Air Quality in Association with Rural Coal Mining and Combustion in New South Wales Australia

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Abstract

Purpose. Rural areas may face under-recognized threats to air quality. We tested two hypotheses that 1) rural areas in New South Wales, Australia would have better air quality than metropolitan Sydney, and that 2) the rural Upper Hunter region characterized by coal mining and coal combustion would have worse air quality than other rural areas of the state.

Methods. We analyzed 2017 daily mean values for New South Wales, Australia for particulate matter (PM2.5 and PM10), sulfur dioxide (SO2), nitric oxide (NO), nitrogen dioxide (NO2) and NOx (sum of NO and NO2). Forty-six air monitoring stations were grouped into six rural and urban regional areas. Linear regression models examined pollution levels in association with rural and urban regions and meteorological covariates.

Results. Findings show that daily mean pollutant levels in the rural Upper Hunter were the highest of all regions, and were significantly higher than metropolitan Sydney, with and without control for weather conditions, for every pollutant. For example, daily mean PM2.5 was 8.64 $\mu g/m^3$ in the rural Upper Hunter, compared to 7.23 $\mu g/m^3$ in metropolitan Sydney.

Conclusions. Results highlight the need to consider both urban and rural sources of pollution in air quality studies, and appropriate policy steps to address likely rural air pollution from coal mining.

Key words: rural; particulate matter; gaseous pollutants; coal mining; coal combustion; Australia

Ambient air pollution in developed and developing countries is well-established as a risk to public health [1], and Australia is no exception to this pattern. In studies of urban areas in Australia and New Zealand, higher levels of air pollution increased the risk of elderly adult cardiovascular hospital admissions [2] and child respiratory hospital admissions [3]. Other studies conducted in urban areas in Australia have shown that air pollution is associated with childhood asthma hospitalizations [4], respiratory emergency hospital admissions [5], emergency department visits [6], or cardiac arrest [7]. Although most published studies in Australia show adverse health associations with air pollution, others have been inconclusive or reported null findings [8-10].

General sources of urban pollution include traffic, domestic heating, industry, and power generation that are linked to the large populations of cities, [11] although in Australia, power generation is not a feature of most large cities. In contrast to studies of urban areas, few research studies of Australian rural air quality have been reported. This is generally true of air quality research globally, which has focused most attention on urban areas. Of particular interest for the current study are the possible contributions from coal mining and coal combustion. Globally, there is an extensive body of literature that has established the air polluting effects of coal power generation [12-15]. To a lesser extent, the effects of surface mining for coal on air pollution have also been reported internationally [16-18].

Peer-reviewed academic papers describing coal mining's effects in Australia are few in number, although Higginbotham et al. [19] described environmental injustice issues related to coal mining in the rural Upper Hunter region of New South Wales (NSW), and the political, regulatory, and methodological obstacles to health studies there of mining's effects. Ewald [20] estimated that monetary public health costs of sulfur dioxide emissions from coal power plants in New South Wales far exceeded the pollution fees paid by existing generators. Werner et al. [21]

reported that children's hospital admission rates in Queensland were highest in an area of coal seam gas development, followed by a coal mining area, and were lowest in a rural area without these features.

Additional studies on air quality in Australia have been presented in government and institute reports [22]. Hime et al. [23], for example, provided a review of Australian and international evidence of the health effects of air pollution from coal mining, coal combustion and other sources. A NSW government report provided limited comparative air quality data between Sydney and two other NSW regions (Wollongong and Newcastle), but did not include the Upper Hunter Valley region [24].

The Upper Hunter is largely rural with a population of about 50,000. The Upper Hunter hosts two coal fired power stations with combined annual emissions of 84,000 tons of sulfur dioxide and 51,000 tons of nitrogen oxides. The majority of coal production in New South Wales occurs in the Upper Hunter Valley (171.2 million tons in 2017), and most of this is open cut or surface mining [25]. Open cut mines are spread over more than 16% of the valley floor in the Upper Hunter [26]. Over 253 million tons of coal are produced in the state, more than 75% for export, and the majority of this coal is transported to the Port of Newcastle, the world's largest coal export port [27] in uncovered coal trains that wind their way through the countryside and converge on the Lower Hunter suburbs of Newcastle. The Greater Sydney area, in contrast, does not contain coal mines or coal power plants within the region of the air sampling stations, but has a population of over 5 million people covering approximately 12,368 km^2 [28]. Survey results have indicated that a majority of Hunter Valley residents believe that coal mining in the region has adverse impacts on air quality and health [29].

The objective of the current study was to examine regional differences in air pollution levels across urban and rural areas of New South Wales, Australia. Of particular interest was to test air pollution levels for urban areas, especially Sydney, compared to rural areas in the Upper Hunter region with smaller populations but extensive coal mining and burning activities. We test two hypotheses. First, we test the hypothesis, founded on prior research [11, 30], that pollutant levels will be higher in relation to greater population centers, such that Sydney will demonstrate significantly higher air pollution metrics compared to other areas. Second, we hypothesize that the rural coal mining region will have higher levels of air pollution than other rural portions of New South Wales.

Methods

Design. We conducted an analysis of 2017 data from the New South Wales air quality monitoring stations. Forty-six monitoring stations were grouped into six regions as identified by the NSW Office of Environment and Heritage Air Monitoring Network [31], including Sydney, Illawarra, Upper Hunter community, Upper Hunter monitoring, Lower Hunter, and other Rural. Sydney, Illawarra, and the Lower Hunter are metropolitan areas; the two Upper Hunter regions and the other rural region are classified as rural. We divided the Upper Hunter stations into two groups, community and monitoring, to distinguish those proximate to population community settlements and others used as monitoring stations that are close to mining sites but not as close to communities; we used designations provided by a NSW air quality report for this purpose [32].

Figure 1 shows a map of New South Wales. Sydney is indicated with a single sample location, rather than each sampling station, due to the scale of the map. Illawarra is the coastal area south of Sydney with Wollongong as the major population center; the population of the

region is over 400,000. The Lower Hunter (population over 500,000) is northeast of Sydney with Newcastle as the major center. The rural Upper Hunter (population approximately 50,000) is inland and northwest of Newcastle and includes the community of Singleton. The Upper Hunter community and monitoring stations are marked with labels 'A' and 'B' respectively. The other rural monitoring stations include a large inland area from Albury in the south to Tamworth in the northeast; populations range from about 41,000 in Tamworth to 13,000 in Narrabri.

Measures. Daily mean values for five criteria pollutants were examined including particulate matter <10 and < 2.5 μm in diameter (PM10 and PM2.5), nitric oxide (NO), nitrogen dioxide (NO2), and sulfur dioxide (SO2). The daily average was the mean value across hourly or continuous observations for each day of the year as provided in the air monitoring network database. We also summed NO and NO2 into a total nitrogen oxides (NOx) indicator. Ozone was not included in our analysis because it was not collected across multiple regions. The Upper Hunter non-population monitoring sites collected only PM10, and the other Rural stations collected only PM2.5 and PM10, but in other regions at least two stations collected all five pollutants.

Particles were measured as micrograms per cubic meter ($\mu g/m^3$), and gases as parts per hundred million (pphm). PM2.5 was measured using beta attenuation monitoring (BAM) (Thermo Scientific Model 5014i), and PM10 was measured continuously using tapered element oscillating microbalance (Thermo Scientific TEOM 1405). NOx was measured by chemiluminescence (Thermo Scientific Model 42i and Teledyne Model T200), and SO2 was measured by fluorescence (Thermo Scientific Model 43i and Teledyne Model T100). All monitoring stations met quality assurance standards set by the government [33] and were accredited by the National Association of Testing Authorities.

Table 1 lists the air monitoring stations by region and lists which pollutants were assessed at each station in 2017. Most pollutant data were provided for each day of the year although there were occasional missing observations, and one station (Parramatta North) had data for only about the last month of the year. (In results not shown we removed Paramatta North and re-conducted analyses with no effect on final results.)

Meteorological data including average daily Celsius temperature, relative humidity, wind speed, and wind direction were recorded for each monitoring station. In most cases all four of these variables were available on an hourly basis and were aggregated into daily values for each station. Wind direction was originally measured as degrees from 0 to 360, but we converted wind direction into a four-group categorical variable capturing winds from the most commonly occurring groupings including the northeast through southeast (i.e. primarily onshore), south, west, and northwest. Occasions when the humidity levels were above 95% for the daily average were used to identify days when rain had likely occurred.

Analysis. Analyses were constructed to test null hypotheses that air quality indicators would not be significantly different between regions, and when overall regional differences were present, to test for differences between pairwise regional values with Tukey correction for Type I error rates. Linear regression models used daily mean values of the criteria pollutants as dependent variables, with region as a categorical independent variable. We first estimated models with only the regional dependent variable, and then in subsequent models added weather variables as covariates. Weather variables were considered because of the possible effects of these variables on pollutant levels [34, 35]. We conducted a sensitivity analysis that excluded days with humidity>95%. A second sensitivity analysis was conducted by eliminating outlier observations based on an examination of model residuals. We conducted a stratification analysis

to examine pollutant levels in the Upper Hunter on days when wind direction was coming from the urban Lower Hunter, to examine whether pollution in the rural Upper Hunter may be due to this urban influence. Finally, we examined days of exceedances of established air quality standards across regions for particulate matter and sulfur dioxide. Statistical significance was set at $p<.05$. We used SAS software version 9.4 for analyses, including Proc GLM for regression models.

Results

Table 2 compares the annual daily mean values for 2017 for each of the regions across pollutants, both with and without adjustment for meteorological variables. Table superscript notation shows pairwise means not different from each other with Tukey correction; all means without superscript are different from each other. Without adjustment, daily mean pollutant levels were significantly highest in the Lower and Upper Hunter valley regions, and were significantly higher than the metropolitan regions of Sydney or Illawarra on all five pollutants. The Upper Hunter area was significantly higher than every other region for PM2.5, NO, NO2 and NOx.

With adjustment for weather variables, the results were essentially unchanged. Upper and Lower Hunter areas consistently had significantly higher levels of all pollutants after controlling for weather conditions. For example, daily mean PM2.5 averaged 8.64 $\mu g/m^3$ in the rural Upper Hunter, compared to 7.23 $\mu g/m^3$ in metropolitan Sydney. PM10 levels were not significantly different between the Upper Hunter monitoring and Upper Hunter community stations, and were both significantly higher than Sydney. Nitrogen oxides were also significantly highest in the Upper Hunter, followed by the Lower Hunter. Results of the sensitivity analysis

that eliminated outlier observations were unchanged with respect to significance of regional differences.

Table 3 includes daily average meteorological conditions. There were significant differences for all weather variables across regions. The Hunter Valley regions on average were warmer than other regions and winds were slightly stronger. Prevailing winds for all regions were predominantly from the southeast to southwest sectors. Wind direction is shown in the table as degrees (north=360) but this variable was categorized into four main directions for regression analysis as previously described.

Table 4 shows the results of the stratification analysis. All models were significant ($p<.0001$). The purpose of this analysis was not to repeat all of the pairwise comparisons, but rather to examine whether pollution levels observed in the Upper Hunter might reflect pollution entering the valley from the Lower Hunter. There was little evidence that this was the case; although SO2 levels were higher when winds were from the direction of the Lower Hunter, but may reflect the fact that there is an SO2 monitoring station 10 km northwest from an Upper Hunter power station.

Australian daily maximum permissible values have been established for PM2.5, PM10 and SO2. Daily 24-hour maximum values are 25 $\mu g/m^3$ for PM2.5, 50 $\mu g/m^3$ for PM10, and 8.0 pphm for SO2. (NO and NO2 have maximum hourly and annual permissible levels but they are not established for a daily basis.) These are the maximum permissible limits established by the Australian government [36]. No exceedances of SO2 standards were observed for 2017. PM10 exceedances were most common in the Upper and Lower Hunter. PM2.5 exceedances occurred less frequently than for PM10, and were more common in Sydney than in the Hunter (Table 5). We conducted additional chi-square tests and observed that the combined Upper Hunter sites had

significantly more PM10 exceedances compared to other sites combined (chi-square=15.6, df=1, p<.0001), Sydney (chi-square=53.9, df=1, p<.0001), and other rural areas (chi-square=7.4, df=1, p<.01). The Upper Hunter sites combined had fewer PM2.5 exceedances than other sites combined (chi-square=10.0, df=1, p<.01) or Sydney (chi-square=17.4, df=1, p<.0001), but did not differ from other rural sites (chi-square=3.1, df=1, p<.08).

In a final sensitivity analysis, we excluded days when the average relative humidity was above 95% to exclude days when active precipitation was likely. Results for both adjusted and unadjusted models (not shown) were unchanged.

Discussion

The results supported the hypothesis that the Upper Hunter, a rural area characterized by coal mining and burning, would show higher air pollution levels than other rural areas of New South Wales. Results did not support the hypothesis that pollutant levels would be highest in Sydney as the major population center of New South Wales. Instead, we observed that the Upper and Lower Hunter Valley regions had significantly higher levels of particulate matter relative to Sydney. This was the case for PM2.5 and PM10, with and without adjustment for meteorological variables. For PM2.5, the Upper Hunter had higher levels than any other region including even the Lower Hunter. For PM10, the highest levels were observed in the Lower Hunter, followed by the Upper Hunter. PM10 findings for the Upper Hunter community stations were similar to those from the monitoring-only stations, indicating that pollutants are not restricted to immediate mining sites with few residents, but are present in the Upper Hunter population centers as well.

Gaseous pollutants showed the same pattern. NO, NO2, NOx and SO2 levels were also highest in the Upper and Lower Hunter Valley region and significantly higher than levels observed in Sydney, with and without adjustment for meteorological variables. For NO, NO2 and NOx, the Upper Hunter had the highest levels of all regions.

A stratification analysis suggested that the higher pollution levels in the Upper Hunter could not be accounted for by pollution from the nearby, more urban Lower Hunter. The highest pollution levels in the Upper Hunter did not coincide with prevailing wind from the Lower to the Upper Hunter.

The Lower Hunter region contains Newcastle and Lake Macquarie, a metropolitan area of more than half a million people. The Lower Hunter also contains two coal power plants (Eraring [2880 MW] and Vales Point [1320 MW].) The Upper Hunter contains a population of about 50,000 people, much smaller than the urban centers, but is characterized by multiple coal mines as described in the introduction, and two coal power plants (Bayswater [2640 MW] and Liddell [2000 MW]). It seems, at least in the case of these environments in New South Wales, that the effects of the coal industry in terms of mines and power plants exceeds the effects of a much larger metropolitan population in its contributions to air pollution.

No exceedances of SO2 standards were observed. This may be because Australian coals are relatively low in sulfur, although it should also be recognized that Australia's 24-hour SO2 standard is 10 times higher than the WHO standard. PM10 exceedances of regulatory limits were most common in the Hunter Valley. PM2.5 exceedances were relatively more common in Sydney. This could be partially attributed to bush fires or controlled burnings, which we were not able to examine in this study. Unfortunately, levels below a regulatory standard are no guarantee of safety, and in fact there is substantial literature documenting the strong connection

between adverse population health outcomes and air pollution when analyses are restricted to days when air pollution levels are within regulatory standards [37, 38]. The significantly higher daily mean levels observed in the Lower and Upper Hunter are reason for concern.

The sources of air pollution in the different regions will of course vary to some extent. In Sydney and other metropolitan areas, for example, mobile emission sources will contribute substantially to totals. Both particulate and gaseous pollutants included in the current study may originate from multiple sources, including cars and trucks, power plants, mines, and other industrial sources. Wildfires or dust particles may be contributing factors to particulate matter as well. These sources are not directly known or comparable across regions. The purpose of the current study was not to attempt source apportionment, or equate one type of source to another, but only to examine comparative pollutant levels in the various regions with an emphasis on the rural Hunter Valley.

Research conducted in other international settings has documented public health problems associated with surface coal mining [39-43]. These health problems include elevated rates of birth defects, and also morbidity and mortality from chronic respiratory and cardiovascular disease that are well-known to occur in conjunction with air pollution. Pollution from coal-fired power plants is also injurious to human health [14, 20]. Studies of cities in Australia have documented significant health impairments from air pollution [2-7], and our study demonstrates that levels of air pollution are even higher in areas outside these large cities that are characterized by coal mining and combustion.

Our findings offer an evidence base for stronger NSW government policies governing coal mine approvals and power station emissions in rural regions. For many years, Upper Hunter communities have expressed concerns about the perceived cumulative impact of coal industry

expansion on air quality and residents' health [19, 26]. These perceptions are validated by the region-wide monitor data reported in this study. Priority should be given to consideration of cumulative impacts in approval criteria for new mines and mine expansion. Moreover, dangerous coal-powered generator emissions identify Upper Hunter communities as facing the greatest potential health harm and add weight to calls for upgrading pollution control to capture primary PM2.5 in addition to post-combustion capture of SO2 and NOx [44]

Limitations of the study should be recognized. We analyzed data for one year only and for one state in Australia. Meteorological variables were represented in the raw data on an hourly basis and were converted to daily averages for this analysis, such that weather conditions do not match pollution readings in exact time, but inclusion or exclusion of these variables had no meaningful effect on the findings. Exact pollution sources are unknown but were only estimated based on regional differences. Different regions have different local topographies, prevailing winds, and different mixes of pollution types and sources, and locations of monitoring sites relative to specific features were not examined.

The present findings extend the evidence base for the ubiquity of air pollution beyond cities and into rural environments. Most previous research has focused on urban air pollution, but rural areas should be considered in studies of air quality and its effects. In the current study, the focus has been on coal mining and burning as a potential source of rural air pollution, but other contributing factors may be present as well in specific rural environments such as agriculture [45], animal husbandry [46], or mining for other products besides coal [47].

There are many arguments to be made for transitioning from coal to alternative methods of metal production [48] and energy generation. Among these arguments are public health considerations [14, 20, 49]. Coal contributes to air pollution and to human health problems in all

phases of its extraction, transportation, processing, use, and disposal [50]. As the use of coal in many places is largely a rural phenomenon, this has implications for rural health. The current study has taken a comparative approach to find that a rural region characterized by intensive coal mining and burning had poorer air quality than other rural areas or urban areas, and thus that coal mining and burning activities might impact pollution levels in rural areas potentially even more than pollution levels in densely populated urban areas.

Declaration of Interest Statement: The authors declare no conflicts of interest.

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Table 1. Pollutants measured by region and station.

Region	Station	Pollutant				
		PM2.5	**PM10**	**NO**	**NO2**	**SO2**
Upper Hunter (community)	Aberdeen		X			
	Bulga		X			
	Camberwell	X	X	X		
	Jerrys Plains		X			
	Maison Dieu		X			
	Muswellbrook	X	X	X	X	X
	Singleton	X	X	X	X	X
	Warkworth		X			
	Wybong		X			
Upper Hunter (monitoring only)	Merriwa		X			
	Mt. Thorley		X			
	Muswellbrook NW		X			
	Singleton NW		X			
	Singleton South		X			
Lower Hunter	Beresfield	X	X	X	X	X
	Carrington	X	X	X	X	X
	Mayfield	X	X	X	X	X
	Newcastle	X	X	X	X	X
	Stockton	X	X	X	X	X
	Wallsend	X	X	X	X	X
	Wyong	X	X	X	X	X
Sydney	Bargo	X	X	X	X	X
	Bringelly	X	X	X	X	X
	Camden	X	X	X	X	
	Cambelltown West	X	X		X	X
	Chullora	X	X	X	X	X
	Earlwood	X	X	X	X	
	Lindfield		X	X	X	X
	Liverpool	X	X	X	X	X
	Macquarie Park	X	X	X	X	X
	Oakdale	X	X	X	X	

	Parramatta North	X	X	X	X	X
	Prospect	X	X	X	X	X
	Randwick	X	X	X	X	X
	Richmond	X	X	X	X	X
	Rozelle	X	X	X	X	X
	St Marys	X	X	X	X	
Illawarra	Albion	X	X	X	X	X
	Kembla	X	X	X	X	
	Wollongong	X	X	X	X	X
Other rural	Albury	X	X			
	Bathurst	X	X			
	Gunnedah	X	X			
	Narrabri	X	X			
	Tamworth	X	X			
	Wagga Wagga	X	X			

Table 2. Daily mean values of pollutants by region, 2017, without and with covariate adjustment. Superscript numbers indicate post-hoc pairwise means not different from each other with Tukey correction for type I error.

Region	**Without adjustment**					
	PM2.5	**PM10**	**NO**	**NO2**	**NOx**	**SO2**
Illawarra	6.85	17.96 [1]	0.26	0.48	0.74	0.07
Sydney	7.31 [1]	17.24 [1]	0.56	0.75	1.29	0.06
Lower Hunter	7.71	22.87	0.66	0.79	1.45	0.18 [1]
Upper Hunter community	8.35	20.46	0.88	0.91	1.71	0.18 [1]
Upper Hunter monitoring	--	20.06	--	--	--	--
Other rural	7.29 [1]	16.33	--	--	--	--
	With adjustment					
	PM2.5	**PM10**	**NO**	**NO2**	**NOx**	**SO2**
Illawarra	7.21 [1,2]	18.19 [1]	0.43	0.58	1.03	0.08
Sydney	7.23 [1]	17.31 [1]	0.62	0.79	1.38	0.06
Lower Hunter	8.24	23.20	0.85	0.92	1.78	0.18 [1]
Upper Hunter community	8.64	19.87 [2]	1.07	0.98	1.95	0.18 [1]
Upper Hunter monitoring	--	19.62 [2]	--	--	-	--
Other rural	7.02 [1,2]	15.96	--	--	--	--

Table 3. Average meteorological variables by region. 2017.

Region	**Variable**			
	Temperature (C)	Relative humidity	Wind direction (degrees)	Wind speed (km/hr)
Illawarra	17.54	68.06	183.22	2.22
Sydney	17.50	68.68	185.06	1.68
Lower Hunter	18.49	70.60	198.71	2.55
Upper Hunter community	18.03	65.48	194.90	2.25
Upper Hunter monitoring	17.95	65.53	192.27	2.77
Other rural	16.34	62.83	193.78	1.66

Table 4. Daily mean values of pollutants by region, 2017. Least square means adjusted for meteorological variables. Stratified by wind direction.

Region	**Wind direction from urban Lower Hunter to rural Upper Hunter**					
	PM2.5	**PM10**	**NO**	**NO2**	**NOx**	**SO2**
Illawarra	7.66	22.90	0.17	0.53	0.71	0.12
Sydney	6.75	19.05	0.24	0.53	0.76	0.05
Lower Hunter	7.51	27.51	0.38	0.53	0.91	0.16
Upper Hunter community	7.81	20.09	0.67	0.78	1.40	0.28
Upper Hunter monitoring	--	17.81	--	--	-	--
Other rural	6.93	14.39	--	--	--	--
	Other wind direction					
	PM2.5	**PM10**	**NO**	**NO2**	**NOx**	**SO2**
Illawarra	6.81 2	15.91	0.39	0.51	0.92	0.06
Sydney	7.33 1	16.95	0.61	0.80	1.38	0.06
Lower Hunter	8.40	21.93	0.86	0.99	1.86	0.19
Upper Hunter community	8.92	20.15	1.06	0.96	1.89	0.13
Upper Hunter monitoring	--	21.05	--	--	--	--
Other rural	6.98 1,2	16.69	--	--	--	--

Table 5. Particulate matter exceedance days (and percent of observations across stations) by region.

Region	PM10 [1]	PM2.5 [2]
Illawarra	5 (0.46)	0 (0)
Sydney	20 (0.36)	31 (0.64)
Lower Hunter	75 (2.99)	2 (0.12)
Upper Hunter community	56 (1.72)	3 (0.08)
Upper Hunter monitoring	36 (2.00)	--
Rural/regional	12 (0.81)	4 (0.30)

1. Chi-square (df=5) = 113.76, p<.0001.
2. Chi-square (df=4) = 27.93, p<.0001.

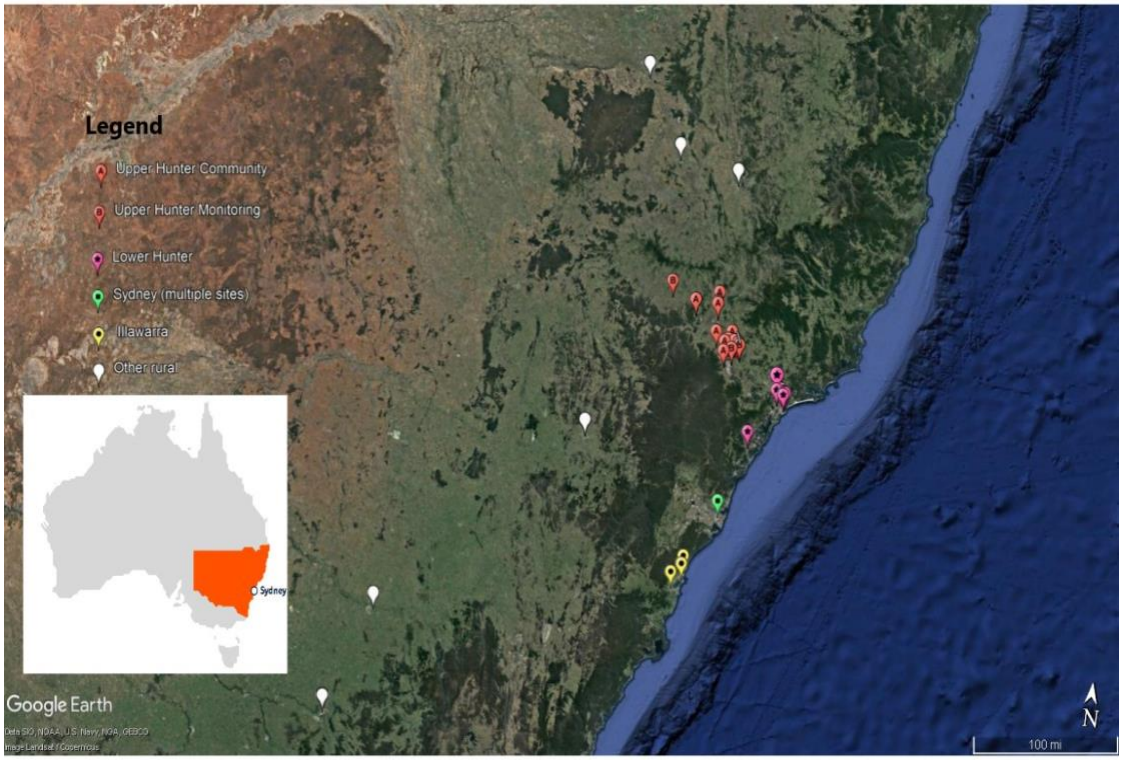

Figure 1. Map of air monitoring stations and regions, New South Wales, Australia.