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# Prevalence of childhood lead poisoning and respiratory disease associated with lead smelter emissions

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ABSTRACT

*Background:* The city of Port Pirie in South Australia has been a world leading centre for lead and zinc smelting and processing since 1889 that continues to cause contamination of its environment and resident population. This study quantifies the effect of lead and $SO_2$ emissions from Nyrstar Port Pirie Pty Ltd's smelter on blood lead and respiratory health outcomes, respectively, and establishes what air quality values are required to better protect human health.

*Method:* Blood lead and emergency department presentation data collected by South Australia Health (SA Health) and lead in air and $SO_2$ data collected by the South Australian Environment Protection Authority (SAEPA) were obtained and analysed to quantify health outcomes due to smelter emissions in Port Pirie. Regression analysis was used to assess the relationship between the concentration of lead in air and children's blood lead levels between the years of available data: 2003 to 2017. Ambient $SO_2$ concentrations (SAEPA) measured continuously between 2008 and 2018 were 24-hour averaged and compared to daily local emergency department respiratory presentation rates (available from July 2012 to October 2018). Rates of emergency department respiratory presentations at Port Pirie and regional comparators were calculated as age-standardised rates.

*Results:* The data show that increases in ambient $SO_2$ concentrations are associated with increased rates of emergency department respiratory presentations of Port Pirie residents, in which children are over-represented. The 30-day rolling average of respiratory presentations was significantly associated ($p < 0.05$) with incremental increases in $SO_2$. Analysis of the relationship between lead in air and blood lead shows that annual geometric mean air lead concentrations need to be $< 0.11\ \mu g/m^3$ to ensure the geometric mean blood lead of Port Pirie children under 5 years is $\leq 5\ \mu g/dL$. For children aged 24 months, lead in air needs to be no greater than $0.082\ \mu g/m^3$ (annual geometric mean) to ensure geometric mean blood lead does not exceed 5 µg/dL.

*Conclusion:* Current smelting emissions continue to pose a clear risk of harm to Port Pirie children. Allowable emissions must be lowered significantly to limit adverse childhood health outcomes including respiratory illness and IQ, academic achievement and socio-behavioural problems that are associated with lead exposure at levels experienced by Port Pirie children. Current $SO_2$ levels are likely to be responsible for increased rates of emergency department respiratory presentations in Port Pirie compared with other South Australian locations. As a minimum, Australian $SO_2$ air quality standards need to be enforced in Port Pirie to better protect human health. Lead in air needs to be approximately 80% lower than the current national standard ($0.5\ \mu g/m^3$) to ensure that the geometric blood lead of children under 5 years is less than or equal to 5 µg/dL.

## 1. Introduction

Although Australia continues to be a world leader in lead mining, smelting and processing, the adverse impacts associated with production have yet to be adequately addressed in affected towns, where blood lead exposures in children continue to be elevated (Rossi, 2008; Queensland Department of Health, 2017; Western NSW Health Intelligence Unit, 2017; Simon et al., 2018). Port Pirie in South Australia (Fig. 1) is an example of the conflict between the different expectations of government: protection of environment and public health versus maintaining and improving economic opportunities for industry and individuals. At Port Pirie, lead smelting has been ongoing since

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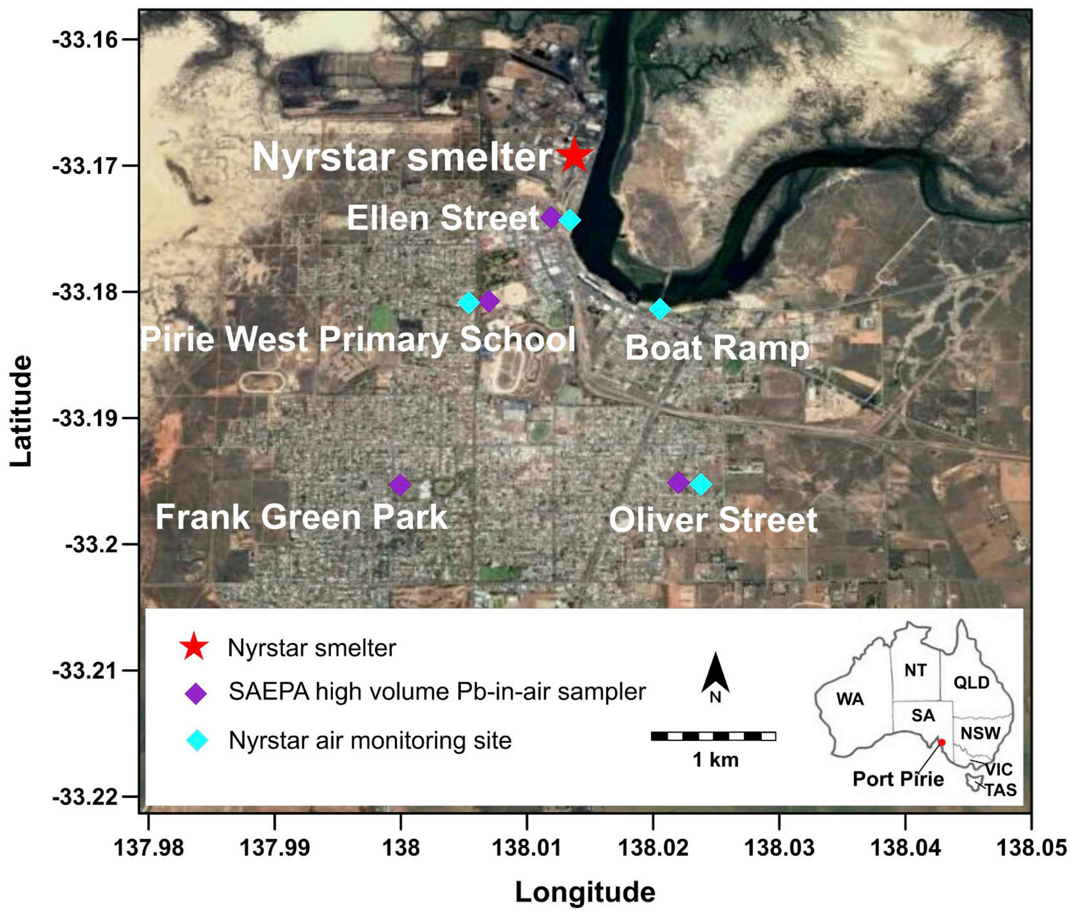


**Fig. 1.** Map of Port Pirie showing the four South Australian Environment Protection Authority (SAEPA) high volume lead in air sample sites. The SAEPA's $SO_2$ air monitoring is conducted at the Oliver Street site. The Nyrstar Port Pirie Pty Ltd smelter is located at the north of the city. Also shown is the Boat Ramp lead in air sample site, which forms part of Nyrstar's licence monitoring requirements along with air monitoring co-located at the SAEPA sites of Ellen Street, Pirie West Primary School and Oliver Street. Image from Google LLC (2018).
Abbreviations for state and territory names are as follows: NSW – New South Wales; NT – Northern Territory; QLD – Queensland; SA – South Australia; TAS – Tasmania; VIC – Victoria; WA – Western Australia.

1889, with the adjoining community receiving over a century of environmental lead emissions (Fowler and Grabosky, 1989), akin to '*living in a sea of lead*' (p. 248, Simon et al., 2007).

Childhood exposure to lead has been linked to lower IQ and academic achievement, and to a range of socio-behavioural problems such as attention deficit hyperactivity disorder (ADHD), learning difficulties, oppositional/conduct disorders, and delinquency (National Toxicology Program (NTP), 2012). The disabling mental health issues from lead exposure often persist into adolescence and adulthood. The mounting evidence for adverse outcomes from even low-level exposures led to the US Centers for Disease Control and Prevention in May 2012 to lower their action threshold for blood lead levels to 5 μg/dL. In May 2015, the Australian National Health and Medical Research Council (NHMRC) followed suit by lowering the level for intervention to 5 μg/dL. Internationally, the paradigm is that there is no safe level of exposure (Bellinger, 2008; Centers for Disease Control and Prevention, 2013). The NHMRC contends that the evidence for health effects at exposures < 10 μg/dL is less clear than for exposures above this level, a view that deviates from the views expressed by a range of globally respected environment and health bodies such as the WHO, US CDC, US EPA and Health Canada (National Health and Medical Research Council (NHMRC), 2015).

Lead exposure from environmental sources continues to be a persistent global health problem. In 2016, lead exposure resulted in an estimated 13.9 million Disability-Adjusted Life Years (DALYs) and 540,000 deaths globally (GBD 2016 DALYs and HALE Collaborators, 2017). With the adverse health effects of lead exposure being well known, especially to children but also in adults (Lanphear et al., 2018), there remains ongoing concern for Australia's most severely lead-contaminated communities of Broken Hill, Port Pirie and Mount Isa (Gruszin et al., 2012; Earl et al., 2016).

### 1.1. Sources of lead exposure

Lead emissions from mineral extraction and processing are the primary source of lead exposure in Australia since lead use in automotive gasoline was eliminated in 2002. Port Pirie is a seaport on the east coast of South Australia's Spencer Gulf, approximately 220 km north of Adelaide, the state capital of South Australia (Fig. 1). The city hosts one of the world's largest lead smelters, currently owned and operated by Nyrstar Pty Ltd. As far back as 1925, the South Australia Royal Commission on Plumbism (1925) identified that the principal cause of lead poisoning (plumbism) was from fine lead dust emitted from the smelter. Lead rich emissions continue to impact the local environment, with the Nyrstar Port Pirie facility in 2016/17 emitting 50,000 kg of lead into the atmosphere and 9600 kg into water (National Pollutant Inventory, 2018). Emitted atmospheric dusts settle on surfaces, which form a pathway for exposure. This has been demonstrated to constitute a significant exposure risk in children's playgrounds (Fig. 1, Taylor et al., 2013), with deposition/exposure levels being clearly related to atmospheric lead loadings (Taylor et al., 2015b), as they are elsewhere (Dong et al., 2019). The legacy of past emissions also remains an exposure risk in affected soils near the smelter (SA Health, 2013). Legacy contamination from lead paint usage in the home may present an additional health risk (Jacobs et al., 2002) albeit one that has not been well quantified in the Australian context.

In 1976, and again in 1981, the CSIRO demonstrated that smelter emissions were the principal source of lead contaminating soil, grain, and vegetables around Port Pirie (ECOS, 1976; ECOS, 1981). Throughout the 1980s and 1990s, historical (legacy) lead-smelter dust-emissions held in the city's soil and home environments were considered to be the primary cause of elevated blood lead in children (Body et al., 1991). However, data collected by the SAEPA (lead in air measurements) and SA Health (blood lead measures in children aged 0–4 years) show that smelter lead in air emissions are likely to be the primary cause of elevated blood lead levels in Port Pirie children. Legacy lead held in soil and dust in the city environment is considered to be a minor source (Maynard et al., 2005; Taylor, 2011).

### 1.2. Sources and health effects of $SO_2$ exposure

Globally, emissions from smelting activities constitute a significant local source of $SO_2$ (Strømmen et al., 2016). At Port Pirie, $SO_2$ is emitted due to the smelting of ores containing sulfur as well as from combustion of sulfur-containing fuels (Dougherty et al., 2006). In the 2016/17 reporting year, 58,000 t of $SO_2$ was emitted by the Nyrstar facility at Port Pirie (National Pollutant Inventory, 2018), contributing to exceedances of the national 1-hour standard for $SO_2$ of 0.2 ppm. In addition, 1.4 t of sulfuric acid was released to the atmosphere (National Pollutant Inventory, 2018).

The Australian child health and air pollution study (Williams et al., 2012) demonstrated that $SO_2$ adversely affects respiratory and lung function. However results from Port Pirie were notably excluded from this study because '… *Port Pirie has high ambient levels of $SO_2$*' (p.144, Williams et al., 2012). The relationship between the emissions and human health outcomes at Port Pirie was identified as an important knowledge gap, which has never been subject to any form of detailed assessment (Maynard et al., 2005). This knowledge gap is surprising given that elevated $SO_2$ levels affect the respiratory tract and can cause coughing, mucus secretion, aggravation of asthma (Smargiassi et al., 2008; Kim et al., 2013; Akhtar et al., 2014; Brand et al., 2016; Byers et al., 2016), chronic bronchitis and increased susceptibility to infection (Pope et al., 1995; WHO, 2018). Increased ambient $SO_2$ concentrations are also associated with increased hospital admissions for cardiac disease, higher mortality rates (Zhang et al., 2015; Wang et al., 2018), elevated C-reactive protein, a measure of infection and/or inflammation in the body (Peters et al., 2001) and low birthweight (Rogers et al., 2000). As well as adverse health impacts, environmental damage, including deforestation and damage to buildings (Cheng et al., 1987; Greenberg et al., 2016), is caused when $SO_2$ combines with water, forming sulfuric acid (acid rain) (Parungo et al., 1987).

Given the extent of the lead and $SO_2$ emissions in the city and the known health risks, the objective of this study was to evaluate the effect of smelter emissions (lead and $SO_2$) on health outcomes and to establish what interventions are required to better protect human health. This study closes an important knowledge gap in that there has never been an assessment of the lead and $SO_2$ emissions with the goal of determining the levels required to ensure the Port Pirie community is more appropriately protected from smelter pollution.

## 2. Methods, data sources and approach

This study draws on a range of environmental data collected by SAEPA and health measures collected by SA Health covering the period 2003–2018 in order to quantify the effect of smelter emissions on the Port Pirie community. The most detailed health and environmental data were available for the period between 2008 and 2018 and formed the focus of analysis. Select time-periods were also examined to nuance the environmental health relationships present in the data. The assessment below focuses on lead and $SO_2$ emissions because other neurotoxic elements such as arsenic and cadmium and $PM_{2.5}$ concentrations are not routinely measured by the SAEPA, even though they are known to be present in elevated concentrations in Port Pirie (Taylor et al., 2013; Taylor et al., 2014; Csavina et al., 2014).

### 2.1. Lead in air

The SAEPA's monitoring for lead in air (measured in total suspended particulates - TSP) is currently undertaken at four sites in Port Pirie – Ellen Street, Frank Green Park, Oliver Street and Pirie West Primary (Fig. 1). In terms of Australian national standards reporting for lead in air, the SAEPA relies on data collected at the Frank Green Park and the Oliver Street sites. Lead in air is collected and reported according to AS/NZS 3850.9.3:2015 (Standards Australia, 2015), i.e. every 6th day. From October 2010 to June 2012, the SAEPA also collected lead in air data from Pirie West Primary School on a daily basis. Although SAEPA also collects lead in $PM_{10}$ at its Oliver Street site, the analyses presented here focus on TSP lead, which aligns with the national air quality standard. The national standard for lead in air is 0.5 $\mu g/m^3$ measured in TSP, averaged over a year. Samples collected for reporting against the national air quality standard for lead use high volume air samplers at the Oliver Street and Frank Green Park sites, which comply with AS/NZS 3580.1.1:2016 (Standards Australia, 2016) for siting air monitoring equipment (SAEPA, 2015). The same equipment and sampling process is used at the SAEPA's Ellen Street and Pirie West Primary School monitoring sites. Determination of particulate lead was analysed via inductively coupled plasma optical emission spectroscopy (ICP-OES) according to AS/NZS 3580.9.15:2014 (SAEPA, 2015; Standards Australia, 2014). Analysis is conducted by Queensland Health Scientific Services (which is accredited for this analysis by the National Association of Testing Authorities, accreditation #41). The reported uncertainty at the 95% confidence interval for lead in air measurements was ± 0.09 $\mu g/m^3$ (SAEPA, 2015). The calculation and reporting methods comply with data quality control measures according to the Australian National Environment Protection Council Peer Review Committee (NEPCPRC, 2010).

In addition, Nyrstar Port Pirie Pty Ltd has an extensive network of its own monitors at 13 sites across the city with four of these co-located next to the SAEPA sites (see Fig. 1). Unlike the SAEPA data collected for national standards reporting, Nyrstar is obliged pursuant to its licence to collect samples every 24-hours.

### 2.2. Sulfur dioxide

The SAEPA measures sulfur dioxide ($SO_2$) every 10 min at the Oliver Street monitoring station (Fig. 1), and reports hourly average concentrations (in ppm). Sulfur dioxide is determined by ultraviolet fluorescence, read directly by field instrumentation (Ecotech ML® 9850B $SO_2$ Sulfur Dioxide Analyzer) according to AS 3580.4.1-2008 (Standards Australia, 2008). The reported uncertainty at the 95% confidence interval for sulfur dioxide was ± 0.011 at 0.200 ppm (SAEPA, 2015). Equipment specifications are detailed in Riordan and Adeeb (2004).

There is no requirement in Nyrstar's licence to meet a particular air quality standard in relation to $SO_2$ in the city of Port Pirie. Consequently, no air quality standards for $SO_2$ are triggered including those promulgated in the Australian national standards (National Environment Protection Council, 2016).

This study utilises lead in air and $SO_2$ data collected at Oliver Street for assessment against health metrics for the following reasons: (a) it is the only SAEPA site at Port Pirie with both lead in air and $SO_2$ monitoring; (b) the site complies with Australian Standards for siting air quality monitoring equipment; (c) SA Health advised that it considers the Oliver Street site to be the most representative site for the city.

### 2.3. Health metrics

Summary annual reports on child blood lead concentrations for children 0–4 years are publicly available from SA Health (2018c). These reports contain data on the last test undertaken on a child in any one year. In addition, the geometric mean of the maximum blood lead results (typically the first reading) taken on a child in any one year was supplied separately by SA Health (2018b). These have been analysed to explore the effectiveness of environmental lead controls in Port Pirie over time. The voluntary blood screening program is provided by SA Health's local Environmental Health Centre. For young children and pregnant women, the Australian Standard method for fingerprick sampling is used, whereby the finger is cleaned and blood is collected into a glass capillary tube (AS 2636-1994, Standards Australia, 1994). This testing method is preferred for young children because it is less distressing than venous blood sampling, increasing the likelihood that more children will return for subsequent testing. Routine analytical quality assurance is carried out in a subset of samples by taking blood using both capillary and venous methods from the same subject (Maynard et al., 2003; Simon et al., 2007). The blood samples are analysed by SA Pathology, Adelaide, South Australia, which is accredited for blood lead analysis by the National Association of Testing Authorities (Australia) (NATA). SA Health also receives and incorporates into its public reports (Simon et al., 2018) blood lead data on pregnant women that have been taken by Port Pirie general practitioners using venesection. These samples have been analysed by various other (unspecified by SA Health) pathology labs. The data are accepted as being suitable for use by SA Health on the basis that the laboratories are similarly accredited by NATA for blood lead analysis.

Implications of daily $SO_2$ emissions are considered in light of emergency department respiratory presentation data (SA Health, 2018a). Port Pirie, as referred to in the emergency department data, is represented by the Statistical Local Area for the city of Port Pirie (Australian Bureau of Statistics, 2011).

Different averaging and data lag periods (i.e. the time between $SO_2$ air concentrations and emergency department data) were explored in order to examine the most relevant relationship between ambient $SO_2$ concentrations and human health outcomes. Daily and 30-day average/geometric mean data, both for $SO_2$ concentration and emergency presentations are detailed here, with the full data set provided in Supplementary Table S4.

## 3. Results

Lead in air and $SO_2$ results arising from the Nyrstar smelting operations in Port Pirie are evaluated below with respect to their effect on blood lead and respiratory health indicators.

### 3.1. Lead in air emissions

According to the SAEPA's own monitoring, lead in air concentrations in Port Pirie exceeded the annual national standard (0.5 μg/m$^3$) every year at Oliver Street from 2002 to 2007 (SAEPA, 2014). Since 2007, lead in air levels remained below the national standard until 2013 but continued to be elevated (i.e. > 0.23–0.45 μg/m$^3$, SAEPA, 2014) relative to major Australian urban centres. From mid-2013 to the present (Fig. 2), atmospheric lead emissions at Port Pirie have risen, fallen and then continued on an upward trajectory (SAEPA, 2018b). Data collected every 6th day by the SAEPA (2018b) show that the annual mean concentration for ground level lead in air concentration at its Pirie West Primary monitoring station exceeded 0.5 μg/m$^3$ in 2017. The SAEPA's standard measurement of lead in air every 6$^{th}$ day may be less optimal at characterising the burden of lead in air than Nyrstar's daily measurements. Nyrstar's daily sampling at the same location (Pirie West Primary), as required by its licence conditions, showed that lead in air concentrations did not exceed 0.5 μg/m$^3$ (SAEPA, 2018a). In terms of regulation, Nyrstar is governed by the values collected at its monitors at the sites stipulated in its environmental licence (SAEPA, 2008, Fig. 2).

Across the four SAEPA sites (Fig. 1, Table 1), Port Pirie's lead in air in 2017 averaged 1.13 μg/m$^3$, a concentration skewed by the Ellen Street site, which is closest to the smelter. Recent measurements (2015–2017) at Port Pirie show that lead in air has been increasing since 2015, which has been associated with a rise in the number of 24-hour average concentration spikes above 0.5 μg/m$^3$ (the maximum annual average standard, Table 1).

### 3.2. Sulfur dioxide emissions

Since 2003, $SO_2$ concentrations in the city of Port Pirie have exceeded the 1-hour standard of 0.2 ppm 1001 times, peaking in 2018 (data available to October 2018) at 135 times (Supplementary Fig. S1; Supplementary Table S2). By contrast, $SO_2$ 1-hour exceedances associated with Australia's leading $SO_2$ emitter, Mount Isa Mines, which discharged 190,000 t into the atmosphere in 2016/2017 (National Pollutant Inventory, 2018) have been lower (Taylor et al., 2014; Queensland Government, 2018a).

At Port Pirie, 24-hour mean values of $SO_2$ were elevated from 2014 by comparison to previous years (Fig. 3). Exceedances of the 24-hour 0.08 ppm Australian standard for $SO_2$ (NEPC, 1998) are also evident in Fig. 3. According to the Australian national standards, one exceedance of the 24-hour standard is permitted per year. For example, in 2014, 2015 and 2017 three exceedances occurred and in 2016 there were six exceedances. The annual (mean) Australian standard for $SO_2$ (0.02 ppm) has not been exceeded since 2008.

A recent study in the USA (Greenberg et al., 2016) demonstrated a significant dose-response effect on the severity of asthma at ambient concentrations below the USA air quality standard, which is set at 0.075 ppm based on the 3 year average of the 99th percentile 1-hour daily maximum concentrations. Although the causality of the effects of low concentrations of $SO_2$ is still uncertain, studies indicate that a proportion of people with asthma experience changes in pulmonary function and respiratory symptoms after periods of exposure to elevated $SO_2$ concentrations as short as 10 min. (WHO, 2018a). The World Health Organization (WHO, 2018a) recommends more stringent $SO_2$ standards than those set for Australia: 0.175 ppm (500 μg/m$^3$) for a 10-minute mean and 0.007 (20 μg/m$^3$) for a 24-hour mean concentration. It is evident from Fig. 3 that the air quality at Port Pirie has exceeded the more conservative WHO $SO_2$ 24-hour standard for most of the last decade.

### 3.3. Human health metrics associated with smelter emissions

Previous studies have identified that emissions from global lead smelting operations (Durand et al., 2015; Beyer et al., 2018; Shin et al., 2018), including those at Port Pirie (Taylor et al., 2014; Taylor et al., 2015a), are associated with a range of toxic trace element contaminants (e.g. arsenic, cadmium, lead) along with significant $SO_2$ concentrations in adjoining urban environments. The effects of the smelter's emissions on the Port Pirie community are considered below.

#### 3.3.1. Lead in air concentrations and community effects

Current data (2017) show that at least 47.4% of the city's children aged between 0 and 4 years have blood lead levels > 5 μg/dL (Simon et al., 2018), the revised 2015 Australian blood lead intervention value (National Health and Medical Research Council (NHMRC), 2015). In 2017, 20.2% of Port Pirie children exceeded the former Australian maximum blood lead goal of 10 μg/dL (Fig. 4).

Assessment of SA Health data shows that blood leads have started to rise or at best stabilise in the most recent years, which is likely a reflection of the smelter emissions and corresponding air quality. For example, the number of children with a blood lead > 5 μg/dL has increased each successive year from 2015 to 2017: 42.0, 43.4 to 47.4%

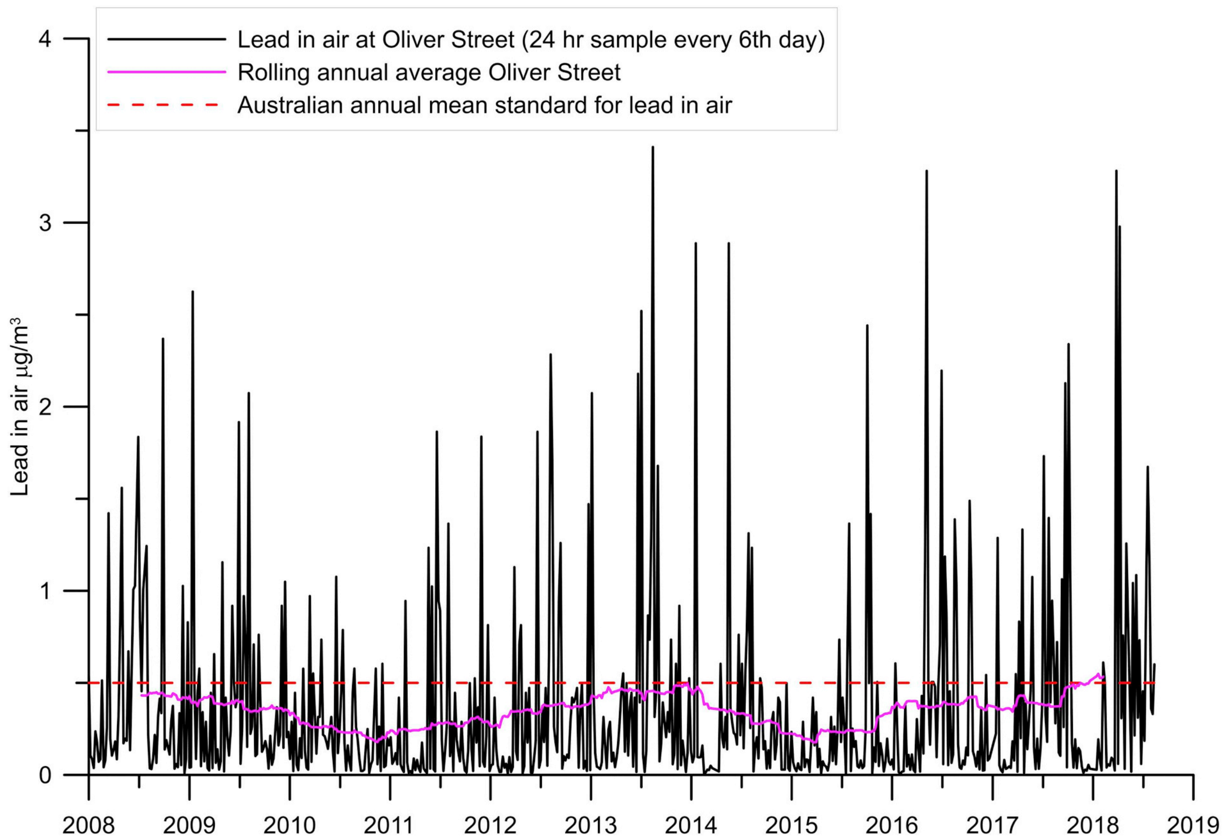


**Fig. 2.** Ambient lead in air concentrations (μg/$m^3$) measured at Oliver Street by SAEPA between 2008 and 2018. Results are for 24-hour samples. The full dataset is provided in Table S1. Note that the Australian national air quality standard for lead (0.5 μg/$m^3$) is based on the annual mean calculated for a calendar year and not the rolling average.

(Simon et al., 2018). Fig. 4 also reveals that the percentage of children exceeding the former 10 μg/dL limit have increased in the last two years after a long decline.

Annual geometric mean data were available for both lead in air (Oliver Street and Pirie West Primary) and children's maximum blood lead in any one year for the period 2003 to 2017 (SA Health, 2011, 2018b). Bi-variate analysis of the data demonstrates that children's blood lead is a function of the prevailing lead in air concentration (Fig. 5). Resolution of the linear regression shows that for children < 5 years of age to remain below the maximum blood lead level of 5 μg/dL, maximum annual lead in air concentrations must not exceed 0.11 μg/$m^3$ (geometric mean) at either the Oliver Street or Pirie West Primary monitoring site. For 24-month-old children, the lead in air concentration needs to be lower to ensure geometric blood lead levels are < 5 μg/dL: 0.090 μg/$m^3$ at Oliver Street and 0.073 μg/$m^3$ at Pirie West Primary (average 0.082 μg/$m^3$).

### *3.3.2. Sulfur dioxide concentrations and community effects*

The adverse effects of elevated $SO_2$ in ambient air on lung and respiratory function are summarised above. There have not been any epidemiological studies conducted in Port Pirie demonstrating the impact of $SO_2$ on respiratory health, although Maynard et al. (2005) identified it as a research need. The respiratory emergency department presentation rate in Port Pirie of 6166.1 per 100,000 population in 2017/18 is 2.27 times greater than regional South Australia (the area of the state outside of Adelaide), where it is 2719.2 per 100,000 population. Further, it is 2.46 times the rate in Adelaide, where it is 2511.5 per 100,000 population (SA Health, 2018a). Respiratory emergency department presentation rates for Port Pirie were highest amongst the 0–4 years age group, comprising 21.0% of total emergency department respiratory presentations in the July 2012–October 2018 period. Children in Port Pirie aged 5–9 years accounted for a further 9.1% of presentations.

Previous studies have showed varied temporal lag between $SO_2$ exposure and health effects, ranging from same-day effects to multiple

**Table 1**
Summary data for lead (Pb) in air concentrations, Port Pirie for 2015–2017. The data from Ellen Street and Pirie West primary sites do not form part of SAEPA's national reporting for lead in air concentrations.

| Air monitoring sites | Ellen Street | Pirie West Primary | Frank Green Park | Oliver Street |
|---|---|---|---|---|
| Lead in air summary data 2015 | | | | |
| Samples (n) | 60 | 59 | 59 | 60 |
| Mean Pb in air (μg/$m^3$) | 1.30 | 0.23 | 0.08 | 0.23 |
| Max Pb in air (μg/$m^3$) | 13.66 | 2.57 | 1.21 | 2.44 |
| Pb spikes (n) > 0.5 (μg/$m^3$) | 42 | 7 | 1 | 6 |
| TSP city Pb average | 0.47 μg/$m^3$ | | | |
| Lead in air summary data 2016 | | | | |
| Samples (n) | 59 | 59 | 59 | 59 |
| Mean Pb in air (μg/$m^3$) | 1.94 | 0.40 | 0.16 | 0.38 |
| Max Pb in air (μg/$m^3$) | 16.42 | 3.53 | 0.98 | 3.28 |
| Pb spikes (n) > 0.5 (μg/$m^3$) | 43 | 15 | 10 | 14 |
| TSP city Pb average | 0.72 μg/$m^3$ | | | |
| Lead in air summary data 2017 | | | | |
| Samples (n) | 51 | 51 | 51 | 50 |
| Mean Pb in air (μg/$m^3$) | 3.18 | 0.60 | 0.28 | 0.45 |
| Max Pb in air (μg/$m^3$) | 16.17 | 3.86 | 1.62 | 2.34 |
| Pb spikes (n) > 0.5 (μg/$m^3$) | 44 | 19 | 9 | 14 |
| TSP city Pb average | 1.13 μg/$m^3$ | | | |

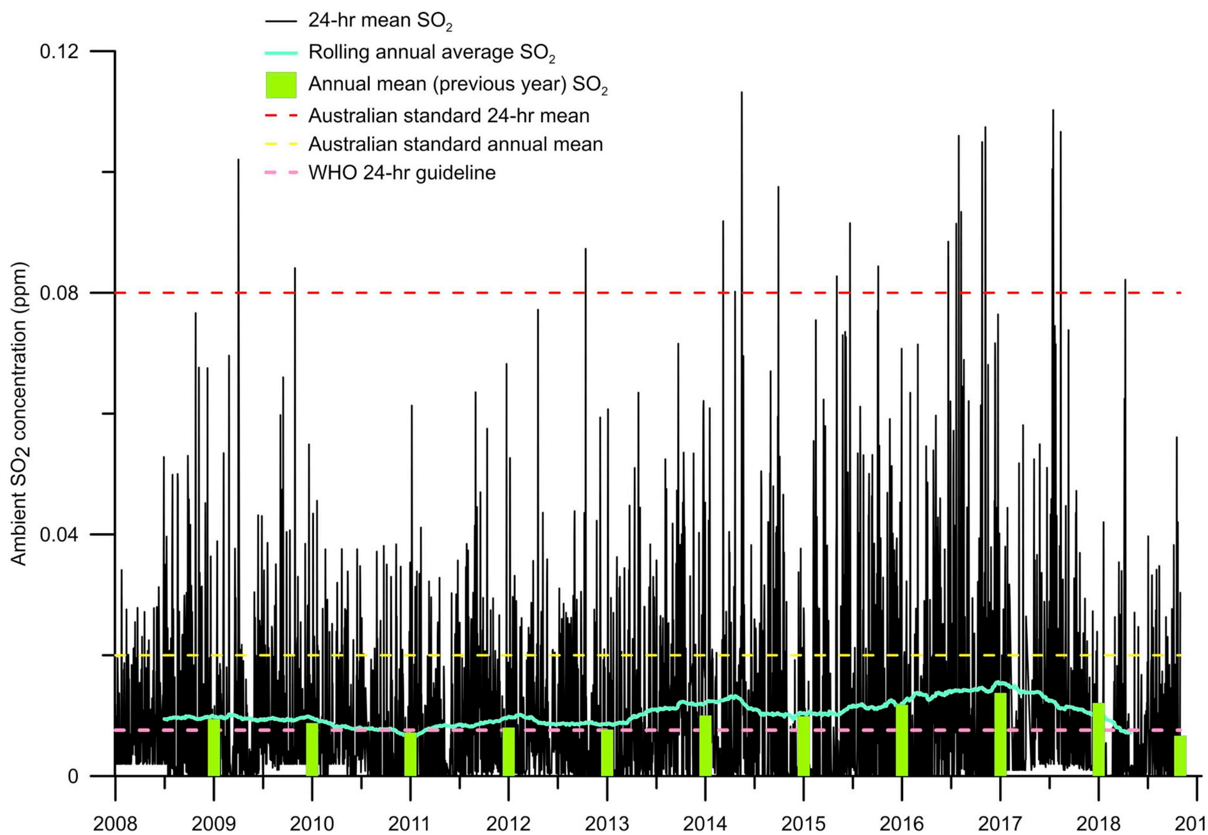


**Fig. 3.** Annual and 24-hour mean $SO_2$ concentrations (ppm) at Port Pirie. Also shown are the rolling annual average $SO_2$ values and relevant air quality standards. Data are provided in Table S2. Data for 2018 were available only up to and including October.

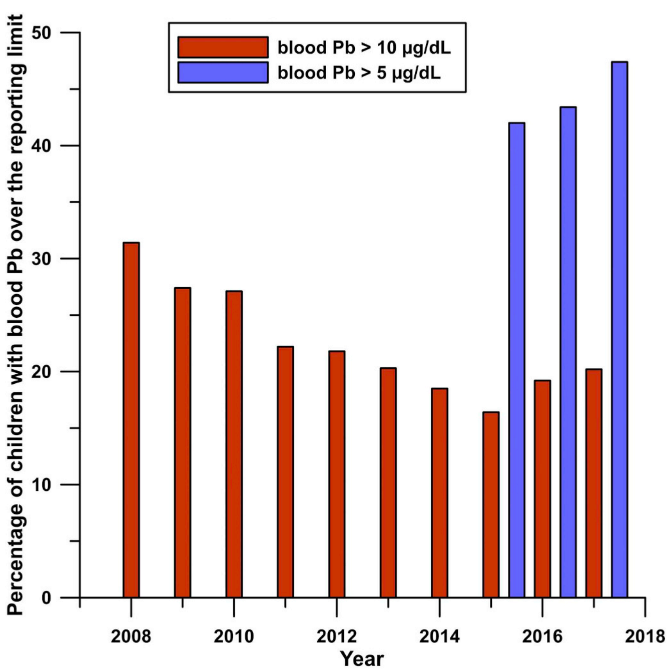


**Fig. 4.** Percentage of blood lead concentrations (μg/dL) in Port Pirie children < 5 years old that exceeded 10 μg/dL (data from: Simon et al., 2018). Since 2015, the revised limit of 5 μg/dL has also been reported.

weeks, with the duration of exposure being an important factor (Lee and Schwartz, 1999; Klein et al., 2004; Rodriguez-Villamizar et al., 2015; Yao et al., 2016; Chen et al., 2019). At Port Pirie, the relationship between ambient $SO_2$ concentration and emergency department respiratory presentations was not clear for time lags or averaging periods of 14 days or less. However, 30-day rolling average emergency respiratory presentation data yielded a significant relationship ($p < 0.05$) with respect to the 30-day rolling geometric mean ambient $SO_2$ concentrations. The rate of respiratory presentations to the emergency department (all ages) increased in tandem with incremental rises in ambient $SO_2$ concentrations (Fig. 6). However, no statistically significant relationship was able to be defined for any individual age group from the 30-day data. For incremental increases (Fig. 6), Tukey's multiple comparison method was used with ANOVA to create confidence intervals for all pairwise differences between factor level means whilst controlling for the family error rate using $\alpha = 0.05$. Geometric mean values for ambient $SO_2$ concentration were used for statistical analysis because data were non-normally distributed, being skewed towards lower $SO_2$ concentrations (see Table S2). For all-age data (Fig. 6), each $SO_2$ concentration category of < 0.001 ppm, 0.001-0.002 ppm and > 0.002 ppm (based on geometric rolling 30-day mean) was statistically different ($p < 0.05$). The data were further examined to ascertain if different age categories were sensitive to increases in ambient $SO_2$ concentration. For children aged 0–4 years, increases in $SO_2$ concentrations were not associated with increased emergency department respiratory presentation rates. This is likely due to the limited temporal information on emergency department respiratory presentations (July 2012-October 2018), for which the 0-4 years age group comprised 21.0% of total emergency department respiratory presentations (n = 899/4288).

For children aged 5–9 years, mean respiratory presentation rates for $SO_2$ concentrations in the > 0.002 ppm category were higher, but not statistically different, from those in the 0.001 to 0.002 ppm category. Again, this is likely due to insufficient data for the 5-9 year age category (n = 392, 9.1 % of total respiratory presentations).

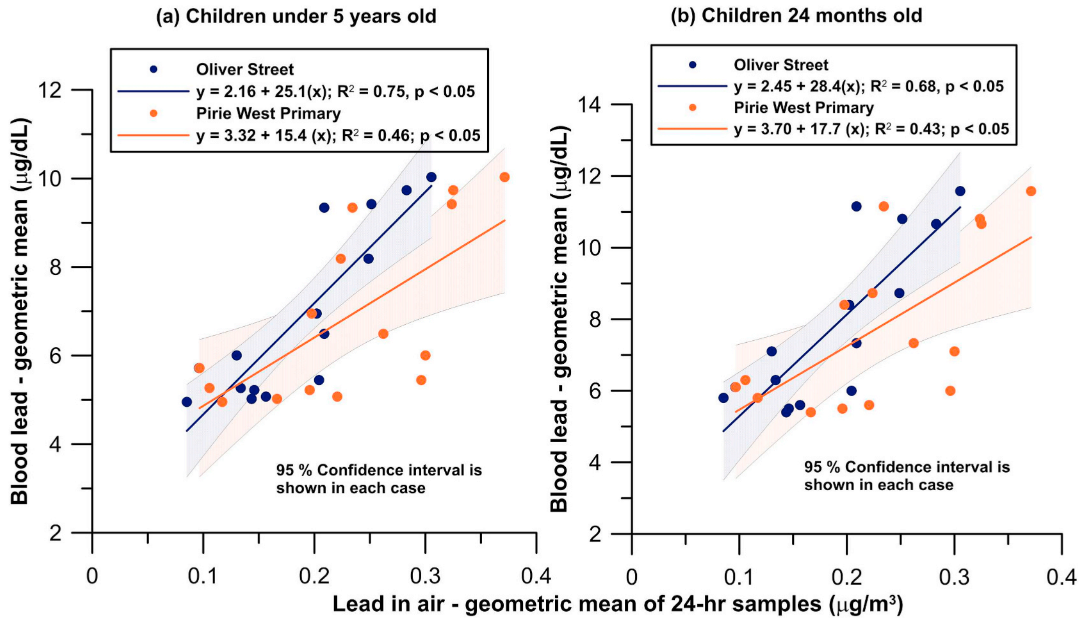


**Fig. 5.** Geometric mean (annual) lead in air concentrations at Port Pirie (for the years 2003-2017) compared to (a) blood lead concentrations in children aged < 5 years (annual geometric mean); (b) blood lead concentration in children 24-months old (annual geometric mean). Blood lead data are from SA Health (2011, 2018b) and Simon (2018) and are provided in Table S3. Lead in air data were provided by SAEPA and are provided in Table S1.

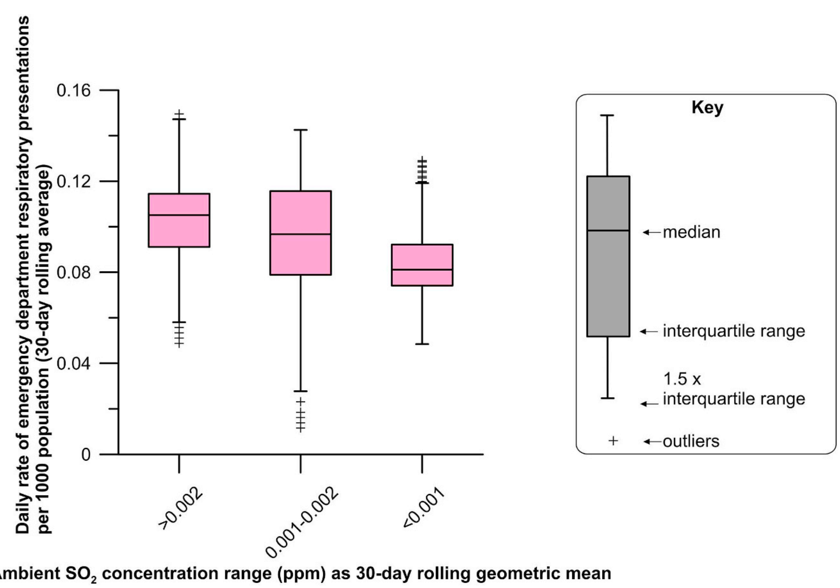


**Fig. 6.** Respiratory emergency department presentations compared to ambient $SO_2$ concentrations at Port Pirie between July 2012–October 2018. Data are provided in Supplementary Tables S2 and S4.

Using data from China, Chen et al. (2019) reported that increased $SO_2$ concentrations were related to an increase in adverse respiratory disease impacts when considered on an annual average basis. Other studies investigating $SO_2$ impacts on respiratory health have refined analyses by adjusting data for cold weather, cold and flu outbreaks and even day of the week (Rodriguez-Villamizar et al., 2015). These potentially confounding factors have not been accounted for here, likely moderating the significance of the $SO_2$ data. Nevertheless, it is clear that increasing $SO_2$ concentrations are associated with emergency department respiratory presentation rates at Port Pirie (Fig. 6). The evidence supports the need to enforce, as a minimum, the existing Australian $SO_2$ standards in Port Pirie. Currently, the 1-hour (Fig. S1) and 24-hour (Fig. 3) Australian ambient $SO_2$ standards are not being met at Port Pirie. The Australian annual ambient $SO_2$ standards are currently satisfied in Port Pirie (Fig. 3).

## 4. Discussion

The association between industrial air pollution (including elevated concentrations of ambient particulates and sulfur dioxide) and respiratory disease have been detailed in epidemiological studies (e.g. Heinrich et al., 1999, 2002; Frye et al., 2003; Williams et al., 2012), though it has been debated by others (e.g. Donoghue and Thomas, 1999). The impact of smelting emissions on human health is well understood globally, with the worst examples typically emanating from low to middle income countries (von der Goltz and Barnwal, 2018). In particular, informal and poorly controlled lead acid battery recycling is now emerging as major environmental health problem (Ericson et al., 2016; WHO, 2017). It is also well-established that lead smelter emissions contaminate aerosols, soils and dusts resulting in elevated blood lead concentrations even where emission controls have been implemented (e.g. Soto-Jimenez and Flegal, 2011).

The Port Pirie smelter remains a significant source of pollution to the local environment, with 50 t of lead being emitted in 2016/2017 (National Pollutant Inventory, 2018). Its impacts have been hemispheric. Isotopic analysis of ice cores shows that lead smelting at Port Pirie has contaminated distant and remote environments including Antarctica (Vallelonga et al., 2002; McConnell et al., 2014). Lead-rich particulates from the Port Pirie smelter operations continue to contaminate indoor and outdoor surfaces, soils and the atmosphere, causing harmful exposures to children. In 1983, Dr. Phillip Landrigan called for urgent action to mitigate unsafe exposures in his South Australian government commissioned report (Landrigan, 1983). He identified that airborne lead and its accidental ingestion from atmospherically contaminated dust and soil were the main sources of exposure. Whilst blood lead levels have since fallen, the former goal of reducing blood lead levels in 95% of children < 5 years old to below 10 μg/dL by the end of 2010 was not achieved (Simon et al., 2018). By 2010, over 25% of children reported blood lead levels above 10 μg/dL (Fig. 4, Simon et al., 2018), placing them at serious risk of neurological damage including marked IQ decrements (Earl et al., 2016), which do not remit with age (Searle et al., 2014; Reuben et al., 2017). By way of comparison, between 2012 and 2016, 9.3% of USA children aged < 5 years were tested, of which an average of 4.0% presented with a blood lead concentration > 5 μg/dL (Centers for Disease Control and Prevention, 2018). Further, current mean blood lead in USA children is approximately 1 μg/dL (Centers for Disease Control and Prevention, 2019).

Despite extensive public health programs and environmental licencing and monitoring to address Port Pirie's environmental lead issues, lead in air also remains a significant problem. Absent the Ellen Street site data, in 2017 lead in air in the city of Port Pirie averaged 0.44 μg/m$^3$. This is > 100 times greater than in Sydney and 2.2 and 5.5 times greater than Broken Hill and Mount Isa (Table 2), respectively (Zhou et al., 2018). Both Broken Hill and Mount Isa are also home to major lead mining and processing operations, with significant lead emissions affecting adjoining residential environments (Mackay et al., 2013; Dong and Taylor, 2017; Noller et al., 2017).

Atmospheric concentrations of lead at the SAEPA's four sites across the city averaged 0.89 μg/m$^3$ between 2008 and 2017. Corresponding blood lead measures over the same time period show that 22.4% (mean of all years) of children (n = 1490/6653 tested between 2008-2017, SA Health, 2011; Simon et al., 2018) presented with a blood lead > 10 μg/dL.

More recently, strategies such as washing playgrounds have been introduced to limit exposures. Such approaches only deal with a very limited geographical area and cannot address exposure across the wider city, as evidenced by the current percentage of children with blood lead exceeding 5 μg/dL. Additionally, residents are advised to protect themselves in their homes by washing hands, surfaces and food and to limit the transport of contaminated dust and soil from outside (Targeted Lead Abatement Program, 2018). This approach is problematic because it pushes the burden of responsibility onto individuals rather than onto the polluter, who should limit emissions at the source via more effective emission capture technology. A recent review of household interventions for preventing domestic lead exposure in children found that household education interventions were not effective as population health measures for reducing blood lead levels in children (Nussbaumer-Streit et al., 2016). Moreover, expecting home owners to mitigate risks is contrary to the public health principle of primary prevention (Committee on Environmental Health, 2005), which is '… *the only truly effective public health response to lead poisoning*' (p. 368 Meyer et al., 2003).

In order to ensure that children present with a blood lead below 5 μg/dL, the data (Fig. 5) show that there needs be a significant reduction of lead emissions from the Port Pirie smelter. Geometric mean annual lead in air concentrations at Oliver Street have only fallen below 0.11 μg/m$^3$ twice since 2003 (2011 and 2015). This is the level required to ensure the geometric blood lead level in children < 5 years of age does not exceed 5 μg/dL (Fig. 5). Moreover, lead in air levels have never fallen below the threshold required to protect 24 month-old children (0.082 μg/m$^3$) in any year since 2003. Therefore, it is unsurprising that geometric mean blood lead concentrations in Port Pirie children < 5 years of age have continued to exceed 5 μg/dL in most years and for all years since 2003 with respect to children aged 24 months. The dose-response estimates show that the annual lead in air concentration needs to be ~80% lower than the Australian lead in air standard of 0.5 μg/m$^3$. By way of comparison, in 2008, the United States EPA set a similar standard in that lead in air must not exceed 0.15 μg/m$^3$ averaged over a rolling 3-month period (USEPA, 2008).

Fig. 5 implies that there is an additional environmental lead source affecting Port Pirie's children apart from atmospheric exposure. The Oliver Street data show that for children < 5 years old and 24-months old, this additional source contributes 2.16 μg/dL and 2.45 μg/dL of blood lead, respectively (Fig. 5). This indicates that other sources such as those from contaminated soils and dusts (Maynard et al., 2005; Simon et al., 2007) are contributing to children's blood lead, with atmospheric exposure providing an additional critical pathway, pushing children's blood lead over 5 μg/dL. Along with reductions to lead in air, these additional sources also need to be identified and remediated.

According to the World Health Organization (WHO, 2018b), there is no known safe level of lead exposure. Blood lead concentrations < 5 μg/dL have also been associated with decreased intelligence in children, behavioural difficulties and learning problems (National Toxicology Program (NTP), 2012; Budtz-Jørgensen et al., 2013; WHO,

**Table 2**
Ambient lead in air concentrations compared with percentages of children presenting with blood lead concentrations over the Australian standard (5 μg/dL). Lead in air is measured in total suspended particulates (TSP) except for Sydney where values are based on $PM_{2.5}$.

| City | Lead in air (TSP) annual average ambient concentration (μg/m$^3$) | Percentage of children (0–4 yrs) with blood lead concentration > 5 μg/dL | Data source |
|---|---|---|---|
| | (Data collection year shown in brackets) | | |
| Port Pirie | 0.44 (2017) | 47 (2017) | Simon et al. (2018) |
| Broken Hill (NSW) | 0.20 (2017)[a] | 54 (2017) | Western NSW Health Intelligence Unit (2018), Perilya (2018) |
| Mount Isa, (Qld) | 0.08 (2017) | 25 (2017)[b] | Queensland Department of Health (2018), Queensland Government (2018b) |
| Sydney (NSW) | 0.001 (2017, Pb in $PM_{2.5}$) | Recent data not available | ANSTO Australia (2018) |
| Australian standard for lead in air | 0.5 | – | – |

[a] Compiled from monthly reports from Perilya (2018) for high volume air sampling at licence points 12 (mean 0.207 μg/m$^3$) and 26 (mean 0.197 μg/m$^3$).
[b] Average of all results (Queensland Department of Health, 2018): venous (n = 253, 18% > 5 μg/dL) and fingerprick (n = 757, 28% > 5 μg/dL). Fingerprick results were collected from Sept 2016 to Feb 2017).

2018). Children with elevated blood lead concentrations are at greater risk of damage to neurological development and changes in behaviour and cognitive abilities (McMichael et al., 1988; Tong et al., 1996; Burns et al., 1999; Calderón et al., 2001; Lanphear et al., 2005; Huang et al., 2015; Earl et al., 2016). Given the extent of the exposures in the Port Pirie community it is not surprising that other researchers have identified negative health effects from exposures. For example, Earl et al. (2016) showed using a small cohort of 127 children from Broken Hill (n = 49) and Port Pirie (n = 78) that when blood lead rose from 1 to 10 μg/dL, 13.5 full scale IQ points were lost. Searle et al. (2014) assessed their 30 year Port Pirie cohort (n = 723) and concluded that childhood exposure was associated with small but significant negative health outcomes including cognitive development, IQ, and mental health problems, which appeared to persist in females who presented with anxiety problems and phobia. Early intervention is key to mitigating long-term effects of Pb exposure. Billings and Schnepel (2018) demonstrated that in North Carolina early life interventions into Pb exposure were able to successfully mitigate negative outcomes.

Even though Port Pirie has the highest lead in air concentration of the cities listed in Table 2, it is surprising that Broken Hill reports a higher percentage of children (0–4 yrs) exceeding the Australian blood lead standard (5 μg/dL). This may be due in part to the high participation rate of children in the Broken Hill blood testing program, where 88% of children presented for lead screening compared (Western NSW Health Intelligence Unit, 2017) with an estimated 67% in Port Pirie (Supplementary Fig. S5). Relevantly, the percentage of children exceeding the former upper maximum blood lead value of 10 μg/dL rose in Broken Hill after 2011, following successful efforts by NSW Health to increase participation (Lesjak and Jones, 2015).

Considering the elevated $SO_2$ concentrations in Port Pirie (Fig. 3), it is not surprising that the residents of Port Pirie have one of the highest rates of emergency department presentations for respiratory system disease in regional South Australia. The Port Pirie rate of 6166.1 presentations per 100,000 population compares with the regional South Australian rate of 2719.2 presentations per 100,000 population in 2017/2018 (SA Health, 2018a). Only Renmark (280 km east of Adelaide) reported a higher presentation rate, which may be due to climatic differences (colder nights) and environmental hazards from crop-spraying. Moreover, children in Port Pirie are over-represented in emergency department respiratory presentations. The disproportionate effect of $SO_2$ on children's respiratory health is evidenced by the fact that while children aged 0-4 and 5-9 years comprise 5.2% and 5.9% of Port Pirie's population, they represent 30.1 % of the total emergency department respiratory presentations.

The absence of limits on $SO_2$ emissions at Port Pirie has contributed to ambient $SO_2$ concentrations above Australian and WHO standards (Fig. 3) and consequent adverse human health outcomes. The true cost of industrial pollution on impacted communities such as those in Port Pirie needs to be given proper weight when balancing the economic benefits of industrial activity. This is particularly concerning in light of the harm to human health from industrial pollution and the environmental inequities that prevail in affected communities (Landrigan et al., 2017; Filippelli and Taylor, 2018).

Despite the long history of contamination and associated human health problems at Port Pirie (Landrigan, 1983; Taylor, 2012; Taylor et al., 2014), only recently has there been a marked shift in willingness to address the status quo and reduce smelter emissions. This shift in attitudes led to an industry-driven proposal (COOE Pty Ltd., 2013) to upgrade the smelter at an estimated cost (in 2015) of AU$514 million (Government of South Australia, 2015); with works to be completed in 2018. The recent cost estimate for the smelter upgrade was AU$660 million (Nyrstar, 2017a). In addition, Nyrstar committed AU$3 million per year for 10 years for the new Targeted Lead Abatement Program (2018) (TLAP) with an additional AU$5 million to accelerate the TLAP objectives. The South Australia Government has also committed AU $1.5 million a year for 10 years towards the TLAP. Irrespective of these commitments, it is evident from the available emissions and health data that risks have increased, with warnings about smelter performance occurring in late 2018 (Lysaght et al., 2018).

It is anticipated that the Nyrstar upgrade will lower lead and $SO_2$ emissions by approximately 50% (COOE Pty Ltd., 2013). However there has yet to be a specific commitment to the actual level of future improvement to ambient air quality in Port Pirie (Nyrstar, 2017b). Currently, Nyrstar produces 45 kt of sulfuric acid as a by-product from sintering processes (Nyrstar, 2018). The plant upgrade includes the replacement of the existing acid plant with a plant of larger capacity that is expected to reduce $SO_2$ emissions from the main stack by 90% (Government of South Australia, 2013).

### *4.1. Limitations of the data*

One important limitation of this study is that health data are not spatially resolved across Port Pirie. That is, some children live near the smelter, where lead in air and $SO_2$ concentrations would be greater than for those children living distant to the smelter. Yet in this community-wide analysis, it is clear that lead in air and ambient $SO_2$ emissions are demonstrably affecting the health of children in Port Pirie. An additional limitation is that the pool of children tested each year changes, both as children age and because testing is carried out on a voluntary basis. As noted previously, lower presentation rates of children are likely to affect the results presented here. Comparison of the annual geometric mean of lead in air and blood lead (Fig. 2) is limited to 30 annual data points, yet these are underpinned by ~2000 measurements of lead in air (based on sampling every 6$^{th}$ day at the Oliver Street and Pirie West Primary School sites) and > 10,000 blood lead assessments between 2003 and 2017 (SA Health, 2011, 2018c).

This study considers only atmospheric lead and does not investigate the role of lead in soils or lead deposited on surfaces. Whilst lead in air is clearly a factor for health, future research should include dust deposition data, as lead deposited on surfaces is an established exposure pathway for ingestion by children. The measurement and inclusion of other known contaminants associated with smelter emissions in future analyses would enable assessment of synergistic effects and related associations to respiratory outcomes. Contaminants of concern might include arsenic, cadmium (Csavina et al., 2014; Taylor et al., 2014) and $PM_{2.5}$ concentrations, which are known to be more closely associated with adverse health effects than coarser particles (Schwartz and Neas, 2000) such as $PM_{10}$ that is routinely measured by the SAEPA at Port Pirie. Although the SAEPA has collected the aforementioned data in small campaigns its sporadic nature makes it unsuitable for inclusion here and is a limitation for this study.

In terms of health impacts from $SO_2$, only emergency department presentations for respiratory illnesses were considered. Apart from emergency department presentations, exposure to $SO_2$ would likely cause less severe, sub-clinical symptoms for a larger percentage of the population. Further study of prescription medications purchased or presentations to general practitioners would provide useful additional data. Emergency respiratory presentation data for Port Pirie were only available from July 2012 to October 2018, limiting statistical analysis. A longer period of data would enable more accurate calculation of health impacts from $SO_2$. A further limitation is that presentation data with diagnosis was only available for major regional South Australian emergency departments. As previously noted, this study did not account for respiratory presentations that may have been related to or exacerbated by colds, influenza or weather conditions.

## 5. Conclusions

It is evident that, in the last few years, smelter emissions have been significantly elevated and that these are associated with adverse outcomes in the receiving population of Port Pirie. There are several changes that need to be implemented promptly to limit exposures in the community now and into the future. Given that the source and extent of the problem in Port Pirie has been well documented and solutions are well known to industry and government, there is no justifiable reason to not prevent, as a matter of urgency, further adverse exposures. Whilst closing the smelter would cease further emissions, there is a need to balance economic needs with risk. It is anticipated that the smelter transformation project, which includes a refit with modern, clean technology coupled to comprehensive soil and household dust remediation across the city, should reduce exposures significantly. Analysis of lead in air and in children's blood demonstrates that a clear relationship exists between these variables. The modelled lead in air threshold to achieve a geometric mean child blood lead of < 5µg/dL for Port Pirie is ~80% lower than the current Australian lead in air criteria (0.5 µg/$m^3$). The fact that current regulatory frameworks impose no licence limits on $SO_2$ exceedances in Port Pirie also needs to be addressed. This study has demonstrated that increased ambient $SO_2$ concentrations are related to additional emergency department respiratory presentations in Port Pirie. Hence, there is a need to enforce as a minimum, Australian air quality standards for $SO_2$. Further study is warranted to determine what level of ambient $SO_2$ provides acceptable protection for the community and for the role of confounders (e.g. seasonality, colds, influenza) in explaining the relationship between ambient $SO_2$ and emergency department respiratory presentations. Nevertheless, the forward projections are that both lead in air and $SO_2$ will be significantly reduced to approximately 50% of existing levels (COOE Pty Ltd., 2013). This engenders an expectation that continued testing of Port Pirie's children's blood lead levels will reveal a marked reduction and that emergency department presentations for respiratory conditions will also be significantly reduced.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.01.062.

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