pyrene and formaldehyde. Burning 10 kg of wood in a modern Australian heater produces more benzo[a] pyrene than in the smoke from 270,000 cigarettes and more benzene and formaldehyde than in the smoke of 60,000 cigarettes. Tests on mouse skin show that wood smoke causes 12 to 30 times as many tumors and mutations as the same amount of cigarette smoke [70].

Because of the substantial variation in DWH smoke and impact of local sources, policies should also protect the health of nearby residents, especially young children and the elderly. In 2005, New Zealand introduced stricter standards for new wood heaters than currently required in Australia, but every additional wood heater per hectare was recently found to increase by 7% the risk of non-accidental hospital emergency presentations in children under 3 [71]. Given this and the NSW Chief Medical Officer’s recommendation, allowing new wood heaters to be installed seems inconsistent with the principles of ecologically sustainable development required under section 89 of the NSW Local government Act (LGA). Section 89 of the LGA [72] requires councils to consider the public interest including (a) protection of the environment and (b) protection of public health, safety and convenience. A single, modern AS4013 wood-stove is likely to increase PM<sub>2.5</sub> pollution at nearby homes by more than 4 µg/m<sup>3</sup>, the level above which the risk of hospital admission increased in the Tasmanian study [50]. Costs are currently borne by neighbors, taxpayers and the government. Wood-heating would most likely be less popular if users were required to pay the health costs of their pollution—thousands of dollars per heater per year.

New wood heaters continue to be installed in Australia; there is no effective counter to the misleading information promulgated by vested interests who profit from selling wood heaters, including 15 documented incorrect and misleading claims [66]. Campaigns by health promotion groups, together with effective legislation against cigarette smoking created a powerful message that convinced the vast majority that tobacco smoke causes significant harm and is best avoided. With smoking rates of 13% and up to two-thirds of deaths in current smokers attributed to smoking [73], active smoking is estimated to increase mortality by up to 8.7% (13% × 0.67). This is less than the 10.5% increase in mortality from wood-heating in Armidale. The World Health Organization noted that: “Residential heating with wood is a sector in which PM<sub>2.5</sub> and BC emissions can potentially be reduced with greater cost-effectiveness than many other emission reduction options” [74].

Few Armidale residents are aware that, because of improved technology, reverse cycle heater-air-conditioners have lower running costs than buying firewood and contribute less to the global

temperature rise than wood-heating [75]. Like other public health campaigns (e.g., random breath testing), success will require public understanding, as well as effective legislation. Not permitting new heaters to be installed until new standards have been developed to ensure wood heaters comply with the principles of ecologically sustainable development would cost almost nothing but generate considerable community discussions and interest. Such discussions represent one of the most cost-effective ways of helping communities understand the health impacts and monetary costs of wood-heating.

## 5. Conclusions

The calibration equations developed here enable low-cost PurpleAir monitors to provide accurate estimates of wood smoke  $PM_{2.5}$  pollution that are almost identical to those from the NSW government equipment. For most locations, calibrated PA  $PM_{2.5}$  are more accurate than those from a central monitor a few hundred meters away because spatial variation in wood smoke pollution is substantial and depends on local sources such as nearby wood heaters. More accurate exposure estimates allow improved estimates of both exposure–response relationships and health costs.

Accurate low-cost real-time  $PM_{2.5}$  measurements of wood and biomass smoke have many uses, e.g., measuring  $PM_{2.5}$  exposure in small towns, measuring indoor pollution, providing bushfire smoke warnings, alerts to use HEPA filters before indoor  $PM_{2.5}$  builds up to dangerous levels and showing when outdoor air is clean enough to open windows or exercise outside. The calibration equations developed here were noted to be accurate, except in the presence of much larger particle sizes typical of dust storms and not significantly affected by temperature or moisture.

At the NSWGov station in Armidale, National air quality standards were exceeded 32 times from May–August 2018 compared to 63 times in one residential area. Wood heater use by about 50% of households increased estimated annual  $PM_{2.5}$  exposure by at least eight micrograms per cubic meter, suggesting increased mortality of about 10% and estimated health costs of thousands of dollars per wood heater per year.

Studies to measure and model air pollution create benefits only if the information is used to develop effective ways to counter the problem. Efforts in Armidale to reduce wood smoke pollution proved ineffective, partly because many residents do not understand the health costs, which greatly exceed any likely benefits of wood heaters [61]. Accurate real-time community-based monitoring can increase awareness of this much-neglected issue and encourage governments to develop new policies to protect public health. The World Health Organization noted: “Residential heating with wood is a sector in which  $PM_{2.5}$  and BC emissions can potentially be reduced with greater cost–effectiveness than many other emission reduction options” [74]. The NSW Chief Medical Officer said wood-heating is “so detrimental to health she supports banning and phasing them out in built-up urban areas” [65] and in July 2020 the Australian Medical Association backed a call for subsidies to remove home wood heaters “pouring pollution through urban neighborhoods and adding billions of dollars to Victoria’s health costs” [76].

Residents of urban areas would most likely prefer nonpolluting heating to paying the cost of their wood smoke pollution, estimated to amount to thousands of dollars per heater per year. New policies are needed to protect public health, e.g., not permitting new heaters until new standards have been developed to ensure they comply with the principles of ecologically sustainable development and have greater benefits than health costs. This policy would cost almost nothing but stimulate considerable discussions in the community and so provide one of the most cost-effective ways of educating the community about the health impacts and monetary costs of wood-heating.

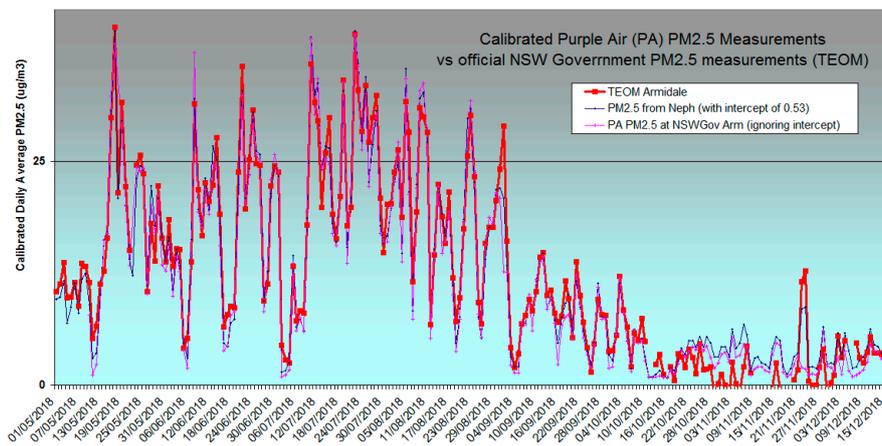
**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2073-4433/11/8/856/s1>, Figure S1: Two PurpleAir Monitors installed on the roof of the NSW government station, Figure S2: Comparison of daily average  $PM_{10}$  and  $PM_{2.5}$  at the Armidale NSW government station, including dates (month and day in 2018) when major dust storms were reported, Figure S3: Daily Average  $PM_{2.5}$  measurements at the NSW government air pollution stations in Sydney (Rozelle, Macquarie Park), Muswellbrook, Singleton (two Hunter Valley mining and power-generation towns) and Armidale, together with PurpleAir  $PM_{2.5}$  measurements at the NSW government station and two residential areas in Armidale.

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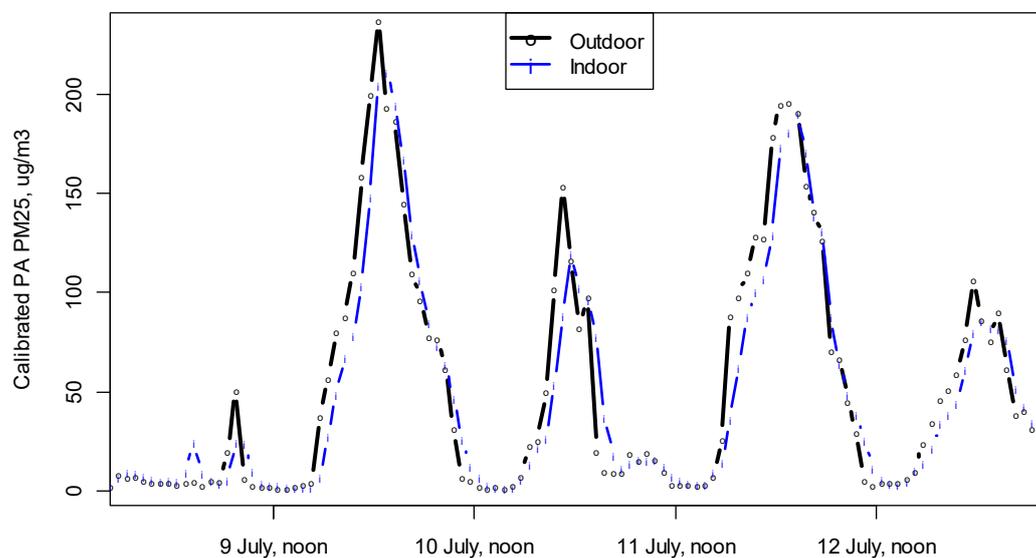
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**Conflicts of Interest:** The author declares no conflict of interest.

## Appendix A



**Figure A1.** Comparison of calibrated nephelometer and PurpleAir PM<sub>2.5</sub> measurements with NSW government tapered element oscillating microbalance (TEOM) PM<sub>2.5</sub> measurements, Armidale 2018.



**Figure A2.** Comparison of hourly average PM<sub>2.5</sub> inside and outside a house in south Armidale, 9–13 July 2018.

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