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Environmental Lead Risks at Broken Hill, New South Wales, Australia: Sources, Exposures and Forward Solutions

Report prepared for the Broken Hill Environmental Lead Program Steering Committee

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Delivered by email to: peter.oldsen@.epa.nsw.gov.au

Mr Peter Oldsen
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Environmental Lead Risks at Broken Hill, New South Wales, Australia: Sources, Exposures and Forward Solutions

Dear Mr Oldsen

Please find attached our Report for the Broken Hill Environmental Lead Program Steering Committee: ***Environmental Lead Risks at Broken Hill, New South Wales, Australia: Sources, Exposures and Forward Solutions*.**

The author team are grateful for your assistance along with that provided by Dr Frances Boreland from the Broken Hill Environmental Lead Program in compiling this report.

Yours sincerely

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Summary list of findings and options for addressing Pb exposures

This Report's summary findings and options for moving forward are set out below and should be read in conjunction with the detailed research and analysis provided in Section 2 of the Report.

Childhood blood Pb in Broken Hill remains elevated. In 2018 49 % of children under five years old presented with blood Pb ≥ 5 μg/dL and of the Indigenous population, 76 % of children tested exceeded 5 μg/dL (NSW Ministry of Health 2019). Blood Pb levels in Australian children who are not residing in high risk areas like Broken Hill are now ~ 1 μg/dL (Symeonides *et al.* 2020), which is similar to levels in the USA (NHANES 2019). Children's Pb exposure in Broken Hill is not due to a single source, but rather to multiple sources of exposure, including Pb in air and dust, Pb in soils and for some children, exposure to leaded paints.

That said, the evidence is clear: emissions from the Line of Lode including from ongoing operations are instrumental in terms of driving blood Pb and must be curtailed alongside remediation at homes to have the effect of controlling and then mitigating further preventable exposures.

A short video summarising of the history and environmental context of blood Pb exposures in Broken Hill can be viewed here.

Question 1 – Historical and current sources of Pb exposure in Broken Hill children

1. **Both legacy and current Pb emissions must be addressed if children's blood Pb is to be reduced in Broken Hill.**

   Research at Broken Hill area has evaluated multiple potential sources of environmental Pb exposure. Whilst there is evidence that natural Pb-bearing minerals present in soil, paints and past leaded petrol usage contribute to the total burden of exposure, the available research is clear in that it shows that past and current emissions from mining operations are the leading source of Pb exposure in Broken Hill. Neither legacy emissions from mining (retained in soils and dust) or current mining emissions (in deposited dusts) alone are singularly responsible for current Pb exposure. Rather, it is these two sources in combination that drive current childhood Pb concentrations. This fact has been is demonstrated in multiple research papers that show associations between blood Pb levels, soil Pb and current mining emissions, which are characterised by Pb in air and dust concentrations.

Question 2 – Current trends in blood Pb levels in Broken Hill children

2. **A city-wide solution is required to reduce exposure and blood Pb. Children across the whole of Broken Hill are at risk from elevated blood Pb concentrations.**

   Some groups of children, including those in the highest-risk zones (i.e. those closest to the Line of Lode) and Aboriginal children, have a higher likelihood of presenting with elevated blood Pb. However, most of the children in Broken Hill presenting with elevated blood Pb levels (≥ 5 μg/dL) neither reside in the high-risk area or are Aboriginal. Indeed, only around 30 % of children in Broken Hill are able to keep their blood Pb at < 5 μg/dL in the first three years of their life. Hence, whilst more can be done to reduce the current inequalities, all children in Broken Hill are at risk of elevated Pb exposures irrespective of their residential address.

Question 3 – Potential strategies for lowering children's blood Pb levels in Broken Hill

3. **Identifying exposure: Blood testing should continue to be conducted at 6-months of age.**

   By 12 months of age, around half of children in Broken Hill have already exceed the 5 µg/dL of blood Pb threshold. Earlier testing, which is now occurring, will allow identification of risks and early intervention to occur. There may even be some merit, resources depending, on assessing children at 3 months of age to determine their blood Pb trajectory, allowing for even earlier intervention. In this regard, SA Health uses a blood Pb of 3 µg/dL to intervene with children in Port Pirie (Dr David Simon, SA Health, personal communication).

4. **Identifying and reducing emissions: Determine and set an acceptable trigger value for Pb in deposited dust and introduce environmental licensing regulations limiting Pb in deposited dust.**

   Blood Pb concentrations correlate with dust Pb. Dust Pb is measured across Broken Hill and these data could be used more effectively to control emissions and reduce Pb exposure. Environmental licensing for the Pb-Zn-Cu mining and smelting at Mount Isa Mines (Queensland) requires Pb in deposited dust to be less than 100 µg/m^2/day. The data evaluated in this review suggests that Pb in dust needs to be reduced to ~ 90 µg/m^2/day to ensure children's blood Pb is below 5 µg/dL. Therefore, the level of 100 µg/m^2/day, which is used as a trigger value at Mount Isa and is also promulgated in the German air quality guidelines TA Luft (2017) may be a suitable target to introduce for Broken Hill. Lead in air emissions from the operations are managed against the national standard of 0.5 µg/m^3. There is no equivalent standard or trigger value for Pb in deposited dust required as part of the licence requirements for the mining operations. Current dust Pb deposition values measured in the community exceed those used in Mount Isa, presenting a significant exposure risk.

5. **Reducing exposure to airborne emissions and dust: Continue dust deposition monitoring and continue to investigate ways to mitigate dust deposition.**

   Continued dust deposition monitoring will determine how effective the newly installed dust controls are (e.g. dust extraction on crushing activities). If Pb in deposited dust targets (see point 4 above) are still unable to be met, further measures need to be investigated, such as ceasing crushing activities on windy days, increased watering and further use of dust suppressants etc.

   As an interim measure until more complete control of environmental Pb sources is resolved, there is merit in undertaking a trial of in-home HEPA (high efficiency air particulate) air purifiers to reduce the burden of Pb-rich dust in homes. HEPA air purification filters have previously been shown to be effective at removing $PM_{2.5}$ and Cd in homes and Pb in industrial environments, but have yet to be proven for Pb in residential environments.

6. **The feasibility of relocating some or all families should be investigated.**

   a. Relocation from high risk to low risk areas
   This option is not likely to be effective in broadly reducing children's blood Pb considering that most Pb affected children currently reside in lower-risk areas, however it may assist in lowering blood Pb for children most at risk.

b. Relocation a suitable distance from the mine (away from current town area)
This option is costly and not likely to be acceptable to families who have invested in life in Broken Hill (i.e. jobs, family, schools etc) yet would very effectively remove children from contaminated areas for the long-term. This would also eliminate exposures to Pb in contaminated soils.

Consideration must be given to the lifespan of mining in Broken Hill and to population projections beyond mine closure. If mining is not projected to continue more than a few decades and the local population is projected to decline after this time, relocation may not be a feasible option. Instead, it may be more feasible to employ further dust emissions controls and remediate soil and dust, even if the soil amendments require rejuvenation every ten years.

c. Relocation of families away from Broken Hill following mine closure
This may also be an option, preventing ongoing exposure to legacy Pb contamination. This possibility can be circumvented if there is proper clean-up of legacy contamination in the city.

7. **Reducing exposure to Pb in soil: Soil abatement of surface soils to below 300 mg/kg (NEPM residential soils) or 150 mg/kg on a city-wide basis.**

   Children with elevated blood Pb live all across Broken Hill and not just in high-risk zones close to the Line of Lode. Children also spend significant time each week at other homes, childcare/preschool/school or in public areas, extending the potential for exposure beyond their primary residential environment. Modelling of soil exposure impacts on blood Pb predicted that a level of below 150 mg/kg was required to keep levels below 5 µg/dL. Whilst the soil Pb level of 150 mg/kg is below the NEPM standard for residential homes (300 mg/kg), the research shows that this level is a necessary step to reduce children's blood Pb to acceptable levels.

   The provision of soil Pb and household dust Pb testing using portable XRF should be made available for Broken Hill residents. Any testing should be coupled to practical advice and affordable intervention actions for residents.

   Broken Hill residents should be encouraged to use raised beds for any vegetable gardening and to wash produce before consumption.

8. **Replacement of aged housing**

   Aged housing is an increased Pb exposure risk; replace with new, well-sealed housing.

9. **Provision of safe renovation assistance to households with high Pb in paint.**

   High levels of Pb in paint, particularly when in a deteriorated state can contribute to children's blood Pb. The provision of paint Pb testing using portable XRF should be made available for Broken Hill residents. Paint Pb abatement without adequate precautions results in increased child blood Pb. Education and or assistance to perform safe paint Pb abatement is therefore advised.

Question 4 – Strategies applied in Australia and overseas to reduce blood Pb exposures

10. **Testing, and where needed, renewal of soil abatements after 10 years.**

    Soil abatement strategies (as opposed to remediation – dig up and removal) have been shown to significantly reduce in effectiveness after 10 years, meaning that children could again be exposed, perhaps unknowingly, to hazardous levels of Pb. Soil abatement can only be considered as a temporary solution. Any financial consideration of this strategy should include funding for future renewal of abatement areas. If the same family remains in abated property, a period of ten years may be adequate if, after that time, children are aged > 5 years old as they will be at a much reduced a risk of Pb exposure from soil contact. A well-maintained register of abatement works is also needed, plus guidelines on how to best maintain abated land. This is especially important in cases where properties are sold and new owners are unaware of abatement history and the extent of capped contaminated soil. This information could be added to rental contracts as it is to s 10.7 *Environmental Planning and Assessment Act 1979* (NSW) certificates that are required on the sale and purchase of homes.

11. Effectiveness of strategies: Pilot testing of phosphate amendments as a potential additional soil abatement strategy.

Phosphate amendments of soils have been demonstrated to decrease the bioavailability of Pb in soils. These should not replace other soil abatement strategies in highly Pb affected soils, but may be useful in providing an additional measure of protection where Pb levels are close to abatement criteria. Pilot testing is required on local soils as results vary between soil types and in some cases, bioavailability of other toxic components may be influenced by phosphate amendments. Bauxsol™ and Bauxaline® soil amendments could also be considered as alternative options.

12. Continue to involve the local community in decision making, particularly for highly-affected groups such as the Aboriginal community.

Studies of communities that have not received adequate communication have shown that it results in a long-term lack of trust and community co-operation with abatement strategies. The community relations aspect in Broken Hill is currently very positive, particularly following the LeadSmart campaign and needs to be retained to ensure continued community 'buy-in' and engagement with the problem and the solution.

SECTION 1

Introduction

1.1 Terms of Reference

In executing the Review, the project team was required to engage with scientists and practitioners that have current research knowledge of the sources of lead (Pb) contamination in Broken Hill. The review team was requested to answer four questions, detailing:

1. Historical and current sources of Pb exposure in Broken Hill children
2. Current trends in blood Pb levels in Broken Hill children
3. Potential strategies for lowering children's blood Pb levels in Broken Hill
4. Strategies applied in Australia and overseas to reduce blood Pb exposures

1.2 Review process

From late June 2018 through to July 2019, the Review team undertook its research using a range of processes:

- developing search terms for the literature review in consultation with the Broken Hill Environmental Lead Program (BHELP)[1]
- consulting with government agencies/regulators and scientists/practitioners
- undertaking a literature search of Pb pathways in Broken Hill
- providing the BHELP an opportunity to undertake fact checking and content review of the Review's Report
- the final draft document was subject to an internal review process completed by Emeritus Professor Brian Gulson (Macquarie University) who has expertise in the subject matter of this Report.

1.3 Summary of the consultations undertaken for this Report

The Review received advice from the BHELP Office as to suitable researchers who would be able to provide constructive insight with respect to the Review's terms of the reference.

In addition, the Review team were invited by BHELP, to discuss the Review at a meeting attended by Peter Oldsen (BHELP) and Craig Bretherton (NSW EPA).

In addition to the above consultations, numerous phone calls and e-mail discussions were undertaken with the BHELP Office and the NSW EPA and other parties to assist in clarifying matters raised during compilation of this Report.

[1] The Broken Hill Environmental Lead Program is managed by the independent Broken Hill Environmental Lead Program Steering Committee, which has an independent chair.

1.4 Acknowledgements

The Review acknowledges and thanks staff from agencies, departments and organisations with whom it consulted for their time and effort in providing information and assistance to the Review. In particular, the Review acknowledges and thanks the BHELP for accommodating its requests for information and providing time to assist the Review.

1.5 Structure of the report

Pursuant to the terms of reference and the requirements of the BHELP, the Review has limited its findings with facts and advice with supporting reasons for ways to move forward to Section(s) 2 and 3 of this Report. The Review's findings and advice to the BHELP are set out below each question addressed as part of the literature review and are then provided in summary at the start of the Report.

The Report structure is set out below.

Section 1	Introduction
Section 2	Recent environmental Pb research at Broken Hill
Section 3	Summary and forward options for addressing Pb exposures

Appendix A	List of abbreviations
Appendix B	Annotated bibliography
Appendix C	Additional submissions to the Review

1.6 Overview of Pb in Broken Hill

Broken Hill, in far-west NSW, is located approximately 1100 km from Sydney and 500 km from Adelaide (South Australia). Broken Hill's population was 17,814 in 2016, with approximately 8.4 % of people being of Aboriginal or Torres Strait Islander descent (Australian Bureau of Statistics 2018).

Mining in Broken Hill has continuously occurred since the discovery of ore (silver (Ag), lead (Pb) and zinc (Zn)) at Broken Hill in 1883 (Solomon 1988). More than 200 Mt of ore have been extracted in this time (Morland and Webster 1998, Perilya 2018). Initially, smelting processes occurred in Broken Hill but by 1897, all smelting operations had moved to Port Pirie, South Australia, due to a lack of fuel for the smelters (Woodward 1952, Solomon 1988). Mining in Broken Hill has been of great significance to the local and national economy, bringing about the formation of BHP and Rio Tinto (Blainey 1968), two of the world's largest mining companies. Perilya Limited (Perilya) and CBH Resources Limited (CBH) currently operate mines in Broken Hill, generating a significant share of the region's economic output ($318 million of $1.45 billion in 2016/2017) and employing 813 people (Broken Hill City Council 2018).

Early mining operations and smelting activities in Broken Hill were not subject to environmental controls, resulting in widespread Pb contamination in the adjoining residential community. Smelting operations in Broken Hill resulted in an estimated emission of approximately 11,000 t to 18,000 t of Pb to the environment from 1886 to 1897 (Van Alphen 1991). During this time, the oxidised surface of the ore body being mined was predominately Pb carbonate ($PbCO_3$) (Blainey 1968). Thompson *et al.* (1892), (1893) provided the first published account of Pb poisoning in Broken Hill in both residential and occupational settings.

However, it was not until nearly a century later in the 1990s that environmental emission controls were introduced along with a systematic soil, dust and child blood Pb screening program (Lyle *et al.* 2006). These works were paralleled with a program of remediation of contaminated areas around Broken Hill city including capping of the main mine area known locally as the Line of Lode with uncontaminated waste rock to reduce contaminated dust movement. Consequently, environmental emissions of mine-related contaminants are now significantly lower those than during the early period of mining in part due to the fact that all extraction activities now occur underground. In order to control contemporary dust emissions, CBH conduct the processing and concentrating of ore under negative pressure conditions (Wilson 2010). According to National Pollutant Inventory records (National Pollutant Inventory 2018), CBH emitted 88 kg of Pb to air in the 2016/2017 reporting period. Perilya's reported emissions were much higher at 27 t Pb to air during the same period, ranking it as the nation's second highest emitter of Pb to air (National Pollutant Inventory 2018). Perilya's emissions may have reduced from this 2018 reported level, as Perilya Northern Operations have installed a fully enclosed ROM pad (run of mine ore stockpiles) and crushing facility, as recommended by the NSW Environment Protection Authority (2016).

The human health risks associated with Pb exposure are well established (National Toxicology Program (NTP) 2012). According to the World Health Organization (WHO 2018), there is no known level of Pb exposure that is considered to be safe. Blood Pb concentrations of < 5 µg/dL have also been associated with decreased intelligence in children, behavioural difficulties and learning problems (National Toxicology Program (NTP) 2012, WHO 2018) Children with elevated blood Pb concentrations are at greater risk of damage to neurological development and changes in behaviour and cognitive abilities, as demonstrated in Australian (McMichael *et al.* 1988, Tong *et al.* 1996, Burns *et al.* 1999, Earl *et al.* 2016) and international studies (Calderón *et al.* 2001, Lanphear *et al.* 2005, Huang *et al.* 2015, Hirtz *et al.* 2017). Lead exposure continues to affect individuals throughout their life (Jaishankar *et al.* 2014, Bellinger and Mazumdar 2015, Cabral *et al.* 2015, Li *et al.* 2016, Bellinger 2017, Reuben *et al.* 2017, Beckwith *et al.* 2018, Bellinger *et al.* 2018, Lanphear *et al.* 2018, Reuben *et al.* 2019) and is estimated to have accounted for 63.8 % of the global burden of idiopathic developmental intellectual disability as well as 540,000 deaths in 2016 (WHO 2018).

1.7 BHELP Strategy for the management of Pb at Broken Hill

Since the introduction of Pb monitoring in 1991, more than 25,000 child blood samples and 10,000 soil and dust samples have been tested in Broken Hill (Dong *et al.* 2020). A city-wide investigation in the 1990s (Lyle et al., 2006) of Pb in soil at parks, schools and footpaths showed that 37 % of samples exceeded 600 mg/kg, the Australian Health Investigation Level 'Recreational C'[2] (National Environment Protection Council 2013). Remediation of selected public areas and residential properties has occurred since this time, using capping or excavation and filling techniques.

In 2015, the NSW Government allocated over $13 million (over 5 years to 2020) to address the issue of ongoing Pb exposure in Broken Hill (Humphries 2015), particularly elevated blood Pb levels in local children. Funding was acquired via the NSW EPA to establish the Broken Hill Environmental Lead Program (BHELP). Of particular concern at that time was the fact that 78 % of Aboriginal children under 5-years-old in Broken Hill had blood Pb levels above the National Health and Medical Research Council (NHMRC) guideline of 5 µg/dL (BHELP 2018). In order to ensure that all stakeholders were appropriately represented the BHELP steering committee was set up to include representatives from the NSW EPA, NSW Health, the Broken Hill Lead Reference Group (BHLRG, which includes mining industry members) and the Aboriginal Lead Reference Group (ALRG). The administrative structure of the BHELP is detailed in the BHELP Steering Committee Annual Report 2017–2018 (BHELP 2019).

BHELP has partnered with the Far West Local Health District and Maari Ma Health Aboriginal Corporation to carry out prevention programs and management of children presenting with elevated

[2] HIL Recreational C is classified under the NEPM (2013) under Schedule B1 as follows: Public open space such as parks, playgrounds, playing fields (e.g. ovals), secondary schools and footpaths. This does not include undeveloped public open space where the potential for exposure is lower and where a site-specific assessment may be more appropriate.

blood Pb (BHELP 2018). Further, the BHELP has also undertaken research and evaluation with external research experts and consultancies to better understand Pb risks and the effectiveness of control measures in Broken Hill in order to provide appropriate evidence-based guidance for its forward program. In collaboration with the NSW Office of Environment and Heritage (OEH), a dust-gauge monitoring network was established in 2017, whose aim was to measure deposited Pb dust at five sites across Broken Hill (OEH 2018) to provide insight on the amount, source and location of environmental Pb as well as the effectiveness of Pb abatement projects.

Research partnerships with Sydney University and Macquarie University have included a review of the long-term effectiveness of previous Pb abatement and a study to determine the risk of Pb exposure in parks, playgrounds and ovals (Section 2). BHELP has also partnered with the Broken Hill University Department of Rural Health (BHUDRH) to investigate the risk factors for children to develop elevated blood Pb levels (Section 2). Already, this work has led to implementation of new early intervention programs, with blood Pb testing being introduced for 6-month old children to provide an opportunity for early intervention.

Investigation of Pb concentrations on public lands continues with a program of targeted research being directed by the BHELP. An outcome of this work is that in partnership with Broken Hill City Council, 10 ha of land (parks, playgrounds, ovals and open land accessible to the public) have been remediated using soil abatement measures (including covering with clean topsoil) after identification that they presented a community Pb risk (BHELP 2018).

The LeadSmart community engagement strategy, running from November 2016 to March 2017 included the development of the LeadSmart website[3], radio, TV and social media advertising as well as story books, colouring books, recipe cards and brochures (BHELP 2018). Further information for the community is also provided on the NSW EPA's Pb information website[4]. The LeadSmart advertising campaign in Broken Hill was extremely effective in raising awareness of the Pb issue and on how locals can reduce Pb exposure. Television and Facebook campaigns and to a lesser extent, radio advertising, reached 85 % of the community with 77 % able to recall three or more points from the message (NSW Government 2017). Community feedback indicated that the information provided was considered to be highly relevant, easily understood and trustworthy. Perhaps the best indicator of effectiveness is that over 43 % of people surveyed had made positive behavioural changes, based on the information provided, to reduce Pb exposure for themselves or others.

1.8 Broken Hill climate

Broken Hill lies within the NSW arid zone and experiences a generally hot, dry climate. Mean annual rainfall in Broken Hill is 250.8 mm, based on data from 1947 to 2019 (Bureau of Meteorology 2019). Rainfall > 1mm is experienced, on average, 28.1 days per year. Monthly rainfall data are presented in Fig.1, which shows that every month has mean rainfall less than 30 mm over 3 rain days or less.

Mean minimum and maximum temperatures for Broken Hill are 11^{o}C and 24^{o}C, respectively (Fig. 2) (Bureau of Meteorology 2019).

On an annual basis, wind direction in Broken Hill (Fig. 3) is predominantly from the south-southwest (through to south-southeast), also including a significant a north-easterly component.

[3] Available at: http://leadsmart.nsw.gov.au (accessed 25 February 2020).
[4] Available at: https://www.epa.nsw.gov.au/your-environment/household-building-and-renovation/lead-safety (accessed 25 February 2020).

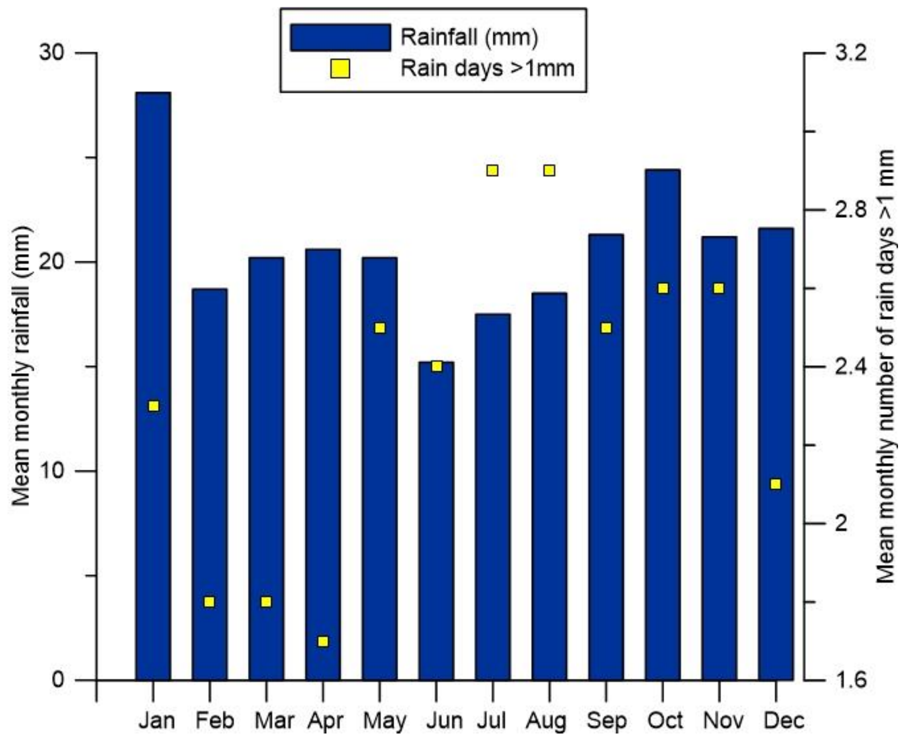


Figure 1. Mean monthly rainfall statistics for Broken Hill city, New South Wales.

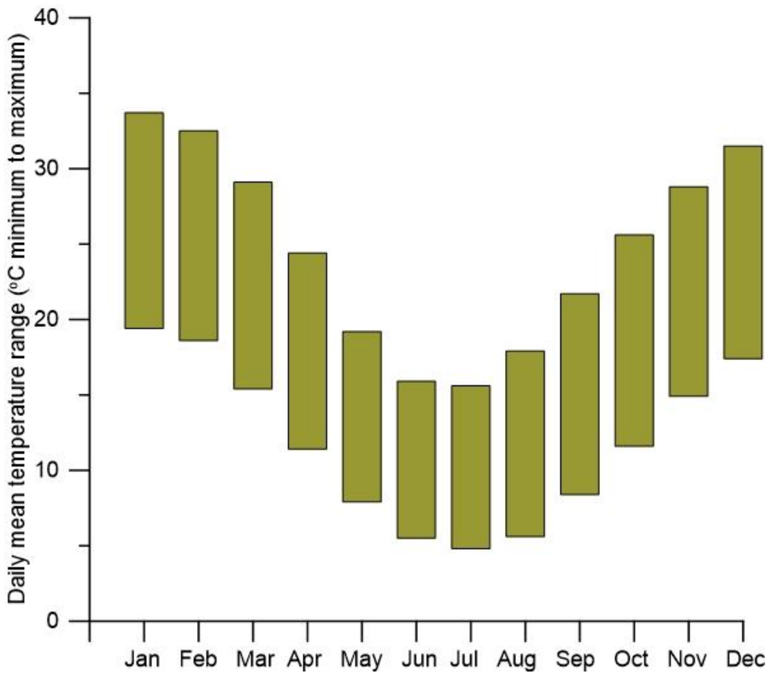


Figure 2. Mean monthly temperature statistics for Broken Hill (Bureau of Meteorology 2019).

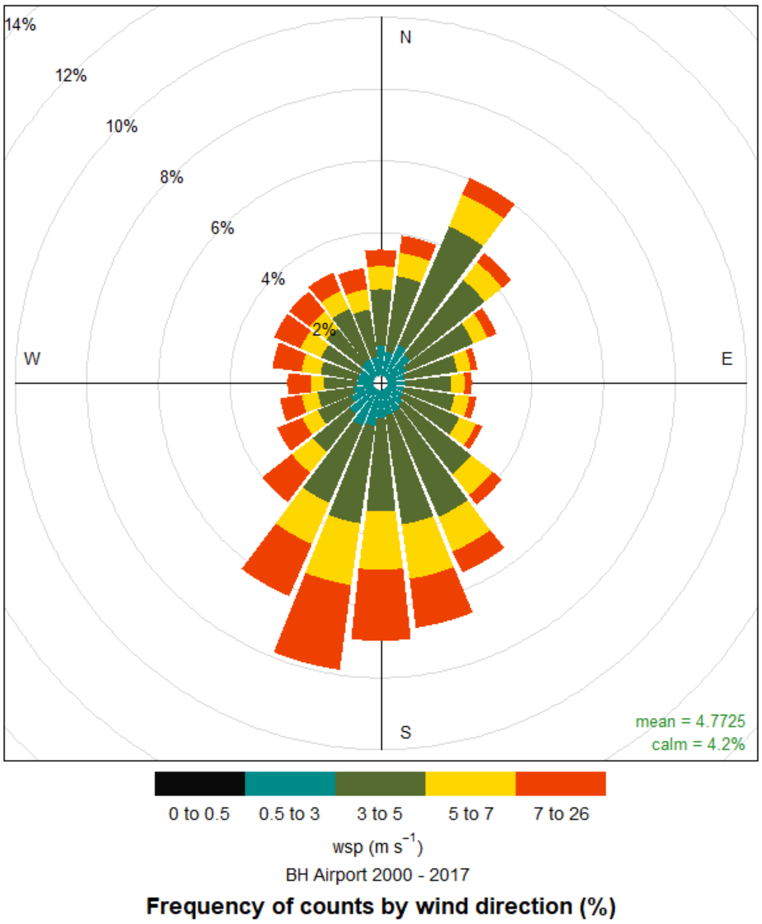


Figure 3. Annual wind rose for Broken Hill Airport, Australian Bureau of Meteorology station number 047048. Data from 2010-2017, 4.2 % calms.

SECTION 2

Recent environmental Pb research at Broken Hill

2.1 Research review process

Multiple independent research studies along with industry and government reports have addressed different facets of the ongoing Pb contamination and subsequent blood Pb exposure issue in Broken Hill. This study aims to bring together all the available relevant research into a cohesive document to help establish the way forward for effective, permanent reductions in children's blood Pb concentrations in the city of Broken Hill. Whilst the focus is on research specifically addressing Broken Hill, other Australian and international research is referred to where appropriate.

Question 1 – Historical and current sources of Pb exposure in Broken Hill children

Lead exposure results from multiple sources and occurs in the workplace, in the home and in public places such as parks. Mining operations, both past and present, contribute to Pb in these environments, yet Pb may also be present due to naturally occurring Pb-bearing minerals in soils, and more locally due to the former use of leaded paints, as well as from past depositions from Pb additives used in petrol.

Research into Pb exposure in the Broken Hill area has considered these potential Pb sources. Whilst there is evidence that Pb from naturally-occurring soil minerals, paints and past petrol usage contribute to exposure, the latest research shows that past and current emissions from mining operations are the leading source of Pb exposure in Broken Hill, as concluded previously by Woodward-Clyde (1993).

Extent of Pb contamination

According to Perilya (2018), Pb in air (total suspended particulates) in Broken Hill was 0.2 µg/m^3 in 2017 (average of monthly reports for high volume air sampling at licence points 12 (mean 0.207 µg/m^3) and 26 (mean 0.197 µg/m^3)). This falls within the Australian standard for Pb in air (0.5 µg/m^3) as an annual average (National Environment Protection Council 2016), yet is many times higher than for Sydney (Pb in fine particles ($PM_{2.5}$) = 0.001 µg/m^3 in 2017 (ANSTO Australia 2018). Elevated Pb concentrations in Broken Hill, as compared to Sydney, are also reflected in the Pb content of bees (> 5 times higher), honey (> 13 times higher) and wax (> 39 times higher) (Zhou *et al.* 2018).

Lead dust is also deposited on the ground and other surfaces around Broken Hill, including public areas. Measurement of deposited dust in Broken Hill using dust gauges reported an annual mean Pb in dust in 2017 of 0.0012 g/m^2/month (CBH dust deposition gauges), 0.023 g/m^2/month (Southern Operations), and 0.14 g/m^2/month (North and Potosi mines), which in each case was the highest Pb in dust result for at least 5 years (OEH 2018). Measurement of Pb levels on playground surfaces demonstrated that substantial amounts of up to 60.9 mg Pb/m^2 near the Line of Lode were transferred to hands after 10 minutes of simulated child play (Taylor *et al.* 2014).

Lead has also been released to the local environment from transport of ores including uncovered trucks using city roads and uncovered rail wagons. Using Pb isotopic compositions, Kristensen *et al.* (2015) showed that Pb dust has been deposited along rail corridors where trains have carried Pb-bearing ores away from Broken Hill for over 125 years. For much of this time, Pb was transported in uncovered rail wagons. Soil around the rail lines contained elevated Pb concentrations and other trace element contaminants adjacent to rail lines and decreased with distance away from the rail lines. This contamination extends for hundreds of kilometres along the rail line from Broken Hill (Body 1986). Isotopic analysis of Pb in houses along the rail corridor in Broken Hill found unweathered galena (PbS) particles, characteristic of those in transported ore (Kristensen *et al.* 2015, Davis *et al.* 2016). Whilst rail wagons are now covered, the legacy of past Pb contamination remains along rail lines, with the movement of trains and wind erosion means these contaminated corridors are subject to re-suspension of Broken Hill Pb held in the adjoining soils and dusts.

Sources of elevated Pb concentrations in Broken Hill

Within approximately 0.4 km north of the Line of Lode and 0.8 km south of the Line of Lode, both the topsoil and the subsoil are Pb-rich, with mean subsoil Pb value of 805 mg/kg (range 24–6507 mg/kg) across Broken Hill (Yang and Cattle 2016). This indicates that for the soils adjacent to the ore body, a substantial proportion of Pb in soil may have been derived from natural weathering of the rocks that comprised the Line of Lode. In this regard, Webster (2004) indicated that up to 3 million tonnes of low grade ore have been lost to erosion. However, the soil in these areas have been grossly disturbed since mining activities commenced (Fig. 4), meaning that separating natural processes from mining impacts is for all intents and purposes, impossible.

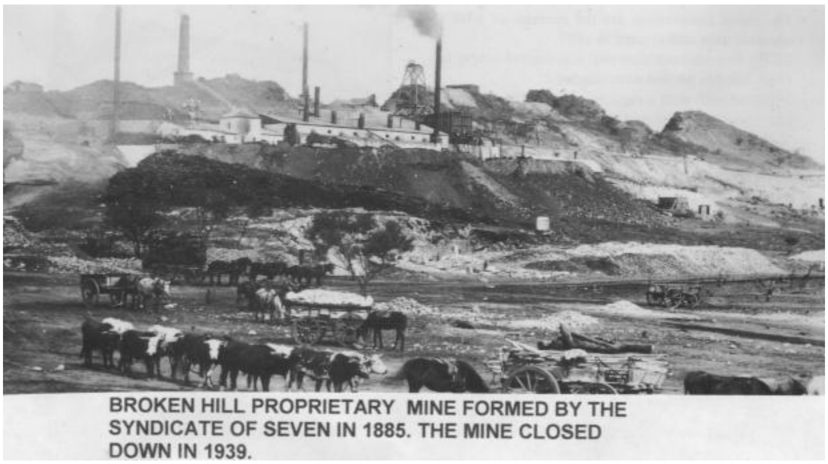


Figure 4. Imagery of Broken Hill Mine. Source: National Library of Australia (https://trove.nla.gov.au).

Beyond the area immediately adjacent to the Line of Lode (0.4 km north and 0.8 km south of ore body), dust from mining operations appears to be the most likely source of Pb-enrichment in topsoil (Kristensen and Taylor 2016, Dong *et al.* 2020). Close to the Line of Lode, mining dust has also had an enrichment effect on soils, but this is partially masked by the Pb-rich nature of the soil parent material (Yang and Cattle 2016).

Davis *et al.* (2016)[5] used microscopic techniques to investigate the origin of Pb in soil and dust around Broken Hill. Soil and dust (pavement and gutter sweepings, dust depositional gauges, long-term dust accumulation, vacuum cleaner dust and ceiling dust) were investigated using a combination of optical microscopy with scanning electron microscopy (SEM) and energy-dispersive analyses (EDS), along with X-ray diffraction (XRD). This study reported different types of particles and hence different origins for these Pb particles. The first and most common were Pb-bearing particles consisting of Pb, Fe (iron), Mn (manganese), Al (aluminium), Si (silicon) and O (oxygen). The majority of grains were rounded with cavities and overgrowths, and showed evidence of transport and recrystallisation, probably deriving from post-mining activities and/or earlier geological processes. The second type, a smaller number of samples from ceiling dust, pavement sweepings, vacuum cleaner dust and long-term dust accumulation, contained galena with a high degree of crystallinity. This galena is likely sourced from recent mining and ore concentration activities. A third source category was evidenced by the high-precision Pb isotopic analyses, which showed that some samples with extensive oxidation and weathering had absorbed Pb from sources other than mine Pb, which may include gasoline, paint or weathering of rocks. In summary, this microscopy study of dusts showed that Pb in soil and dusts around Broken Hill are derived from a range of sources: past mining and erosion activities, current mining activities and other sources, with an overriding imprint of contamination coming from mining activities.

A further pilot study by Morrison *et al.* (2017) used the QEMSCAN® technique (quantitative evaluation of minerals by scanning electron microscopy) for deposited dust from six residential locations across Broken Hill, during 2015 to 2016. This showed that 44-96 % of the Pb phases had undergone significant alteration from the original galena as observed in dust deposits from recent mining emissions. Again, this demonstrates that past and present mining activities contribute to Pb dusts in Broken Hill, with Pb derived from past mining emissions or eroded materials having undergone transport. This work does not however distinguish between contemporary mining Pb emissions from wind erosion of exposed mining areas and re-suspension of past Pb emissions contained in soils across Broken Hill, including from the existing mining sites. Both of these sources would produce altered/weathered Pb particles.

Analysis of Pb isotopes in Broken Hill bees, honey, wax and dust has shown that these were very similar to Pb isotopes in the ore body (Dong and Taylor 2017, Zhou *et al.* 2018). Past studies of Pb isotopes in children's blood indicated that the sources of elevated blood Pb were also attributable to exposure from Broken Hill ores, along with other sources, such as Pb-based paint and leaded petrol (Gulson *et al.* 1994). Importantly, Pb isotopic composition analyses of environmental and human samples cannot distinguish between Pb derived from historical mining and smelting emissions and that sourced from contemporary mining activities.

Role of past and current emissions

Over the years there has been uncertainty about the role that past emissions (present in soils) and current emissions (Pb in air and contemporary dust deposition) play in Pb exposure in Broken Hill. There is evidence showing that both historical and current emissions impact childhood blood Pb concentrations in Broken Hill.

In the 1990s Gulson *et al.* (1994) concluded that, due to high Pb bioavailability, ingestion of soils and dust were responsible for elevated child blood levels in Broken Hill. Further analysis of isotopic

[5] The Davis et al. (2016) study relied on samples collected and analysed predominantly in the 1990s. However, this does not change the significance of the study's broader findings that showed that emissions from mining operations contribute significantly to contaminated dusts in the city of Broken Hill.

compositions (Gulson *et al.* 1995) showed stronger correlations between child blood Pb and dust fall than with soil Pb.

Dust

More recently, Dong and Taylor (2017) used SEM and EDS methods to show that unweathered galena (PbS) found in contemporary dust deposits (dust gauge samples) contrasted markedly to Pb-bearing particles from mine tailings and weathered gossan (original ore body) samples. Contemporary dust particles were more angular, had higher sulphur content and contained little or no iron or manganese. Dust adjacent to the mine had Pb isotopic compositions that were a close match (99 %) to the ore body with values slightly lower (94 %) at the edge of the city; similar observations were noted by Boreland *et al.* (2002) and Boreland and Lyle (2006) for dust from vacuum cleaner and petri dish samples, as well as wipes from household surfaces (Gulson *et al.* 1994). The Dong and Taylor (2017) study showed that contemporary dust Pb contamination in Broken Hill was sourced primarily from current mining activities rather than the remobilization of materials from weathering or legacy sources (Dong and Taylor 2017). Total and bioaccessible Pb (the fraction of Pb that is solublised in the gastrointestinal tract) in dust deposition gauges in Broken Hill decreased with increased distance from the Line of Lode. The fraction of bioaccessible Pb in deposited dust samples (mean 68 %, range 23-92 %) was very similar to those observed in Broken Hill soil samples (discussed below (Yang and Cattle 2015, Juhasz 2018)). Gauges within 1.5 km had mean Pb deposition rates more than double the investigation/intervention value used at Mount Isa (Queensland Department of Environment and Science 2018) of 100 µg/m^2/day[6] (Dong and Taylor 2017).

The significance of deposited dust Pb to exposures in Broken Hill children is also shown in data collected over a longer period of time from mine-operated dust deposition gauges (Fig. 5). At these sites, on average, Pb in dust (over the past 5 to 10 years), has exceeded the benchmark value of 100 µg/m^2/day at almost all sites, including those located in residential areas.

Annual deposition of Pb in dust at Broken Hill does not correlate well with annual total dust deposition (OEH 2018) indicating that not all sources of dust in Broken Hill are equal in terms of their source, Pb concentration and contribution to Pb exposure. For example, whilst Pb in dust deposition rates were high in 2017, compared to the previous five years, the total dust deposition rates in 2017 were only moderately high. In terms of spatial variation, site D3 (CBH, Fig. 5) reported elevated Pb in dust in 2017 (mean 2.65 g/m^2/month), likely due to its proximity to the railyards, where Pb is loaded into rail cars (OEH 2018). Other CBH sites close to the mine showed higher Pb in deposited dust than sites further from mining activities. Gauge D6 (CBH), 1 km southeast of mining operations, consistently recorded the highest total monthly dust deposition (i.e. total dust inclusive of Pb and other materials) of all the CBH sites in 2017, yet it recorded less than half the annual average Pb in dust of sites D3, D5 and D7, which are closer to mining activities. This demonstrates the lack of correlation between total deposited dust mass and the Pb content within that dust. Total dust deposition rates appear to be related to monthly rainfall, whereas total Pb is more related to proximity to the Line of Lode. This indicates that dust originating from mining areas, either from active mining activities or erosion of open areas, leads to increased Pb in dust in adjacent locations. This same trend is seen for the dust gauges operated by Perilya North/Potosi and South Operations (OEH 2018).

[6] The same value of 100 µg/m^2/day is also referenced by the German TA Luft (2017).

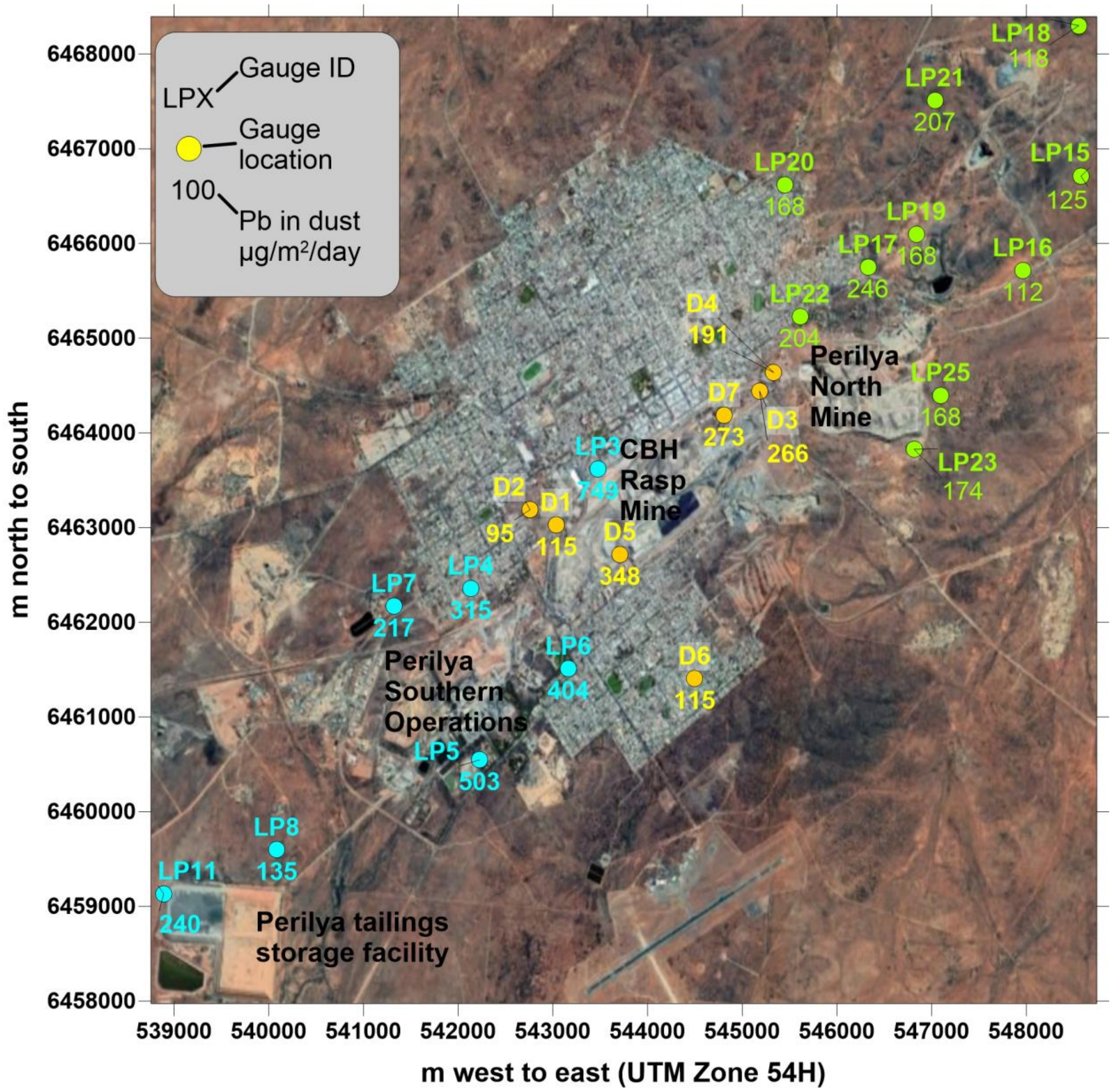


Figure 5. Mean deposited dust Pb concentrations (µg/m²/day). Yellow dots show CBH Rasp mine dust deposition gauges, showing mean Pb for 2007–2017. Green and blue dots show Perilya North and South operations, respectively, with mean Pb for 2013–2017. By comparison, the investigation value used at Mount Isa (Queensland Department of Environment and Science 2018) is 100 µg/m²/day, which, on average, was exceeded at most sites shown, including in residential areas (data extracted from OEH 2018).

Suspended Pb concentrations (Pb in TSP – total suspended particulates and PM_{10} – particulate less than 10 µm) also demonstrate that peaks in total atmospheric particulate load do not always correlate with peak Pb in air. The Office of Environment and Heritage (OEH 2018) conclude that "*it is therefore not the degree of dustiness, but rather the source of dust that determines lead content.*" In the past five years (2013 - 2017), the highest mean Pb in TSP levels were recorded at HV7 (0.32 µg/m³ near Perilya North/Potosi, Fig. 6) and HV1 (0.28 µg/m³ CBH, 2007 - 2017).

A recent study by the NSW Office of Environment and Heritage (OEH 2018) set out to distinguish airborne Pb concentrations primarily associated with active mining operations compared with non-mining areas of Broken Hill. The OEH undertook this assessment by co-locating separate high-volume air samplers (HVAS) to sample TSP when winds were coming from the direction of mining activities (Sector A, including winds from rail corridors) and when winds were coming from other directions (Sector B, non-mine affected, see Figs 6 and 7). Results for all sites showed that when winds were sourced from mining areas (Sector A), Pb concentration in air (TSP μg/m^3) and the Pb content of collected TSP (mg/kg) were higher than when winds were from non-mining areas (Sector B). This Sector A: Sector B difference was most pronounced for sites located closer to mining activities and is shown in Figs 6 and 7. For example, south of Perilya Southern Operations "Silver City Highway" site, Fig. 6, Pb concentration in air for Sector A was almost ten times that of Sector B.

Lead concentrations in windblown dust across Broken Hill are elevated even when the wind is blowing from non-mining areas. For example, sector B Pb in air concentrations (μg/m^3) and Pb content (mg/kg) in dust are up to 60 % of sector A (winds from mining area) levels. This indicates that recycling of deposited Pb is occurring, with previously deposited Pb particles in soils and on surfaces being re-suspended by winds, regardless of wind direction. These particles will include legacy Pb deposited over the decades since production commenced and contemporary deposits associated with emissions from across the Line of Lode. The "Wetlands" site (Fig. 6) also appears to show Pb resuspension, recording dust released from Potosi Mine and Perilya North Mine. Although the active mining areas may be limited at present by comparison to historical situations, wind-erosion emissions from exposed former mining areas continue. In this regard, Sector A at the "Wetland" site may not fully capture the range of wind directions that relate to emissions from these mining areas.

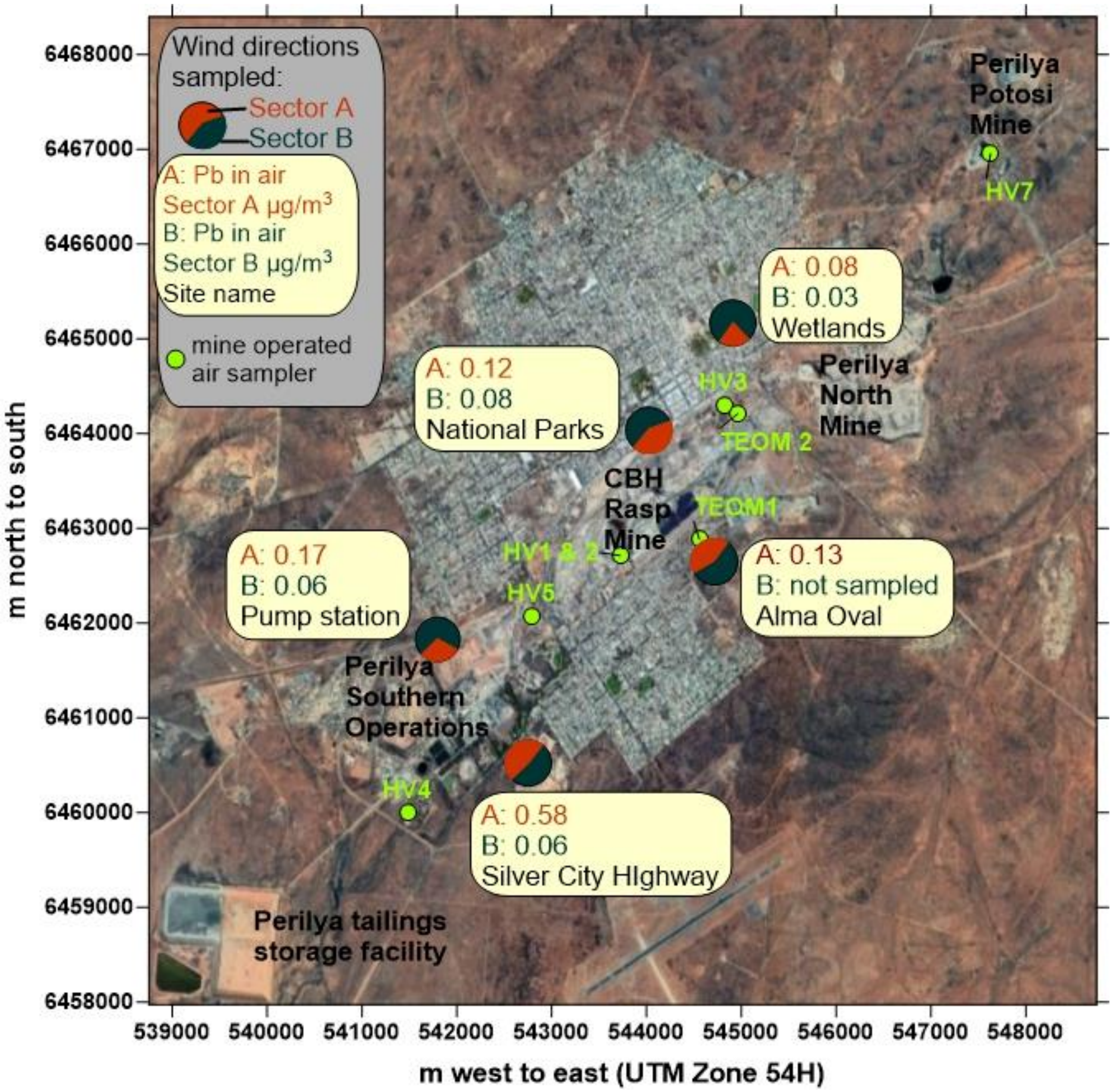


Figure 6. Median ambient Pb concentrations in air (µg/m^3 in TSP fraction) at monitoring sites (green) for winds from mining areas (Sector A) and winds from non-mining areas (Sector B). Sampling from January 2017 to January 2018. The Silver City highway site was sampled for 15 weeks only (September 2017 to January 2018). Data from (OEH 2018).

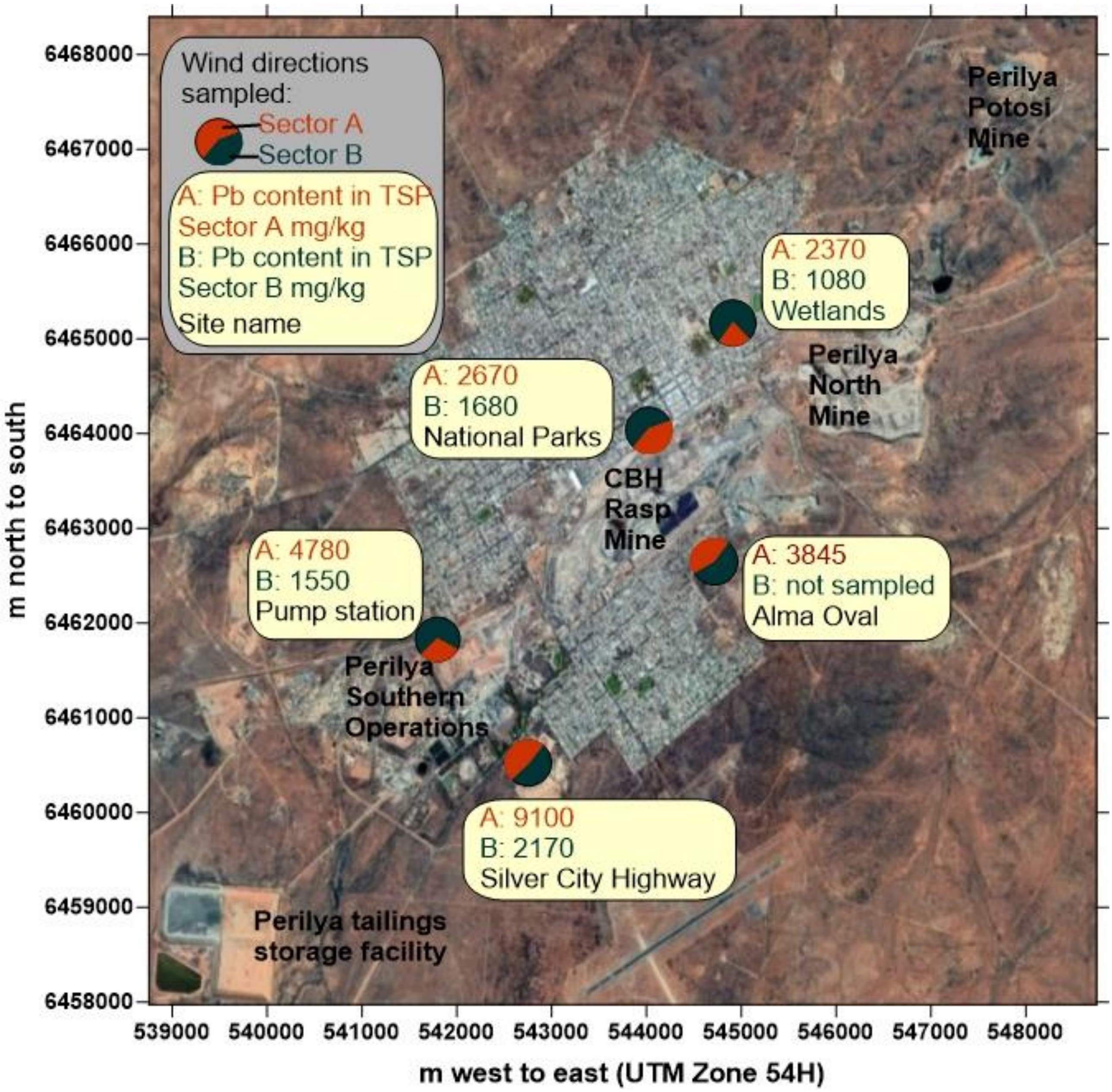


Figure 7. Median Pb content in TSP (mg/kg) in air for winds from mining areas (Sector A) and winds from non-mining areas (Sector B). Sampling from January 2017 to January 2018. The Silver City highway site was sampled for 15 weeks only (September 2017 to January 2018). Data from OEH (2018).

Indoor dust

Macquarie University students sampled 62 houses in Broken Hill in 2018 (Dani *et al.* 2018), recording Pb concentrations in outdoor soil and in indoor dust using vacuum cleaner dust. Outdoor soil levels were an average of the verge and front yard Pb concentrations. Half of the front yards sampled exceeded Australian guidelines for Pb (300 mg/kg (National Environment Protection Council 2013)). Indoor dust levels were on average twice those of outdoor levels (Dani *et al.* 2018). Whilst there are no Australian guidelines for indoor dust Pb, only one house reported indoor dust Pb levels within the Canadian benchmark value of 119 mg/kg which was based on data from 1025 Canadian homes (Rasmussen *et al.* 2013). The indoor Pb levels for Broken Hill were based on the 250 μm size fraction, whereas outdoor results were based on the bulk sample which may account for some of the indoor/outdoor difference. Nevertheless, the mean and median indoor dust Pb levels of 783 mg/kg and 535 mg/kg) were also elevated compared to the median of all Australian house dust samples (Pb = 125 mg/kg, n = 378) (Dani *et al.* 2018). Lead in bulk vacuum cleaner samples collected from 230 houses by the NSW Department of Health from 1992 had considerably higher mean Pb concentrations of 1758 mg/kg (Woodward-Clyde 1993) although the geometric mean levels for a smaller number (n=31) of bulk vacuum cleaner samples gave a lower value of 670 mg/kg (Gulson *et al.* 1994). Indoor dust Pb concentration decreased with distance from the mine (Fig. 8). Households within 1 km of the Line of Lode reported average dust Pb levels of more than two times higher than households 1-3 km away (Dani *et al.* 2018). Therefore, distance from mining activities is an important predictor of household dust Pb, the concentrations of which were exacerbated by aged and poorly sealed housing.

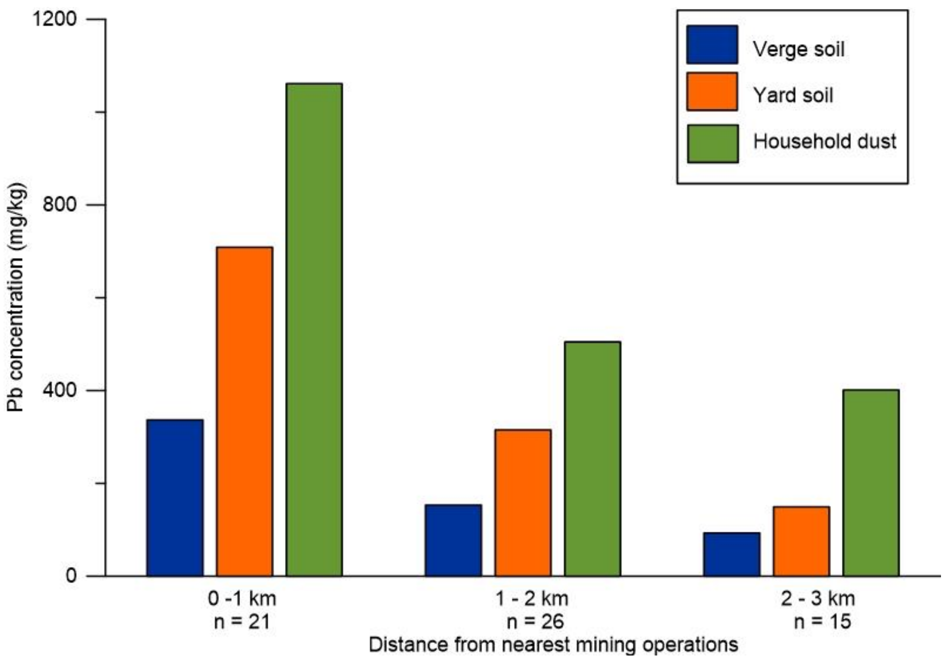


Figure 8. Lead concentrations for verge soil, yard soil and house dust at 1 km intervals from the Line of Lode. The mean for the whole 0-3 km distance range is 783 mg/kg, median 535 mg/kg Pb (Dani *et al.* 2018).

Lead isotopic compositions were also analysed in 20 selected indoor dust samples to determine the sources of Pb (Fig. 9). As per Dong and Taylor (2017), the measurements show that as distance from the Line of Lode increases, the isotopic signature shifts increasingly towards background values. Nevertheless, the effect of emissions associated with mining the Pb ore body at Broken Hill remains evident across the city with all Pb isotopic compositions being > 90% similar to the isotopic composition of the Broken Hill ore body (unpublished data; source apportionment modelling completed using the method detailed in Larsen *et al.* 2012). The same conclusions for distance from mining activities and proportion of ore-derived Pb were enunciated by (Gulson *et al.* 1994).

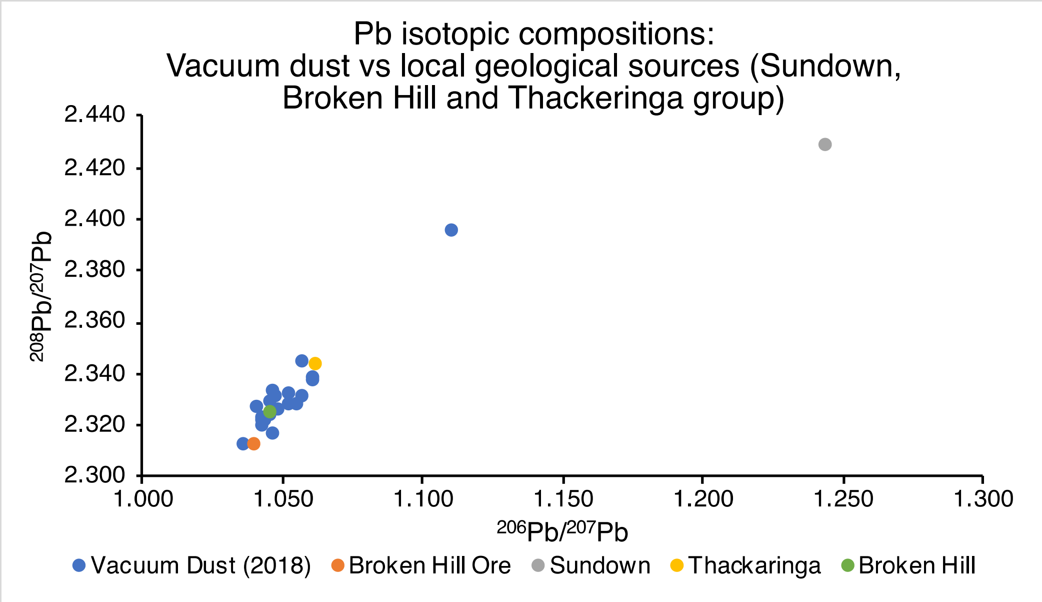


Figure 9. House vacuum dust plotted alongside the Pb isotopic composition of the Broken Hill ore body Pb isotope. Local 'background' compositions from deep soils overlying the three main rock strata of Sundown, Broken Hill and Thackaringa are also shown (Kristensen and Taylor 2016).

Soil Pb contamination

Yang and Cattle (2015) completed a soil Pb-blood Pb modelling study, using the Integrated Exposure Uptake Bio Kinetic Model (IEUBK) with the aim of predicting blood Pb levels in children (detailed at Question 2D). Using soil concentrations measured by Yang and Cattle (2015) in Broken Hill, the model predicted that 23.2 % of children would have a Pb blood level of ≥ 10 µg/dL. This model matched closely with the 20.2 % of children who presented with a < 10 µg/dL Pb in 2012 (Lesjak *et al.* 2013). The Yang and Cattle (2015) study indicated that soil Pb concentrations are likely to be a major factor in childhood blood Pb concentration. The IEUBK model default values regarding Pb bioavailability can be modified using site-specific data. Yang and Cattle (2015) estimated these bioavailability values using methods outlined by the National Environment Protection Council (2013), as discussed below.

Care must be taken to distinguish between the bioaccessibility and bioavailability of Pb in soils. Bioaccessibility is defined as the portion of Pb that is released from ingested materials in the gastrointestinal tract, becoming available for absorption. This can be measured by simulating gastrointestinal fluids with laboratory chemicals. Bioavailable Pb is a further subset of this bioaccessible Pb, being the fraction of Pb that is absorbed and reaches the circulation system and is transported throughout the body. Bioavailable Pb is therefore more difficult to measure as it requires to be tested on living subjects. Juhasz (2018) tested Broken Hill soils for Pb bioavailability using mice, as detailed below.

In order to refine the key Pb exposure parameters of total and bioavailable Pb, Juhasz (2018) assessed Pb bioaccessibility and relative bioavailability in Broken Hill soil samples. Twelve Broken Hill soil samples were collected along a transect (predominantly along King St, South Broken Hill, Fig. 10) away from the Line of Lode; in order to assess the elemental composition of the soil and determine its bioaccessibility via a gastrointestinal extraction method and bioavailability using an *in vivo* mouse model. Soil Pb concentrations ranged from 215 ± 0.9 mg/kg to 8036 ± 651 mg/kg, with all but two of the samples (BHK7 & BHK8, Fig. 10) exceeding the NEPM for the Assessment of Site Contamination (Residential A: 300 mg/kg (National Environment Protection Council 2013)). Lead in the < 250 µm soil fraction was predominantly present as sorbed phases (determined by X-ray absorption spectroscopy) on oxides and clays (45-66 %) but also as plumbjarosite (6-35 %), Pb phosphate (5-19 %) or bound to organic matter (8-22 %). Results were similar for the < 150 µm soil fraction. Lead bioaccessibility following gastric phase extraction was > 60 % of total Pb for most samples (9 out of 12, < 250 µm soil); however, for the intestinal phase, this was reduced to 1.9-25.3 %. Lead relative bioavailability was further assessed by determining the accumulation of Pb in target organs (kidney, liver, femur) using the USEPA (2018) integrated systems toxicology division mouse model protocol (Juhasz 2018).

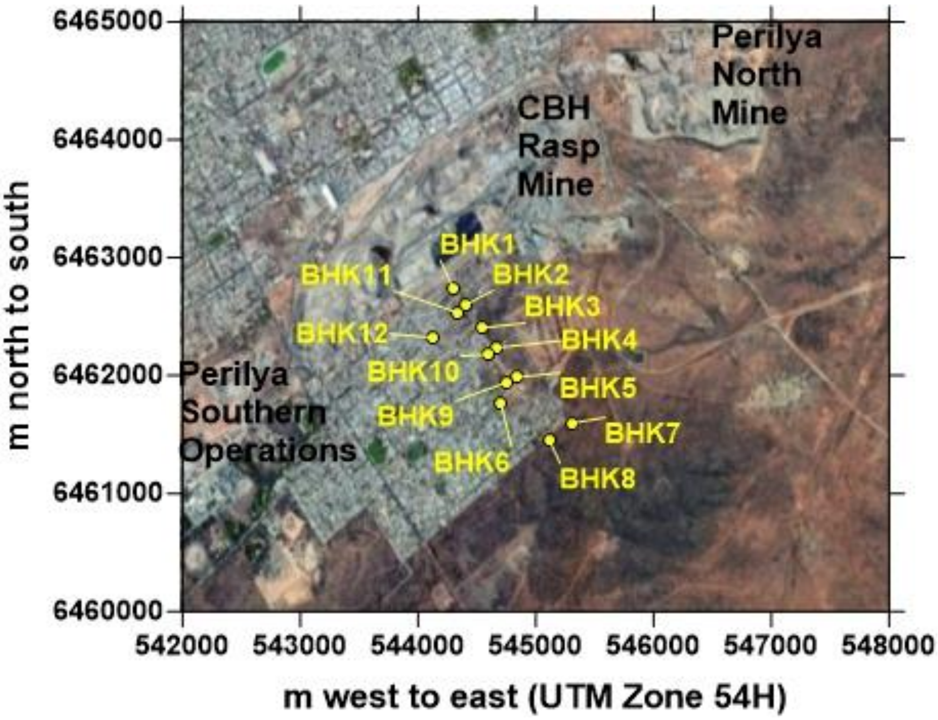


Figure 10. Location of sampling sites for bioavailability and bioaccessibility analyses (Juhasz 2018).

Ten soils (0-10 cm depth) were assessed for their bioavailability using the mouse model. Two soil samples were excluded, BHK1 due to a very high Pb concentration in the < 250 mm size fraction and BHK8 due to low Pb concentration. The mean relative bioavailability ranged from 7 % to 45 %, with the upper 95 % confidence interval of the mean for Pb relative bioavailability being 21.5 %. The bioavailability results, using a mouse model, were up to 10-fold less than bioaccessibility results from gastric phase extraction. These results have important implications for the prediction of blood Pb levels using the IEUBK Model. Juhasz (2018) identified that Pb relative bioavailability (6.8-44.8 %) of soil on the southern side of the Line of Lode was significantly lower than the default value used to derive the NEPM health based investigation level of 300 mg/kg (National Environment Protection Council 2013). It is not known, however, how well these data represent other areas in Broken Hill; particularly sites where smelting activities have occurred in the past. These may well vary with respect to their relative bioavailability. Given the limited samples analysed by Juhasz (2018), it is evident that further sampling and bioavailability analysis would be beneficial. Any such work should target areas where high blood Pb concentrations occur, which would enable refinement of the IEUBK model. Future bioavailability investigations should also consider mineral phases of Pb (Yan *et al.* 2019). In addition, it is important to note that Pb-contaminated soil is just one of the exposure routes in Broken Hill. This document identifies dust deposition as being a key element of exposure that has previously received limited attention, although the importance of dust to blood Pb was previously proposed by Woodward-Clyde (1993), Gulson *et al.* (1995) and again by Boreland *et al.* (2006).

Therefore, in any further work, the relative importance of the different sources and bioavailability needs to be properly taken into account (*cf*. Rasmussen *et al.* (2011)).

In summary, whilst the levels of Pb in the soils tested (Juhasz 2018) were elevated (according to National Environment Protection Council (2013) guidelines), relative bioavailability (as measured in mice) was lower than had been assumed in exposure modelling studies (Yang and Cattle 2015), meaning that the uptake of Pb from these soils by the human body may not be as high as previously predicted. However, the soils tested (0-10 cm depth) represent only a limited area of Broken Hill (on the southern side of the Line of Lode) and so bioavailability in other areas may be higher.

Soil and dust together influence children's blood Pb levels

If bioavailability values are less than those used in the IEUBK model, this suggests that the IEUBK modelling may have over predicted the influence of soil Pb in children's blood levels, meaning that other Pb sources (such as contemporary dust deposition) are likely to be contributing to elevated blood Pb levels measured in Broken Hill children. In this regard (Dong *et al.* 2020), showed that even children living in houses with very low soil Pb were likely to exceed 5 and 10 µg/dL blood Pb (Fig. 11), suggesting that there are other (non-soil) sources of Pb exposure.

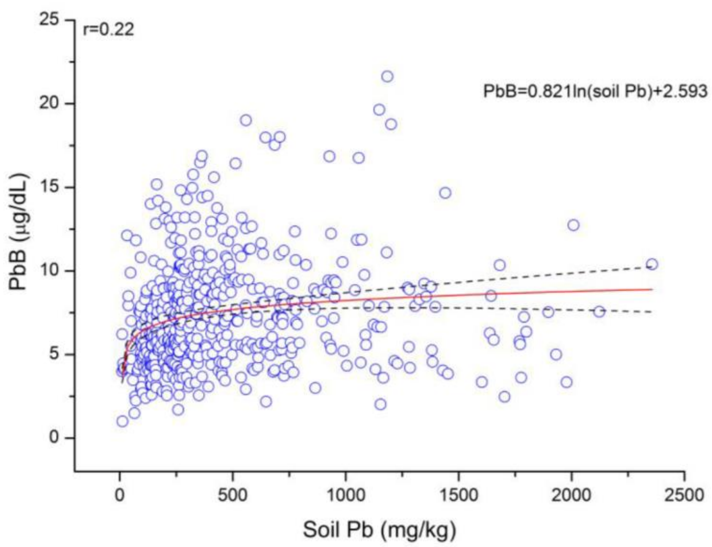


Figure 11. Blood Pb (geometric mean) in Broken Hill children (0-4 years of age) compared to soil Pb (geometric mean) at their residential address (Dong *et al.* 2020). Data are based on the blood Pb of children between 1994-2015 (n = 499). The solid line represents the non-linear regression model; dashed lines show the 95 % confidence interval.

Analysis of dust concentrations from static dust deposition gauges compared with children's blood Pb (Fig. 12) in Broken Hill shows that the two parameters are related. In years of higher geometric mean annual dust deposition, blood Pb concentrations were also higher. Data for the initial years, 2008 and 2009 do not fit the model as well as other years. Interventions to reduce blood Pb, such as soil amendments, were in their early stages and participation rates in blood Pb testing were low, hence results from these years may not capture population blood Pb trends. Nevertheless, it can be inferred from Fig. 12 that an underlying level of Pb exposure (from soil and other sources) contributes approximately 3.4 µg/dL to children's annual geometric mean blood Pb. In addition, exposure to Pb in deposited dust contributes at a rate of approximately 0.018 times the annual geometric mean of Pb in deposited dust (in µg/m^2/day). This means that when deposited dust Pb exceeds approximately

90 µg/m²/day, the annual geometric mean of children's blood Pb is likely to exceed 5 µg/dL. This value is similar to the Mount Isa investigation level of 100 µg/m²/day (Queensland Department of Environment and Science 2018) based on German recommendations. Gulson and Taylor (2017) advocate a much more stringent 'action level' for protecting Australian children: 100 µg/m²/30 days. Data for dust deposition used in Fig. 12 were available for 1992-1996 and then from 2012-2017, addition of further data would allow this relationship to be more accurately defined. It is noteworthy that this modelled threshold (90 µg/m²/day Pb in dust) has been exceeded in all these years of available data (1992-1996, 2012-2017).

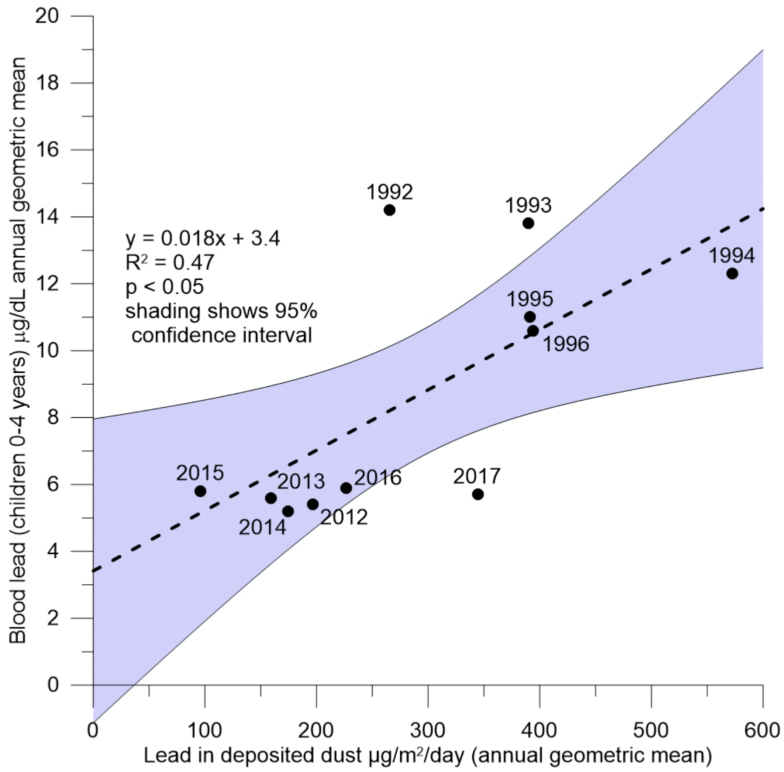


Figure 12. Child blood Pb compared to dust deposition for Broken Hill. Data were available for 1992 to 1996 and then from 2012 to 2017. Graphed Pb dust deposition concentrations are the geometric mean of monthly results from all available gauges within the residential area of Broken Hill.

Dong *et al.* (2020) also showed that children's blood Pb was significantly correlated with both soil and dust Pb. A 100 mg/kg increase in soil Pb was associated with a 0.12 µg/dL increase in childhood blood Pb for the entire Broken Hill area. In addition, indoor petri-dish dust samples showed that blood Pb concentrations increased with indoor dust Pb loadings (0.08 µg/dL per 100 µg/m²/30 days). Thus, the data in Fig. 12 and given in Dong *et al.* (2020) demonstrate that while childhood blood Pb levels in Broken Hill are influenced by past emissions (in soil), dust depositions from current emissions or resuspended soil form a critical source of exposure. Similar results were shown from investigations in the 1990s using surface dust wipes from 27 houses (Gulson *et al.* 1994).

The role of annual precipitation in Broken Hill was investigated to determine whether it influenced blood Pb levels on an annual basis (Fig. 13). Wetter periods result in less dusty conditions, partially due to greater vegetation growth, including residential lawns and gardens. This vegetation growth may reduce the remobilisation of Pb contaminated soil and dust into homes, in turn resulting in lower blood Pb concentrations. Annual mean blood Pb was regressed against mean annual precipitation, which was further explored by lagging blood Pb by one year to allow for delayed uptake and exposure. In both cases there was no evidence of significant relationship between rainfall and blood Pb.

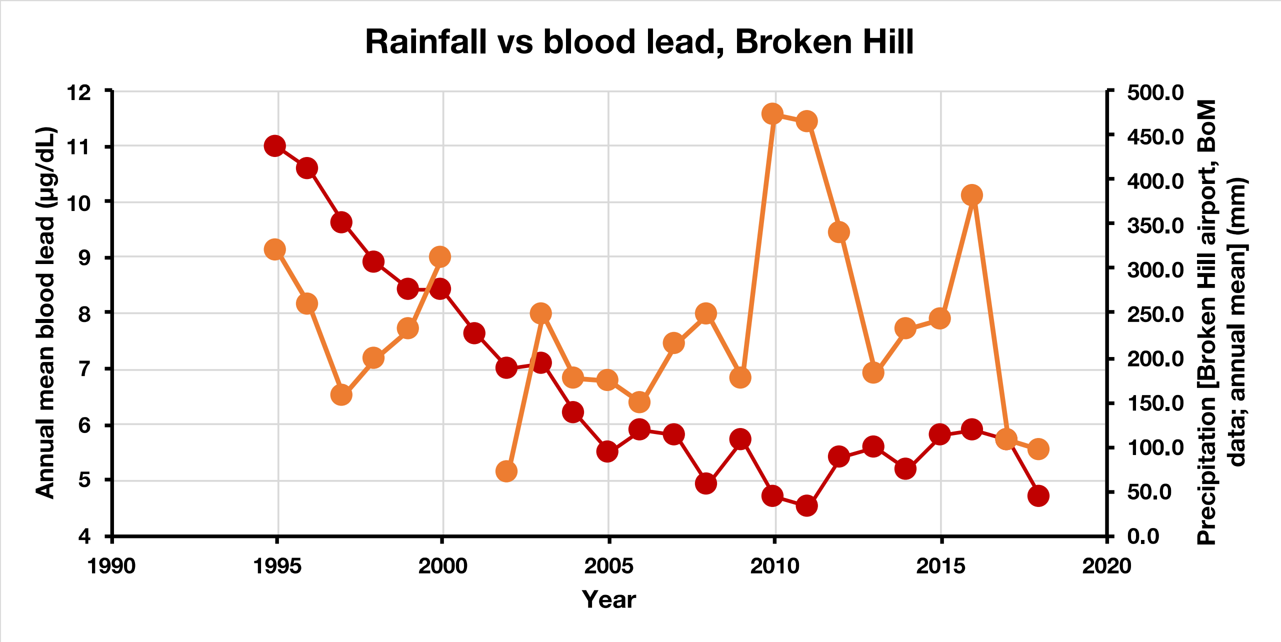


Figure 13. Annual geometric mean blood Pb levels plotted against annual precipitation at Broken Hill. Data gaps in the annual precipitation before 1995 and in 2002 limited the available temporal series.

Dong *et al.* (2019) provide further evidence for the effect of current mining activities and associated emissions on blood Pb levels. This study showed that over a 25-year period blood Pb responds with near unit elasticity to ore production. As ore production levels declined from 1991 to 2013, blood Pb levels also declined (Fig. 14). Therefore, despite the fact that various Pb emission controls were implemented over this period, it is evident from Dong *et al.* (2019) and Figs 14 and 15 that ore production is significantly associated with Pb dust deposition across Broken Hill. The production rates and their consequent emissions are also related to blood Pb concentrations over time (Fig. 14).

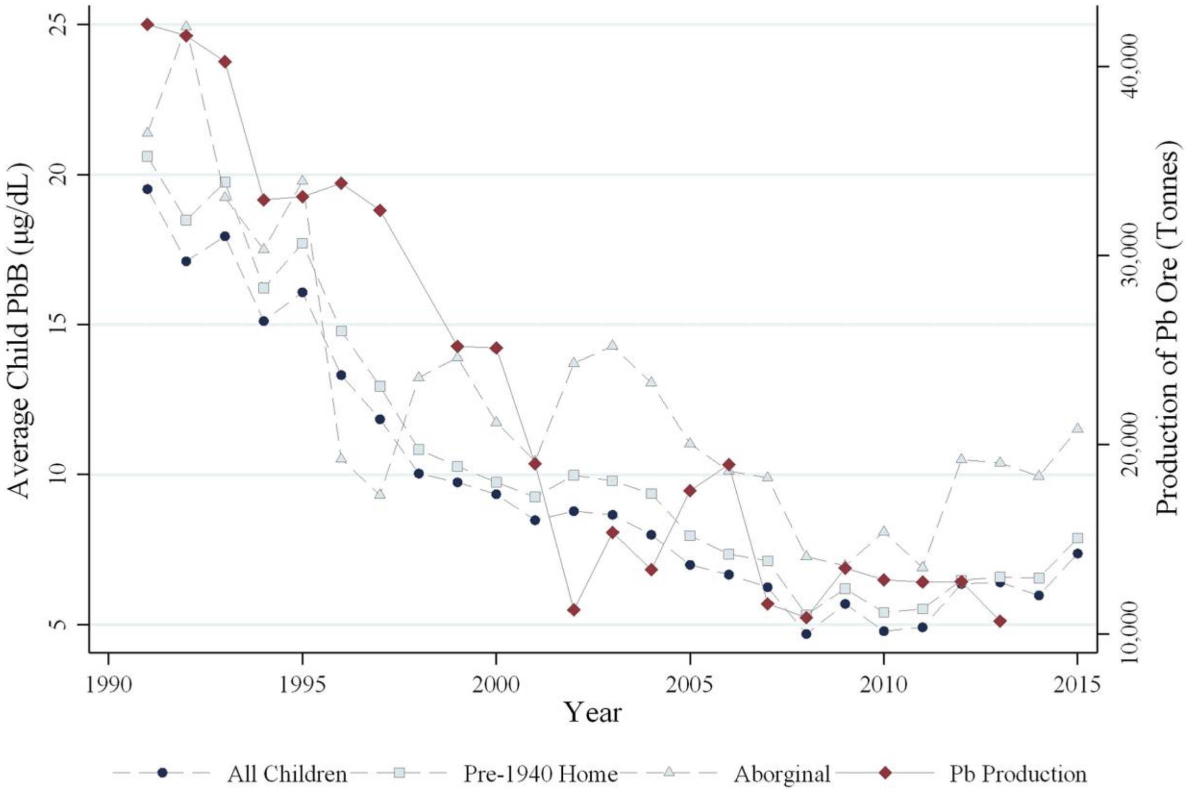


Figure 14. Geometric mean blood Pb concentration in Broken Hill children (0–4 years of age) compared to ore production.

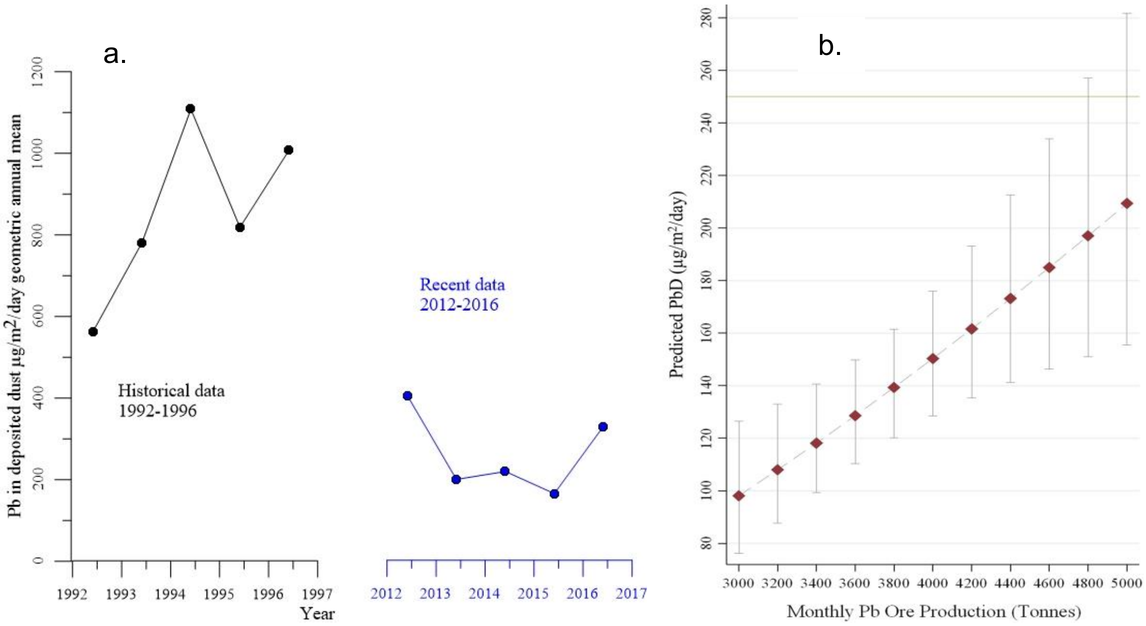


Figure 15. Dust deposition rates for Broken Hill **a.** Annual dust deposition rates in Broken Hill for available years of data. Data shown are the annual geometric mean of monthly results of all available dust gauges located in the residential area of Broken Hill. **b.** Modelled dust deposition rates from Dong *et al.* (2019). A 1 % increase in production intensity at the mine increased the expected amount of PbD by 1.5 % (95 % CI: 0.547, 2.447 %) Dong *et al.* (2019).

Modelled child blood Pb also decreases with distance from the Line of Lode, as demonstrated by Dong *et al.* (2019) in Fig. 16.

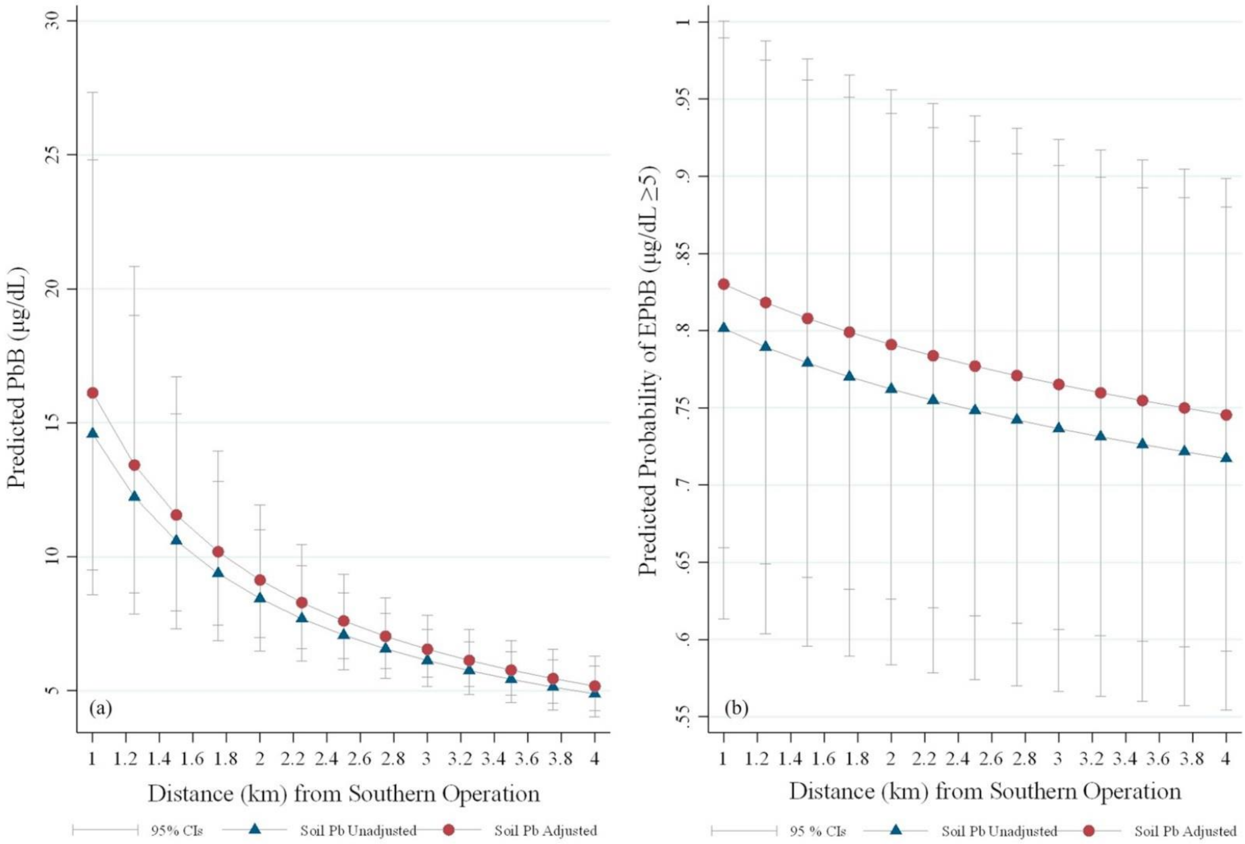


Figure 16. (a) Predicted child blood Pb (PbB, µg/dL) and (b) the probability of a child having elevated PbB (EPbB, ≥5 µg/dL) by distance for downwind children by Pb soil adjustment.

Use of leaded paint

The use of Pb-based paints in older housing constitutes a potential Pb exposure source. Records from the Broken Hill Environmental Lead Program (BHELP 2018) showed that 25 % of properties referred for consideration of remediation had mean Pb in paint levels of ≥ 3 mg/cm^2. The USEPA guideline value for paint is 1 mg/cm^2 (USEPA 2017).

Ten percent of all properties referred for remediation had soil Pb concentrations below 700 mg/kg and paint Pb ≥ 1 mg/cm^2; in these cases, paint Pb was considered to be a significant risk (BHELP 2018). Phillips and Hall (1994) also list Pb in paint as a risk factor for elevated childhood blood Pb in Broken Hill. In an assessment of the Pb paint risk in New York (USA) homes, Spanier *et al.* (2013) observed a 7.5 % higher mean childhood blood Pb for every 10 mg/cm^2 increase in paint Pb loading. If this were applied to Broken Hill, a paint Pb of 3 mg/cm^2 may mean a blood Pb increase of around 2.3 %. Lanphear and Roghmann (1997) demonstrated that Pb paint was a significant contributor to Pb in house dust in New York; however, more recently Lucas *et al.* (2014) argued that the impacts of Pb in paint are no longer as significant, unless a house has remained unrenovated, supporting this claim with Pb data from 484 housing units in France.

A 1993 survey of Broken Hill housing (BHELP (2019), Fig. 17) showed that most houses were built prior to 1970 and are hence likely to retain some leaded paint. Considering that there is little new construction in Broken Hill, these 1993 survey results remain relevant. Older houses (built pre-1940) account for over half of the housing stock and are likely to contain higher Pb concentrations in paint than more recently constructed homes. Half of the Aboriginal children in Broken Hill lived in houses built before 1940, putting them at risk of Pb paint exposure. Of the 51 homes referred to BHELP for remediation in 2018, 72 % (36 homes) had unstable paint. Twenty homes had Pb paint levels > 1.0 mg/cm^2 and 16 of these had Pb paint levels > 3.0 mg/cm^2.

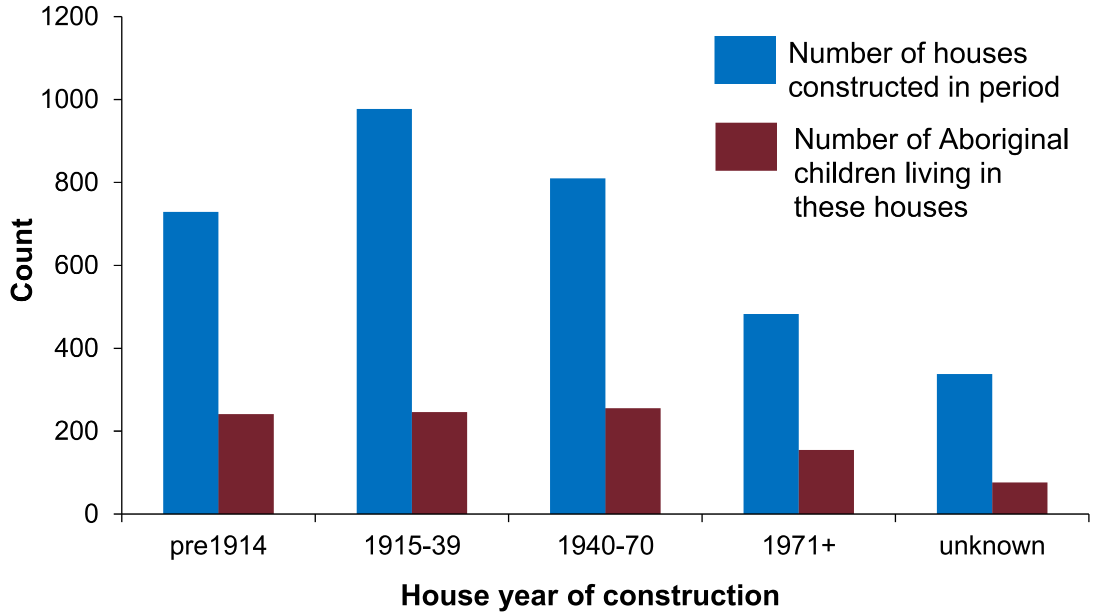


Figure 17. Number of houses constructed by year for Broken Hill. Data from BHELP (2019).

The potential for legacy Pb exposures from Pb-based paints in Broken Hill was explored by Dong *et al.* (2019), showing that the impact of leaded paint appears to be secondary to mining sources of Pb in Broken Hill. Potential evidence of leaded-paint impacts were seen upwind of the mine, where mining-related impacts were not as pronounced (Dong *et al.* 2020). While Gulson *et al.* (1994) reported that due to the age of many houses in Broken Hill, paint was a potential source of Pb, they did not consider it as a critical source for investigation in Broken Hill, due to the fact that many children who exhibited elevated blood Pb (> 20 µg/dL) concentrations lived in relatively new, Pb-paint-free houses and the source of the Pb in blood was overwhelmingly from ore-body sources.

This risk from leaded paint is greatest during renovation activities. Whilst local studies are lacking, Spanier *et al.* (2013) observed that interior housing renovation in New York was associated with a 12 % increase in children's blood Pb. By contrast, exterior renovation activity was not identified as a significant risk factor. Relevantly, Spanier *et al.* (2013) showed that the geometric mean floor Pb levels were only slightly higher in unrenovated housing compared to housing which had been renovated.

In summary, it appears that while leaded paint may have some potential influence on children's blood Pb in Broken Hill any such risk is overshadowed by the Pb exposure risk coming from mining emissions. With respect to children residing in older, unrenovated housing, Pb paint sources may have led to increased blood Pb and continue to contribute to increased risk of high blood Pb. Given the limited data on the specific Pb paint risk, this is an area of research that is worthy of further investigation, especially given the ease of *in situ* measurements with portable XRF. Additional clarity around Pb paint's contribution from pica (eating of non-food items such as paint chips) and in dust will provide essential evidence-based data for targeted remediation strategies.

Other legacy sources

A study by Gulson *et al.* (1994) found that leaded gasoline was a significant contributor to Pb in air in Broken Hill during 1991/1992. Whilst legacy Pb from previous usage of leaded petrol may remain in Broken Hill soils, its impact on current children's blood Pb is unlikely to be significant (Dong and Taylor 2017). This is seen in data from Sydney (Kristensen 2015) and other Australian metropolitan areas (Kristensen *et al.* 2017), where children's blood Pb levels dropped dramatically following the phasing out of leaded petrol usage.

Uptake of Pb by plants presents a further potential exposure pathway that requires consideration. Low *et al.* (2005) studied the uptake of Pb by bluebush and saltbush species in Broken Hill, finding that mean leaf Pb levels ranged from 253 - 379 mg/kg over the three locations studied (soil Pb 3000 – 9000 mg/kg), which may be particularly significant if these plants are foraged by stock. This has relevance when considering that other plants grown for food in residential gardens are also at risk of uptake of Pb from the soil (Kachenko and Singh 2006, Taylor *et al.* Unpublished) and from deposition of atmospheric Pb. Current research by Macquarie University indicates that vegetables grown in soils with Pb concentrations > 270 mg/kg (typically exceeded across Broken Hill) are likely to exceed Australian Government (2017) food standards. Where soils have a Pb concentration of > 319 mg/kg, produced food would likely exceed World Health Organization food standards (Codex Alimentarius Commission 2011). Producers of home-grown food should be encouraged to have their soil tested. Portable XRF technology allows soils to be quickly tested for Pb and other trace element concentrations. If BHELP were to offer this as a routine community service, it would markedly assist residents to better understand their risk and take appropriate steps to grow food with a minimum of risk. This program should not be limited to households wishing to grow vegetables but should also be offered as a service to all households in order to understand contaminant levels and safe interaction with residential soils, dust and paint.

Similar advice that was offered to community participants in other Australian community orientated soil testing programs (Rouillon *et al.* 2017), where soil Pb levels are found to be above Australian residential standards (300 mg/kg), includes use of raised beds containing known imported clean soils to grow vegetables. Produce should also be thoroughly washed before consumption, to remove any deposited Pb in dust.

Whilst local studies are lacking on the impacts of smoking and demolition of old buildings, these have been researched elsewhere e.g. Gaitens *et al.* (2009) in the USA. Gaitens *et al.* (2009) found, using 2,065 floor samples, that income, ethnicity, floor surface/condition, windowsill dust Pb, year of construction, recent renovation and smoking were significant predictors of floor dust Pb. Lucas *et al.* (2014) observed, in France, that Pb loadings in household dust were associated with smoking. In regard to the demolition of old buildings, Dixon *et al.* (2012) observed that dust Pb level increased by approximately 30 % in areas near demolition works and Rabito *et al.* (2007) also found that increases in child blood Pb were associated with nearby demolition activity.

Summary

In summary, historical mining emissions and naturally occurring Pb minerals contained in soils and suspended dusts, and current emissions (Pb in air and dust) remain as significant sources of Pb exposure for children currently living in Broken Hill. Leaded paint may also contribute to Pb exposure in houses where this is present but is overwhelmed by soil and dust Pb sources. Soil and dust testing should be offered to all households in Broken Hill along with advice as to how to reduce Pb exposure from these sources.

Question 2 – Current trends in blood Pb levels in Broken Hill children

Trends in blood Pb concentrations to date

Investigation of blood Pb levels of children 1-4 years of age in 1991 revealed that 86 % of children (Lyle *et al.* 2006) had a blood Pb above 10 µg/dL. Abatement of homes where children's blood Pb exceeded 15 µg/dL occurred from 1997 to 2004 (Lesjak and Jones 2015). By 2004, 73 % of children tested had blood Pb levels below 10 µg/dL and only 11 % of children had blood Pb levels of 15 µg/dL or higher (Lesjak and Jones 2015). An increase in mean children's blood Pb levels was seen in 2012 and 2013, however, this coincided with a significant increase in the total number of children being tested in Broken Hill and in particular, with a greater number of Aboriginal children presenting for blood Pb testing (Lesjak and Jones 2015). Thus, rather than an actual increase in blood Pb, it is likely that the additional sampling provided a more accurate assessment of the true population exposure.

In 2015, the National Health and Medical Research Council (NHMRC) (2015) lowered the blood Pb intervention level to 5 µg/dL. Geometric mean blood Pb concentration and the number of children with a blood Pb below this 5 µg/dL intervention level are the major population measures of Pb exposure. In 2015, 47 % of all Broken Hill children tested (< 5 yrs), including 79 % of Aboriginal children, exceeded 5 µg/dL blood Pb (Lesjak and Jones 2015). In 2018, 49 % of children under five years old in Broken Hill presented with blood Pb ≥ 5 µg/dL with the geometric mean over all children falling from 5.7 in 2017 to 4.7 µg/dL (NSW Ministry of Health 2019). The participation rate for Pb screening is currently high, with 82 % of children under five presenting for testing in 2018 (NSW Ministry of Health 2019). Thus the current Pb blood test results provide an accurate picture of children's blood Pb levels in Broken Hill.

A small decrease in exposure for a large proportion of Broken Hill children would have the effect of reducing the geometric mean of blood Pb. However, individual children can still have very high blood Pb levels. Conversely, a focus on reducing blood Pb for the relatively small number of children with the highest exposures will have limited impact on the geometric mean for all Broken Hill children. Exposure is the daily amount of Pb a person is subject to, whilst body burden relates to the amount of Pb stored in a person's bones, organs and blood. How quickly blood Pb reduces after a source of exposure has been controlled depends on how effectively the source is reduced, how significant the identified source was in contributing to exposure and how much Pb had already been stored in the body (Battelle Memorial Institute 1995). Where prolonged exposure has occurred and Pb body burden is high, reductions in blood Pb will occur more slowly compared with acute Pb exposures. For example, after the source is removed; an exposure reduction of 50 % is estimated to give a blood Pb reduction of 25 % over 12 months (Battelle Memorial Institute 1995). At Broken Hill, the evidence indicates that there are multiple potential sources of Pb (e.g. dust, paint, older housing and soil) and hence a multi-faceted approach is required to reduce impacts from exposure.

Residential Location

It is clear that where children live in Broken Hill influences their blood Pb levels over time. Fig. 18 depicts children's blood Pb between 2011-2015. Over a 25-year period, median blood Pb levels were highest for children living within 3 km of Line of Lode, with the highest blood Pb levels for children living within ~ 1 km downwind of the southern operations (Dong *et al.* 2020). Children living downwind of the mining area have substantially higher blood Pb outcomes than similarly distant upwind children (Dong *et al.* 2019). High-risk areas have been determined previously using data quantifying Pb concentrations in soil, dust and blood (Phillips and Hall 1994, Boreland *et al.* 2006). Based on the assessment of children who had tests at each of the scheduled test points at ages 1, 2 and 3 years, 60 % of children in the highest soil Pb hazard zones (i.e. close to the Line of Lode) compared with 27 % other Broken Hill children presented with at least one test result at ≥10 µg/dL. However, the majority (70 %) of children presenting with elevated blood Pb levels (≥10 µg/dL) live elsewhere in the community (BHUDRH 2017), in part because the majority of Broken Hill children live outside the high-risk zone.

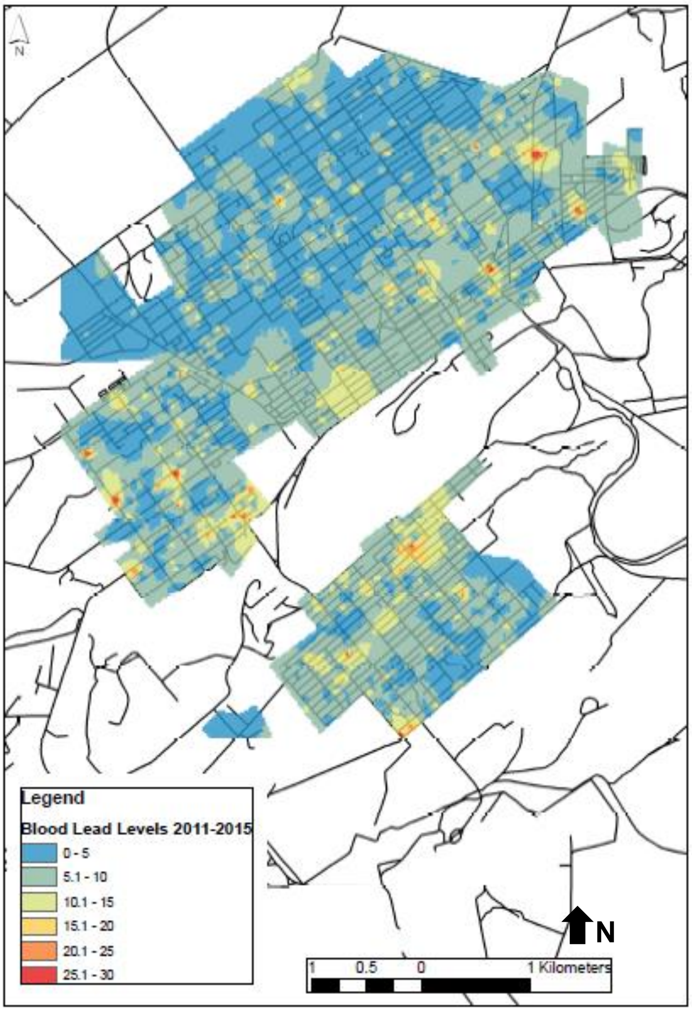


Figure 18. Children's blood Pb levels (µg/dL) in Broken Hill from 2011 to 2015. Source: Broken Hill Environmental Lead Program.

Soil Pb levels from 1995 to 2002 are shown in Fig. 19a alongside blood Pb levels (Fig. 19b) from a similar period (1996-2000). The relationship between soil Pb levels and blood levels is not completely clear from these maps, however, in general terms, it can be seen that in the northern part of Broken Hill, where soil Pb levels were largely below 500 mg/kg, more children had blood Pb below 10 µg/dL. Yet, for the area south of the Line of Lode, where soil Pb was less than 500 mg/kg, the effect on blood Pb was not as pronounced (Figs 19a,b). Until 2001, children living in areas with higher environmental Pb levels had significantly higher blood Pb levels, however the difference between areas substantially reduced after 2001 (Boreland *et al.* 2008).

As already discussed in Question 1 above, children living in areas where Pb is elevated in deposited dusts are at higher risk of elevated blood Pb concentrations. High deposited dust concentrations south of the Line of Lode (Fig. 5), along with elevated soil Pb values, may explain the skewed blood Pb results shown in Fig. 19b. However, it is clear from the recent, and earlier 1993 data, that elevated deposited Pb concentrations occur across much of Broken Hill (Fig. 5; Dong and Taylor 2017). As also noted in Question 1 above, decreasing production at the Broken Hill mines are also associated with falling blood Pb levels in children over time, indicating that mining production quantities (a proxy for mining emissions) are a risk factor for elevated Blood Pb.

Importance of socio-economic factors

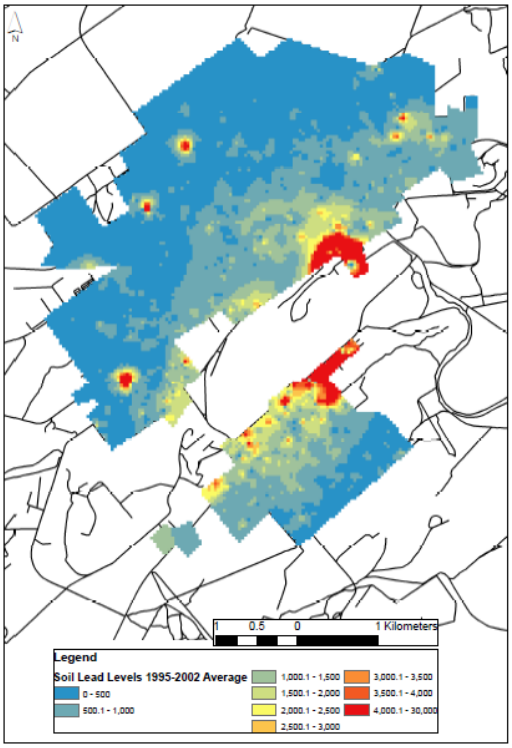
In terms of risk factors for elevated childhood blood Pb in Broken Hill, research by Dong *et al.* (2020) showed that children's blood Pb concentrations increased significantly ($p < 0.01$) with decreased socio-economic status and for children living in houses built before 1940 ($p < 0.01$), however this was only true for children upwind of the Line of Lode.

Quality of housing and exposures

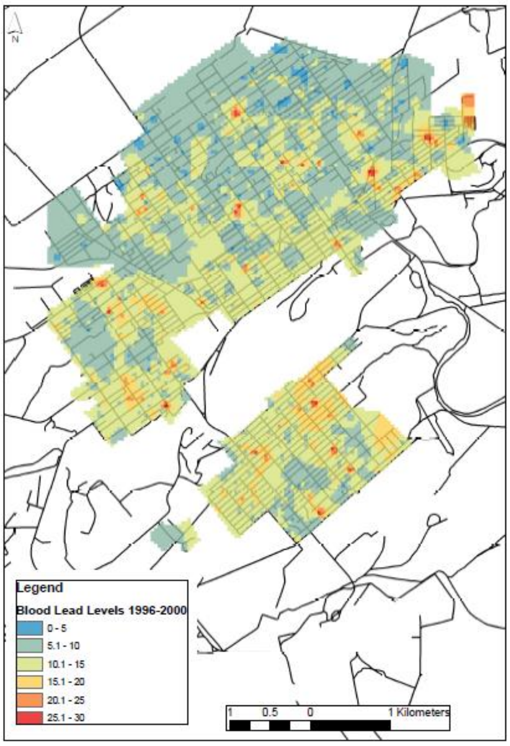
For children downwind of the mining area Dong *et al.* (2020) found the impacts of housing age (indicative of Pb-paint exposure) were negligible, being overshadowed by wind-direction impacts and the delivery of Pb-rich dust. Nevertheless in Fig. 19b, there does appear to be some overlap of aged/poor condition housing and elevated blood Pb. As well these houses potentially contain leaded paints. Studies on Port Pirie (Maynard *et al.* 2006) noted that older houses allow increased Pb dust deposition due to gaps in construction materials, poor sealing of windows or design features such as fireplaces or ceiling ventilation that allow dust entry. Older houses may also contain an accumulation of Pb-rich dust in ceilings, carpets and other areas from decades of dust deposition. Any housing defects, especially in older dwellings, would be exacerbated by the desert climate and wind in Broken Hill where in the absence of air conditioning residents might leave doors and windows open to increase ventilation.

Other Australian data from 224 houses in Sydney shows that older housing, regardless of location, have high dust Pb loadings and hence present a significant Pb exposure risk (Doyi *et al.* 2019). Indeed, a similar observation using a smaller sample of Sydney houses (n = 38) was made previously by Davis and Gulson (2005).

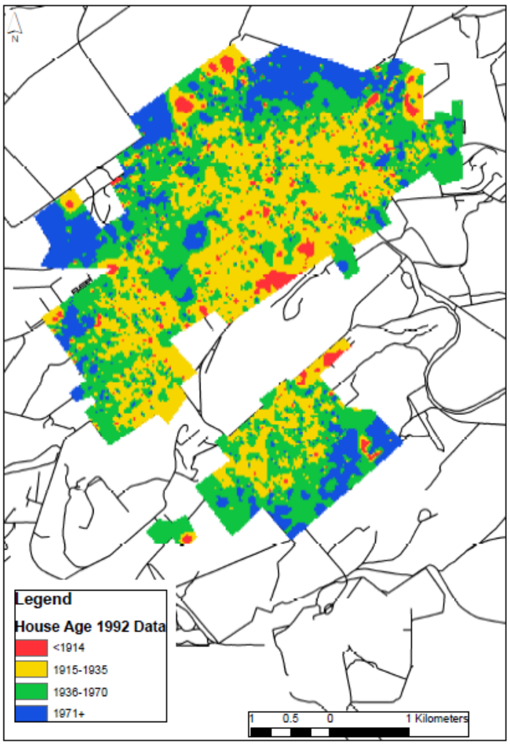
In order to understand the risk of Pb dust in Broken Hill households, and to determine which households face greater risk, a dust testing program should also be implemented (cf. Dani *et al.* 2018). This could involve passive sampling with petri dishes (Gulson et al. 1995; Boreland et al. 2002) complemented by surface wipes (Boreland and Lyle 2006) and vacuum dust (Doyi *et al.* 2019). As noted above, these increased risks may be due to proximity to the mining area, type and age of housing and Pb paint usage. Identification of households with elevated dust Pb concentrations would allow targeted abatement to occur and could be offered locally by BHELP alongside residential soil testing.



A: Soil Pb (mg/kg

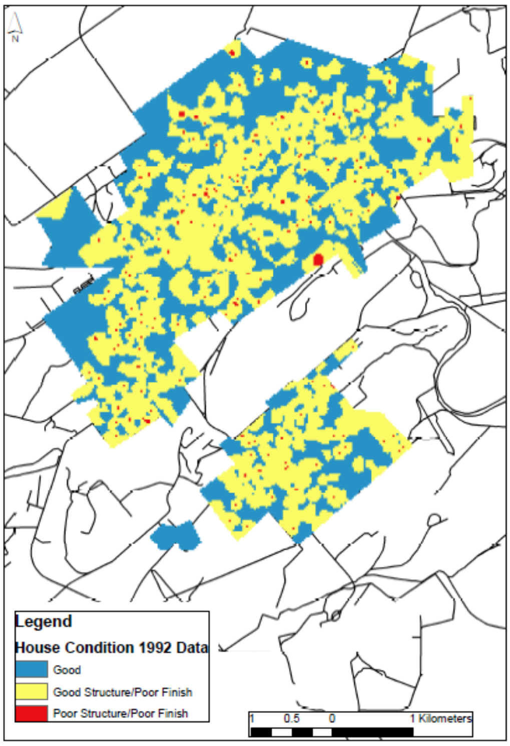


B: Blood Pb (µg/dL)



C: Housing age (year constructed)

N



D: Housing condition

Figure 19. (A): Soil Pb levels (mg/kg) in Broken Hill from 1995 to 2002 (B): blood Pb levels (µg/dL) from 1996–2000 (C): Housing age (year constructed) and (D): housing condition from 1992 data. Source: Broken Hill Environmental Lead Program.

Aboriginality and exposures

Blood Pb levels in Aboriginal children are consistently higher on average than those in non-Aboriginal children. The difference between these groups generally decreased over time from 1995 to 2014 (Lesjak and Jones 2015), however the most recent results for 2018 have seen this gap widen to 3.9 µg/dL, with a geometric mean blood Pb of 7.9 µg/dL for Aboriginal children and 4.0 µg/dL for non-aboriginal children (NSW Ministry of Health 2019). The blood Pb concentration gap of approximately 4.0 µg/dL between Aboriginal and non-Aboriginal children has remained consistent from 2015 to 2018 (NSW Ministry of Health 2019). In 2018, 480 non-Aboriginal children and 154 Aboriginal children were screened, representing a total of 82 % of all Broken Hill children aged < 5 years in 2018 (NSW Ministry of Health 2019).This is concerning, as 76 % of Aboriginal (compared to 39 % non-Aboriginal) Broken Hill children that were tested in 2018 exceeded the acceptable blood Pb level of 5 µg/dL (NSW Ministry of Health 2019); 32 % of Aboriginal children (10 % of other children) also exceeded 10 µg/dL blood Pb. Along with well-established socio-economic disadvantages experienced by the Aboriginal community such as lower average weekly income, increased reliance on welfare, higher unemployment rate, lower school completion rate, inadequate housing and poor housing access (Maari Ma 2017), it is evident that Pb exposure is another unnecessary and preventable burden that has potential to further diminish lifetime educational, economic and health outcomes. It is critical to the long-term equity and welfare of the Aboriginal community that the modifiable environmental Pb burden is addressed.

Importance of age and exposures

The first year of life is a critical time for Pb exposure, with much of the increase in blood Pb levels at a population level being evident by 12 months of age (BHUDRH 2017). Almost half of the Broken Hill children presenting for testing at 12 months of age (from 2009-2015) had blood Pb levels ≥ 5 µg/dL. The proportion of children with blood Pb ≥ 5 µg/dL at 2, 3 and 4 years did not differ greatly from the 12-month test (BHUDRH 2017). From these results it is evident that Pb exposure in the first 12 months of a child's life provides a reasonable indication of a child's blood Pb levels in later years. These data highlight the importance of early intervention programs for families with newborn children and for this reason, BHELP have re-introduced testing at 6 months of age. Early intervention is key to mitigating long-term effects of Pb exposure as childhood exposure affects *inter alia* long-term educational, socio-economic and health outcomes (Reuben *et al.* 2017, Lanphear *et al.* 2018, Reuben *et al.* 2019). Relevantly for Broken Hill, Dong *et al.* (2015) showed that children living in the more contaminated locations of Broken Hill performed less well in both National Assessment Program - Literacy and Numeracy (NAPLAN) and Australian Early Development Census assessments. Earl *et al.* (2016) also showed, using a small cohort of 127 children from Broken Hill (n = 49) and Port Pirie (n = 78), that when blood Pb rose from 1 to 10 µg/dL, 13.5 full scale IQ points were lost (or about 13.5 % based on an average IQ of 100). Billings and Schnepel (2018) demonstrated that in North Carolina, early life interventions to prevent Pb exposure were able to successfully mitigate such negative outcomes.

Population shifts in blood Pb levels

Based on the number of children whose blood Pb levels were < 5 µg/dL at the 12 month, 2 and 3 year scheduled tests, the data show that only around 30 % of Broken Hill children over this period of their lives are able to keep their blood Pb level below the upper level of concern (5 µg/dL) (BHUDRH 2017). This means that most children (70 %) living in Broken Hill will, at some time in their first three years of life, exceed the 5 µg/dL blood Pb threshold.

Question 3 – Potential strategies for lowering children's blood Pb levels in Broken Hill
(a) Identifying and mitigating the dominant sources of Pb exposure.
(b) Identification and reduction of emissions and fugitive emissions from current and former Pb industries (in particular ore extraction, processing and transport).
(c) Airborne (aerosol and dust deposition) and water-borne emissions, where relevant to exposures in the community.
(d) Abatement of soils with elevated levels of Pb including establishing the most appropriate upper maximum concentration to ensure blood Pb levels remain below 5 µg/dL (the NHMRC upper acceptable level).
(e) Abatement of paint hazards.

(a) Identifying and mitigating the dominant sources of Pb exposure

In order to address the main Pb exposure routes and reduce children's blood Pb concentrations across Broken Hill city, it is necessary to consider exposure both within and outside of a child's home. It is also necessary to address both current mining emissions and legacy Pb risks.

Exposure outside of the home

A further study, currently underway by Broken Hill University Department of Rural Health (BHUDRH 2018), asked parents of children presenting for blood Pb testing about time the child spent outside the family home. Preliminary results show that 75 % (of 81 children) spend more than 10 hours outside the family home each week. The range of places included childcare centres, public spaces and private residences (family and friends). While the full results are yet to be analysed, preliminary analysis indicates that children are potentially exposed to Pb at multiple places within the community, including at more than one residence. This means that abatement of the child's residence alone may not be sufficient to achieve a major reduction in the number of children with blood Pb ≥ 5 µg/dL. Studies in the USA have shown that only home-yard remediation in the absence of community wide clean-up and in-home intervention was less effective at lowering blood Pb levels (von Lindern *et al.* 2003, 2003). At Broken Hill (Boreland and Lyle 2006, Boreland *et al.* 2009), individual home Pb abatement of outdoor and indoor sources reduced indoor Pb levels, but it did not change the rate of decline in blood Pb levels significantly (Boreland and Lyle 2006, Boreland *et al.* 2009). Recent research on Port Pirie, in South Australia showed that Pb in air was a significant contributor to children's blood Pb concentrations (Taylor *et al.* 2019). At Port Pirie as well as Broken Hill, airborne Pb and associated Pb dust deposition exposure risks are not limited to child's place of residence. The effects of environmental contamination would be experienced across the city areas but with decreasing intensity with distance from the point source (see Figs 16a,b, 19a,b).

(b) Identification and reduction of emissions and fugitive emissions from current and former

Examples from Australia (Dalton and Bates 2005, Hunter New England Health 2015) and overseas (von Lindern *et al.* 2003, Lin *et al.* 2011) show that where Pb emitting operations (mining, processing and smelting) have ceased, Pb levels in air and in children's blood (and animals (Berglund *et al.* 2010)) were subsequently reduced. Given that mining operations at Broken Hill are important to the regional and even national economy, their closure to facilitate lower blood Pb levels would not be an economically or realistic viable option. Nevertheless, Gough *et al.* (2012) estimated that if blood Pb levels of Broken Hill preschool-aged children could be reduced to those of Sydney preschool-aged children, between 4 and 17 families would each benefit by $73,000 a year. The cost savings (Gough *et al.* 2012) are attained through not having to care for someone with a mild intellectual disability.

Other than ending mine operations to facilitate a reduction in childhood Pb exposures, there are a suite of interventions that are likely to significantly reduce emissions and in turn exposures in the community.

Identifying emissions

As discussed in Question 1 above, child blood Pb concentration was found by Dong *et al.* (2020) to be significantly correlated with dust deposition measured indoors at the rate of 0.08 µg/dL blood Pb per 100 µg Pb/m^2 dust/30 days. Whilst dust fall and its Pb content is currently measured across Broken Hill using dust deposition gauges by the Office of Environment and Heritage and mining companies (see section on 'Dust', p.18), there is no standard or condition in any of the Broken Hill mine licences for Pb in deposited dust. Given that dust Pb so clearly relates to child blood Pb, there is a case for integrating deposited dust Pb regulations into environmental licensing agreements. Environmental licensing for Mount Isa mines (Queensland Department of Environment and Science 2018) requires Pb in deposited dust to be less than 100 µg/m^2/day. Above this trigger value at Mount Isa, investigation of sources and mitigation measures are required. This benchmark value of 100 µg Pb/m^2/day is not currently met in Broken Hill at locations close to the Line of Lode (Dong and Taylor 2017, Perilya 2017); indeed, Fig. 5 shows this value to be exceeded at all but one monitoring location.

Reducing emissions

Perilya has recently introduced enhanced use of sprinklers and water carts on haul roads and open areas at all sites. Emissions from exposed and unsealed surface areas, even those currently not in use for mining, are likely to contribute significantly to Pb in windblown dust. In response to the NSW EPA's 2016 Pollution Reduction Plan (Southern Operations), Perilya is also required to install new dust extraction filter systems at the primary and secondary crushing facilities (NSW Environment Protection Authority 2016). Being a more recently developed mine, CBH Resources Limited (CBH) utilise a number of measures to reduce emissions, including the operation of crushing activities under negative pressure dust extraction conditions (Wilson 2010). CBH's emissions controls have recently been refined through the NSW EPA's Pollution Reduction Plan process. Best practice emission reduction measures to be included in the new Perilya Northern Operations include minimisation of drop heights for loading and dumping of product and tailings; use of water carts and speed limits for unsealed haul roads; use of a wheel wash; use of water sprays on crushing and sizing activities and on product or tailings stockpiles; use of dust suppressants on open unused areas and consideration of wind conditions when planning works (Perilya 2017, Perilya 2017). These best-practice dust mitigation measures at both the Northern and Southern Operations, once fully implemented, have the potential to reduce Pb emissions. The impact of their adoption has yet to be fully quantified and should be assessed as part of ongoing evaluation of de-contamination and intervention efforts. In particular, if these dust-mitigation measures at the Southern Operations are effective, it is anticipated this will be expressed via reductions on the Pb loadings recorded in deposited dusts across Broken Hill.

Table 1. Potential strategies for identification and reduction of emissions and fugitive emissions from current and former Pb industries (in particular ore extraction, processing and transport)

Strategy	Details	Cost	Examples
Do nothing	Continue current programs	Approximately $2.5 million a year	
Ongoing and targeted monitoring of deposited dust.	Demonstrate the effectiveness of emissions controls.	To be determined.	
Introduction of a maximum Pb in deposited dust requirement e.g. 100 µg Pb/m^2/day.	Pb in dust guidelines added to licensing conditions requiring investigation and mitigation of sources if trigger values are exceeded.	If targets are unable to be met, additional measures may be required e.g. further decreased activity on windy days (cost to productivity).	Mount Isa (Department of Environment and Heritage Protection 2017).
Tighter emissions controls.	Many practices have been recently implemented or are scheduled to be implemented to bring the mines in line with international best practice, yet there may be further emissions controls technologies that become available in the future.	To be determined.	
Closure of mine.	Cease all mine activity.	$318 million a year cost annually to the regional economy and loss of 813 jobs in Broken Hill (Broken Hill City Council 2018).	Lin *et al.* (2011).

(c) Airborne (aerosol and dust deposition) emissions, where relevant to exposures in the community

Community Pb exposures can be mitigated by emission reduction or via other measures such as relocation, remediation and behavioural changes. The primary and most effective of these would be to prevent emissions from occurring, or to reduce emissions at the point of release.

Residential relocation

One rather drastic and probably unrealistic but effective way to reduce the exposure of the community to these emissions would be to relocate the residential area of Broken Hill away from the mine or have families move away from Broken Hill (Gulson *et al.* 1996). Based on the most recent and comprehensive available dust, air and blood Pb data (Dong and Taylor 2017, OEH 2018, Dong *et al.* 2020), this would need to be at least 4 km from the current operations. There is precedent for relocation of residential centres in Australia. Between 1962 and 1964, the rural towns of Jindabyne and Adaminaby in NSW were relocated for the purpose of Snowy River Hydroelectric dam construction after it was determined it was clearly unsafe for residents to remain in the original locations if they were to be flooded under the hydroelectric scheme. The town of Wittenoom, Western Australia, with a population of 20,000, slightly larger than Broken Hill, experienced significant contamination from the mining of blue asbestos. Whilst the mine closed in 1966, residents continued to live in Wittenoom and experience legacy asbestos contamination until 1978, whereafter the government began to encourage them to leave by acquiring residential properties. In the Pb and zinc mining town of Picher (Oklahoma, USA), one third of children were found to have elevated blood Pb levels in the 1990s. Combined with the risk of ground collapse, a federal relocation property buyout occurred (U.S. Army Corps of Engineers 2008). There are many similar global examples of property buyout and acquisition, including near the Pb smelter at Boolaroo, NSW, Australia (Sweetnam 2010) which is also common practice for mining operations that seek to extend their mine area (Planning NSW 2014). Relocation is a costly alternative and is significantly disruptive of people's sense of place versus a situation where comprehensive mitigation and effective abatement is achievable (Jordan 2010).

Given that atmospheric emissions are ongoing, it is inevitable that soil and dust remediation efforts will diminish in their effectiveness over time (Question 4). Moreover, as Broken Hill mining is integral to the economy of the region and the nation, relocation of the city residential living area offers a viable alternative that would permit the industry to continue its operations whilst ensuring that its children can reside in an environment that is not Pb contaminated. If mining activity is not expected to continue in Broken Hill beyond the next decade, the future of the town beyond this point should be also considered. Similar to Wittenoom, the legacy Pb contamination risks may make re-location of residents after mine closure a viable and effective alternative.

A variation of the relocation strategy is to gradually shift families with vulnerable children away from high-risk areas to lower-risk areas, as was suggested previously by Woodward-Clyde (1993). This strategy has been applied in Port Pirie (Maynard *et al.* 2006), where development restrictions were applied to the highest risk areas and families were supported financially to move away from these most contaminated zones. Whilst this works to reduce the exposure of the children most at risk, it is evident in Broken Hill that the majority of children with elevated blood Pb concentrations live outside of these high-risk zones (i.e. those areas close to the Line of Lode, particularly in South Broken Hill, (BHUDRH 2017). Whilst this strategy may have reduced the blood Pb of Port Pirie's most affected children, it has not reduced child blood Pb to desired levels more broadly across the city's population. Like Broken Hill, Port Pirie continues to have a large proportion (47 % in 2017 (Simon *et al.* 2018)) of children under 5 years old presenting annually with elevated blood Pb (> 5 µg/dL).

Controlling emissions at point of release

There are two main sources of Pb-laden dust in Broken Hill: the contemporary release of Pb from mining activities (via ore extraction, processing and transport) and the resuspension of Pb contained in soils around Broken Hill. The latter of these is most effectively addressed by abatement of soil Pb, which is discussed at point D below. The most effective point at which to mitigate Pb in air and subsequent deposited Pb dusts is to prevent or reduce Pb emissions from mining operations at Broken Hill, i.e. at its source, Dust mitigation from mining operations is discussed at point B above.

Whilst the costs of emissions reduction can be argued to be prohibitive, it is worth noting that economic benefits also arise from reducing Pb exposures. For example, Gould (2009) calculated that for every dollar spent on controlling Pb exposure in the USA, $17–221 was returned to society. Similarly, in China there were measurable benefits from reduction of Pb emissions (Tang et al., 2014). The annual costs of Pb exposure for New Orleans (USA) were estimated at US$76 million a year for health, education and societal harm (Mielke *et al.* 2006) and US$50.9 billion for the USA as a whole (Attina and Trasande 2013).

Beyond city-wide interventions, mitigating measures may be applied at the individual household level.

Household level exposures

The first priority in mitigating Pb dusts at a household level is to prevent dust from entering the home. Removing and replacing older housing stock would significantly reduce the in-home Pb risks of children currently living in aged, poor-quality housing. Sealing of older homes (Maynard *et al.* 2006, Dong *et al.* 2020) to minimise dust penetration would also likely reduce Pb exposures. The benefits of such an approach is evidenced by the Boreland *et al.* (2002) study that showed 'poorly sealed' homes and 'adequately sealed' homes reported 4.3 and 2.9 times the amount of daily deposited Pb compared with 'well sealed' homes (see also (Taylor 2011)). However, as noted above (section '*Housing'* p. 34) the practice of leaving windows and doors open in the absence of air conditioning would limit the efficacy of such measures.

The Broken Hill Environmental Lead Program has been very effective, via its television and social media LeadSmart campaign, in communicating practical ways to reduce transport of Pb soils into the home. For renovation or earthworks on residential properties, Broken Hill City Council (2016) provide guidance as to how works should be carried out to address Pb contamination. While this advice in itself might be adequate for addressing Pb contamination issues at individual residences, it is effectively, a piecemeal approach and does provide uniform clean up nor does it stop re-contamination from emissions associated with the Line of Load.

Exposures from dust deposition can be further mitigated on a household level by dust cleaning using wet mopping and wiping techniques, vacuuming of carpets and furnishings. Household education interventions and dust cleaning have, however, been shown to be relatively ineffective at reducing blood Pb levels in children as compared to population level health measures (Nussbaumer-Streit *et al.* 2016). For this reason, such interventions should be considered as supplementary only to other abatement measures, as primary prevention is '*the only truly effective public health response to lead poisoning*' (Meyer *et al.* 2003).

A further strategy to reduce Pb exposures and blood Pb levels is to install HEPA air filters in homes. There is evidence for their effectiveness in reducing ambient contaminant levels (Sublett *et al.* 2010), including removal of airborne virus particles (Zuraimi *et al.* 2011). Of particular relevance is a recent Mongolian study (Barn *et al.* 2018), which showed significant reduction of $PM_{2.5}$ (see also Du *et al.* (2011)) and cadmium concentrations in indoor air. These reductions were associated with reduced blood cadmium concentrations for participants who used the HEPA air filters.

Table 2. Strategies for reduction of airborne contaminants (aerosol and dust deposition) where relevant to exposures in the community

Strategy	Details	Cost	Examples
Relocation of town	Moving residential areas, schools and playgrounds away from areas most impacted by current mine emissions.	To be determined.	Wittenoom, Western Australia. Jindabyne and Adaminaby, NSW. Picher USA.
Moving children out of high-risk areas (to lower risk areas).	Offering relocation assistance for families in areas closest to the Line of Lode.	To be determined.	Port Pirie (Maynard *et al.* 2006), limited success.
Household level interventions.	Vacuuming, mopping, preventing entry of dust on pets and shoes, washing home-grown produce, covering sand-pits when not in use, washing toys used outside.	Borne by households.	Interventions are ineffective in reducing blood Pb (Boreland *et al.* 2009, Nussbaumer-Streit *et al.* 2016).
In-home air filters	Air filters to remove Pb particulate.	Approximately $500 per unit. A trial on effectiveness for Pb removal would be required cost ~$50,000.	Du *et al.* (2011) Barn *et al.* (2018) No studies on Pb removal using air purifiers/filters were found.
Sealing and or replacement of older homes	Older homes are more susceptible to dust entry (Boreland *et al.* 2002, Dong *et al.* 2020)	Cost to be determined.	Broken Hill: well-sealed homes showed lower Pb in deposited dust (Boreland *et al.* 2002) and newer housing was associated with lower child blood Pb (Dong *et al.* 2020).

(d) Abatement of Pb-contaminated soils to ensure blood Pb levels remain below 5 µg/dL

In order to determine the average soil Pb level required for the majority of Broken Hill children to have blood Pb levels less than 5 µg/dL, Yang and Cattle (2015) used the Integrated Exposure Uptake BioKinetic model (IEUBK), as mentioned in Question 1 above. The IEUBK model predicts blood Pb level at population level for children less than 7 years old who are exposed to environmental Pb from multiple sources (including air, soil, dust, water). Yang and Cattle (2015) measured soil Pb concentrations in Broken Hill in 2012, estimated indoor dust Pb levels using a ratio of 1.5 to 1 (indoor dust Pb to soil Pb) and used other locally collected measures for water Pb, air Pb and maternal blood Pb. Yang and Cattle (2015) used IEUBK default values for all children's behaviour parameters such as dietary intake of Pb. The output of their model predicted blood Pb values matching closely to the measured values in Broken Hill children (Yang and Cattle 2015), as per Woodward-Clyde (1993). Model inputs were then varied to determine the desired soil Pb concentration. Yang and Cattle (2015) predicted that an average soil Pb level of < 150 mg/kg would be necessary to ensure 80 % of Broken Hill children aged 1-4 years of age had a blood Pb level < 5 µg/dL (Yang and Cattle 2015, BHUDRH 2017). The soil Pb value of 150 mg/kg is below the current NEPM for the Assessment of Site Contamination in residential soils (Residential A: 300 mg/kg (National Environment Protection Council 2013)) and as such would indicate that a greater number of residences and public places would require remediation than if the remediation goal were to be based on the NEPM. However, as noted elsewhere in this report, reliance only on an intervention that requires soil Pb to be reduced to 150 mg/kg fails to address the significance of other sources and their impact on child blood Pb concentrations. These other sources include Pb-rich dust generated from the Line of Lode area, indoor dust (Dong *et al.* 2020) and Pb-based paints. Pb contaminated indoor sources would likely be more significant in the first year of children’s lives when they have limited contact with outdoor environments.

Broken Hill University Department of Rural Health (BHUDRH 2017) recommend zonal abatement as an effective strategy for reducing blood Pb levels in children from areas with high soil Pb concentrations. This strategy would target the high soil Pb zones based on the high individual risk to children residing there. However, for greatest effect, abatement efforts would need to be extended to other localities where most (70 %) of the children with high blood Pb levels live. Moreover, targeted abatement of soils was implemented between 1994 and 2006 (Cattle and Wimborne 2016), which, based on the continued elevated blood Pb values in children, has not been adequately effective. This is not surprising given the role of contemporary dust Pb driving childhood blood Pb outcomes (Dong *et al.* 2019).

Considering the potential for exposure outside of the home (BHUDRH 2018), remediation of the child’s residence alone may not be sufficient to achieve a major reduction in the number of children with blood Pb ≥ 5 µg/dL (BHUDRH 2018). Depending on the outcome of assessment of these risks (see Question 3 (a) Exposure outside the home), this could involve extensive remediation activity across the entire Broken Hill city area.

For locations where total Pb in soil marginally exceeds the desired level, in-situ treatment to minimise Pb relative bioavailability may be the most cost-effective risk management strategy (Juhasz 2018). Phosphate amendments to Pb-impacted soil have the potential to decrease relative Pb bioavailability by creating insoluble Pb phosphate minerals that would be absorbed poorly (Juhasz *et al.* 2014). While the effectiveness of phosphate amendment remains untested on Broken Hill soils, it may form a cost-effective option in conjunction with soil capping strategies, which are known to be effective at contributing to lowering blood Pb exposure. For example, in the Dominican Republic (Fig. 20), blood Pb levels reduced after soil abatement measures (capping of Pb-contaminated surface soils) were implemented (Ericson *et al.* 2018). It is important to note that, in Ericson *et al.* (2018) soil abatement followed smelter closure (removal of the primary Pb contaminant source) and was combined with community education programs.

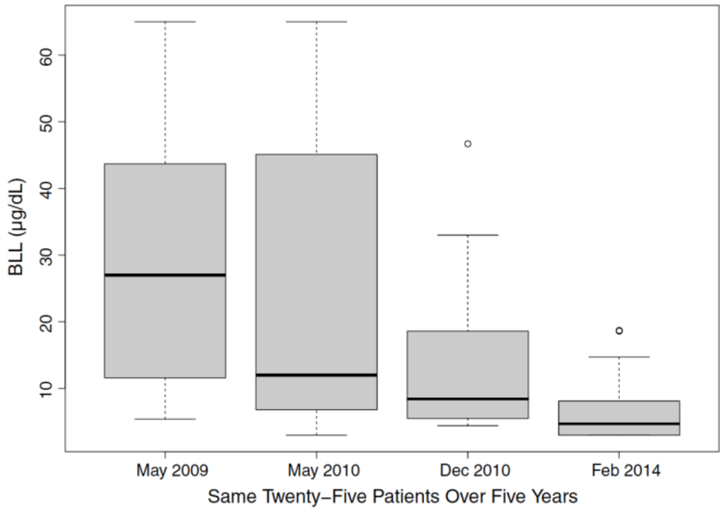


Figure 20. Blood Pb levels (BLL) for the same 25 patients over 5 years, demonstrating decreased blood Pb levels following smelter closure followed by remediation of Pb contaminated soil during 2009–2010.

Another example from Vietnam (Ericson *et al.* 2018) shows the potential of reducing blood Pb by combining soil abatement strategies (capping Pb-contaminated surface soils) with other interventions, which in this case included cleaning of homes, an education campaign, and the provision of workplace-clothes washing and bathing facilities (Fig. 21).

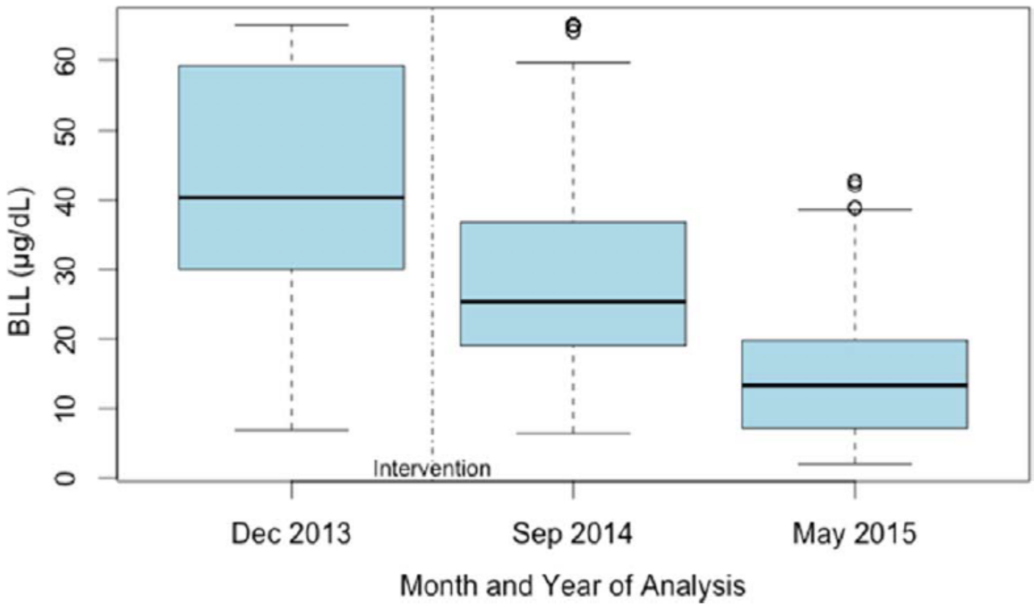


Figure 21. Results of blood Pb (BLL) analysis of children in the Dong Mai village, Vietnam, before and after implementation of co-ordinated soil abatement and intervention programs. Post intervention BLLs were statistically lower ($p < 0.005$) than pre-remediation values.

A further option for soil amendment is the use of bauxite residues (Bauxsol™ and Bauxaline®), which have been successfully used to immobilise trace elements (including Pb) in France (Taneez *et al.* 2015).

Table 3. Strategies for abatement of soils with elevated levels of Pb.

Strategy	**Details**	**Cost**	**Examples**
Zonal abatement	Focusing on high-risk soils (BHUDRH 2017) for 3 km distance from Line of Lode (Dong *et al.* 2020).	To be determined.	Successful Pb exposure reduction in the short term (Lesjak and Jones 2015), eg. Broken Hill parks (Cattle and Wimborne 2017). Reduce in effectiveness over time eg. Broken Hill (Cattle and Wimborne 2016) and Boolaroo (Harvey *et al.* 2016).
Widespread remediation of soils across Broken Hill.	Target of < 300 mg/kg Pb (National Environment Protection Council 2013) Capping contaminated soil with clean fill to depth 30 cm (Dong 2018).	$10,000/home $12M total (Dong 2018) 67 % of 1900 homes tested exceed 300 mg/kg Pb.	
	Target of < 150 mg/kg Pb as determined by (Yang and Cattle 2015). This would require more properties to be remediated than the target of < 300 mg/kg.	To be determined.	
Removal of soil.	Removal of contaminated topsoil prior to capping with clean soil.	To be determined.	Limited effectiveness (see Question 4).
Phosphate amendment of soils	Mixing phosphate with soils marginally exceeding desired Pb concentrations to decrease bioaccessibility of Pb. Usiung Bauxsol™/Bauxaline® as potential soil amendments to to decrease Pb bioaccessibility could also be considered.	To be determined Pilot testing is required.	Effectiveness is dependent on soil type and may have unwanted side effects Question 4 (Li *et al.* 2017).
Capping playground soils.	Capping contaminated soil with clean fill.	To be determined.	Long-term effectiveness of abatement is dependent on the method used and its maintenance (Cattle and Wimborne 2017).

(e) Abatement of Pb paint hazards

Lead-based paint remains on ongoing hazard in Broken Hill in part due to the age of homes and the condition of some of the paint in those homes i.e. peeling, flaking or remobilised due to recent renovations. Lead-based paint hazards remain part of the risk profile of Pb in Broken Hill but evidence for its significance as a main source of exposure across the population is limited. Certainly, BHELP have identified individual cases where Pb paint hazards are prominent in homes where children are reporting with elevated levels, but its pervasiveness as an issue is less certain. A recent systematic review (Ericson *et al.* 2019) of Pb exposures and sources of lower to middle income countries (LMIC) showed that despite the absence of Pb paint bans in most LMIC countries, it does not appear to be a major source of exposure. In the review, Ericson *et al.* (2019) considered 477 papers containing 979 sampled populations (i.e. subsamples); totalling 702,069 individuals from 50 countries. The evidence from this systematic review showed that industrial sources e.g. mining and smelting emissions were far more prominent as a source of exposure than Pb-based paints and other sources.

In terms of addressing the legacy Pb paint problem in residential homes, an example of a grant funding scheme for Pb paint remediation from North Carolina (Billings and Schnepel 2017) may be applicable to the Broken Hill situation. In the North Carolina case, assistance was made available to owners of properties built before 1978 who met income eligibility requirements and had children under six years of age. Signage was erected outside the home warning about the presence of Pb, then the house was sealed with plastic with the workers wearing protective suits and respirators performed remediation. The average cost of Pb abatement works on each house was US$7,291 ($10,000 AUD). The works involved removing and replacing windows and doors (most common); painting or installing siding on the exterior of homes and repairing doors to avoid chipping within the door frame when opening and closing. For areas not involving moving parts (walls and ceiling), existing Pb paint was sealed where possible, however in many cases, areas with old and deteriorating paint had to be removed.

A different approach was used in New York (Greene *et al.* 2015) where a media campaign was used firstly to increase knowledge of Pb paint exposure sources and then to increase knowledge of preventive behaviours. Improvements in understanding of risks from paint Pb were observed broadly across the community.
The ‘Build smart’ component of the Broken Hill ‘LeadSmart’ campaign has already addressed this to some extent. Nonetheless, it may be desirable to provide further public education on risks of paint Pb in Broken Hill.

Table 4. Strategies for abatement of Pb paint hazards.

Strategy	Details	Cost	Examples
Provision of paint testing	Utilising portable XRF technology	This capability / instrumentation already exists within BHELP	Jakarta, Indonesia (Ericson *et al.* 2019)
Paint remediation.	Removing and replacing windows and doors, painting or installing siding on the exterior of homes and repairing doors to avoid chipping within the door frame when opening and closing,	Approximately $10,000 per home.	North Carolina (Billings and Schnepel 2017).
Continued media campaigns about Pb in paint as part of Leadsmart.	Increase knowledge of Pb paint exposure sources and preventive behaviours.	To be determined.	New York (Greene *et al.* 2015).

Question 4 – Strategies applied in Australia and overseas to reduce blood Pb exposures

(a) Effectiveness of strategies developed in Australia and overseas for reducing children's blood Pb levels for the environmental risk factor targeted (e.g. soil, dust, paint).
(b) Factors critical to the success of the strategies in the communities in which they were undertaken—e.g. for a soil abatement program this might include the number (percentage) of contaminated residential homes that were able to be remediated.
(c) Critical success factor(s) for economically feasible emission reduction technology.
(d) Negative effects / consequences of implemented strategies.

(a) Effectiveness of strategies developed in Australia and overseas for reducing children's blood Pb levels for the environmental risk factor targeted (e.g. soil, dust, paint).

Following abatement measures in the early 1990s, including remediation of selected residential properties and public areas as well as capping of waste dumps and railway yards in the centre of Broken Hill, airborne Pb levels reduced significantly (Boreland and Lyle 2014). This was accompanied by a decrease in child blood Pb, from 16.7 µg/dL in 1991 to 7.6 µg/dL in 2001. This is indicative evidence that the abatement measures, *inter alia*, were successful in contributing to the lowering of children's blood Pb in Broken Hill. It was also demonstrated (Fig. 14, Dong *et al.* (2019)) that reduced production levels of Pb-bearing-ore at Broken Hill are related to decreases in child blood Pb. However, overall, it is evident that all of the measures carried out in Broken Hill to date continue to fall short of broadly reducing children's blood Pb to below 5 µg/dL. It is therefore necessary to re-examine the effectiveness of these abatement measures.

Abatement using clean topsoils

Private residences and public areas in Broken Hill that were remediated between 1994 and 2006 were analysed for current topsoil Pb concentration (Cattle and Wimborne 2016). The fill materials used were wood chips, blue metal, garden loam, cracker dust, white rock, coarse sand, or a combination of these. The locations varied in depth of fill and at some locations, contaminated topsoil was removed before covering with clean material, in other locations, contaminated soil was simply covered with clean material. Cut and fill depths varied from 25 mm to 200 mm. A total of 153 measurements were taken over 39 sites using a portable X-ray fluorescence (pXRF) device. Of these

153 measurements, 115 had matching topsoil Pb concentration data for the same location prior to abatement; of these 115 locations, 26 % had a higher topsoil Pb in 2016 than prior to abatement. Over half of all sampling sites had Pb greater than 300 mg/kg, the Australian Health Investigation Level for residential gardens (National Environment Protection Council 2013). There was no significant difference in how well the different strategies performed and each of the strategies was prone to various kinds of disturbance, increasing the potential for contaminated soils to be returned to the surface. Even though some residences may have been remediated, it remains a requirement for Broken Hill section 10.7 certificates to be issued under the *Environmental Planning and Assessment Act 1979* (NSW) to provide information that the land may be Pb contaminated.

Additionally, Pb-rich dust, emitted from mining operations and railway corridors, continues to be deposited on abated areas, replenishing surface Pb concentrations. The likely impact of this dust deposition was evident in properties where soil abatements appeared to be intact (i.e. no sign of disturbance) yet Pb concentrations were elevated (Cattle and Wimborne 2016). In summary, after a period of greater than 10 years, more than half of the abated surfaces required additional abatement work in order to attain a topsoil Pb < 300 mg/kg (Cattle and Wimborne 2016). If the same family remains in an abated property, a period of ten years may be adequate if, after that time, children are > 5 years old and no longer at as high a risk of Pb exposure from soil contact.

The Cattle and Wimborne (2016) data demonstrates that an abatement strategy of ‘cap and cover’ is effective only for a limited period and erroneously suggests the problem is considered to be eliminated. Indeed, if parents believe that their yard is clean of Pb contamination, they may allow children to take greater risks in regard to soil Pb exposure. It is important therefore to have and communicate an understanding of the maintenance requirements of abatement strategies.

Best practice now dictates that a coloured geotextile fabric barrier be placed over contaminated soils before topsoil is added, limiting disturbance and transport of contaminated soils back to the surface (Laidlaw *et al.* 2017). Neglecting this step may be one reason for the reduced effectiveness of previous abatements in Broken Hill, although freshly deposited Pb dusts would also contribute to increased surface Pb.

A further study by Cattle and Wimborne (2017) investigated topsoil Pb in public parks and playing fields. Areas that had been refurbished with clean topsoil in the previous 10 years exhibited generally lower topsoil Pb concentrations. For several parks near the Line of Lode, bare areas on the periphery of fields had high Pb concentrations. Most high-risk areas in public parks have now been addressed under the current abatement program.

Yang and Cattle (2017) investigated sites where cracker dust had been used as a surface capping material over earthen footpaths, concluding that it has been generally effective in minimising potential exposure to soil surface Pb. Numerous sites where cracker dust had been applied, either deliberately as a remediation strategy or as a product of kerbing and guttering, had Pb concentrations below 600 mg/kg. Within 400 m of the Line of Lode, several cracker dust sites had Pb concentrations > 600 mg/kg, suggesting that the long-term effectiveness of cracker dust as a clean capping material is compromised within this Line of Lode catchment where water or wind - borne transport of Pb and mixing with Pb-rich subsoils occurs.

In a meta-analysis of several published studies globally, Nussbaumer-Streit *et al.* (2016) concluded that there is currently insufficient evidence to clarify whether soil abatement or a combination of interventions reduces blood Pb levels. The evidence from studies on Broken Hill soils indicates that soil abatement strategies reduce Pb exposures at least in the short term, however their effectiveness diminishes over time. Evaluation of prior soil abatement measures at Boolaroo in NSW have similarly shown this diminished effectiveness over time (Harvey *et al.* 2016).

Abatement using soil amendments

No studies are available that specifically assess the effectiveness of phosphate amendment on Pb bioavailability/bioaccessibility in Broken Hill soils. Studies conducted in other locations have shown phosphate amendments of both hydroxyapatite and phosphate rocks successfully reduce Pb bioavailability/bioaccessibility (Ryan and Zhang 2000, Ryan *et al.* 2004, Juhasz *et al.* 2014, Li *et al.* 2017). Results are, however, dependant on soil type (Henry *et al.* 2015) and it is difficult to quantify the relationship between different models (mouse v other animals). Phosphate amendment of soils may also have unwanted consequences of increasing the bioavailability of other toxic components, such as arsenic (As) (Li *et al.* 2017). The interaction between phosphate and As is however complex (Kolařík *et al.* 2018). Current research by Juhasz (unpublished) (in swine) has showed that As bioavailability is reduced following application of phosphate amendments. Due to a lack of Broken Hill data on any soil phosphate amendment strategy, it would be necessary to trial the method on pilot test sites and carefully monitor the results before more widespread application (National Research Council 2003). This process would inevitably delay urgently needed city-wide intervention action for Pb contaminated soil.

(b) Factors critical to the success of the strategies in the communities in which they were undertaken—e.g. for a soil abatement program this might include the number (percentage) of contaminated residential homes that were able to be remediated.

Abatement using clean topsoils

Cattle and Wimborne (2016) observed that previously remediated areas may exceed 300 mg/kg Pb where garden cultivation and deliberate movement of soils has occurred. Another reason that previously remediated soils now exceed this threshold is deposition of Pb dust from contemporary mine emissions or as windblown soils from more contaminated zones. Contamination from recently deposited Pb dusts, rather than from soil disturbance, was particularly evident in the elevated surface Pb concentration (829 mg/kg (Cattle and Wimborne 2017)) of an area that had been covered with artificial grass. Further to this, contaminated soils may be transported by stormwater runoff onto remediated areas. Additionally, clean capping materials may also be eroded by water movement or strong winds, exposing the contaminated soils below. The most frequently observed reason for disturbance of cracker dust capping layers was ant nest formation, with ants transporting the capped Pb-rich soil back to the soil surface (Cattle and Wimborne 2016).

In the case of public parks, well-grassed areas typically had lower soil Pb and/or lower risk of exposure than bare areas where greater contact with soil is experienced and topsoil is more easily eroded (Cattle and Wimborne 2017).

Importance of community consultation

Failure to solicit input from the community hampered cooperation between the community and the USEPA in regard to successful remediation at Bunker Hill Idaho USA (Moodie and Evans 2011), although this was disputed by Stifelman *et al.* (2012). Moodie and Evans (2011) argued that remediation efforts should not only focus on harm reduction but also ameliorate environmental and social injustices. In contrast, the Broken Hill Environmental Lead Program (BHELP) has made substantial effort to work collaboratively with community organisations, relevant stakeholders and the wider community. Further, there has been significant effort to reduce blood Pb levels for highly impacted groups such as children living in high-risk areas and those identifying as Aboriginal (Lesjak and Jones 2015). The example of the breakdown in community relations in Bunker Hill serves as a reminder of the importance of continued community consultation in the process of addressing Pb exposure in Broken Hill.

(c) Critical success factor(s) for economically feasible emission reduction technology

Consideration of the life-span of abatements must be made when considering economic feasibility. For example, the economic analysis of soil abatement measures may require funds for repeated amendments after a ten-year period. The future of the town of Broken Hill in terms of projected population after mine closure should also be considered.

The life-span of abatement measures may be significantly improved if geofabrics are used to separate clean and contaminated soil layers, hence minimising disturbance (*cf*. Laidlaw et al. 2017). It would be appropriate for the local council to include such a requirement in their works and development approval procedures. Additionally, community education, which would need to be regularly re-enforced over time, may assist in more effective maintenance of abated areas.

(d) Negative effects / consequences of implemented strategies

When considering paint Pb sources, Spanier *et al.* (2013) cautions that Pb paint abatement renovation can result in an increase in children's blood Pb. Spanier *et al.* (2013) recommended that regulations are required to ensure that contractors use evidence-based hazard control and clearance standards.

SECTION 3

Summary and forward options for addressing Pb exposure

Childhood blood Pb in Broken Hill remains elevated. In 2018 49 % of children under five years old presented with blood Pb ≥ 5 µg/dL and of the Indigenous population, 76% of children tested exceeded 5µg/dL (NSW Ministry of Health 2019). Blood Pb levels in Australian children who are not residing in high risk areas like Broken Hill are now ~ 1 µg/dL (Symeonides *et al.* 2020), which is similar to levels in the USA (NHANES 2019). Children's Pb exposure in Broken Hill is not due to a single source, but rather to multiple sources of exposure, including Pb in air, dust and soils; and for some children, exposure to leaded paints.

Question 1 – Historical and current sources of Pb exposure in Broken Hill children

1. **Both legacy and current Pb emissions must be addressed if children's blood Pb is to be reduced in Broken Hill.**

   Research at Broken Hill area has evaluated multiple potential sources of environmental Pb exposure. Whilst there is evidence that natural Pb-bearing minerals present in soil, paints and past leaded petrol usage contribute to the total burden of exposure, the available research is clear in that it shows that past and current emissions from mining operations are the leading source of Pb exposure in Broken Hill. Neither legacy emissions from mining (retained in soils and dust) or current mining emissions (in deposited dusts) alone are singularly responsible for current Pb exposure. Rather, it is these two sources in combination that drive current childhood Pb concentrations. This fact has been is demonstrated in multiple research papers that show associations between blood Pb levels, soil Pb and current mining emissions, which are characterised by Pb in air and dust concentrations.

Question 2 – Current trends in blood Pb levels in Broken Hill children

2. **A city-wide solution is required to reduce exposure and blood Pb. Children across the whole of Broken Hill are at risk from elevated blood Pb concentrations.**

   Some groups of children, including those in the highest-risk zones (i.e. those closest to the Line of Lode) and Aboriginal children, have a higher likelihood of presenting with elevated blood Pb. However, most of the children in Broken Hill presenting with elevated blood Pb levels (≥ 5 µg/dL) neither reside in the high-risk area or are Aboriginal. Indeed, only around 30 % of children in Broken Hill are able to keep their blood Pb at < 5 µg/dL in the first three years of their life. Hence, whilst more can be done to reduce the current inequalities, all children in Broken Hill are at risk of elevated Pb exposures irrespective of their residential address.

Question 3 – Potential strategies for lowering children's blood Pb levels in Broken Hill

3. **Identifying exposure: Blood testing should continue to be conducted at 6-months of age.**

   By 12 months of age, around half of children in Broken Hill have already exceed the 5 µg/dL of blood Pb threshold. Earlier testing, which is now occurring, will allow identification of risks and early intervention to occur. There may even be some merit, resources depending, on assessing children at 3 months of age to determine their blood Pb trajectory, allowing for even earlier intervention. In this regard, SA Health uses a blood Pb of 3 µg/dL to intervene with children in Port Pirie (Dr David Simon, SA Health, personal communication).

4. **Identifying and reducing emissions: Determine and set an acceptable trigger value for Pb in deposited dust and introduce environmental licensing regulations limiting Pb in deposited dust.**

   Blood Pb concentrations correlate with dust Pb. Dust Pb is measured across Broken Hill and these data could be used more effectively to control emissions and reduce Pb exposure. Environmental licensing for the Pb-Zn-Cu mining and smelting at Mount Isa Mines (Queensland) requires Pb in deposited dust to be less than 100 µg/m^2/day. The data evaluated in this review suggests that Pb in dust needs to be reduced to ~ 90 µg/m^2/day to ensure children's blood Pb is below 5 µg/dL. Therefore, the level of 100 µg/m^2/day, which is used as a trigger value at Mount Isa and is also promulgated in the German air quality guidelines TA Luft (2017) may be a suitable target to introduce for Broken Hill. Lead in air emissions from the operations are managed against the national standard of 0.5 µg/m^3. There is no equivalent standard or trigger value for Pb in deposited dust required as part of the licence requirements for the mining operations. Current dust Pb deposition values measured in the community exceed those used in Mount Isa, presenting a significant exposure risk.

5. **Reducing exposure to airborne emissions and dust: Continue dust deposition monitoring and continue to investigate ways to mitigate dust deposition.**

   Continued dust deposition monitoring will determine how effective the newly installed dust controls are (e.g. dust extraction on crushing activities). If Pb in deposited dust targets (see point 4 above) are still unable to be met, further measures need to be investigated, such as ceasing crushing activities on windy days, increased watering and further use of dust suppressants etc.

   As an interim measure until more complete control of environmental Pb sources is resolved, there is merit in undertaking a trial of in-home HEPA (high efficiency air particulate) air purifiers to reduce the burden of Pb-rich dust in homes. HEPA air purification filters have previously been shown to be effective at removing $PM_{2.5}$ and Cd in homes and Pb in industrial environments, but have yet to be proven for Pb in residential environments.

6. **The feasibility of relocating some or all families should be investigated.**

   a. Relocation from high risk to low risk areas
   This option is not likely to be effective in broadly reducing children's blood Pb considering that most Pb affected children currently reside in lower-risk areas, however it may assist in lowering blood Pb for children most at risk.

   b. Relocation a suitable distance from the mine (away from current town area)
   This option is costly and not likely to be acceptable to families who have invested in life in Broken Hill (i.e. jobs, family, schools etc) yet would very effectively remove children from contaminated areas for the long-term. This would also eliminate exposures to Pb in contaminated soils.

   Consideration must be given to the lifespan of mining in Broken Hill and to population projections beyond mine closure. If mining is not projected to continue more than a few decades and the local population is projected to decline after this time, relocation may not be a feasible option.

Instead, it may be more feasible to employ further dust emissions controls and remediate soil and dust, even if the soil amendments require rejuvenation every ten years.

c. Relocation of families away from Broken Hill following mine closure
This may also be an option, preventing ongoing exposure to legacy Pb contamination. This possibility can be circumvented if there is proper clean-up of legacy contamination in the city.

7. **Reducing exposure to Pb in soil: Soil abatement of surface soils to below 300 mg/kg (NEPM residential soils) or 150 mg/kg on a city-wide basis.**

Children with elevated blood Pb live all across Broken Hill and not just in high-risk zones close to the Line of Lode. Children also spend significant time each week at other homes, childcare/preschool/school or in public areas, extending the potential for exposure beyond their primary residential environment. Modelling of soil exposure impacts on blood Pb predicted that a level of below 150 mg/kg was required to keep levels below 5 µg/dL. Whilst the soil Pb level of 150 mg/kg is below the NEPM standard for residential homes (300 mg/kg), the research shows that this level is a necessary step to reduce children's blood Pb to acceptable levels.

The provision of soil Pb and household dust Pb testing using portable XRF should be made available for Broken Hill residents. Any testing should be coupled to practical advice and affordable intervention actions for residents.

Broken Hill residents should be encouraged to use raised beds for any vegetable gardening and to wash produce before consumption.

8. **Replacement of aged housing**

Aged housing is an increased Pb exposure risk; replace with new, well-sealed housing.

9. **Provision of safe renovation assistance to households with high Pb in paint.**

High levels of Pb in paint, particularly when in a deteriorated state can contribute to children's blood Pb. The provision of paint Pb testing using portable XRF should be made available for Broken Hill residents. Paint Pb abatement without adequate precautions results in increased child blood Pb. Education and or assistance to perform safe paint Pb abatement is therefore advised.

Question 4 – Strategies applied in Australia and overseas to reduce blood Pb exposures

10. **Testing, and where needed, renewal of soil abatements after 10 years.**

Soil abatement strategies (as opposed to remediation – dig up and removal) have been shown to significantly reduce in effectiveness after 10 years, meaning that children could again be exposed, perhaps unknowingly, to hazardous levels of Pb. Soil abatement can only be considered as a temporary solution. Any financial consideration of this strategy should include funding for future renewal of abatement areas. If the same family remains in abated property, a period of ten years may be adequate if, after that time, children are aged > 5 years old as they will be at a much reduced a risk of Pb exposure from soil contact. A well-maintained register of abatement works is also needed, plus guidelines on how to best maintain abated land. This is especially important in cases where properties are sold and new owners are unaware of abatement history and the extent of capped contaminated soil. This information could be added to rental contracts as it is to s 10.7 *Environmental Planning and Assessment Act 1979* (NSW) certificates that are required on the sale and purchase of homes.

11. Effectiveness of strategies: Pilot testing of phosphate amendments as a potential additional soil abatement strategy.

Phosphate amendments of soils have been demonstrated to decrease the bioavailability of Pb in soils. These should not replace other soil abatement strategies in highly Pb affected soils, but may be useful in providing an additional measure of protection where Pb levels are close to abatement criteria. Pilot testing is required on local soils as results vary between soil types and in some cases, bioavailability of other toxic components may be influenced by phosphate amendments. Bauxsol™ and Bauxaline® soil amendments could also be considered as alternative options.

12. Continue to involve the local community in decision making, particularly for highly-affected groups such as the Aboriginal community.

Studies of communities that have not received adequate communication have shown that it results in a long-term lack of trust and community co-operation with abatement strategies. The community relations aspect in Broken Hill is currently very positive, particularly following the LeadSmart campaign and needs to be retained to ensure continued community 'buy-in' and engagement with the problem and the solution.

Appendix A – List of abbreviations

Term	Abbreviation
Aboriginal Lead Reference Group	ALRG
Aluminium	Al
Arsenic	As
Broken Hill Environmental Lead Program	BHELP
Broken Hill Lead Reference Group	BHLRG
Broken Hill University Department of Rural Health	BHUDRH
CBH Resources Limited	CBH
Confidence interval	CI
Energy-dispersive analyses	EDS
Environment Protection Authority	EPA
Greater than	>
Greater than or equal to	≥
Hectare	Ha
Integrated Exposure Uptake Bio Kinetic Model	IEUBK
Iron	Fe
Kilogram	Kg
Kilometre	Km
Lead	Pb
lead(II) sulfide (natural mineral form of lead)	PbS, galena
Less than	>
Less than or equal to	≤
Manganese	Mn
Micron (micro-metre)	µm
Microgram per cubic metre	$\mu g/m^3$
Microgram per decilitre	µg/dL
Microgram per square metre per day	$\mu g/m^2/day$
Milligram per kilogram	mg/kg
Million	M
Metre	m
National Environment Protection Measure	NEPM
National Health and Medical Research Council	NHMRC
Office of Environment and Heritage	OEH
Oxygen	O

Term	Abbreviation
Parts per million	Ppm
Particulate matter (atmospheric) with median aerodynamic diameter of 10 µm	PM_{10}
Perilya Limited	Perilya
Scanning electron microscopy	SEM
Silicon	Si
Silver	Ag
United States dollars	US$
Tonne (1000 kg)	T
Total suspended (atmospheric) particulate	TSP
X-ray diffraction	XRD
Zinc	Zn

Appendix B – Annotated bibliography

ANSTO Australia. 2018. Monthly summary sheet: elemental concentrations in PM2.5. Accessed 25th January 2020 at http://www.ansto.gov.au/cs/groups/corporate/documents/document/mdaw/mdgx/~edisp/acs177795.pdf.

Attina, T. M. and L. Trasande. 2013. Economic Costs of Childhood Lead Exposure in Low- and Middle-Income Countries. Environ Health Perspect **121**(9): 1097-1102.

> Background: Children's blood lead levels have declined worldwide, especially after the removal of lead in gasoline. However, significant exposure remains, particularly in low- and middle-income countries. To date, there have been no global estimates of the costs related to lead exposure in children in developing countries. Objective: Our main aim was to estimate the economic costs attributable to childhood lead exposure in low- and middle-income countries. Methods: We developed a regression model to estimate mean blood lead levels in our population of interest, represented by each 1-year cohort of children < 5 years of age. We used an environmentally attributable fraction model to estimate lead-attributable economic costs and limited our analysis to the neurodevelopmental impacts of lead, assessed as decrements in IQ points. Our main outcome was lost lifetime economic productivity due to early childhood exposure. Results: We estimated a total cost of $977 billions of international dollars in low- and middle-income countries, with economic losses equal to $134.7 billion in Africa [4.03% of gross domestic product (GDP)], $142.3 billion in Latin America and the Caribbean (2.04% of GDP), and $699.9 billion in Asia (1.88% of GDP). Our sensitivity analysis indicates a total economic loss in the range of $728.6–1162.5 billion. Conclusions: We estimated that, in low- and middle-income countries, the burden associated with childhood lead exposure amounts to 1.20% of world GDP in 2011. For comparison, in the United States and Europe lead-attributable economic costs have been estimated at $50.9 and $55 billion, respectively, suggesting that the largest burden of lead exposure is now borne by low- and middle-income countries.

Australian Bureau of Statistics. 2018. 2016 Census QuickStats: Broken Hill. Accessed 25th January 2020 at http://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/SSC10592.

Australian Government. 2017. Australian New Zealand Food Standards Code - Schedule 19 - Maximum levels of contaminants and natural toxicants. Accessed 25th February 2020 at https://www.legislation.gov.au/Details/F2017C00333/Download.

Barn, P., E. Gombojav, C. Ochir, B. Laagan, B. Beejin, G. Naidan, B. Boldbaatar, J. Galsuren, T. Byambaa, C. Janes, et al. 2018. The effect of portable HEPA filter air cleaners on indoor PM2.5 concentrations and second hand tobacco smoke exposure among pregnant women in Ulaanbaatar, Mongolia: The UGAAR randomized controlled trial. Science of The Total Environment **615**: 1379-1389.

> Background Portable HEPA filter air cleaners can reduce indoor fine particulate matter (PM2.5), but their use has not been adequately evaluated in high pollution settings. We assessed air cleaner effectiveness in reducing indoor residential PM2.5 and second hand smoke (SHS) exposures among non-smoking pregnant women in Ulaanbaatar, Mongolia. Methods We randomized 540 participants to an intervention group receiving 1 or 2 HEPA filter air cleaners or a control group receiving no air cleaners. We followed 259 intervention and 253 control participants to the end of pregnancy. We measured one-week indoor residential PM2.5 concentrations in early (~11weeks gestation) and late (~31weeks gestation) pregnancy and collected outdoor PM2.5 data from centrally-located government monitors. We assessed blood cadmium in late pregnancy. Hair nicotine was quantified in a subset (n=125) to evaluate blood cadmium as a biomarker of SHS exposure. We evaluated air cleaner effectiveness using mixed effects and multiple linear regression models and used stratified models and interaction terms to evaluate potential modifiers of effectiveness. Results The overall geometric mean (GM) one-week outdoor PM2.5 concentration was 47.9μg/m3 (95% CI: 44.6, 51.6μg/m3), with highest concentrations in winter (118.0μg/m3; 110.4, 126.2μg/m3). One-week

indoor and outdoor PM2.5 concentrations were correlated (r=0.69). Indoor PM2.5 concentrations were 29% (21, 37%) lower in intervention versus control apartments, with GMs of 17.3µg/m3 (15.8, 18.8µg/m3) and 24.5µg/m3 (22.2, 27.0µg/m3), respectively. Air cleaner effectiveness was greater when air cleaners were first deployed (40%; 31, 48%) than after approximately five months of use (15%; 0, 27%). Blood cadmium concentrations were 14% (4, 23%) lower among intervention participants, likely due to reduced SHS exposure. Conclusions Portable HEPA filter air cleaners can lower indoor PM2.5 concentrations and SHS exposures in highly polluted settings.

Battelle Memorial Institute. 1995. Review of studies addressing lead abatement effectiveness, USEPA. Accessed 25th February 2020 at https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000JK00.TXT.

Beckwith, T. J., K. N. Dietrich, J. P. Wright, M. Altaye and K. M. Cecil. 2018. Reduced regional volumes associated with total psychopathy scores in an adult population with childhood lead exposure. NeuroToxicology **67**: 1-26.

Childhood lead exposure has been correlated to acts of delinquency and criminal behavior; however, little research has been conducted to examine its potential long term influence on behavioral factors such as personality, specifically psychopathic personality. Neuroimaging studies have demonstrated that the effects of childhood lead exposure persist into adulthood, with structural abnormalities found in gray and white matter regions involved in behavioral decision making. The current study examined whether measurements of adult psychopathy were associated with neuroanatomical differences in structural brain volumes for a longitudinal cohort with measured childhood lead exposure. We hypothesized that increased total psychopathy scores and increased blood lead concentration at 78 months of age (PbB78) would be inversely associated with volumetric measures of gray and white matter brain structures responsible for executive and emotional processing. Analyses did not display a direct effect between total psychopathy score and gray matter volume; however, reduced white matter volume in the cerebellum and brain stem in relation to increased total psychopathy scores was observed. An interaction between sex and total psychopathy score was also detected. Females displayed increased gray matter volume in the frontal, temporal, and parietal lobes associated with increased total psychopathy score, but did not display any white matter volume differences. Males primarily displayed reductions in frontal gray and white matter brain volume in relation to increased total psychopathy scores. Additionally, reduced gray and white matter volume was associated with increased blood lead levels in the frontal lobes; reduced white matter volume was also observed in the parietal and temporal lobes. Females demonstrated gray and white matter volume loss associated with increased PbB78 values in the right temporal lobe, as well as reduced gray matter volume in the frontal lobe. Males displayed reduced white matter volumes associated with increased PbB78 values in the frontal, temporal, and parietal lobes. Comparison of the two primary models revealed a volumetric decrease in the white matter of the left prefrontal cortex associated with increased total psychopathy scores and increased blood lead concentration in males. The results of this study suggested that increased psychopathy scores in this cohort may be attributable to the neuroanatomical abnormalities observed and that childhood lead exposure may be influential to these outcomes.

Bellinger, D. C. 2017. Childhood lead exposure and adult outcomes. JAMA **317**(12): 1219-1220.

The discovery that the water in Flint, Michigan, was contaminated with lead shows that excessive exposure to this toxic metal remains a threat to human health. The episode resulted from a series of poor decisions by politicians that allowed lead to leach from pipes and fixtures into the water flowing into residents' homes. But Flint is by no means unique with regard to lead hazards. A 2016 report identified 3000 US communities in which the percentage of children with a blood lead concentration greater than 5 µg/dL, the current Centers for Disease Control and Prevention (CDC) reference value, exceeded that among affected children in Flint.1

Bellinger, D. C., A. Malin and R. O. Wright. 2018. Chapter One - The Neurodevelopmental Toxicity of Lead: History, Epidemiology, and Public Health Implications. Advances in Neurotoxicology. M. Aschner and L. G. Costa, Academic Press. **2:** 1-26.

Despite great successes in reducing children's exposure to lead, it remains the most important environmental contaminant in terms of impact on children's cognitive and behavioral development. In this chapter, we discuss what is known about the relationships linking greater lead exposure and neurodevelopmental impairment. Among most salient conclusions are that a "safe" level of lead exposure has not been identified, and that the inverse relationship between blood lead concentration and children's IQ scores is non-linear such that the rate of decline in IQ per μg/dL is greater for concentrations <10μg/dL than for concentrations >10μg/dL. Greater blood lead concentrations are also associated with reduced academic achievement, greater risk of ADHD, and greater propensity to engage in anti-social behaviors. Although data are limited, neuroimaging studies reveal persistent relationships between childhood blood lead concentration and alterations in brain structure and function in young adulthood. Although lead's effects on neurodevelopment are often described as "irreversible," it is more appropriate to describe them as "persistent," as few studies have evaluated whether interventions, such as the provision of increased neurodevelopmental supports, alters the time course of the deficits. Which genetic factors alter lead neurotoxicity is at present largely unknown but is a topic of much current work. It seems likely that the critical window of vulnerability to lead neurotoxicity is endpoint-specific. It is hoped that lessons learned over the course of the long history of research on lead can be applied proactively to other neurotoxic environmental contaminants so that the risks to children can be reduced more expeditiously.

Bellinger, D. C. and M. Mazumdar. 2015. Chapter 19 - Late Neurological Effects of Early Environmental Exposures. Environmental Factors in Neurodevelopmental and Neurodegenerative Disorders. M. Aschner and L. G. Costa. Boston, Academic Press**:** 409-422.

This chapter addresses studies that attempt to discern the relationships between early-life exposures to environmental chemicals and late neurological effects. Particular emphasis is afforded the concept of "delayed" or "silent" neurotoxicity that is only evident long after an exposure occurred. The challenges in conducting such studies are identified, including the long follow-up intervals required and the difficulties in securing valid estimates of exposures during critical developmental windows. Studies are reviewed that suggest persistent, perhaps permanent, adverse effects of early-life exposures on cognition and psychiatric status, as well as on brain structure, organization, and function. Finally, the hypothesis that one mechanism of the effects of early-life exposure is epigenetic modification is illustrated using lead exposure as an example.

Berglund, Å. M., P. Ingvarsson, H. Danielsson and N. Nyholm. 2010. Lead exposure and biological effects in pied flycatchers (Ficedula hypoleuca) before and after the closure of a lead mine in northern Sweden. Environ Pollut **158**(5): 1368-1375.

Mining activities affect the surrounding environment by increasing exposure to metals. In this study, metal accumulation and its effects on reproduction and health of pied flycatcher (Ficedula hypoleuca) nestlings were monitored before and up to five years after a lead mine and enrichment plant closed down. The lead concentration in moss, nestling blood, liver and feces all indicated decreased lead exposure by at least 31% after closure, although only blood lead decreased significantly. Although the birds responded fairly well to the changed atmospheric deposition (based on moss samples), concentrations were still higher compared with birds in a reference area, and breeding was affected at the mine (smaller clutches and higher mortality). Surviving nestlings suffered from lower hemoglobin levels, mean cell hemoglobin concentrations and inhibited delta-aminolevulinic acid dehydratase activity. Lead poisoning contributed to poor health and adverse reproductive effects, but other factors (e.g. increased parasitic load) probably also affected the birds.

BHELP. 2018. Broken Hill Environmental Lead Program Steering Committee Annual Report 2016-2017. Accessed 25th February 2020 at http://leadsmart.nsw.gov.au/wp-content/uploads/2018/05/TAB-2-BHELP-Steering-Committee-2016-17Annual-Report.pdf.

BHELP. 2018. Lead paint studies. Personal communication from Frances Boreland, Frances.Boreland@epa.nsw.gov.au, 25th September 2018.

BHELP. 2019. Broken Hill Environmental Lead Program Steering Committee annual report 2017-2018. Accessed 25th February 2020 at http://leadsmart.nsw.gov.au/wp-content/uploads/2019/06/DOC19-437202-4-TAB-4-BHELP-Steering-Committee-2017-2018-Annual-Report.pdf.

BHELP. 2019. Housing condition reports. Personal communication from Frances Boreland, Frances.Boreland@epa.nsw.gov.au, 15th August 2019.

BHUDRH. 2017. Blood lead levels among Broken Hill Children born 2009-2015: Implications for the Broken Hill Environment Lead Management Program. Broken Hill University Department of Rural Health.

> This is based on an analysis of blood lead level among Broken Hill children born between 2009 and 2015. Almost half of all Broken Hill children have a blood lead level <5 µg/dL at any time, based on the results of annual testing. Around 30% of children in Broken Hill are able to live safely with lead over time, based on the number of children whose blood lead levels were <5 µg/dL at each of the 12 month, 2 and 3 year scheduled tests. The first year of life is a critical time for lead exposure, with much of the increase in blood lead levels at a population level being evident by 12 months of age. Individual lead risk for children varies by locality. 60% of children in the highest soil lead hazard zones have at least one test result at ≥10 µg/dL during the first three years. However, most children (70%) experiencing high blood lead levels live elsewhere in the community. Early Intervention for Individual Children 1. We recommend the re-introduction of a blood lead test for infants at the 6 months immunization appointment. Access to data on blood lead data among Broken Hill children during the first year of life could be used to monitor trends in early exposure to lead and as a potential trigger for early intervention. 2. We propose to conduct a second phase study to describe the potential sources and pathways of lead for children both in the family home and other places where children spend time to inform the development of an early intervention program. Zonal Abatement 3. Zonal abatement is an effective strategy for reducing blood lead levels in children from areas with high soil lead concentrations. These data make the case for zonal abatement in high soil lead zones based on the high individual risk to children residing there. However for greatest effect, abatement efforts would need to be extended to other localities where most (70%) of the children with high blood lead levels live. 4. We plan to undertake GIS mapping of children with blood lead levels ≥10 µg/dL to provide more accurate data on any sub-zones that also carry high risk for children. This information could be used for targeting any abatement efforts in the low to moderate soil lead hazard zones.

BHUDRH. 2018. Preliminary results from survey. Broken Hill University Department of Rural Health. E-mail communication from D. Lyle. 5th September 2018.

Billings, S. B. and K. T. Schnepel. 2017. The value of a healthy home: Lead paint remediation and housing values. Journal of Public Economics **153**: 69-81.

> The presence of lead paint significantly impairs cognitive and behavioral development, yet little is known about the value to households of avoiding this residence-specific environmental health risk. In this paper, we estimate the benefits of lead-paint remediation on housing prices. Using data on all homes that applied to a HUD-funded program in Charlotte, North Carolina, we adopt a difference-in-differences estimator that compares values among remediated properties with those for which an inspection does not identify a lead paint hazard. Results indicate large returns for public and private investment in remediation with each $1 spent on lead remediation generating $2.60 in benefits as well as a reduction in residential turnover.

Billings, S. B. and K. T. Schnepel. 2018. Life after lead: Effects of early interventions for children exposed to lead. American Economic Journal: Applied Economics **10**(3): 315-344.

> Lead pollution is consistently linked to cognitive and behavioral impairments, yet little is known about the benefits of public health interventions for children exposed to lead. This paper estimates the long-term impacts of early life interventions (e.g., lead remediation, nutritional assessment, medical evaluation, developmental surveillance, and public assistance referrals) recommended for lead-

poisoned children. Using linked administrative data from Charlotte, NC, we compare outcomes for children who are similar across observable characteristics but differ in eligibility for intervention due to blood lead test results. We find that the negative outcomes previously associated with early life exposure can largely be reversed by intervention.

Blainey, G. 1968. The Rise of Broken Hill, Macmillan of Australia.

Body, P. 1986. Port Pirie lead project railway lane survey: Port Pirie to Broken Hill. South Australia Department of Environment and Planning Report(80).

Boreland, F., M. Lesjak and D. Lyle. 2009. Evaluation of home lead remediation in an Australian mining community. Science of The Total Environment **408**(2): 202-208.

In 1994 a comprehensive program was established to reduce children's blood lead levels in Broken Hill, NSW, Australia. Home remediation (abatement of lead hazards in a child's home) was included as part of a case management strategy for children with blood lead levels ≥ 15 µg/dL. Children with blood lead levels ≥ 30 µg/dL were offered immediate home remediation. Children with blood lead levels of 15–29 µg/dL were allocated to 'immediate' or 'delayed' home remediation; a subset of these participated in a randomized controlled trial (RCT) to evaluate the effectiveness of home remediation for reducing blood lead levels. One hundred and seventeen children received home remediation. One hundred and thirteen returned for follow-up blood tests, 88 of whom participated in the RCT. On average children's blood lead levels decreased by 1.7 µg/dL (10%) in the 6 months after remediation and by 2.2 µg/dL (13%) in the 6–12 months after remediation. However, remediation did not significantly change the rate of decline in blood lead levels (P = 0.609). There was no evidence of association between change in children's blood lead levels and changes in lead loading in their homes. The results are consistent with the published literature, which suggests that home remediation does not reduce children's exposure to lead sufficiently to cause a moderate or greater decrease in their blood lead level. In communities where lead is widely dispersed, the study suggests that it is important to assess potential sources and pathways by which children are exposed to lead when developing an intervention plan, and the need for multiple interventions to effectively reduce blood lead levels. The findings reinforce the ongoing need for rigorous epidemiological evaluation of lead management programs to improve the evidence base, and for effective primary prevention to avoid children being exposed to lead in the first place.

Boreland, F., M. S. Lesjak and D. M. Lyle. 2008. Managing environmental lead in Broken Hill: a public health success. NSW Public Health Bulletin **19**(10): 174-179.

To describe locality-specific changes in blood lead levels of 1-4-year-old children in Broken Hill, NSW between 1991 and 2007. Annual age-sex standardised mean blood lead levels, blood lead screening clinic attendance rates and lead-dust levels for five lead-risk zones were calculated from routinely collected data. Blood lead levels were similar in all localities in 2002, 2003, 2005 and 2006, after having been consistently higher in localities with highest environmental lead since 1991. Combining health promotion with a targeted clean-up has reduced the effect of locality on blood lead levels. Results are consistent with reduced contamination due to effective soil stabilisation and storm-water control.

Boreland, F. and D. Lyle. 2006. Lead dust in Broken Hill homes: Effect of remediation on indoor lead levels. Environ Res **100**(2): 276-283.

This study was undertaken to determine whether home remediation effectively reduced indoor lead levels in Broken Hill, a long-established silver–lead–zinc mining town in outback Australia. A before–after study of the effect of home remediation on indoor lead levels was embedded into a randomized controlled trial of the effectiveness of remediation for reducing elevated blood lead levels in young children. Moist towelettes were used to measure lead loading (µg/m2) on internal windowsills and internal and entry floors of 98 homes; samples were collected before, immediately after, and 2, 4, 6, 8, and 10 months after remediation. Data were log10 transformed for the analysis. Remediation

reduced average indoor lead levels by approximately 50%, and lead levels remained low for the duration of the follow-up period (10 months). The greatest gains were made in homes with the highest initial lead levels; homes with low preremediation lead levels showed little or no benefit. Before remediation, homes located in areas with high soil lead levels or with "poor" dust proofing had higher lead levels than those in areas with lower soil lead levels or with "medium" or "good" dust proofing; these relative differences remained after remediation. There was no evidence that lead loading was reduced by an increased opportunity to become aware of lead issues. We conclude that remediation is an effective strategy for reducing the lead exposure of children living in homes with high indoor lead levels.

Boreland, F. and D. Lyle. 2014. Putting the genie back in the bottle: protecting children from lead exposure in the 21st century. A report from the field. Public Health Res Pract **25**(1): e2511403.

This paper highlights progress on an important public health issue which, despite significant progress, has now stalled and is in need of renewed investment. The objective is to describe the effectiveness of efforts to reduce childhood lead exposure in Broken Hill – a historic mining town in western NSW – and what is required to further reduce exposure. Lead has no known function in the human body, and emerging evidence suggests that no level of exposure is without health effects. A 1991 blood lead survey of 1–4-year-old children identified lead exposure as a significant public health issue in Broken Hill. A major NSW Government-funded program to reduce lead exposure began in 1994, and, by 2001, blood lead levels had reduced by two-thirds. The program was then integrated into other services nd funding significantly reduced; blood lead levels have remained relatively unchanged since 2005. At present, 53% of children in Broken Hill have blood lead levels above the recently released National Health and Medical Research Council draft reference value for lead. Participation in annual blood lead screening declined from 52% to 38% after project funding decreased, but recent changes have doubled participation rates. A comprehensive abatement program is required to further reduce lead exposure in this community, and further research is required into how to maintain low blood lead levels and how best to engage the community about reducing individual lead risks. Findings from such studies would be relevant to the broader Australian community

Boreland, F., D. M. Lyle, J. Wlodarczyk and W. A. Balding. 2006. Lead dust in Broken Hill homes: relationship between house dust and children's blood lead levels. Environmental Health **6**(4): 15.

To determine the influence of indoor lead dust on children's blood lead levels in Broken Hill, Australia. Method: Indoor lead flux (g/m2/30 days) was measured in the homes of 74 preschool aged children and compared with their routinely collected blood lead samples. Ecological analysis was used to confirm whether findings for individual children were consistent across the whole population. Results: Compared with homes in the lowest indoor lead category, homes in the highest category had 11 times the lead flux, and children living in them had 50% higher geometric mean blood lead levels and were five times more likely to have significantly elevated blood lead levels (>15 g/dL). Increasing indoor lead fallout from 100 to 1000 g/m2/30 days was associated with 32% (95% CI 4-67%) higher blood lead levels. The correlation noted for individual children was supported by the ecological analysis. Conclusions: Indoor lead flux is a useful predictor of elevated blood lead. Home remediation is most likely to reduce children's blood lead levels if indoor lead levels are reduced by an order of magnitude; small changes in indoor lead are unlikely to be effective. Implications: Reducing indoor lead levels is likely to be an important component of a multi-faceted strategy for reducing blood lead levels among young children from lead mining or smelting communities such as Broken Hill. A useful indicator for identifying children who are most likely to benefit from home remediation is the indoor lead flux level.

Boreland, F., D. M. Lyle, J. Wlodarczyk, W. A. Balding and S. Reddan. 2002. Lead dust in Broken Hill homes - a potential hazard for young children? Australian and New Zealand Journal of Public Health **26**(3): 203-208.

Objective: To determine the potential hazard posed by indoor lead dust to young children in Broken Hill, a silver-lead-zinc mining town in outback Australia, and the degree to which lead flux is influenced by factors such as geographical location, house construction type and condition. Methods: 116 homes were selected and 93 (80%) studied from 10 localities in Broken Hill during the

spring of 1995. Lead flux was measured using 85 mm diameter polystyrene petri dishes. Dishes were placed in four rooms of each house to collect dust over a six-to-eight-week period. Data on the location, condition and construction type of each house were recorded. Multiple linear regression was used to determine predictors of lead flux. Flux data were log transformed for the analysis. Results: Average household lead flux varied nearly seven-fold across districts from a low of 166 (distant from the mines), to a high of 1,104 μg/m2/30-day period adjacent to the mines). Houses that were 'adequately sealed' had 2.9 times the lead flux, and 'poorly sealed' houses 4.3 times the flux, of 'very well sealed' houses. Construction material did not significantly affect these flux levels, and no statistically significant interactions were found between house condition and location or house type. Conclusions: Many Broken Hill homes have high levels of lead flux that pose a potential risk to young children. Quantification of this hazard provides useful information for the community that can help focus efforts on actions required to minimise lead dust in the home. Implications: Household dust is a potential source of lead for young children in at-risk communities. Information on lead flux in homes can assist these communities and public health agencies to better understand and deal more effectively with the problem.

Broken Hill City Council. 2016. Broken Hill Development Control Plan. Accessed 25th February 2020 at https://www.brokenhill.nsw.gov.au/sites/brokenhill/files/public/documents/Plans_and_Strategies/Broken%20Hill%20Development%20Control%20Plan%202016_1.pdf.

Broken Hill City Council. 2018. Industry sector reports - Mining -economic profile. Accessed 3rd September 2018 at https://economy.id.com.au/reporter/collect/0715a387-e2bf-475c-b86f-f0ef470f2d24.

Bureau of Meteorology. 2019. Climate statistics for Broken Hill. Accessed 24 April 2019 at http://www.bom.gov.au/climate/averages/tables/cw_047048.shtml.

Burns, J. M., P. A. Baghurst, M. G. Sawyer, A. J. McMichael and S.-l. Tong. 1999. Lifetime low-level exposure to environmental lead and children's emotional and behavioral development at ages 11–13 years: The Port Pirie Cohort Study. Am J Epidemiol **149**(8): 740-749.

The Port Pirie Cohort Study is the first study to monitor prospectively the association between lifetime blood lead exposure and the prevalence of emotional and behavioral problems experienced by children. Lead exposure data along with ratings on the Child Behavior Checklist were obtained for 322 11-13-year-old children from the lead smelting community of Port Pirie, Australia. Mean total behavior problem score (95% confidence interval (CI)) for boys whose lifetime average blood lead concentration was above 15 microg/dl was 28.7 (24.6-32.8) compared with 21.1 (17.5-24.8) in boys with lower exposure levels. The corresponding mean scores (95% CI) for girls were 29.7 (25.3-34.2) and 18.0 (14.7-21.3). After controlling for a number of confounding variables, including the quality of the child's HOME environment (assessed by Home Observation for Measurement of the Environment), maternal psychopathology, and the child's IQ, regression modeling predicted that for a hypothetical increase in lifetime blood lead exposure from 10 to 30 microg/dl, the externalizing behavior problem score would increase by 3.5 in boys (95% CI 1.6-5.4), and by 1.8 (95% CI -0.1 to 11.1) in girls. Internalizing behavior problem scores were predicted to rise by 2.1 (95% CI 0.0-4.2) in girls but by only 0.8 (95% CI -0.9 to 2.4) in boys.

Cabral, M., A. Toure, G. Garçon, C. Diop, S. Bouhsina, D. Dewaele, F. Cazier, D. Courcot, A. Tall-Dia, P. Shirali, et al. 2015. Effects of environmental cadmium and lead exposure on adults neighboring a discharge: Evidences of adverse health effects. Environ Pollut **206**: 247-255.

The purpose of the study was to determine Pb and Cd concentrations in humans and to assess the effect of co-exposure to these metals on biomarkers of oxidative stress and nephrotoxicity. Blood and urine levels of Pb and Cd, oxidative stress and urinary renal biomarkers were measured in 77 subjects neighboring a discharge and 52 in the control site. Exposed subjects showed significantly higher levels of lead and cadmium in blood and urine than the controls. Excessive production of reactive oxygen species induced by these metals in exposed subjects conducted to a decrease in antioxidant defense system (GPx, Selenium, GSH) and an increase in lipid peroxidation (MDA).

Moreover, changes in markers of nephrotoxicity (high urinary concentrations of total protein, RBP and CC16, as well as GSTα and LDH increased activities) suggested the occurrence of discrete and early signs of impaired renal function for the discharge neighboring population.

Calderón, J., M. E. Navarro, M. E. Jimenez-Capdeville, M. A. Santos-Diaz, A. Golden, I. Rodriguez-Leyva, V. Borja-Aburto and F. Díaz-Barriga. 2001. Exposure to Arsenic and Lead and Neuropsychological Development in Mexican Children. Environ Res **85**(2): 69-76.

This cross-sectional study examined the effects of chronic exposure to lead (Pb), arsenic (AS) and undernutrition on the neuropsychological development of children. Two populations chronically exposed to either high (41 children) or low (39 children) levels of As and Pb were analyzed using the Wechsler Intelligence Scale for Children, Revised Version, for México (WISC-RM). Geometric means of urinary arsenic (AsU) and lead in blood (PbB) were 62.9±0.03 (μgAs/g creatinine) and 8.9±0.03 (μg/dl) for the exposed group and 40.2±0.03 (μgAs/g creatinine) and 9.7±0.02 (μg/dl) for the reference group. The height for age index (HAI) was used as an indicator of chronic malnutrition and sociodemographic information was obtained with a questionnaire. Lead and arsenic were measured by atomic absorption spectrophotometry. Data on full, verbal, and performance intelligence quotients (IQ) scores, long-term memory, linguistic abstraction, attention span, and visuospatial organization were obtained through the WISC-RM. After controlling for significant potential confounders verbal IQ ($P<0.01$) decreased with increasing concentrations of AsU. The HAI correlated positively with full-scale and performance IQ ($P<0.01$). Higher levels of AsU were significantly related to poorer performance on WISC-RM factors examining long-term memory and linguistic abstraction, while lower scores in WISC-RM factors measuring attention were obtained at increasing values of PbB. Our results suggest that exposure to As and chronic malnutrition could have an influence on verbal abilities and long-term memory, while Pb exposure could affect the attention process even at low levels.

Cattle, S. and S. Wimborne. 2016. An audit of previously remediated sites in Broken Hill. Prepared for Broken Hill Environmental Lead Program.

During the period 1994-2006, at least 225 residential yards in Broken Hill underwent some form of remediation or abatement, as part of a program run by the Broken Hill Environmental Lead Program. Antecedent topsoil lead (Pb) concentrations were measured around the yards, and a variety of abatement strategies were subsequently used, including excavation and/or topdressing of existing soil with clean garden loam, cracker dust, wood chips, road base, gravel/pebbles and coarse sand. There was not a strong correlation of abatement strategy with antecedent Pb concentration due to factors such as residents' preferred usage of the yards and preferences for abatement materials. Approximately 10-20 years after the abatement, this audit investigated the current condition of abated surfaces at thirty-nine locations and the current topsoil Pb concentrations of these abated surfaces. Our results indicate that the abatement program has been broadly successful - the topsoil Pb concentrations of the previously abated surfaces were significantly less than the antecedent topsoil Pb concentrations prior to abatement, and no particular abatement strategy was found to be significantly more effective than the others. However, more than half of the abated surfaces now have Pb concentrations exceeding 300 mg/kg, suggesting that some degree of re-contamination or enrichment with Pb has occurred at these locations. Our observations indicate that a combination of anthropic, physical and biotic processes is responsible for this. Anthropic processes include garden cultivation and moving soil materials around yards, as well as the generation of Pb-rich dust that is subsequently deposited onto abated surfaces. Physical processes include water and wind erosion of abatement capping materials, as well as the redistribution of Pb-rich soil materials around the landscape. Biotic processes are most prominent as ant nest formation, which we observed was an effective mechanism for the return of capped, Pb-rich soil back to the soil surface. Although many previously-abated surfaces are still keeping surface Pb concentrations low, others are showing signs of 'wear and tear', suggesting that abatement rejuvenation is warranted.

Cattle, S. and S. Wimborne. 2017. An assessment if legacy soil Pb contamination of ten public parks in Broken Hill. Prepared for Broken Hill Environmental Lead Program.

A monitoring survey of ten parks and ovals in Broken Hill has been carried out to determine the spatial distribution of topsoil lead (Pb) concentrations and to provide recommendations on abatement priorities. For each park, a stratified random sampling design was used to select points for the measurement of topsoil Pb concentration, which was carried out using a portable X-ray fluorescence (pXRF) device. The raw data from all ten parks was combined to generate a prediction model for topsoil Pb concentration, and kriged maps of topsoil Pb concentration for all ten parks were subsequently produced. Topsoil Pb concentrations under canopies of large trees were also assessed in several parks to ascertain whether trees might be acting as dust traps and causing accumulation of Pb beneath the canopy. In broad terms, and in keeping with many other previous studies, the parks and ovals furthest from the Line of Lode and mining works have the lowest topsoil Pb concentrations, while those closer to the Line of Lode tend to have at least some small sections with topsoil Pb concentrations higher than the Health Investigation Limit (HIL) for public recreational spaces. Those sections of parks with well-maintained grass or turf coverage generally contain low concentrations of topsoil Pb, while sections of exposed soil or patchy exposed soil in parks close to the Line of Lode tend to exhibit topsoil Pb concentrations that exceed the HIL for public recreational spaces. Sections of Patton St Park and O'Neil Park are the most heavily contaminated with topsoil Pb and deserve the highest priority for abatement. Smaller parts of Alma Oval, Kintore Reserve and Sturt Park are somewhat Pb contaminated and therefore have medium priority for abatement, while the North Family Play Centre, Picton Sports Ground and Memorial Oval have low topsoil Pb concentrations and therefore low priority for abatement. The Duke of Cornwall Park and Jubilee Oval have some isolated spots of high topsoil Pb concentration, but taking into account the small risk of exposure of children to these areas, the priority for abatement is regarded as low. Topsoil Pb concentrations were also determined at various locations under the canopies of several large trees, to assess whether these trees have the potential to act as dust traps and therefore accumulators of Pb. There were no strong trends in the topsoil Pb data to indicate significant accumulation of Pb under these trees. The location with the strongest indication of an accumulation of Pb in the dust-sized fraction is the Centre for Community; here, the artificial grass bowling rinks have a very high Pb concentration in the <100 μm fraction of the sand material and relatively low concentration in the bulk soil. This site is likely to have been acting as a passive Pb-rich dust trap since installation of the bowling rinks.

Codex Alimentarius Commission. 2011. Joint FAO/WHO Food Standards Programme Codex Committee On Contaminants in Foods. Working document for information and use in discussions on the GSCTF.

Dalton, C. and L. Bates. 2005. Impact of closure of a large lead-zinc smelter on elevated blood lead levels of children in adjacent suburbs, Boolaroo, Australia. WIT Transactions on Ecology and the Environment **85**.

Over several decades, there has been considerable disagreement about heavy-metal contamination in mining communities as to whether the contamination arose from natural processes such as oxidation and weathering over millennia or from mining activities. More sophisticated geochemical methods and isotopic tracing especially for lead (Pb) may or may not provide definitive answers. We suggest that relatively simple approaches using the microscopic techniques of optical microscopy complemented by scanning electron microscopy and energy-dispersive analyses along with X-ray diffraction can provide definitive answers to the conundrum. Heavy liquid and –53 + 48 μm fractions of soil, pavement and gutter sweepings, dust depositional gauges, long-term dust accumulation, vacuum cleaner dust and ceiling dust were investigated using the above methods. The most common Pb-bearing particles consisted of Pb, Fe, Mn, Al, Si and O. The majority of grains were rounded with cavities and overgrowths, and showed evidence of transport and recrystallisation, probably deriving from post-mining activities and/or earlier geological processes. A small number of samples from ceiling dust, pavement sweepings, vacuum cleaner dust and long-term dust accumulation contained galena with a high degree of crystallinity suggesting a derivation from recent mining and ore concentration activities. High-precision Pb isotopic analyses showed that some samples with extensive oxidation and weathering had absorbed Pb from sources other than mine Pb, and these could be from gasoline, paint or weathering of the country rocks.

Dani, A., K. Fry, R. Kingswell, M. McLennan-Gillings and A. Palaversich. 2018. Measurement and assessment of Pb exposure risk from indoor dust in homes in Broken HIll, NSW. Prepared for the Broken HIll

Environmental Lead Program. Department of Environmental Sciences, Macquarie University. Unpublished report to BHELP.

> While the risks associated with industrial contaminants have been studied extensively, the majority of investigations into this issue have focused on outdoor environments. However, contaminants contained in household dust pose a potentially greater hazard than those present within outdoor soils as exposure risk in indoor environments is significantly higher. Identifying the sources of contaminants in household dust and the pathways through which they move from exterior to interior environments is therefore an important step in reducing the health risks associated with living in close proximity to mining and smelting operations. The following study investigates relationships between contaminant concentrations in indoor dust and outdoor soils and examines the implications that links between contaminants in these environments have for the health and wellbeing of the Broken Hill community. Vacuum cleaner dust donated by Broken Hill residents is analysed to determine indoor lead concentrations, while in-situ analysis of verge and front yard soils is used to measure outdoor lead levels. For the 62 sampled houses, lead concentrations in surface soils at approximately a quarter of verges and half of front yards exceeded levels recommended by the Australian NEPC guidelines. For household dust, only one house recorded values within the 'safe' limits given by Canadian guidelines relating to indoor lead concentrations. Front yard lead concentrations were, on average, twice those taken at the verge, while averaged indoor lead values were two times as high as the overall outdoor average. Results demonstrated a strong negative correlation between lead concentrations and distance to the nearest mining operation, with households within 1 km of the slag heap recording an average lead levels over two times higher than those located within a 1-3 km distance from these same operations. The above results indicate that indoor and exterior lead concentrationsn Broken Hill are currently at levels deemed unsafe by both national and international guidelines. Elevated levels of lead in household dust can be attributed to contemporary deposition associated with pathways between indoor and outdoor environments, while soil lead levels are more likely to represent deposition over a longer period. Our results demonstrate the need for community wide efforts to reduce exposure to household dust and the contaminants contained therein.

Davis, J., A. Morrison and B. Gulson. 2016. Uncovering pathways of metal contamination with microscopic techniques and lead isotopic tracing. Australian Journal of Earth Sciences **63**(6): 795-803.

> Over several decades, there has been considerable disagreement about heavy-metal contamination in mining communities as to whether the contamination arose from natural processes such as oxidation and weathering over millennia or from mining activities. More sophisticated geochemical methods and isotopic tracing especially for lead (Pb) may or may not provide definitive answers. We suggest that relatively simple approaches using the microscopic techniques of optical microscopy complemented by scanning electron microscopy and energy-dispersive analyses along with X-ray diffraction can provide definitive answers to the conundrum. Heavy liquid and –53 + 48 µm fractions of soil, pavement and gutter sweepings, dust depositional gauges, long-term dust accumulation, vacuum cleaner dust and ceiling dust were investigated using the above methods. The most common Pb-bearing particles consisted of Pb, Fe, Mn, Al, Si and O. The majority of grains were rounded with cavities and overgrowths, and showed evidence of transport and recrystallisation, probably deriving from post-mining activities and/or earlier geological processes. A small number of samples from ceiling dust, pavement sweepings, vacuum cleaner dust and long-term dust accumulation contained galena with a high degree of crystallinity suggesting a derivation from recent mining and ore concentration activities. High-precision Pb isotopic analyses showed that some samples with extensive oxidation and weathering had absorbed Pb from sources other than mine Pb, and these could be from gasoline, paint or weathering of the country rocks.

Department of Environment and Heritage Protection. 2017. Environmental authority EPML00977513. Accessed 25th February 2020 at https://environment.ehp.qld.gov.au/env-authorities/pdf/epml00977513.pdf.

Dixon, S. L., D. E. Jacobs, J. W. Wilson, J. Y. Akoto, R. Nevin and C. Scott Clark. 2012. Window replacement and residential lead paint hazard control 12 years later. Environ Res **113**: 14-20.

Window replacement is a key method of reducing childhood lead exposure, but the long-term effectiveness has not been previously evaluated. Windows have the highest levels of interior lead paint and dust compared to other building components. Our objective was to conduct a follow-up study of residential window replacement and lead hazard control 12 years after homes were enrolled in an evaluation of the HUD Lead Hazard Control Grant Program, sampling settled lead dust in housing in four cities (n=189 homes). Previous work evaluated lead hazard controls up to 6 years after intervention using dust lead measurements and two years after intervention using both dust and blood lead data. But the earlier work could not examine the effect of window replacement over the longer time period examined here: 12 years. The individual homes were assigned to one of three categories, based on how many windows had been replaced: all replacement, some replacement, or non-replacement. Windows that were not replaced were repaired. We controlled for covariates such as site, housing condition, presence of lead paint, and season using longitudinal regression modeling. Adjusted floor and sill dust lead geometric mean dust lead loadings declined at least 85% from pre-intervention to 12 years after the intervention for homes with all replacement windows, some windows replaced and no windows replaced. Twelve years after intervention, homes with all replacement windows had 41% lower interior floor dust lead, compared to non-replacement homes (1.4 versus 2.4μg/ft2, p<0.001), and window sill dust lead was 51% lower (25 versus 52μg/ft2, p=0.006) while controlling for covariates. Homes with some windows replaced had interior floor and window sill dust lead loadings that were 28% (1.7 versus 2.4μg/ft2, p=0.19) and 37% (33 versus 52μg/ft2, p=0.07) lower, respectively, compared to non-replacement homes. The net economic benefit of window replacement compared to window repair (non-replacement) is $1700–$2000 per housing unit. Homes in which all windows were replaced had significantly lower lead dust. New windows are also likely to reduce energy use and improve home value. Lead-safe window replacement is an important element of lead hazard control, weatherization, renovation and housing investment strategies and should be implemented broadly to protect children.

Dong, C. 2018. Chapter 7: Discussion in Environmental and geochemical analysis of lead contamination: its sources and pathways of exposure and impact on children.

Resolving the source of environmental contamination is a critical first step in planning remediation and intervention strategies to adduce exposure prevention. However, a major challenge in established mining and smelting communities is that the sources of contamination and related potential health risks are often minimised by polluters and government agencies, often using unsupported scientific claims. A significant and longstanding example of this vexed issue is the protracted dispute over contamination sources and causes of childhood blood Pb exposures in Broken Hill (New South Wales), Australia's longest-operating Pb–Ag–Zn mining city.

Dong, C. and M. P. Taylor. 2017. Applying geochemical signatures of atmospheric dust to distinguish current mine emissions from legacy sources. Atmospheric Environment **161**: 82-89.

Resolving the source of environmental contamination is the critical first step in remediation and exposure prevention. Australia's oldest silver-zinc-lead mine at Broken Hill (>130 years old) has generated a legacy of contamination and is associated with persistent elevated childhood blood lead (Pb) levels. However, the source of environmental Pb remains in dispute: current mine emissions; remobilized mine-legacy lead in soils and dusts; and natural lead from geological weathering of the gossan ore body. Multiple lines of evidence used to resolve this conundrum at Broken Hill include spatial and temporal variations in dust Pb concentrations and bioaccessibility, Pb isotopic compositions, particle morphology and mineralogy. Total dust Pb loading (mean 255 μg/m2/day) and its bioaccessibility (mean 75% of total Pb) is greatest adjacent to the active mining operations. Unweathered galena (PbS) found in contemporary dust deposits contrast markedly to Pb-bearing particles from mine-tailings and weathered gossan samples. Contemporary dust particles were more angular, had higher sulfur content and had little or no iron and manganese. Dust adjacent to the mine has Pb isotopic compositions (208Pb/207Pb: 2.3197; 206Pb/207Pb: 1.0406) that are a close match (99%) to the ore body with values slightly lower (94%) at the edge of the city. The weight of evidence supports the conclusion that contemporary dust Pb contamination in Broken Hill is sourced primarily from current mining activities and not from weathering or legacy sources.

Dong, C., M. P. Taylor and B. Gulson. 2020. A 25-year record of childhood blood lead exposure and its relationship to environmental sources. Environ Res: 109357.

> Broken Hill, the oldest silver (Ag)–zinc (Zn)–lead (Pb) mining community in Australia, has a legacy and ongoing problem of environmental Pb exposure that was identified as early as 1893. To reduce Pb exposure risks, identifying potential exposure pathways and related factors is a critical first step. This study examined blood lead (PbB) levels of children ≤60 months old (n = 24,106 samples), along with Pb concentrations in corresponding soil (n = 10,160 samples), petri-dish dust (n = 106 houses) and ceiling dust (n = 80 houses) over a 25-year period from 1991 to 2015. Regression analysis was used to examine the relationships between environmental Pb sources and children's blood lead (PbB) outcomes. Analysis of the dataset showed Aboriginal children in Broken Hill had a geometric mean PbB of 7.4 μg/dL (95% CI: 6.7–7.4) being significantly higher ($p < 0.01$) than non-Aboriginal children (PbB 6.2 μg/dL, 95% CI: 6.2–6.3) for all years between 1991 and 2015. Children at the age of 24–36 months had a higher PbB compared with other age groups. Higher PbB levels were also statistically associated with lower socio-economic status and children living in houses built before 1940 ($p < 0.01$). Blood Pb was also significantly correlated with both soil Pb and indoor petri-dish dust Pb loadings, confirming that these are important pathways for exposure in Broken Hill. A 100 mg/kg increase in soil Pb was associated with a 0.12 μg/dL increase in childhood PbB. In addition, PbB concentrations increased with indoor petri-dish dust Pb loadings (i.e., 0.08 μg/dL per 100 μg/m2/30 days). The 25-year data show that the risk of exposure at ≥ 10 μg/dL was seemingly unavoidable irrespective of residential address (i.e., children of all ages presenting with a ≥10 μg/dL across the whole city area). In terms of moving forward and mitigating harmful early-life Pb exposures, all children aged 24–36 months should be prioritised for feasible and effective intervention practices. Primary intervention must focus on mitigating contemporary ongoing dust emissions from the mining operations and the associated mine-lease areas along with household soil remediation, to help prevent recontamination of homes. Additional practices of dust cleaning using wet mopping and wiping techniques, vacuuming of carpets and furnishings, ongoing monitoring of children and household dust remain important but short-lived abatement strategies. Overall, the key goal should be to eliminate risk by removing contamination in the wider environment as well as in individual homes.

Dong, C., M. P. Taylor, L. J. Kristensen and S. Zahran. 2015. Environmental contamination in an Australian mining community and potential influences on early childhood health and behavioural outcomes. Environ Pollut **207**: 345-356.

> Arsenic, cadmium and lead in aerosols, dusts and surface soils from Australia's oldest continuous lead mining town of Broken Hill were compared to standardised national childhood developmental (year 1) and education performance measures (years 3,5,7,9). Contaminants close to mining operations were elevated with maximum lead levels in soil: 8900 mg/kg; dust wipe: 86,061 μg/m(2); dust deposition: 2950 μg/m(2)/day; aerosols: 0.707 μg/m(3). The proportion of children from Broken Hill central, the area with the highest environmental contamination, presented with vulnerabilities in two or more developmental areas at 2.6 times the national average. Compared with other school catchments of Broken Hill, children in years 3 and 5 from the most contaminated school catchment returned consistently the lowest educational scores. By contrast, children living and attending schools associated with lower environmental contamination levels recorded higher school scores and lower developmental vulnerabilities. Similar results were identified in Australia's two other major lead mining and smelting cities of Port Pirie and Mount Isa.

Dong, C., M. P. Taylor and S. Zahran. 2019. The effect of contemporary mine emissions on children's blood lead levels. Environ Int **122**: 91-103.

> Background Broken Hill is home to Australia's oldest silver–zinc–lead mine. However, the precise source of childhood blood lead (PbB) exposures has been subject to considerable debate. Lead sources include natural soil Pb enrichment, legacy deposition, contemporary mining emissions, and Pb-based paint. Objective To test whether contemporary mining emissions independently affect childhood PbB in Broken Hill. Methods Children's (<5 years old) PbB measures from 2011 to 2015 (n = 4852), obtained from Broken Hill Child & Family Health Centre, were analyzed using generalised linear regression models, including covariates of household soil Pb, city dust Pb concentrations

(PbD), demographic factors and Pb ore production. Two natural experiments involving wind direction and the 2009 dust storm were examined to test whether the PbB-distance gradient from the mining operations was influenced by contemporary emissions. The influence of contemporary emissions was further interrogated by examining the effect of ore production on PbB and PbD. Results Children living downwind and proximate to the mine had substantially higher PbB outcomes than children similarly distant but upwind. Dust Pb deposition increased significantly with proximity to mining operations as well to Pb production (1991–2013). Average annual PbB correlated with Pb ore production ($p < 0.01$) with all subsets of children PbB levels responding with near unit elasticity to Pb ore production ($p < 0.01$). Pre- and post-analysis of the dust storm showed the PbB-distance gradient remained statistically unaltered further confirming contemporary emissions as a source of exposure. Conclusions Contemporary mining emissions influence children's PbB measures independent of other sources and need to be remediated to facilitate reductions in harmful exposure.

Doyi, I. N. Y., C. F. Isley, N. S. Soltani and M. P. Taylor. 2019. Human exposure and risk associated with trace element concentrations in indoor dust from Australian homes. Envionment International **133**: 105-125.

This study examines residential indoor dust from 224 homes in Sydney, Australia for trace element concentrations measured using portable X-ray Fluorescence (pXRF) and their potential risk of harm. Samples were collected as part of a citizen science program involving public participation via collection and submission of vacuum dust samples for analysis of their As, Cr, Cu, Mn, Ni, Pb and Zn concentrations. The upper 95% confidence level of the mean values for 224 samples (sieved to < 250 µm) were 20.2 mg/kg As, 99.8 mg/kg Cr, 298 mg/kg Cu, 247 mg/kg Mn, 56.7 mg/kg Ni, 364 mg/kg Pb and 2437 mg/kg Zn. The spatial patterns and variations of the metals indicate high homogeneity across Sydney, but with noticeably higher Pb values in the older areas of the city. Potential hazard levels were assessed using United States Environmental Protection Agency's (US EPA) carcinogenic, non-carcinogenic and Integrated Exposure Uptake Biokinetic (IEUBK) model human health risk assessment tools for children and adults. US EPA hazard indexes (HI) for Cr and Pb were higher than the safe level of 1.0 for children. HI > 1 suggests potential non-carcinogenic health effects. Carcinogenic risks were estimated for As, Cr and Pb whose carcinogenic slope factors (CSF) were available. Only the risk factor for Cr exceeded the US EPA's carcinogenic threshold (1 × 10-4) for children. Children of 1-2 years category had the highest predicted mean child blood lead (PbB) of 4.6 µg/dL, with 19.2 % potentially having PbB exceeding 5 µg/dL and 5.80 % exceeding 10 µg/dL. The Cr and Pb levels measured in indoor dust therefore pose potentially significant adverse health risks to children.

Du, L., S. Batterman, E. Parker, C. Godwin, J.-Y. Chin, A. O'Toole, T. Robins, W. Brakefield-Caldwell and T. Lewis. 2011. Particle concentrations and effectiveness of free-standing air filters in bedrooms of children with asthma in Detroit, Michigan. Building and Environment **46**(11): 2303-2313.

Asthma can be exacerbated by environmental factors including airborne particulate matter (PM) and environmental tobacco smoke (ETS). We report on a study designed to characterize PM levels and the effectiveness of filters on pollutant exposures of children with asthma. 126 households with an asthmatic child in Detroit, Michigan, were recruited and randomized into control or treatment groups. Both groups received asthma education; the latter also received a free-standing high efficiency air filter placed in the child's bedroom. Information regarding the home, emission sources, and occupant activities was obtained using surveys administered to the child's caregiver and a household inspection. Over a one week period, we measured PM, carbon dioxide (CO2), environmental tobacco smoke (ETS) tracers, and air exchange rates (AERs). Filters were installed at midweek. Before filter installation, PM concentrations averaged 28 µg m−3, number concentrations averaged 70,777 and 1471 L−1 in 0.3–1.0 and 1–5 µm size ranges, respectively, and the median CO2 concentration was 1018 ppm. ETS tracers were detected in 23 of 38 homes where smoking was unrestricted and occupants included smokers and, when detected, PM concentrations were elevated by an average of 15 µg m−3. Filter use reduced PM concentrations by an average of 69–80%. Simulation models representing location conditions show that filter air flow, room volume and AERs are the key parameters affecting PM removal, however, filters can achieve substantial removal in even "worst" case applications. While PM levels in homes with asthmatic children can be high, levels can be dramatically reduced using filters.

Earl, R., N. Burns, T. Nettelbeck and P. Baghurst. 2016. Low-level environmental lead exposure still negatively associated with children's cognitive abilities. Australian Journal of Psychology **68**(2): 98-106.

> We explored relationships between children's cognitive abilities measured with the W echsler I ntelligence S cale for C hildren-F ourth E dition and blood lead levels. Participants were 127 children (mean age = 7.9 years, standard deviation = 0.6) from A ustralian cities, P ort P irie, and B roken H ill, with low-level blood lead concentrations (mean = 4.8 microgram/decilitre, standard deviation = 3.3, range = 1.0–19.3). Potential covariates (demographic, parental, familial, psycho-social, pre- and post-natal factors) were controlled statistically. Unadjusted analyses found moderate, continuous, and statistically significant inverse, non-linear associations between blood lead level and three of the four cognitive indices that combine to deliver F ull S cale IQ . In addition to blood lead level, variables that consistently explained most variance in cognitive performance were breastfeeding up to 6 months and stressful life events reported within the family for the past 12 months. In multiple regression analyses, after controlling for these, blood lead level remained a significant predictor of cognitive outcomes. These results support the hypothesis that blood lead levels below 10 micrograms/decilitre may still have a detrimental impact on children's cognitive abilities, supporting recent concern that there is no safe level of paediatric lead exposure.

Ericson, B., J. Caravanos, C. Depratt, C. Santos, M. G. Cabral, R. Fuller and M. P. Taylor. 2018. Cost Effectiveness of Environmental Lead Risk Mitigation in Low-and Middle-Income Countries. GeoHealth **2**(2): 87-101.

> Environmental remediation efforts in low- and middle-income countries have yet to be evaluated for their cost effectiveness. To address this gap we calculate a cost per Disability Adjusted Life Year (DALY) averted following the environmental remediation of the former lead smelter and adjoining residential areas in Paraiso de Dios, Haina, the Dominican Republic, executed from 2009 to 2010. The remediation had the effect of lowering surface soil lead concentrations to below 100 mg/kg and measured geometric mean blood lead levels (BLLs) from 20.6 μg/dL to 5.34 ug/dL. Because BLLs for the entire impacted population were not available, we use environmental data to calculate the resulting disease burden. We find that before the intervention 176 people were exposed to elevated environmental lead levels at Paraiso de Dios resulting in mean BLLs of 24.97 (95% CI: 24.45–25.5) in children (0–7 years old) and 13.98 μg/dL (95% CI: 13.03–15) in adults. We calculate that without the intervention these exposures would have resulted in 133 to 1,096 DALYs and that all of these were averted at a cost of USD 392 to 3,238, depending on assumptions made. We use a societal perspective, meaning that we include all costs regardless of by whom they were incurred and estimate costs in 2009 USD. Lead remediation in low- and middle-income countries is cost effective according to World Health Organization thresholds. Further research is required to compare the approach detailed here with other public health interventions.

Ericson, B., T. T. Duong, J. Keith, T. C. Nguyen, D. Havens, W. Daniell, C. J. Karr, D. Ngoc Hai, L. Van Tung, T. Thi Nhi Ha, et al. 2018. Improving human health outcomes with a low-cost intervention to reduce exposures from lead acid battery recycling: Dong Mai, Vietnam. Environ Res **161**: 181-187.

> This study details the first comprehensive evaluation of the efficacy of a soil lead mitigation project in Dong Mai village, Vietnam. The village's population had been subject to severe lead poisoning for at least a decade as a result of informal Used Lead Acid Battery (ULAB) recycling. Between July 2013 to February 2015, Pure Earth and the Centre for Environment and Community Development (Hanoi, Vietnam) implemented a multi-faceted environmental and human health intervention. The intervention consisted of a series of institutional and low-cost engineering controls including the capping of lead contaminated surface soils, cleaning of home interiors, an education campaign and the construction of a work-clothes changing and bathing facility. The mitigation project resulted in substantial declines in human and environmental lead levels. Remediated home yard and garden areas decreased from an average surface soil concentration of 3940mg/kg to <100mg/kg. One year after the intervention, blood lead levels in children (<6 years old) were reduced by an average of 67%—from a median of 40.4μg/dL to 13.3μg/dL. The Dong Mai project resulted in significantly decreased environmental and biological lead levels demonstrating that low-cost, rapid and well-

coordinated interventions could be readily applied elsewhere to significantly reduce preventable human health harm.

Ericson, B., E. Nash, G. Ferraro, J. Sinitsky, V. Masek and M. P. Taylor. 2019. Sources of lead exposure and resulting blood lead levels in low- and middle-income countries: a systematic review and meta-analysis.

Gaitens, J. M., S. L. Dixon, D. E. Jacobs, J. Nagaraja, W. Strauss, J. W. Wilson and P. J. Ashley. 2009. Exposure of U.S. Children to Residential Dust Lead, 1999–2004: I. Housing and Demographic Factors. Environ Health Perspect **117**(3): 461-467.

Lead-contaminated house dust is a major source of lead exposure for children in the United States. In 1999–2004, the National Health and Nutrition Examination Survey (NHANES) collected dust lead (PbD) loading samples from the homes of children 12–60 months of age. In this study we aimed to compare national PbD levels with existing health-based standards and to identify housing and demographic factors associated with floor and windowsill PbD. We used NHANES PbD data (n = 2,065 from floors and n = 1,618 from windowsills) and covariates to construct linear and logistic regression models. The population-weighted geometric mean floor and windowsill PbD were 0.5 µg/ft2 [geometric standard error (GSE) = 1.0] and 7.6 µg/ft2 (GSE = 1.0), respectively. Only 0.16% of the floors and 4.0% of the sills had PbD at or above current federal standards of 40 and 250 µg/ft2, respectively. Income, race/ethnicity, floor surface/condition, windowsill PbD, year of construction, recent renovation, smoking, and survey year were significant predictors of floor PbD [the proportion of variability in the dependent variable accounted for by the model (R2) = 35%]. A similar set of predictors plus the presence of large areas of exterior deteriorated paint in pre-1950 homes and the presence of interior deteriorated paint explained 20% of the variability in sill PbD. A companion article [Dixon et al. Environ Health Perspect 117:468–474 (2009)] describes the relationship between children's blood lead and PbD. Most houses with children have PbD levels that comply with federal standards but may put children at risk. Factors associated with PbD in our population-based models are primarily the same as factors identified in smaller at-risk cohorts. PbD on floors and windowsills should be kept as low as possible to protect children.

Gough, N., M. Lesjak, S. Kirby, Party TBHACW and D. Lyle. 2012. The impact of lead and a change of lead guidelines for Broken Hill: an inquiry into community concern and desire for action. Broken Hill (NSW):. B. H. Broken Hill University Department of Rural Health (UDRH). Located at: Broken Hill UDRH Library, NSW.

Gould, E. 2009. Childhood lead poisoning: conservative estimates of the social and economic benefits of lead hazard control. Environ Health Perspect **117**(7): 1162.

BACKGROUND: This study is a cost-benefit analysis that quantifies the social and economic benefits to household lead paint hazard control compared with the investments needed to minimize exposure to these hazards. OBJECTIVES: This research updates estimates of elevated blood lead levels among a cohort of children < or = 6 years of age and compiles recent research to determine a range of the costs of lead paint hazard control ($1-$11 billion) and the benefits of reduction attributed to each cohort for health care ($11-$53 billion), lifetime earnings ($165-$233 billion), tax revenue ($25-$35 billion), special education ($30-$146 million), attention deficit-hyperactivity disorder ($267 million), and the direct costs of crime ($1.7 billion). RESULTS: Each dollar invested in lead paint hazard control results in a return of $17-$221 or a net savings of $181-269 billion. CONCLUSIONS: There are substantial returns to investing in lead hazard control, particularly targeted at early intervention in communities most likely at risk. Given the high societal costs of inaction, lead hazard control appears to be well worth the price.

Greene, D., P. Tehranifar, D. P. DeMartini, A. Faciano and D. Nagin. 2015. Peeling lead paint turns into poisonous dust. Guess where it ends up? A media campaign to prevent childhood lead poisoning in New York City. Health Education & Behavior **42**(3): 409-421.

Successful public health media campaigns promote messages, increase awareness, engage the public, and encourage behavior change. Between 2004 and 2006, the Lead Poisoning Prevention

Program of the New York City Department of Health and Mental Hygiene conducted a media campaign grounded in social learning theory and the social marketing model to increase parents' awareness of childhood lead poisoning, ways to protect their children, and property owners' legal responsibility to fix peeling lead paint safely, and increase awareness of regulatory changes and encourage enforcement of New York City's Local Law 1 of 2004. Campaign materials were focus group tested and the campaign was refined annually. The campaign ran city-wide and in targeted high-risk neighborhoods. Neighborhoods and media venue (bus, train, kiosk, and store) changed annually, based on population risk factors and venue availability. Exposure to the campaign, campaign-related knowledge, and behavior were assessed using pre- and postcampaign street intercept surveys. Results showed that campaign reached the targeted population, and had an impact on knowledge of lead poisoning prevention measures as evidenced by increased knowledge of lead paint exposures sources in one year and increased knowledge of preventive behaviors in another year; these improvements were observed for both genders and most ethnic, primary language, educational attainment, and age groups in each year. Lessons learned indicate that well-targeted media campaigns, designed with audience participation, can reach parents through various venues, and improve key knowledge areas. Evaluation challenges faced include high levels of knowledge at baseline, competing media messages, and balancing between program needs and evaluation design.

Gulson, B., J. Davis, K. Mizon, M. Korsch and J. Bawden-Smith. 1995. Sources of lead in soil and dust and the use of dust fallout as a sampling medium. Science of The Total Environment **166**(1-3): 245-262.

Pilot investigations using stable lead isotope and scanning electron microscopic analyses have been undertaken in different environments ranging from mining and smelting to urban in order to better understand the source of, and relationships between, soil and house dust. House dust is characterised by vacuum cleaner dust and/or surface wipes and compared with long-term dust (dust fall) accumulations over a > 3-month interval or with airborne particulates. Finer grain sizes of soils have lead concentrations from 2 to 9 times those measured in the bulk fractions. In Broken Hill isotopic ratios show that the major source of lead in soils is from the orebody, with rare examples containing lead from paint sources. In inner Sydney, soil lead values vary from 37 to 2660 ppm Pb in bulk samples and up to 3130 ppm in the finer fractions. The lead may be from diverse sources such as gasoline or paint. Finer fractions of vacuum cleaner dust from both Broken Hill and Sydney may contain up to three times the amount of lead measured in the bulk samples. In Broken Hill, the percentages by weight of total lead in the −250-μm fraction range from 11 to 51%. Bulk vacuum cleaner dusts from Broken Hill contain up to 4490 ppm Pb. Bulk vacuum cleaner dusts from inner Sydney contain up to 2950 ppm Pb. Isotopic variations in fractions of vacuum cleaner dust containing > 1000 ppm Pb from inner Sydney indicate that the lead in dust has come from different sources and such differences lessen the usefulness of analyses of bulk vacuum cleaner dust. Our results reinforce the importance of analysing the finer fraction of soil and house dust, especially those in the −150-μm (or even −100-μm) fraction for soils and the −100-μm fraction for vacuum cleaner dust. Dust-fall accumulations have many advantages over more conventional methods for estimating lead in house dust, such as vacuum cleaner dust or surface wipes. These advantages include: low cost; no power source required; can be set up by a technician; minimal inconvenience to householder (i.e., no power required, no noise, out of the way, a few minutes to set up and collect); integrates lead flux over a specific period; usually unbiased (in contrast to vacuuming or wipes where the householder may clean prior to a sampling visit); easy to 'control' by placement of other dishes in the same house. For Broken Hill, a strong correlation (r = 0.95) was obtained between the isotopic composition of lead in blood and dust-fall accumulation.

Gulson, B., K. Mizon, M. Korsch, D. Howarth, A. Phillips and J. Hall. 1996. Impact on blood lead in children and adults following relocation from their source of exposure and contribution of skeletal tissue to blood lead. Bulletin of environmental contamination and toxicology **56**(4): 543-550.

The goal of hazard abatement is the identification and systematic elimination of lead hazards in the community, which should ultimately result in lowering of blood lead (PbB), especially in children. Such a goal is a daunting task in mining or smelting communities such as Broken Hill in Australia where industrial activities operating for more than 100 years and natural weathering over millennia have resulted in widespread contamination. {open_quotes}The single most important factor in managing of childhood lead poisoning is reducing the child`s exposure to lead{hor_ellipsis}{close_quotes}. Luke reviewed the remediation programs in seven large smelter operations outside Australia using environmental and biological indices, before and after intervention, to gauge the success. He concluded that outcomes varied from temporary improvements in Kellog, Idaho to apparently more successful outcomes in El Paso and Dallas, Texas. At Port Pirie, Luke identified that the most significant predictor of a reduction in PbB levels was permanent relocation out of the high risk areas, whereas in a later assessment Maynard identified, in addition to permanent relocation, level of expenditure on house dedusting and refurbishment, improved dust hygiene practices, and improved early morning diet as likely to reduce PbB levels. The aim of this study was to evaluate the impact on PbB of relocation of two families from their source of lead, in this case from the Broken Hill mining community. To gauge the impact of relocation, the results are compared with twenty seven children who relocated within the Broken Hill community from high to low risk areas.

Gulson, B. and A. Taylor. 2017. A simple lead dust fall method predicts children's blood lead level: New evidence from Australia. Environ Res **159**: 76-81.

We have measured dust fall accumulation in petri dishes (PDD) collected 6 monthly from inside residences in Sydney urban area, New South Wales, Australia as part of a 5-year longitudinal study to determine environmental associations, including soil. with blood lead (PbB) levels. The Pb loading in the dishes (n = 706) had geometric means (GM) of 24 µg/m2/30d, a median value of 22 µg/m2/30d with a range from 0.2 to 11,390 µg/m2/30d. Observed geometric mean PbB was 2.4 µg/dL at ages 2–3 years. Regression analyses showed a statistically significant relationship between predicted PbB and PDD. The predicted PbB values from dust in our study are consistent with similar analyses from the US in which floor dust was collected by wipes. Predicted PbB values from PDD indicate that an increase in PDD of about 100 µg/m2/30d would increase PbB by about 1.5 µg/dL or a doubling PbB at the low levels currently observed in many countries. Predicted PbB values from soil indicate that a change from 0 to 1000 mg Pb/kg results in an increase of 1.7 µg/dL in PbB, consistent with earlier investigations. Blood Pb levels can be predicted from dust fall accumulation (and soil) in cases where blood sampling is not always possible, especially in young children. Petri dish loading data could provide an alternative or complementary “action level” at about 100 µg Pb/m2 /30 days, similar to the suggested level of about 110 µg Pb/m2 for surface wipes, for use in monitoring activities such as housing rehabilitation, demolition or soil resuspension.

Gulson, B. L., J. J. Davis, K. J. Mizon, M. J. Korsch, A. J. Law and D. Howarth. 1994. Lead bioavailability in the environment of children: blood lead levels in children can be elevated in a mining community. Archives of Environmental Health: An International Journal **49**(5): 326-331.

Lower blood lead averages in mining communities, compared with other child exposure settings, e.g., innercity areas of the United States and smelter communities, have been attributed to lower bioavailability of lead to children in the mining areas. Direct supporting evidence of the lower bioavailability has, however, generally been lacking. Elevated blood lead levels for approximately 85% of children with > 10 µg/dl have been reported from the Broken Hill mining community in Australia. Lead isotope, optical, and scanning electron microscope analyses on the lead species from soils and dusts show them to be derived mainly from weathered ore body material. Solubility tests using 0.1 M HCl on the −53+38 µm fraction of soil and dust show the lead species to have a high degree of bioavailability. Ingestion of soil and dust, either directly or via mouthing activity, is the main source and pathway for elevated blood lead in children from this community.

Gulson, B. L., D. Howarthl, K. J. Mizon, A. J. Law, M. J. Korsch and J. J. Davis. 1994. Source of lead in humans from Broken Hill mining community. Environmental Geochemistry and Health **16**(1): 19-25.

This paper documents the first precise lead isotope measurements for men, women and children from the same family in an attempt to determine the source of lead in their blood. The subjects reside in one of the world's largest lead mining cities, Broken Hill, NSW, Australia. Biological and environmental samples have been compared using isotopic compositions and lead contents. Adult males have isotopic profiles (or compositions) which appear to be related to their occupations. Adult females have low blood leads (<10 µg dL−1) and their main source of lead is not from the mine dumps around which the city is built but probably from a mixture of petrol, food and perhaps water. The blood lead contents in children from 1 to 14 years old vary and are partly dependent on age. There is a moderate correlation of blood lead and isotopic compositions (r = 0.73) indicating that a significant component of blood lead derives from the mine dumps in children with elevated blood leads. Some children with blood leads <20 µg dL−1, however, also have a dominant component of mine lead in their blood.

Gulson, B. L., K. J. Mizon, A. J. Law, M. J. Korsch, J. J. Davis and D. Howarth. 1994. Source and pathways of lead in humans from the Broken Hill mining community; an alternative use of exploration methods. Economic Geology **89**(4): 889-908.

To assist in recommendations for the most suitable lead abatement policies in Broken Hill, New South Wales, Australia, knowledge of the sources and pathways of the lead into humans is critical. We have approached these problems using the lead isotope fingerprinting method, combined with mineral speciation and "bioavailability" tests, approaches which have in the past been largely applied to mineral exploration.High precision lead isotope ratio measurements and lead contents were determined by thermal ionization mass spectrometry on biological samples (blood, urine) and environmental samples from 27 families, encompassing 60 children, 41 female adults, and 17 male adults. Environmental samples analyzed (not from every household) included soils, gutter sweepings, ceiling dust, vacuum cleaner dust, long-term dust, surface dust wipes, external and internal air, food, water, and gasoline.Sources of lead have been identified in the blood of children, using lead isotopes, with dominant contributions from the Broken Hill orebody, but with individual cases having a dominant source of lead from gasoline or paint. Nevertheless, of 28 children with a blood lead level (Pb B) > 15 mu /dl, approximately 30 percent have more than 50 percent of their Pb B from sources other than orebody lead. Female adults generally have a low Pb B , <10 mu /dl, and the source of their lead is attributed to air (gasoline, orebody), food, and water. The source of lead in male adults can usually be correlated with their occupation, depending on whether it is related to high risk activities, such as mining (dominantly orebody lead) or service stations (gasoline lead), or "nonexposed." Knowledge of the occupation and lead isotope composition in the father's blood is an important indicator of lead pathways. Other potential sources of lead, such as food and water, have lead contents too low to be significant contributors to lead levels in most children.Scanning electron microscopy (energy dispersive X-ray analyses) identified the most common lead species in soils and dusts to be composed of a complex Pb,Fe,Mn,Ca,Al,Si,O material with rare galena in houses close to the central mining activity. These lead complexes are quite different from ones found in other mining communities, such as those found in the United States, where the lead may be in less soluble forms such as pyromorphite or encapsulated in less soluble anglesite, pyrite, or quartz. Approximations of bioavailability (more correctly, solubility) were made by leaching, with 0.1M HCl for 2 hr at 37 degrees C, bulk (unsized) and a critical size fraction of -53+38 mu m. The 0.1M HCl extracts 33 to 61 percent (mean = 47 + or - 10%, n = 7) of the total leachable lead from gutter sweepings, from 41 to 84 percent (mean = 60 + or - 10%, n = 10) from soils, and 17 to >100 percent (mean = 47 + or - 38%, n = 5) from vacuum cleaner dusts. Thus the currently suggested amounts of approximately 100 mg/d ingested soil (dirt) and dust for a Broken Hill child can readily account for the elevated lead levels compared with the amounts for children in many other mining communities. Based on these investigations it is possible to construct a flow sheet of sources and pathways for the lead into humans at Broken Hill on which to base correct remedial actions.

Harvey, P., M. Taylor, L. Kristensen, S. Grant-Vest, M. Rouillon, L. Wu and H. Handley. 2016. Evaluation and assessment of the efficacy of an abatement strategy in a former lead smelter community, Boolaroo, Australia. Environmental Geochemistry and Health **38**(4): 941-954.

This study examines the recent soil Lead Abatement Strategy (LAS) in Boolaroo, New South Wales, Australia, that was designed to "achieve a reduction in human exposure to lead dust contamination in surface soils". The abatement programme addressed legacy contamination of residential areas following closure of lead smelting operations in 2003 at the Pasminco Cockle Creek Smelter (PCCS). The principal objective of the LAS was to "cap and cover" lead-contaminated soils within the urban environment surrounding the PCCS. Soil lead concentrations of 2500-5000 mg/kg were scheduled for removal and replacement, while concentrations between 1500 and 2500 mg/kg were replaced only under limited circumstances. To date, there has been no industry, government or

independent assessment of the clean-up programme that involved >2000 homes in the township of Boolaroo. Thus, by measuring post-abatement soil lead concentrations in Boolaroo, this study addresses this knowledge gap and evaluates the effectiveness of the LAS for reducing the potential for lead exposure. Soil lead concentrations above the Australian residential soil health investigation level value for residential soils (300 mg/kg) were identified at all but one of the residential properties examined (n = 19). Vacuum dust samples (n = 17) from the same homes had a mean lead concentration of 495 mg/kg (median 380 mg/kg). Bio-accessibility testing revealed that lead in household vacuum dust was readily accessible (% bio-accessible) (mean = 92 %, median = 90 %), demonstrating that the risk of exposure via this pathway remains. Assessment of a limited number of properties (n = 8) where pre-abatement soil lead levels were available for comparison showed they were not statistically different to post-abatement. Although the LAS did not include treatment of non-residential properties, sampling of community areas including public sports fields, playgrounds and schools (n = 32) was undertaken to determine the contamination legacy in these areas. Elevated mean soil lead concentrations were found across public lands: sports fields = 5130 mg/kg (median = 1275 mg/kg), playgrounds and schools = 812 mg/kg (median = 920 mg/kg) and open space = 778 mg/kg (median = 620 mg/kg). Overall, the study results show that the LAS programme that was dominated by a "cap and cover" approach to address widespread lead contamination was inadequate for mitigating current and future risk of lead exposures.

Henry, H., M. F. Naujokas, C. Attanayake, N. T. Basta, Z. Cheng, G. M. Hettiarachchi, M. Maddaloni, C. Schadt and K. G. Scheckel. 2015. Bioavailability-Based In Situ Remediation To Meet Future Lead (Pb) Standards in Urban Soils and Gardens. Environ Sci Technol **49**(15): 8948-8958.

Recently the Centers for Disease Control and Prevention lowered the blood Pb reference value to 5 µg/dL. The lower reference value combined with increased repurposing of postindustrial lands are heightening concerns and driving interest in reducing soil Pb exposures. As a result, regulatory decision makers may lower residential soil screening levels (SSLs), used in setting Pb cleanup levels, to levels that may be difficult to achieve, especially in urban areas. This paper discusses challenges in remediation and bioavailability assessments of Pb in urban soils in the context of lower SSLs and identifies research needs to better address those challenges. Although in situ remediation with phosphate amendments is a viable option, the scope of the problem and conditions in urban settings may necessitate that SSLs be based on bioavailable rather than total Pb concentrations. However, variability in soil composition can influence bioavailability testing and soil amendment effectiveness. More data are urgently needed to better understand this variability and increase confidence in using these approaches in risk-based decision making, particularly in urban areas.

Hirtz, D., C. Campbell and B. Lanphear. 2017. Targeting Environmental Neurodevelopmental Risks to Protect Children. Pediatrics: e20162245.

Pregnant women, infants, and children are continually exposed to chemicals that are toxic to brain development. Yet too little has been done to protect them from the possibility of harm. In 2015, a diverse group of physicians and other health professionals, scientists, and advocates established Project Targeting Environmental Neuro-Developmental Risks (TENDR) to focus awareness and advocate for action against toxic chemicals that contribute to the risk of development of brain-based disorders in children, including intellectual and learning disabilities, autism, and attention-deficit/hyperactivity disorder (ADHD).

Huang, S., H. Hu, B. N. Sánchez, K. E. Peterson, A. S. Ettinger, H. Lamadrid-Figueroa, L. Schnaas, A. Mercado-García, R. O. Wright and N. Basu. 2015. Childhood blood lead levels and symptoms of attention deficit hyperactivity disorder (ADHD): a cross-sectional study of Mexican children. Environ Health Perspect **124**(6): 868-874.

Background: Previous studies suggest that blood lead levels are positively associated with attention deficit/hyperactivity disorder (ADHD) and ADHD-symptoms in children. However, the associations between lead exposure and ADHD subtypes are inconsistent and understudied. Objective: The objective of this study was to explore the association of low-level concurrent lead exposure with subtypes of ADHD symptoms in 578 Mexican children 6-13 years of age. Methods: We measured concurrent blood lead levels using inductively coupled plasma mass spectrometry (ICPMS). We administered the Conners' Rating Scales-Revised (CRS-R) to mothers to evaluate their children's ADHD symptoms. We used imputation to fill missing values in blood lead levels and used segmented regression models adjusted for relevant covariates to model the nonlinear relationship between blood lead and ADHD symptoms. Results: Mean ± SD blood lead levels were 3.4 ± 2.9 µg/dL. In adjusted models, a 1-µg/dL increase in blood lead was positively associated with Hyperactivity and Restless-Impulsivity scores on the CRS-R scale and Hyperactivity-Impulsivity scores on the CRS-R scale of the Diagnostic and Statistical Manual of Mental Disorders, 4th Edition, but only in children with blood lead level ≤ 5 µg/dL. Blood lead was not associated with Inattentive symptoms or overall ADHD behavior. Conclusions: In this population of Mexican children, current blood lead level among children with low exposure (≤ 5 µg/dL) was positively associated with hyperactive/impulsive behaviors, but not with inattentiveness. These results add to the existing evidence of lead-associated neurodevelopmental deficits at low levels of exposure.

Humphries, K. 2015. Media Release: NSW Government Commits More Than $13 Million To Reduce Lead Levels At Broken Hill. Accessed 25th February 2020 at https://www.epa.nsw.gov.au/~/media/EPA/Corporate%20Site/resources/MinMedia/EPAMin150213.ashx.

Hunter New England Health. 2015. Blood Lead Screening in North Lake Macquarie, 2015. Accessed 25th February 2020 at http://www.hnehealth.nsw.gov.au/hneph/EnvironmentalHealth/Documents/blood-lead-screening-2015.pdf.

Jaishankar, M., T. Tseten, N. Anbalagan, B. B. Mathew and K. N. Beeregowda. 2014. Toxicity, mechanism and health effects of some heavy metals. **7**(2): 60.

Heavy metal toxicity has proven to be a major threat and there are several health risks associated with it. The toxic effects of these metals, even though they do not have any biological role, remain present in some or the other form harmful for the human body and its proper functioning. They sometimes act as a pseudo element of the body while at certain times they may even interfere with metabolic processes. Few metals, such as aluminium, can be removed through elimination activities, while some metals get accumulated in the body and food chain, exhibiting a chronic nature. Various public health measures have been undertaken to control, prevent and treat metal toxicity occurring at various levels, such as occupational exposure, accidents and environmental factors. Metal toxicity depends upon the absorbed dose, the route of exposure and duration of exposure, i.e. acute or chronic. This can lead to various disorders and can also result in excessive damage due to oxidative stress induced by free radical formation. This review gives details about some heavy metals and their toxicity mechanisms, along with their health effects.

Jordan, W. 2010. Our place or mine? Sense of place, social impact assessment and coal mining in Gloucester, NSW. Thesis. Accessed 14 February 2019 at https://eprints.utas.edu.au/10228/3/Warrick_Jordan_pdf%5B1%5D.pdf.

This study examines the impact of coal mining and coal seam methane (CSM) extraction on the ‘sense of place’ of the people of the Gloucester Shire, New South Wales. The findings derived from Gloucester inform an analysis of the potential for recognising loss of ‘place’ as a social impact within social impact assessment (SIA). This potential was considered within the geographic context of the Hunter Valley, Gunnedah Basin, and Gloucester Valley, which constitute contiguous and related regions subject to coal development. Previous research in similar contexts indicated that a felt loss of place was likely. A methodology was adopted that combined survey-based quantitative analysis, key informant interviews, and extensive consideration of the literature of place and SIA. Results indicate that loss of place is being felt strongly by the Gloucester community, although considerable divergence exists in both felt loss of place and support for coal-related development. Widespread dissatisfaction with the prevailing levels of community input into development processes also emerged as a significant issue with particular ramifications for the maintenance of place. While a substantial loss of place was in evidence in Gloucester, the recognition of this loss as a social impact is suggested as being hampered by mensuration difficulties, the diversity of ‘place attachments’, and the nature of impact assessment decision-making. The establishment of placeconscious,

participatory SIA processes is suggested as an alternative mechanism for mitigating place loss in the coal mining areas of the Hunter, Gunnedah, and Gloucester regions.

Juhasz, A. 2018. Refining key lead exposure parameters in Broken HIll - Assessment of lead relative bioavailability (Phase 1 and 2 report), University of South Australia. Prepared for Broken Hill Environmental Lead Program.

Broken Hill soil samples (BHK1-BHK12) were collected on the 11th of April 2017 along a transect (predominantly along King St) away from the line of lode from Piper St to the laneway behind Knox St. The study aimed to assess the elemental composition of the soil, determine lead (Pb) bioaccessibility using a gastrointestinal extraction method, and for a sub-set of soils (n = 4: phase 1; n = 6: Phase 2), assess Pb relative bioavailability using an in vivo mouse model. Lead concentration in Broken Hill soil ranged from 215 ± 0.9 mg kg-1 (BHK8) to 8036 ± 651 mg kg-1 (BHK1) in the < 2 mm soil particle size fraction. Only two samples (BHK7 and BHK8) were below the National Environmental Protection Measure for the Assessment of Site Contamination (NEPM-ASC) Health-based investigation level (Residential A [HILa]). Lead was enriched in the < 250 mm soil particle size fraction (on average by ~16%) with Pb concentrations ranging from 267 ± 14 mg kg-1 (BHK8) to 9930 ± 468 mg kg-1 (BHK1). Enrichment of other elements in the < 250 mm soil particle size fraction was also observed, notably, the concentration of Cd, Zn and Mn exceeded NEPM HILa values in BHK1. Strong relationships were observed between the concentration of Pb and Mn or Zn in the < 250 mm soil particle size fraction suggesting that these relationships may be utilise to ascertain the contribution of outdoor soil to indoor dust Pb concentrations. Assessment of Pb concentration in the < 150 mm soil particle size fraction identified that Pb enrichment occurred for 5 of the 12 soils (BHK1, 5, 6, 7, 12) compared to the < 250 mm soil particle size fraction. When Pb speciation in the < 250 mm soil particle size fraction was assessed using x-ray absorption spectroscopy, Pb was present predominantly was sorbed phases to oxides and clays (45-66%). Lead was also present as plumbojarosite (6-35%), Pb phosphate (5-19%) or bound to organic matter (8-22%). When Pb bioaccessibility was assessed using the Solubility Bioaccessibility Research Consortium (SBRC) assay, values were significantly higher when determined using gastric phase extraction compared to the intestinal phase. With the exception of BHK4, 8 and 9 (41.5-54.6%), Pb bioaccessibility following gastric phase extraction was > 60% (ranging from 61.7% [BHK12] to 79.5% [BHK10]). However, when gastric phase conditions were transitioned into the intestinal phase, Pb bioaccessibility significantly decreased (by 2.1-21.8 fold) with values ranging from 1.9 ± 0.2% (BHK8) to 25.3 ± 1.1% (BHK12). Similar trends in Pb bioaccessibility were observed for the < 150 µm soil particle size fraction although lower intestinal phase Pb bioaccessibility values were derived. Presumably differences in the concentration of elements such as Fe and P in these particle size fractions influenced the outcomes of intestinal phase assessments. Lead relative bioavailability in Broken Hill soil was assessed using the USEPA's Integrated Systems Toxicology Division mouse model protocol by comparing the accumulation of Pb in target organs (liver, kidney and femur) following a 10 day exposure to Pb-contaminated soil or Pb acetate in AIN93G mouse chow. Mean Pb relative bioavailability ranged from 6.8 ± 1.2% for BHK3 to 44.8 ± 5.1% for BHK9, however, for 8 of the 10 soils analysed, mean Pb relative bioavailability was < 20%. Higher Pb relative bioavailability was observed in BHK7 (33.3 ± 8.0%) and BHK9 (44.8 ± 5.1%), soils which presented 'low' total Pb concentrations (316 and 452 mg kg-1 respectively). For the 10 soils assessed, the upper 95% confidence intervals of the mean for Pb relative bioavailability was 21.5%. Poor relationships were observed when Pb relative bioavailability and Pb bioaccessibility were compared. The gastric phase of the SBRC assay produced values that were up to 10-fold higher (1.2-10.3) compared to the corresponding Pb relative bioavailability value. Although a poor relationship was also observed when the complete data set of SBRC intestinal phase values were compared to Pb relative bioavailability, this in part, was due to the narrow range of Pb relative bioavailability values in Broken Hill soil. For 4 soils (BHK 5, 6, 10, 12), there was no significant difference (p > 0.05) between SBRC intestinal phase values and Pb relative bioavailability while for BHK2, 3, 4 and 11, in vitro assessment over-predicted Pb relative bioavailability by 1.6-3.1 fold. Where elevated Pb relative bioavailability was observed

(BHK7, 9), assessment of Pb bioaccessibility using the SBRC intestinal phase, significantly underestimated Pb relative bioavailability.

Juhasz, A. L., D. Gancarz, C. Herde, S. McClure, K. G. Scheckel and E. Smith. 2014. In situ formation of pyromorphite is not required for the reduction of in vivo Pb relative bioavailability in contaminated soils. Environ Sci Technol **48**(12): 7002-7009.

The effect of phosphate treatment on lead relative bioavailability (Pb RBA) was assessed in three distinct Pb-contaminated soils. Phosphoric acid (PA) or rock phosphate were added to smelter (PP2), nonferrous slag (SH15), and shooting range (SR01) impacted soils at a P:Pb molar ratio of 5:1. In all of the phosphate amended soils, Pb RBA decreased compared to that in untreated soils when assessed using an in vivo mouse model. Treatment effect ratios (i.e., the ratio of Pb RBA in treated soil divided by Pb RBA in untreated soil) ranged from 0.39 to 0.67, 0.48 to 0.90, and 0.03 to 0.19 for PP2, SH15, and SR01, respectively. The decrease in Pb RBA following phosphate amendment was attributed to the formation of poorly soluble Pb phosphates (i.e., chloropyromorphite, hydroxypyromorphite, and Pb phosphate) that were identified by X-ray absorption spectroscopy (XAS). However, a similar decrease in Pb RBA was also observed in untreated soils following the sequential gavage of phosphate amendments. This suggests that in vivo processes may also facilitate the formation of poorly soluble Pb phosphates, which decreases Pb absorption. Furthermore, XAS analysis of PA-treated PP2 indicated further in vivo changes in Pb speciation as it moved through the gastrointestinal tract, which resulted in the transformation of hydroxypyromorphite to chloropyromorphite.

Kachenko, A. G. and B. Singh. 2006. Heavy metals contamination in vegetables grown in urban and metal smelter contaminated sites in Australia. Water, Air, and Soil Pollution **169**(1-4): 101-123.

Dietary exposure to heavy metals, namely cadmium (Cd), lead (Pb), zinc (Zn) and copper (Cu), has been identified as a risk to human health through the consumption of vegetable crops. This study investigates the source and magnitude of heavy metal contamination in soil and vegetable samples at 46 sites across four vegetable growing regions in New South Wales, Australia. The four regions Boolaroo, Port Kembla, Cowra and the Sydney Basin were a mix of commercial and residential vegetable growing areas. The extent of metal contamination in soils sampled was greatest in regions located in the vicinity of smelters, such as in Boolaroo and Port Kembla. Soil metal concentrations decreased with depth at these two sites, suggesting contamination due to anthropogenic activities. Cadmium, Pb and Zn contamination was greatest in vegetables from Boolaroo, and Cu concentrations were greatest in vegetables sampled from Port Kembla. At Boolaroo, nearly all the samples exceeded the Australian Food Standards maximum level (ML) (0.01 mg kg^{-1} fresh weight) of Cd and Pb in vegetables. Over 63% of samples exceeded international food standard guidelines set by the Commission of the European Communities and the Codex Alimentarius Commission. All vegetables sampled from Cowra, which is a relatively pristine site had Cd and Pb levels below the Australian and international food standards guideline values. This study suggests that the Australian guideline values are more conservative in defining the ML for Cd and Pb in vegetable crops. This investigation highlights the increased danger of growing vegetables in the vicinity of smelters.

Kolařík, J., R. Prucek, J. Tuček, J. Filip, V. K. Sharma and R. Zbořil. 2018. Impact of inorganic ions and natural organic matter on arsenates removal by ferrate (VI): Understanding a complex effect of phosphates ions. Water Research **141**: 357-365.

Arsenic compounds are carcinogenic to humans and are typically removed from contaminated water using various sorbents. The ionic composition plays a significant role in arsenate removal efficiency during the process of water remediation. Here, we quantify the effects of natural ions (chlorides, nitrates, carbonates, sulfates, and phosphates) and humic acid on the removal of arsenates by ferrate(VI) at pH = 6.6. In the experiments, the initial concentration of arsenates was 10 mg L^{-1} (as As) and the concentrations of ions varied in the range from 5 to 100 mg L^{-1} of element in ionic form and humic acid. The achieved results show that only phosphate ions had principle influence on the efficiency of arsenate removal by ferrate(VI). The effect of phosphates was elucidated by applying transmission electron microscopy, energy-dispersive X-ray spectroscopy, and low temperature in-field ^{57}Fe Mössbauer spectroscopy to solid samples, prepared under different weight ratios of ferrate(VI), arsenates, and phosphates. These results show three crucial effects of phosphates on the arsenate removal mechanisms. At low P:As weight ratio (up to 1:1), the incorporation of arsenate ions into the crystalline structure of γ-Fe2O3/γ-FeOOH nanoparticles was found to be suppressed by the presence of phosphates. Thus, arsenates were mainly adsorbed onto the surface of γ-Fe2O3/γ-FeOOH nanoparticles. Further increase in the P:As weight ratio (more than 1:1) resulted in the competition between arsenates and phosphates sorption. With the increased concentration of phosphate ions, the number of arsenates on the surface of γ-Fe2O3/γ-FeOOH nanoparticles was reduced. Finally, the complexation of iron(III) ions with phosphate ions occurred, leading to a decrease in the arsenates removal efficiency, which resulted from a lower content of precipitated γ-Fe2O3/γ-FeOOH nanoparticles. All these aspects need to be considered prior to application of ferrate(VI) for arsenates removal in real natural waters.

Kristensen, L. J. 2015. Quantification of atmospheric lead emissions from 70 years of leaded petrol consumption in Australia. Atmospheric Environment **111**: 195-201.

Lead is a persistent pollutant and the subject of many environmental studies, yet, in Australia, the extent of atmospheric lead emissions from the use of leaded petrol is unquantified. This paper details the first comprehensive account of leaded petrol sales and its lead concentrations over the 70 years of use in Australia. The resulting atmospheric lead emissions are calculated to provide the most complete understanding of the volume of lead released to the Australian continent from the consumption of leaded petrol. Atmospheric emissions of lead to the entire Australian continent from leaded petrol are calculated to total 240,510 tonnes over seven decades of use, peaking at 7869 tonnes in 1974. Total emissions for individual states and territories range from 1745 to 67,893 tonnes, with New South Wales responsible for the largest emissions. The effect of regulations on allowable concentrations of tetraethyl-lead additives are observed in the reduction of lead emissions in New South Wales and Victoria. The consequences to human health and the environment of leaded petrol consumption in Australia's populous cities are examined against historical air quality data and blood lead levels.

Kristensen, L. J. and M. P. Taylor. 2016. Unravelling a ‘miner’s myth’that environmental contamination in mining towns is naturally occurring. Environmental Geochemistry and Health **38**(4): 1015-1027.

Australia has a long history of metal mining and smelting. Extraction and processing have resulted in elevated levels of toxic metals surrounding mining operations, which have adverse health effects, particularly to children. Resource companies, government agencies and employees often construct ‘myths’ to down play potential exposure risks and responsibility arising from operating emissions. Typical statements include: contaminants are naturally occurring, the wind blows emissions away from residential areas, contaminants are not bioavailable, or the problem is a legacy issue and not related to current operations. Evidence from mining and smelting towns shows that such ‘myths’ are exactly that. In mining towns, the default and primary defence against contamination is that elevated metals in adjacent urban environments are from the erosion and weathering of the ore bodies over millennia—hence ‘naturally occurring’. Not only is this a difficult argument to unravel from an evidence-based perspective, but also it causes confusion and delays remediation work, hindering efforts to reduce harmful exposures to children. An example of this situation is from Broken Hill, New South Wales, home to one of the world’s largest lead–zinc–silver ore body, which has been mined continuously for over 130 years. Environmental metal concentration and lead isotopic data from soil samples collected from across Broken Hill are used to establish the nature and timing of lead contamination. We use multiple lines of evidence to unravel a ‘miner’s myth’ by evaluating current soil metal concentrations and lead isotopic compositions, geological data, historical environmental assessments and old photographic evidence to assess the impacts from early smelting along with mining to the surface soils in the city.

Kristensen, L. J., M. P. Taylor and A. R. Flegal. 2017. An odyssey of environmental pollution: The rise, fall and remobilisation of industrial lead in Australia. Applied Geochemistry **83**: 3-13.

The use of lead as an additive in petrol resulted in more than 240,000 tonnes of lead being emitted to the Australian environment over a 70-year period from 1932, until lead additives in petrol were eliminated in 2002. The consequences of Australia's protracted industrial lead emissions and

subsequent depositions caused widespread contamination of urban and peri-urban aerosols, soils, plants, animals, and humans. This paper charts the impact of those lead emissions via environmental archives and proxies and examines the extent of recovery from one of the biosphere's most pervasive and persistent environmental pollutants. The remobilisation of industrial lead is examined by analysis of Sydney air filters that bracket wildfires between 1994 and 2004. Proxy atmospheric measurements of historical wine, lichen and fungi samples extending up to 150 years bp show how both lead concentration and isotopic composition values shifted in the middle to late 20th century to reflect petrol emissions and then recovered rapidly at the end of the century as leaded petrol was phased out. Lead isotopic composition of aerosol filters from Adelaide and Sydney show that air lead composition shifted from values that approximate Broken Hill type ores, the predominant lead source used in petrol (206Pb/207Pb ¼ 1.04; 208Pb/207Pb ¼ 2.32), towards ratios that more closely match local uncontaminated soil and bedrock values in Adelaide (206Pb/207Pb ¼ 1.21; 208Pb/207Pb ¼ 2.52) and Sydney (206Pb/207Pb ¼ 1.14; 208Pb/207Pb ¼ 2.44). However, the recovery from that historic industrial lead contamination is incomplete. Measurements of contemporary surface soils, ash produced from wildfires and aerosols demonstrate legacy industrial lead depositions are declining but are still subject to remobilisation.

Kristensen, L. J., M. P. Taylor and A. L. Morrison. 2015. Lead and zinc dust depositions from ore trains characterised using lead isotopic compositions. Environmental Science: Processes & Impacts **17**(3): 631-637.

This study investigates an unusual source of environmental lead contamination – the emission and deposition of lead and zinc concentrates along train lines into and out of Australia's oldest silver–lead–zinc mine at Broken Hill, Australia. Transport of lead and zinc ore concentrates from the Broken Hill mines has occurred for more than 125 years, during which time the majority was moved in uncovered rail wagons. A significant amount of ore was lost to the adjoining environments, resulting in soil immediately adjacent to train lines elevated with concentrations of lead (695 mg kg^{-1}) and zinc (2230 mg kg^{-1}). Concentrations of lead and zinc decreased away from the train line and also with depth shown in soil profiles. Lead isotopic compositions demonstrated the soil lead contained Broken Hill ore in increasing percentages closer to the train line, with up to 97% apportioned to the mined Broken Hill ore body. SEM examination showed ceiling dusts collected from houses along the train line were composed of unweathered galena particles, characteristic of the concentrate transported in the rail wagons. The loss of ore from the uncovered wagons has significantly extended the environmental footprint of contamination from local mining operations over an area extending hundreds of kilometres along each of the three train lines.

Laidlaw, M. A. S., G. M. Filippelli, S. Brown, J. Paz-Ferreiro, S. M. Reichman, P. Netherway, A. Truskewycz, A. S. Ball and H. W. Mielke. 2017. Case studies and evidence-based approaches to addressing urban soil lead contamination. Applied Geochemistry **83**: 14-30.

Urban soils in many communities in the United States and internationally have been contaminated by lead (Pb) from past use of lead additives in gasoline, deterioration of exterior paint, emissions from Pb smelters and battery recycling and other industries. Exposure to Pb in soil and related dust is widespread in many inner city areas. Up to 20–40% of urban children in some neighborhoods have blood lead levels (BLLs) equal to or above 5 µg per decilitre, the reference level of health concern by the U.S. Centers for Disease Control. Given the widespread nature of Pb contamination in urban soils it has proven a challenge to reduce exposure. In order to prevent this exposure, an evidence-based approach is required to isolate or remediate the soils and prevent children and adult's ongoing exposure. To date, the majority of community soil Pb remediation efforts have been focused in mining towns or in discrete neighborhoods where Pb smelters have impacted communities. These efforts have usually entailed very expensive dig and dump soil Pb remediation techniques, funded by the point source polluters. Remediating widespread non-point source urban soil contamination using this approach is neither economical nor feasible from a practical standpoint. Despite the need to remediate/isolate urban soils in inner city areas, no deliberate, large scale, cost effective Pb remediation schemes have been implemented to isolate inner city soils impacted from sources other than mines and smelters. However, a city-wide natural experiment of flooding in New Orleans by Hurricane Katrina demonstrated that declines in soil Pb resulted in major BLL reductions. Also a growing body of literature of smaller scale pilot studies and programs does exist regarding low

cost efforts to isolate Pb contaminated urban soils. This paper reviews the literature regarding the effectiveness of soil Pb remediation for reducing Pb exposure and BLL in children, and suggests best practices for addressing the epidemics of low-level Pb poisoning occurring in many inner city areas.

Lanphear, B. P., R. Hornung, J. Khoury, K. Yolton, P. Baghurst, D. C. Bellinger, R. L. Canfield, K. N. Dietrich, R. Bornschein and T. Greene. 2005. Low-level environmental lead exposure and children's intellectual function: an international pooled analysis. Environ Health Perspect **113**(7): 894.

Lead is a confirmed neurotoxin, but questions remain about lead-associated intellectual deficits at blood lead levels <10 µg/dL and whether lower exposures are, for a given change in exposure, associated with greater deficits. The objective of this study was to examine the association of intelligence test scores and blood lead concentration, especially for children who had maximal measured blood lead levels <10 µg/dL. We examined data collected from 1,333 children who participated in seven international population-based longitudinal cohort studies, followed from birth or infancy until 5–10 years of age. The full-scale IQ score was the primary outcome measure. The median blood lead concentration of the children peaked at 18.0 µg/dL and declined to 9.7 µg/dL by 5–7 years of age; 258 (19.4%) children had a maximal blood lead concentration <10 µg/dL, and 118 (8.9%) had a maximal blood lead concentration <7.5 µg/dL. After adjustment for covariates, we found an inverse relationship between blood lead concentration and IQ score. Using a log-linear model, we found a 6.7 IQ point decrement [95% confidence interval (CI), 4.1–9.3] associated with an increase in concurrent blood lead levels from 2.4 to 30 µg/dL. The estimated IQ point decrements associated with an increase in blood lead from 2.4 to 10 µg/dL, 10 to 20 µg/dL, and 20 to 30 µg/dL were 3.8 (95% CI, 2.3–5.3), 1.8 (95% CI, 1.1–2.6), and 1.1 (95% CI, 0.7–1.5), respectively. For a given increase in blood lead, the lead-associated intellectual decrement for children with a maximal blood lead level <7.5 µg/dL was significantly greater than that observed for those with a maximal blood lead level ≥7.5 µg/dL (p=0.02). We conclude that environmental lead exposure in children who have maximal blood lead levels <7.5 µg/dL is associated with intellectual deficits.

Lanphear, B. P., S. Rauch, P. Auinger, R. W. Allen and R. W. Hornung. 2018. Low-level lead exposure and mortality in US adults: a population-based cohort study. The Lancet Public Health **3**(4): e177-e184.

Lead exposure is a risk factor for cardiovascular disease mortality, but the number of deaths in the USA attributable to lead exposure is poorly defined. We aimed to quantify the relative contribution of environmental lead exposure to all-cause mortality, cardiovascular disease mortality, and ischaemic heart disease mortality. Our study population comprised a nationally representative sample of adults aged 20 years or older who were enrolled in the Third National Health and Nutrition Examination Survey (NHANES-III) between 1988 and 1994 and followed up to Dec 31, 2011. Participants had completed a medical examination and home interview and had results for concentrations of lead in blood, cadmium in urine, and other relevant covariates. Individuals were linked with the National Death Index. This study presents extended follow-up of an earlier analysis. We included 14 289 adults in our study. The geometric mean concentration of lead in blood was 2·71 µg/dL (geometric SE 1·31). 3632 (20%) participants had a concentration of lead in blood of at least 5 µg/dL (≥0·24 µmol/L). During median follow-up of 19·3 years (IQR 17·6–21·0), 4422 people died, 1801 (38%) from cardiovascular disease and 988 (22%) from ischaemic heart disease. An increase in the concentration of lead in blood from 1·0 µg/dL to 6·7 µg/dL (0·048 µmol/L to 0·324 µmol/L), which represents the tenth to 90th percentiles, was associated with all-cause mortality (hazard ratio 1·37, 95% CI 1·17–1·60), cardiovascular disease mortality (1·70, 1·30–2·22), and ischaemic heart disease mortality (2·08, 1·52–2·85). The population attributable fraction of the concentration of lead in blood for all-cause mortality was 18·0% (95% CI 10·9–26·1), which is equivalent to 412 000 deaths annually. Respective fractions were 28·7% (15·5–39·5) for cardiovascular disease mortality and 37·4% (23·4–48·6) for ischaemic heart disease mortality, which correspond to 256 000 deaths a year from cardiovascular disease and 185 000 deaths a year from ischaemic heart disease. Low-level environmental lead exposure is an important, but largely overlooked, risk factor for cardiovascular disease mortality in the USA. A comprehensive strategy to prevent deaths from cardiovascular disease fshould include efforts to reduce lead exposure.

Lanphear, B. P. and K. J. Roghmann. 1997. Pathways of Lead Exposure in Urban Children. Environ Res **74**(1): 67-73.

> A linear structural equation modeling procedure was used to explore the mechanisms and pathways for lead intake among urban children and the relative contribution of various lead sources to lead-contaminated house dust. Dust lead levels were significantly associated with children's blood lead levels, both indirectly and directly via hand lead. Both soil and paint lead contributed to dust lead levels, but paint contributed significantly more lead to house dust than soil (P< 0.001). Black race and income level both directly affected children's blood lead levels. Finally, time spent outdoors was associated with children putting soil or dirt in their mouths which was, in turn, associated with children's blood lead levels. These data indicate that mouthing behaviors are an important mechanism of exposure among urban children with low-level elevations in blood lead and that lead-based paint is a more important contributor of lead to house dust than is lead-contaminated soil.

Larsen, M. M., J. S. Blusztajn, O. Andersen and I. Dahllöf. 2012. Lead isotopes in marine surface sediments reveal historical use of leaded fuel. Journal of Environmental Monitoring **14**(11): 2893-2901.

> Analyses of lead (Pb) isotopes have been performed in terrestrial and fresh water environments to estimate historical uses of leaded fuel, but so far this method has not been employed in studies of world-wide marine surface sediments. We analyzed Pb and its isotopes in 23 surface sediments from four continents collected during the Galathea 3 expedition in 2006–2007. To enhance the anthropogenic signal, a partial digestion using nitric acid was performed. The concentrations of Pb, Th, U and Al were determined with an ICP-Quadrupole MS, and Pb-isotope ratios with an ICP-multi-collector MS. The samples could be divided into three groups: Harbor areas in larger cities with concentrations of 150 to 265 mg kg−1 dry weight, smaller towns with concentrations between 20 and 40 mg kg−1 dry weight, and remotely located sites with concentrations below 15 mg kg−1 dry weight. Pb-isotope ratios were compared to literature values for gasoline and local or geological background values, and the contribution of leaded-gasoline to total concentrations was calculated for contaminated sites using both a one-dimensional and a novel two-dimensional (vector) method. The North American sites had Pb-isotope ratios corresponding to the US leaded gasoline, with 24–88% of the Pb from leaded gasoline. Samples from Oceania showed Pb-isotope ratios corresponding to Australian gasoline, with 60% attributed to leaded gasoline in Sydney and 21% in Christchurch. Outside Cape Town, 15 to 46% of Pb in sediments was from leaded gasoline.

Lesjak, M., N. Gough, D. Belshaw and J. Tall. 2013. Lead Health Report 2012. Children less than 5 years old in Broken Hill. Population Health Unit, Western NSW & Far West Local Health Districts, Broken Hill, New South Wales. Accessed at BHELP.

Lesjak, M. and T. Jones. 2015. Lead Health Report 2014: Children Less than 5 years old in Broken Hill. Accessed 27th August 2018 at http://leadsmart.nsw.gov.au/wp-content/uploads/2016/12/Broken-Hill-Lead-Health-Report-2015-children-aged-0%E2%80%934.pdf.

Li, S.-W., X. Liu, H.-J. Sun, M.-Y. Li, D. Zhao, J. Luo, H.-B. Li and L. Q. Ma. 2017. Effect of phosphate amendment on relative bioavailability and bioaccessibility of lead and arsenic in contaminated soils. J Hazard Mater **339**: 256-263.

Li, Y., C. Xie, S. K. Murphy, D. Skaar, M. Nye, A. C. Vidal, K. M. Cecil, K. N. Dietrich, A. Puga, R. L. Jirtle, et al. 2016. Lead Exposure during Early Human Development and DNA Methylation of Imprinted Gene Regulatory Elements in Adulthood. Environ Health Perspect **124**(5): 666-673.

> The objective of this study was to determine whether maternal, postnatal, and early childhood lead exposure can alter the differentially methylated regions (DMRs) that control the monoallelic expression of imprinted genes involved in metabolism, growth, and development. Questionnaire data and serial blood lead levels were obtained from 105 participants (64 females, 41 males) of the Cincinnati Lead Study from birth to 78 months. When participants were adults, we used Sequenom EpiTYPER assays to test peripheral blood DNA to quantify CpG methylation in peripheral blood

leukocytes at DMRs of 22 human imprinted genes. Statistical analyses were conducted using linear regression. Mean blood lead concentration from birth to 78 months was associated with a significant decrease in PEG3 DMR methylation (β = –0.0014; 95% CI: –0.0023, –0.0005, p = 0.002), stronger in males (β = –0.0024; 95% CI: –0.0038, –0.0009, p = 0.003) than in females (β = –0.0009; 95% CI: –0.0020, 0.0003, p = 0.1). Elevated mean childhood blood lead concentration was also associated with a significant decrease in IGF2/H19 (β = –0.0013; 95% CI: –0.0023, –0.0003, p = 0.01) DMR methylation, but primarily in females, (β = –0.0017; 95% CI: –0.0029, –0.0006, p = 0.005) rather than in males, (β = –0.0004; 95% CI: –0.0023, 0.0015, p = 0.7). Elevated blood lead concentration during the neonatal period was associated with higher PLAGL1/HYMAI DMR methylation regardless of sex (β = 0.0075; 95% CI: 0.0018, 0.0132, p = 0.01). The magnitude of associations between cumulative lead exposure and CpG methylation remained unaltered from 30 to 78 months. Our findings provide evidence that early childhood lead exposure results in sex-dependent and gene-specific DNA methylation differences in the DMRs of PEG3, IGF2/H19, and PLAGL1/HYMAI in adulthood.

Lin, S., X. Wang, I. T. S. Yu, W. Tang, J. Miao, J. Li, S. Wu and X. Lin. 2011. Environmental lead pollution and elevated blood lead levels among children in a rural area of China. American journal of public health **101**(5): 834-841.

We investigated environmental lead pollution and its impact on children's blood lead levels (BLLs) in a rural area of China. In 2007, we studied 379 children younger than 15 years living in 7 villages near lead mines and processing plants, along with a control group of 61 children from another village. We determined their BLLs and collected environmental samples, personal data, and information on other potential exposures. We followed approximately 86% of the children who had high BLLs (> 15 µg/dL) for 1 year. We determined factors influencing BLLs by multivariate linear regression. Lead concentrations in soil and household dust were much higher in polluted villages than in the control village, and more children in the polluted area than in the control village had elevated BLLs (87%, 16.4 µg/dL vs 20%, 7.1 µg/dL). Increased BLL was independently associated with environmental lead levels. We found a significant reduction of 5 micrograms per deciliter when we retested children after 1 year. Our data show that the lead industry caused serious environmental pollution that led to high BLLs in children living nearby.

Low, C., D. Gore, M. P. Taylor and H. Louie. 2005. Black bluebush and old man saltbush biogeochemistry on a contaminated site: Broken Hill, New South Wales, Australia. Regolith 2005—Ten Years of CRC LEME**:** 213-218.

The mobilisation of heavy metals from soil into the trophic chain can pose a significant environmental and health risk if they accumulate in living organisms to toxic levels or levels that trigger illnesses. One important pathway by which soil-based heavy metals are mobilised into the trophic chain is through uptake by plants growing in metal-rich, often anthropogenically-contaminated soils. While many studies have focused on the soil to plant metal uptake pathway, these have been largely based in temperate areas and comparatively few similar studies have been conducted in arid locations, where a soil's mineral chemistry and environmental conditions are likely to be different those of more humid areas. Understanding how arid zone plants take up, store or alternatively reject metal contaminants has important implications, especially if the plant species are subject to grazing by animals. This paper presents the findings of a study investigating Zn, Cd and Pb phytoavailability trends in two xeromorphic halophyte shrub species (Atriplex nummularia and Maireana pyramidata) growing on a contaminated site at Broken Hill in far western New South Wales, Australia. Particular focus is given to the distribution of selected heavy metal analytes in plant tissue and plant soil, with implications for environmental health. The full results of this study are currently being compiled into a Masters thesis at Macquarie University.

Lucas, J.-P., L. Bellanger, Y. Le Strat, A. Le Tertre, P. Glorennec, B. Le Bot, A. Etchevers, C. Mandin and V. Sébille. 2014. Source contributions of lead in residential floor dust and within-home variability of dust lead loading. Science of The Total Environment **470-471**: 768-779.

Evidence of the impact of exposure to low levels of lead on children's health is increasing. Residential floor dust is the assumed origin of lead exposure by young children. In this study, we estimate the contribution of different lead sources to household interior floor dust contamination. We also estimate the within-home variability of interior floor dust lead loadings. A multilevel model was developed based on data collected in a French survey in 2008–2009 (484 housing units, 1834 rooms). Missing data were handled by multiple imputation using chained equations. The intra-home correlation between interior floor Log dust lead loadings was approximately 0.6. Dust lead from the landing of an apartment, mostly originating outside the building, was the major contributor to interior floor dust lead. Secondary contributors included the lead-based paint on exterior railings, track-in of the exterior soil of the children's play area into the dwelling, smoking inside the home, demolition of nearby old buildings and sites of pollution in the vicinity. Interior lead-based paint contaminated interior floor dust only in old and non-renovated dwellings. To reduce interior floor dust lead levels in the general population of dwellings, common areas should be maintained, and track-in from the outside should be limited as much as possible.

Lyle, D., A. Phillips, W. Balding, H. Burke, D. Stokes, S. Corbett and J. Hall. 2006. Dealing with lead in Broken Hill—trends in blood lead levels in young children 1991–2003. Science of The Total Environment **359**(1-3): 111-119.

The objective of the study was to investigate trends in blood lead concentrations in preschool children between 1991 and 2003, as part of the evaluation strategy of a public health lead management program in Broken Hill, Australia. Since 1991, all Broken Hill children aged 1-4 years have been offered at least annual blood lead screening as part of a community-wide lead management program. Recruitment of children was promoted throughout the period using local media and distribution of promotional material from health care centres and preschool, childcare, and educational facilities around the city. Venous blood samples were collected using standard procedures and analyses were subjected to internal and external quality control programs. Because the frequency distribution of blood lead levels are skewed, geometric rather than arithmetic means were used for comparative purposes. Trend analysis was based on age and sex standardised mean blood lead levels. The number of 1- to 4-year-old children screened ranged between 496 and 948 in any one year and response rates varied between 39% and 73%. The age-sex standardised mean blood lead level decreased from 16.3 microg/dL to 7.1 microg/dL between 1991 and 2003. Overall, blood lead levels declined by 56% over 13 years. These reductions were consistently observed irrespective of age or where a child lived in the town. The rate of decline has slowed since 1997. We conclude that substantial progress has been made in dealing with the lead problem in Broken Hill children, although the rate of decline of blood lead levels has slowed. Continued public health action is still needed to bring the proportion of young children with significantly elevated blood lead levels (>15 microg/dL) down from the 2003 figure of 12% to the NHMRC community-based target for lead in young Australians of 5%.

Maari Ma. 2017. Lead (Pb) and Aboriginal Children in Broken Hill.

Maynard, E., L. J. Franks and M. S. Malcolm. 2006. The Port Pirie lead implementation program: future focus and directions. South Australian Department of Health. Accessed 3rd Jul 2018 at http://www.sahealth.sa.gov.au/wps/wcm/connect/651e880048f416a3a672e70e3d7ae4ad/ptpirie-future-focus-06.pdf?MOD=AJPERES&CACHEID=651e880048f416a3a672e70e3d7ae4ad.

McMichael, A. J., P. A. Baghurst, N. R. Wigg, G. V. Vimpani, E. F. Robertson and R. J. Roberts. 1988. Port Pirie Cohort Study: environmental exposure to lead and children's abilities at the age of four years. New England journal of medicine **319**(8): 468-475.

We studied the effect of environmental exposure to lead on children's abilities at the age of four years in a cohort of 537 children born during 1979 to 1982 to women living in a community situated near a lead smelter. Samples for measuring blood lead levels were obtained from the mothers antenatally, at delivery from the mothers and umbilical cords, and at the ages of 6, 15, and 24 months and then annually from the children. Concurrently, the mothers were interviewed about personal, family, medical, and environmental factors. Maternal intelligence, the home environment, and the children's mental development (as evaluated with use of the McCarthy Scales of Children's Abilities) were formally assessed. The mean blood lead concentration varied from 0.44 mumol per liter in midpregnancy to a peak of 1.03 mumol per liter at the age of two years. The blood lead concentration at each age, particularly at two and three years, and the integrated postnatal average concentration were inversely related to development at the age of four. Multivariate analysis incorporating many factors in the children's lives indicated that the subjects with an average postnatal blood lead concentration of 1.50 mumol per liter had a general cognitive score 7.2 points lower (95 percent confidence interval, 0.3 to 13.2; mean score, 107.1) than those with an average concentration of 0.50 mumol per liter. Similar deficits occurred in the perceptual-performance and memory scores. Within the range of exposure studied, no threshold dose for an effect of lead was evident. We conclude that postnatal blood lead concentration is inversely related to cognitive development in children, although one must be circumspect in making causal inferences from studies of this relation, because of the difficulties in defining and controlling confounding effects.

Meyer, P. A., M. A. McGeehin and H. Falk. 2003. A global approach to childhood lead poisoning prevention. International journal of hygiene and environmental health **206**(4): 363-369.

Childhood lead poisoning is an important, preventable environmental disease affecting millions of children around the world. The effects of lead are well known and range from delayed and adversely affected neurodevelopment to severe health outcomes including seizures, coma, and death. This article reviews the childhood effects of lead poisoning, the approach being taken to the problem in the United States, and the obstacles faced by developing nations in dealing with lead exposure. The United States has attacked the childhood lead poisoning problem by attempting to eliminate sources of exposure, including gasoline, solder in water pipes and cans, and industrial emissions. These actions have resulted in a dramatic reduction in the number of children with elevated blood lead levels in the United States over the last two decades. However, many developing countries are just beginning to address the problem. Successful efforts will need to incorporate epidemiologic methods, source identification, enforced regulations, and a long-term government commitment to eliminating lead as a threat to the next generation of children.

Mielke, H. W., E. T. Powell, C. R. Gonzales, P. W. Mielke, R. T. Ottesen and M. Langedal. 2006. New Orleans soil lead (Pb) cleanup using Mississippi River alluvium: Need, feasibility, and cost. Environ Sci Technol **40**(8): 2784-2789.

In New Orleans, LA prior to hurricane Katrina 20−30% of inner-city children had elevated blood Pb levels ≥10 µg/dL and 10 census tracts had a median surface soil level of Pb >1000 mg/kg (2.5 times the U.S. standard). This project tests the feasibility of transporting and grading contaminated properties (n = 25) with 15 cm (6 in.) of clean Mississippi River alluvium from the Bonnet Carré Spillway (BCS) (median soil Pb content 4.7 mg/kg; range 1.7−22.8). The initial median surface soil Pb was 1051 mg/kg (maximum 19 627). After 680 metric tons (750 tons) of clean soil cover was emplaced on 6424 m2 (69 153 ft2), the median surface soil Pb decreased to 6 mg/kg (range 3−18). Interior entrance wipe samples were collected at 10 homes before and after soil treatment and showed a decreasing trend of Pb (p value = 0.048) from a median of 52 µg/ft2 to a median of 36 µg/ft2 (25th and 75th percentiles are 22 and 142 µg/ft2 and 12 and 61 µg/ft2, respectively). Average direct costs for properties with homes were $3,377 ($1.95 per square foot), with a range of $1,910−7,020, vs $2,622 ($0.61 per square foot), with a range of $2,400−3,040 for vacant lots. Approximately 40% (86,000) of properties in New Orleans are in areas of >400 mg Pb/kg soil and estimated direct costs for treatment are between $225.5 and $290.4 million. Annual costs of Pb poisoning in New Orleans are estimated at ~$76 million in health, education, and societal harm. Urban accumulation of Pb is an international problem; for example, the new Government of Norway established a policy precedence for an isolated soil cleanup program at daycare centers, school playgrounds, and parks to protect children. New Orleans requires a community-wide soil cleanup program because of the extent and quantity of accumulated soil Pb. The post-Katrina benefits of reducing soil Pb are expected to outweigh the foreseeable costs of Pb poisoning to children returning to New Orleans.

Moodie, S. M. and E. L. Evans. 2011. Ethical Issues in Using Children's Blood Lead Levels as a Remedial Action Objective. American journal of public health **101**(Suppl 1): S156-S160.

The Environmental Protection Agency measures the success or failure of Superfund site remediation efforts against remedial action objectives (RAOs). RAOs are frequently based on environmental contaminant concentrations, but with lead exposure, blood lead levels from the population at risk are often used. Although childhood lead screening is an important public health tool, an RAO based on child blood lead levels raises ethical concerns: public health efforts that are more reactive than preventive, a blood lead standard (10 µg/dL) that may not be fully protective, the use of a measure whose validity and reliability may be easily compromised, and exacerbation of environmental injustice and systematic disadvantages. The example of Bunker Hill mine, Kellogg, Idaho, allowed an examination of these ethical concerns.

Morland, R. and A. Webster. 1998. Broken Hill lead-zinc-silver deposit. Geology of Australian and Papua New guinean mineral deposits: 619-626.

Morrison, A. L., M. P. Taylor, P. F. Nelson and C. Dong. 2017. Pilot Study of lead (Pb) phases in deposited particles from Broken Hill, NSW determined using automated mineralogical scanning. Final Report. Accessed at

Dust deposition samples for microscopic examination were successfully obtained for six Broken Hill urban locations for the period December 2015–May 2016. Mineralogical analysis shows the dusts to be a heterogeneous mixture of soil-derived minerals, making up 95 % of the mass of the sample. A distribution of the phases containing lead (Pb) were estimated by QEMSCAN® . Pb phases that have undergone significant alteration from an original galena (PbS) product account for 44–96 % of the Pb in the deposited dust samples depending on sampled location. The pilot study carried out has successfully demonstrated that QEMSCAN® can be used to speciate Pb phases and quantify them into more recently deposited and significantly altered mineralogical groupings. The results justify the implementation of an extended sampling and analysis program to assist in the direction and monitoring of the ongoing Pb remediation/mitigation program.

National Environment Protection Council. 2013. Guideline on investigation levels for soil and groundwater. Accessed 25th February 2020 at http://www.nepc.gov.au/system/files/resources/93ae0e77-e697-e494-656f-afaaf9fb4277/files/schedule-b1-guideline-investigation-levels-soil-and-groundwater-sep10.pdf.

National Environment Protection Council. 2013. National Environment Protection (Assessment of Site Contamination) Measure. Accessed 22nd August 2018 at http://www.nepc.gov.au/nepms/assessment-site-contamination.

National Environment Protection Council. 2016. National Environment Protection (Ambient Air Quality) Measure. Accessed 25th February 2020 at http://www.nepc.gov.au/nepms/ambient-air-quality.

National Health and Medical Research Council (NHMRC). 2015. NHMRC statement: evidence on the effects of lead on human health. Accessed 3rd Jul 2018 at http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh58_nhmrc_statement_lead_effects_human_health_a.pdf.

National Pollutant Inventory. 2018. 2016/2017 data within Australia - Lead & compounds from All Sources. Accessed 17th August 2018 at http://www.npi.gov.au/npidata/action/load/emission-by-facility-result/criteria/substance/52/destination/ALL/source-type/ALL/subthreshold-data/Yes/substance-name/Lead%2B%2526%2Bcompounds/year/2017?sort=airTotal&dir=desc&pageSize=10.

National Pollutant Inventory. 2018. 2016/2017 report for Broken Hill Operations Pty Ltd, CBH Resources-Rasp Mine - Broken Hill , NSW. Accessed 17th August 2018 at http://www.npi.gov.au/npidata/action/load/emission-by-individual-facility-result/criteria/state/NSW/year/2016/jurisdiction-facility/1333.

National Research Council. 2003. Chapter 5 Moving forward with bioavailability in decision-making: Bioavailability of contaminants in soils and sediments: processes, tools, and applications, National Academies Press.

> Soils and sediments are the ultimate sink for many persistent organic and inorganic contaminants and have the potential to impact human and environmental health for a long time. Remediation and management of contaminated soils and sediments is often technically difficult and can be very expensive when there are large volumes of contaminated material. To more rationally allocate limited environmental management and remediation resources, there is a need to improve risk assessment by including more explicit consideration of bioavailability processes.

National Toxicology Program (NTP). 2012. NTP Monograph: Health Effects of Low-Level Lead. U.S. Department of Health and Human Services, pp. 1–185.

NHANES. 2019. National Health and Nutrition Examination Survey (NHANES). Accessed 25th February 2020 at https://www.cdc.gov/nceh/lead/data/nhanes.htm.

> The National Health and Nutrition Examination Survey (NHANES) is a population-based program of studies designed to assess the health and nutritional status of adults and children in the United States. NHANES is conducted by CDC's National Center for Health Statistics (NCHS) on a sample of the U.S. population of all ages to reflect the nation overall, rather than individual states or counties. Beginning in 1960, and as a continuous survey since 1999, NHANES has examined a sample of about 5,000 persons across the country with 15 selected counties visited each year. The sampling plan follows a complex, stratified, multistage, probability-cluster design to select a nationally representative sample of the U.S. civilian, non-institutionalized population based on age, sex, and race/ethnicity. Data on a broad range of health topics are collected through personal household interviews, physical examinations, and laboratory tests.

NSW Environment Protection Authority. 2016. Notice of variation of licence no. 2688. Accessed 25th February 2020 at https://apps.epa.nsw.gov.au/prpoeoapp/ViewPOEONotice.aspx?DOCID=-1&SYSUID=1&LICID=1545186.

NSW Government. 2017. Effectiveness report (post-campaign evaluation for Leadsmart). Supplied by BHELP.

NSW Ministry of Health. 2019. Lead report 2018: Broken HIll children less than 5 years old. Accessed 25th February 2020 at http://www.fwlhd.health.nsw.gov.au/UserFiles/files/About%20us%20(Far%20West)/BH%20Lead%20Report%2020190528.pdf.

Nussbaumer-Streit, B., B. Yeoh, U. Griebler, L. M. Pfadenhauer, L. K. Busert, S. K. Lhachimi, S. Lohner and G. Gartlehner. 2016. Household interventions for preventing domestic lead exposure in children. Cochrane Database of Systematic Reviews(10).

> Lead poisoning is associated with physical, cognitive and neurobehavioural impairment in children, and trials have tested many household interventions to prevent lead exposure. This is an update of the original review, first published in 2008. To assess the effects of household interventions for preventing or reducing lead exposure in children, as measured by improvements in cognitive and neurobehavioural development, reductions in blood lead levels and reductions in household dust lead levels.

OEH. 2018. Broken Hill Environmental Lead Study (BHELS) Year 1 Report. Office of Environment and Hereitage.

Perilya. 2017. Construction air quality management plan Broken Hill North Mine Project. Accessed 11th September 2018 at http://www.perilya.com.au/articles/construction-air-quality-management-plan/H02S02PLN0009_-_North_Mine_Construction_Air_Quality_Management_Plan.pdf.

Perilya. 2017. Response to Submissions. Accessed 12th September 2018 at http://www.rwcorkery.com.au/Portals/0/93809-rts-2017_september-2017_010218092033.pdf.

Perilya. 2018. Broken Hill. Accessed 25th February 2020 at http://www.perilya.com.au/our-business/operations/broken-hill.

Perilya. 2018. Environmental Reports. Accessed 25th February 2020 at http://www.perilya.com.au/health--safety--environment/environment/reports.

Phillips, A. and J. Hall. 1994. Risk factors for blood lead levels in preschool children in Broken Hill 1991–1993. Western NSW Public Health Unit Report, Vols **1**.

Planning NSW. 2014. Voluntary land acquisition and mitigation policy for state significant mining, petroleum and extractive industry developments. Accessed 25th February 2020 at https://www.planning.nsw.gov.au/-/media/Files/DPE/Plans-and-policies/volntary-land-acquisition-policy.ashx?la=en.

> This document describes the NSW Government's policy for voluntary mitigation and land acquisition to address noise and dust (particulate matter) impacts from State significant mining, petroleum and extractive industry developments.

Queensland Department of Environment and Science. 2018. Environmental authority number: EPML00977513 Mount Isa Mines Limited. Accessed 25th February 2020 at https://environment.ehp.qld.gov.au/env-authorities/pdf/epml00977513.pdf.

Rabito, F. A., S. Iqbal, C. F. Shorter, P. Osman, P. E. Philips, E. Langlois and L. E. White. 2007. The association between demolition activity and children's blood lead levels. Environ Res **103**(3): 345-351.

> Urban renewal efforts are a priority for many American cities. As efforts to reconstitute urban centers increase, the demolition of old, deteriorated structures has accelerated. Recent studies have identified demolitions as a potential source of environmental lead exposure. We conducted a study examining the relationship between demolition activity and blood lead levels of children residing in neighborhoods where demolition activity occurred. A retrospective cohort study was conducted in St. Louis City, Missouri. The study period was January 1, 2002 to December 31, 2002. Data were obtained from the Missouri Childhood Lead Poisoning Prevention Program's (CLPPP) lead surveillance system and St. Louis Demolition Permit Database. Children were considered exposed to a demolition if they had a blood lead test within 45 days of any demolition on a census block. Exposure was classified as both a dichotomous (yes/no) and a categorical (none/one/multiple) variable and was analyzed separately. Linear regression models were developed to determine effects of demolitions on blood lead levels. A total of 1196 children 6–72 months of age living in 395 census blocks were included. 314 (26.3%) were exposed and 882 (73.7%) were unexposed to a demolition. In an adjusted model, exposure to multiple demolitions was found to have significant effects on children blood lead levels (coefficient=0.281; 95% CI=0.069, 0.493; P-value=0.010). Age of the child, race, and age of housing where children's resided were also significant predictors. This study suggests that multiple demolitions within a census block may significantly increase children's blood lead levels. The findings may be useful to municipal planners in older cities where demolitions are being used as an urban renewal tool.

Rasmussen, P. E., S. Beauchemin, M. Chénier, C. Levesque, L. C. W. MacLean, L. Marro, H. Jones-Otazo, S. Petrovic, L. T. McDonald and H. D. Gardner. 2011. Canadian House Dust Study: Lead Bioaccessibility and Speciation. Environ Sci Technol **45**(11): 4959-4965.

Vacuum samples were collected from 1025 randomly selected urban Canadian homes to investigate bioaccessible Pb (PbS) concentrations in settled house dust. Results indicate a polymodal frequency distribution, consisting of three lognormally distributed subpopulations defined as “urban background” (geomean 58 µg g–1), “elevated” (geomean 447 µg g–1), and “anomalous” (geomean 1730 µg g–1). Dust PbS concentrations in 924 homes (90%) fall into the “urban background” category. The elevated and anomalous subpopulations predominantly consist of older homes located in central core areas of cities. The influence of house age is evidenced by a moderate correlation between house age and dust PbS content (R2 = 0.34; n = 1025; p < 0.01), but it is notable that more than 10% of homes in the elevated/anomalous category were built after 1980. Conversely, the benefit of home remediation is evidenced by the large number of homes (33%) in the background category that were built before 1960. The dominant dust Pb species determined using X-ray Absorption Spectroscopy were as follows: Pb carbonate, Pb hydroxyl carbonate, Pb sulfate, Pb chromate, Pb oxide, Pb citrate, Pb metal, Pb adsorbed to Fe- and Al-oxyhydroxides, and Pb adsorbed to humate. Pb bioaccessibility estimated from solid phase speciation predicts Pb bioaccessibility measured using a simulated gastric extraction (R2 = 0.85; n = 12; p < 0.0001). The trend toward increased Pb bioaccessibility in the elevated and anomalous subpopulations (75% ± 18% and 81% ± 8%, respectively) compared to background (63% ± 18%) is explained by the higher proportion of bioaccessible compounds used as pigments in older paints (Pb carbonate and Pb hydroxyl carbonate). This population-based study provides a nationally representative urban baseline for applications in human health risk assessment and risk management.

Rasmussen, P. E., C. Levesque, M. Chénier, H. D. Gardner, H. Jones-Otazo and S. Petrovic. 2013. Canadian House Dust Study: Population-based concentrations, loads and loading rates of arsenic, cadmium, chromium, copper, nickel, lead, and zinc inside urban homes. Science of The Total Environment **443**: 520-529.

The Canadian House Dust Study was designed to obtain nationally representative urban house dust metal concentrations (µgg−1) and metal loadings (µgm−2) for arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn). Consistent sampling ofactive dust ofknown age and provenance (area sampled) also permitted the calculation of indoor loading rates (mg m−2 day−1 for dust and µgm−2 day−1 for metals) for the winter season (from 2007 to 2010) when houses are most tightly sealed. Geomean/median indoor dust loading rates in homes located more than 2 km away from industry of any kind (9.6/9.1 mg m−2 day−1; n=580) were significantly lower (pb.001) than geomean (median) dust loading rates in homes located within 2 km of industry (13.5/13.4 mg m−2 day−1; n=421). Proximity to industry was characterized by higher indoor metal loading rates (pb.003), but no difference in dust metal concentrations (.29≥p≤.97). Comparisons of non-smokers' and smokers' homes in non-industrial zones showed higher metal loading rates (.005≥p≤.038) in smokers' homes, but no difference in dust metal concentrations (.15≥p≤.97). Relationships between house age and dust metal concentrations were significant for Pb, Cd and Zn (pb.001) but not for the other fourmetals (.14≥p≤.87). All sevenmetals, however, displayed a significant increase in metal loading rates with house age (pb.001) due to the influence ofhigher dust loading rates in older homes (pb.001). Relationships between three measures ofmetals in house dust – concentration, load, and loading rate – in the context of house age, smoking behavior and urban setting consistently show that concentration data is a useful indicator of the presence of metal sources in the home, whereas dust mass is the overriding influence on metal loadings and loading rates.

Reuben, A., A. Caspi, D. W. Belsky, J. Broadbent, H. Harrington, K. Sugden, R. M. Houts, S. Ramrakha, R. Poulton and T. E. Moffitt. 2017. Association of childhood blood lead levels with cognitive function and socioeconomic status at age 38 years and with IQ change and socioeconomic mobility between childhood and adulthood. JAMA **317**(12): 1244-1251.

Many children in the United States and around the world are exposed to lead, a developmental neurotoxin. The long-term cognitive and socioeconomic consequences of lead exposure are uncertain. Objective To test the hypothesis that childhood lead exposure is associated with cognitive function and socioeconomic status in adulthood and with changes in IQ and socioeconomic mobility between childhood and midlife. Design, Setting, and Participants A prospective cohort study based on a population-representative 1972-1973 birth cohort from New Zealand; the Dunedin Multidisciplinary Health and Development Study observed participants to age 38 years (until

December 2012). Exposures Childhood lead exposure ascertained as blood lead levels measured at age 11 years. High blood lead levels were observed among children from all socioeconomic status levels in this cohort. Main Outcomes and Measures The IQ (primary outcome) and indexes of Verbal Comprehension, Perceptual Reasoning, Working Memory, and Processing Speed (secondary outcomes) were assessed at age 38 years using the Wechsler Adult Intelligence Scale–IV (WAIS-IV; IQ range, 40-160). Socioeconomic status (primary outcome) was assessed at age 38 years using the New Zealand Socioeconomic Index-2006 (NZSEI-06; range, 10 [lowest]-90 [highest]). Results Of 1037 original participants, 1007 were alive at age 38 years, of whom 565 (56%) had been lead tested at age 11 years (54% male; 93% white). Mean (SD) blood lead level at age 11 years was 10.99 (4.63) µg/dL. Among blood-tested participants included at age 38 years, mean WAIS-IV score was 101.16 (14.82) and mean NZSEI-06 score was 49.75 (17.12). After adjusting for maternal IQ, childhood IQ, and childhood socioeconomic status, each 5-µg/dL higher level of blood lead in childhood was associated with a 1.61-point lower score (95% CI, −2.48 to −0.74) in adult IQ, a 2.07-point lower score (95% CI, −3.14 to −1.01) in perceptual reasoning, and a 1.26-point lower score (95% CI, −2.38 to −0.14) in working memory. Associations of childhood blood lead level with deficits in verbal comprehension and processing speed were not statistically significant. After adjusting for confounders, each 5-µg/dL higher level of blood lead in childhood was associated with a 1.79-unit lower score (95% CI, −3.17 to −0.40) in socioeconomic status. An association between greater blood lead levels and a decline in IQ and socioeconomic status from childhood to adulthood was observed with 40% of the association with downward mobility mediated by cognitive decline from childhood. Conclusions and Relevance In this cohort born in New Zealand in 1972-1973, childhood lead exposure was associated with lower cognitive function and socioeconomic status at age 38 years and with declines in IQ and with downward social mobility. Childhood lead exposure may have long-term ramifications.

Reuben, A., J. D. Schaefer, T. E. Moffitt, J. Broadbent, H. Harrington, R. M. Houts, S. Ramrakha, R. Poulton and A. Caspi. 2019. Association of Childhood Lead Exposure With Adult Personality Traits and Lifelong Mental HealthAssociation of Childhood Lead Exposure With Adult Personality Traits and Mental HealthAssociation of Childhood Lead Exposure With Adult Personality Traits and Mental Health. JAMA psychiatry **76**(4): 418-425.

Millions of adults now entering middle age were exposed to high levels of lead, a developmental neurotoxin, as children. Although childhood lead exposure has been linked to disrupted behavioral development, the long-term consequences for adult mental and behavioral health have not been fully characterized.To examine whether childhood lead exposure is associated with greater psychopathology across the life course and difficult adult personality traits.This prospective cohort study was based on a population-representative birth cohort of individuals born between April 1, 1972, and March 31, 1973, in Dunedin, New Zealand, the Dunedin Multidisciplinary Health and Development Study. Members were followed up in December 2012 when they were 38 years of age. Data analysis was performed from March 14, 2018, to October 24, 2018.Childhood lead exposure ascertained as blood lead levels measured at 11 years of age. Blood lead levels were unrelated to family socioeconomic status.Primary outcomes were adult mental health disorder symptoms assessed through clinical interview at 18, 21, 26, 32, and 38 years of age and transformed through confirmatory factor analysis into continuous measures of general psychopathology and internalizing, externalizing, and thought disorder symptoms (all standardized to a mean [SD] of 100 [15]) and adult personality assessed through informant report using the Big Five Personality Inventory (assessing neuroticism, extraversion, openness to experience, agreeableness, and conscientiousness) at 26, 32, and 38 years of age (all scores standardized to a mean [SD] of 0 [1]). Hypotheses were formulated after data collection; an analysis plan was posted in advance.Of 1037 original study members, 579 (55.8%) were tested for lead exposure at 11 years of age (311 [53.7%] male). The mean (SD) blood lead level was 11.08 (4.96) µg/dL. After adjusting for study covariates, each 5-µg/dL increase in childhood blood lead level was associated with a 1.34-point increase (95% CI, 0.11-2.57; P = .03) in general psychopathology, driven by internalizing (b = 1.41; 95% CI, 0.19-2.62; P = .02) and thought disorder (b = 1.30; 95% CI, 0.06-2.54; P = .04) symptoms. Each 5-µg/dL increase in childhood blood lead level was also associated with a 0.10-SD increase in neuroticism (95% CI, 0.02-0.08; P = .02), a 0.09-SD decrease in agreeableness (95% CI, −0.18 to −0.01; P = .03), and a 0.14-SD decrease in conscientiousness (95% CI, −0.25 to −0.03; P = .01). There were no statistically significant associations with informant-rated extraversion (b = −0.09; 95% CI,

−0.17 to 0.004; P = .06) and openness to experience (b = −0.07; 95% CI, −0.17 to 0.03; P = .15).In this multidecade, longitudinal study of lead-exposed children, higher childhood blood lead level was associated with greater psychopathology across the life course and difficult adult personality traits. Childhood lead exposure may have long-term consequences for adult mental health and personality.

Rouillon, M., P. J. Harvey, L. J. Kristensen, S. G. George and M. P. Taylor. 2017. VegeSafe: A community science program measuring soil-metal contamination, evaluating risk and providing advice for safe gardening. Environ Pollut **222**: 557-566.

The extent of metal contamination in Sydney residential garden soils was evaluated using data collected during a three-year Macquarie University community science program called VegeSafe. Despite knowledge of industrial and urban contamination amongst scientists, the general public remains under-informed about the potential risks of exposure from legacy contaminants in their home garden environment. The community was offered free soil metal screening, allowing access to soil samples for research purposes. Participants followed specific soil sampling instructions and posted samples to the University for analysis with a field portable X-ray Fluorescence (pXRF) spectrometer. Over the three-year study period, >5200 soil samples, primarily from vegetable gardens, were collected from >1200 Australian homes. As anticipated, the primary soil metal of concern was lead; mean concentrations were 413 mg/kg (front yard), 707 mg/kg (drip line), 226 mg/kg (back yard) and 301 mg/kg (vegetable garden). The Australian soil lead guideline of 300 mg/kg for residential gardens was exceeded at 40% of Sydney homes, while concentrations >1000 mg/kg were identified at 15% of homes. The incidence of highest soil lead contamination was greatest in the inner city area with concentrations declining towards background values of 20–30 mg/kg at 30–40 km distance from the city. Community engagement with VegeSafe participants has resulted in useful outcomes: dissemination of knowledge related to contamination legacies and health risks; owners building raised beds containing uncontaminated soil and in numerous cases, owners replacing all of their contaminated soil.

Ryan, J. A., K. G. Scheckel, W. R. Berti, S. L. Brown, S. W. Casteel, R. L. Chaney, J. Hallfrisch, M. Doolan, P. Grevatt and M. Maddaloni. 2004. Reducing children's risk from lead in soil, ACS Publications.

Ryan, J. A. and P. Zhang. 2000. Soil lead remediation: Is removal the only option. US EPA Risk Reduction Engineering Laboratory: 260-263.

Lead, a naturally occurring metal, has always been present in soils, surface waters and ground Inner-city neighborhoods in most of our major cities have mean or median soil Pb waters. Lead content of agricultural soils ranges from > 1 mg/kg to 135 mg/kg with a median value of 11 mgkg (1). concentrations in excess of 1000 mg/kg (2-6) with values as high as 50,000 mg/kg being reported (7). Most of these elevated lead concentrations observed in the urban soils are assumed to come from various anthropogenic sources: industrial emissions, vehicular emissions and exterior lead paint (8). Additionally, lead has been added to soil as the insecticide lead arsenate, impurity in fertilizers as well as from mining and smelting activities (9). Further, lead is a contaminant of concern in about one third of the National Priorii List (NPL) sites and over 400 Superfund sites have excessive soil Pb concentrations (10). Thus, its use by society; paints, chemical additives, tools and weapons, as well as other consumer and industrial products, coupled with inadequate disposal or recycling by society have caused environmental systems (soils) to become repositories for the metal. It is also apparent that not only are soils the repository for environmentally released Pb, but it is retained in the zone of addition.

Simon, D., C. Lewis and F. Hayter. 2018. Port Pirie Blood Lead Levels - Analysis of blood lead levels for 1 January – 31 December 2017.

Solomon, R. J. 1988. The Richest Lode: Broken Hill 1883-1988, Hale & Iremonger.

Spanier, A. J., S. Wilson, M. Ho, R. Hornung and B. P. Lanphear. 2013. The contribution of housing renovation to children's blood lead levels: a cohort study. Environmental Health **12**(1): 72.

Routine renovation of older housing is a risk factor for childhood lead poisoning, but the contribution to children's blood lead levels is poorly defined for children with lower exposure levels. We examined a prospective cohort of 276 children followed from 6 to 24 months of age. We conducted surveys of renovation activities and residential lead hazards and obtained blood lead level (B-Pb) every six months. We analyzed B-Pb in a repeated measures design using a mixed effects linear model. Parent reported interior renovation ranged from 11 to 25% of housing units at the four, 6-month periods. In multivariable analysis, children whose housing underwent interior renovation had a 12% higher mean B-Pb by two years of age compared with children whose housing units were not renovated ($p < 0.01$). The time between renovation and the child blood lead sample was associated with higher B-Pb (p-value for trend <0.01); compared to children in non-renovated housing, children whose housing units underwent renovation in the prior month had a 17% higher mean B-Pb at two years of age, whereas children whose housing renovation occurred in the prior 2–6 months had an 8% higher mean B-Pb. We also found an association between higher paint lead loading, measured using an X-ray fluorescence (XRF) based paint lead index, and child B-Pb ($p = 0.02$); for every 10 mg/cm2 increase in paint lead loading index there was a 7.5% higher mean childhood B-Pb. In an analysis of data collected before the recent changes to Environmental Protection Agency's Lead, Renovation, Repair and Painting Rule, routine interior housing renovation was associated with a modest increase in children's B-Pb. These results are important for the provision of clinical advice, for housing and public health professionals, and for policymakers.

Stifelman, M., R. Hanson, J. Cobb, P. Ian von Lindern, S. Spalinger and E. L. Evans. 2012. Misdireected criticisms/Moodie and Evans respond. American journal of public health **102**(9): E11.

In their article, Moodie and Evans raise ethical questions about the blood lead Remedial Action Objective (RAO) used at the Bunker Hill Superfund Site (BHSS), but also mislead by neglecting history and mischaracterizing the remediation.1---3 This response highlights how the BHSS RAO and remedy are designed to be protective and proactive in reducing risk.

Sublett, J. L., J. Seltzer, R. Burkhead, P. B. Williams, H. J. Wedner and W. Phipatanakul. 2010. Air filters and air cleaners: Rostrum by the American Academy of Allergy, Asthma & Immunology Indoor Allergen Committee. Journal of Allergy and Clinical Immunology **125**(1): 32-38.

The allergist is generally recognized as possessing the greatest expertise in relating airborne contaminants to respiratory health, both atopic and nonatopic. Consequently, allergists are most often asked for their professional opinions regarding the appropriate use of air-cleaning equipment. This rostrum serves as a resource for the allergist and other health care professionals seeking a better understanding of air filtration.

Sweetnam, K. 2010. The final whistle.

Symeonides, C., P. Vuillermin, P. D. Sly, F. Collier, V. Lynch, S. Falconer, A. Pezic, N. Wardrop, T. Dwyer, S. Ranganathan, et al. 2020. Pre-school child blood lead levels in a population-derived Australian birth cohort: the Barwon Infant Study. Medical Journal of Australia **n/a**(n/a).

Abstract Objectives To investigate blood lead levels in an Australian birth cohort of children; to identify factors associated with higher lead levels. Design, setting Cross-sectional study within the Barwon Infant Study, a population birth cohort study in the Barwon region of Victoria (1074 infants, recruited June 2010 – June 2013). Data were adjusted for non-participation and attrition by propensity weighting. Participants Blood lead was measured in 523 of 708 children appraised in the Barwon Infant Study pre-school review (mean age, 4.2 years; SD, 0.3 years). Main outcome measure Blood lead concentration in whole blood (μg/dL). Results The median blood lead level was 0.8 μg/dL (range, 0.2–3.7 μg/dL); the geometric mean blood lead level after propensity weighting was 0.97 μg/dL (95% CI, 0.92–1.02 μg/dL). Children in houses 50 or more years old had higher blood lead levels (adjusted mean difference [AMD], 0.13 natural log units; 95% CI, 0.02–0.24 natural log units; P = 0.020), as did children of families with lower household income (per $10 000, AMD, –0.035 natural log units; 95% CI, –0.056 to –0.013 natural log units; P = 0.002) and those living closer to Point Henry (inverse square distance relationship; P = 0.002). Associations between hygiene factors and lead levels were evident only for children living in older homes. Conclusion Blood lead levels in our pre-school children were lower than in previous Australian surveys and recent surveys in areas at risk of higher exposure, and no children had levels above 5 μg/dL. Our findings support advice to manage risks related to exposure to historical lead, especially in older houses.

Taneez, M., C. Hurel and N. Marmier. 2015. Ex-situ evaluation of bauxite residues as amendment for trace elements stabilization in dredged sediment from Mediterranean Sea: a case study. Marine pollution bulletin **98**(1-2): 229-234.

Stabilization of marine dredged sediments contaminated with multi-elements is a challenging task in choosing the appropriate sorbent and application dosage. The present study investigates the possibility of using bauxite residues (Bauxaline® and Bauxsol) as amendment for the treatment of contaminated sediment. A pilot scale experiment was conducted for three months to stabilize trace elements in composted contaminated sediment sample using 5% by-product amendment. The results showed that after 3 months of treatment, cationic trace elements were effectively immobilized but increased leaching of anionic pollutants was observed. Increased leaching of anionic pollutants could be limited by addition of higher quantities of amendments. The total content of available pollutants decreased in stabilized sediments but this treatment has no effect on the classification of waste. The leachates were then evaluated for acute toxicity using estuarine rotifers Brachionus plicatilis. Bauxite residues can be inexpensive choices for the stabilization of cationic pollutants in dredged sediments.

Taylor, M. P. 2011. Report for the Environment Protection Authority, South Australia: Examination of the relationship between Nyrstar Port Pirie Pty Ltd smelter, airborne lead emissions and environmental health impacts. Report for the Environment Protection Authority, South Australia: Examination of the relationship between Nyrstar Port Pirie Pty Ltd smelter, airborne lead emissions and environmental health impacts. Accessed 14 February 2019 at https://www.researchgate.net/publication/324939017_Report_for_the_Environment_Protection_Authority_South_Australia_Examination_of_the_relationship_between_Nyrstar_Port_Pirie_Pty_Ltd_smelter_airborne_lead_emissions_and_environmental_health_impacts.

This report was commissioned by the Environment Protection Authority, South Australia, to evaluate the risk to human health from increased airborne lead emissions from the Nyrstar Port Pirie Pty Ltd smelter between August 2009 and May 2010. The literature on lead-associated human health problems is vast and comprehensive. Thousands of studies have shown that environmental lead exposure in humans, especially children, causes multiple, deleterious health and neurobehavioural impacts. These impacts involve decrements in intelligence measures, learning and behavioural problems including speech, hearing, attention and mental processing impairment. Problems related to lead exposure have also been shown to not remit with age. The longitudinal consequences of lead exposure are extensive and include poorer high school outcomes, reduced economic opportunities and increased predisposition to misconduct-type behaviours, including criminality. Lead exposure has also been shown to affect adults later in life by way of increased prevalence to hypertension, cardio vascular disease and mortality, and reduced renal function. This report finds that emissions from the Port Pirie Nyrstar Pty Ltd smelter have contaminated a wide range of natural and human environments. Impacted systems include air, dusts, sediments, soils, vegetation and human systems, which now all possess significantly elevated concentrations of lead and other toxic metals. The data demonstrates that during the period of interest between August 2009 and May 2010 the whole city of Port Pirie was blanketed periodically with highly elevated lead- in-air concentrations. As a consequence of these emissions, the evidence shows that the threshold of potential harm was surpassed and that adverse environmental and human health effects have occurred. Indeed, the monthly data on children's blood lead level test results above 10 μg/dL show that the elevated lead-in-air concentrations coincided with marked increases in the proportion of tests exceeding this guideline value. The increased emissions not only will have exposed children to a greater risk of contamination, but will have also added to the significant extant lead burden in and around Port Pirie. The evidence shows that lead exposure in Port Pirie is virtually inescapable and that the whole population resides in what has been described as a “sea of lead” (Maynard et al. 2006; Simon et al. 2007). As a result of the smelter emissions, Port Pirie is now the most lead contaminated residential environment in Australia. The data show that every other day a blood lead test on a child aged 0-4 years of age will exceed 10 µg/dL. Consequently, around 1 in 3 children who enter primary school at Port Pirie will have been lead poisoned, resulting in significant challenges in early schooling. Since 2006, Nyrstar has invested approximately $58 million on capital and smelter plant works aimed at improving environmental emissions and human health indicators in the city. These works in association with the ‘tenby10’ community education program have been coincident with reductions in childhood blood lead levels as well as falls in average lead-in-air values. However, numerous studies have shown that educational advice and household interventions about preventing lead exposure will not guarantee a community’s protection. This is particularly the case where the primary source of the contamination remains ongoing. Even where Port Pirie houses are completely closed and vacant, re-contamination occurs. This indicates the pervasive nature of ongoing smelter emissions in addition to contamination from existing lead-rich soil and dust around Port Pirie. The only long- term solution to the lead exposure problem in Port Pirie is comprehensive remediation of the smelter and city environments coupled to a significant reduction or complete cessation of smelter emissions. The arguments against such an extensive remediation program are often economic. However, international studies demonstrate that the long-term costs of not addressing preventable exposure to a known environmental toxin far outweigh the short-term costs of remediation.

Taylor, M. P., C. F. Isley and J. Glover. 2019. Prevalence of childhood lead poisoning and respiratory disease associated with lead smelter emissions. Environ Int **127**: 340-352.

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 SO2 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 SO2 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 SO2 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 SO2 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 SO2. Analysis of the relationship between lead in air and blood lead shows that annual geometric mean air lead concentrations need to be <0.11 µg/m3 to ensure the geometric mean blood lead of Port Pirie children under 5 years is ≤5 µg/dL. For children aged 24 months, lead in air needs to be no greater than 0.082 µg/m3 (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 SO2 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 SO2 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 µg/m3) to ensure that the geometric blood lead of children under 5 years is less than or equal to 5 µg/dL.

Taylor, M. P., C. F. Isley, X. Liu, K. Fry, M. M. Gillings, M. Rouillon, N. S. Soltani, D. B. Gore and G. Filippelli. Unpublished. Is urban gardening safe? Trace element concentrations and exposure risk measured from over 15,000 soils from 3,200 Australian gardens

Taylor, M. P., S. A. Mould, L. J. Kristensen and M. Rouillon. 2014. Environmental arsenic, cadmium and lead dust emissions from metal mine operations: Implications for environmental management, monitoring and human health. Environ Res **135**: 296-303.

> Although blood lead values in children are predominantly falling globally, there are locations where lead exposure remains a persistent problem. One such location is Broken Hill, Australia, where the percentage of blood lead values 410 μg/dL in children aged 1–4 years has risen from 12.6% (2010), to 13% (2011) to 21% (2012). The purpose of this study was to determine the extent of metal contamination in places accessible to children. This study examines contemporary exposure risks from arsenic, cadmium, lead, silver and zinc in surface soil and dust, and in pre- and post-play hand wipes at six playgrounds across Broken Hill over a 5-day period in September 2013. Soil lead (mean 2,450 mg/kg) and zinc (mean 3,710 mg/kg) were the most elevated metals in playgrounds. Surface dust lead concentrations were consistently elevated (mean 27,500 μg/m2) with the highest lead in surface dust (59,900 μg/m2) and post-play hand wipes (60,900 μg/m2) recorded close to existing mining operations. Surface and postplay hand wipe dust values exceeded national guidelines for lead and international benchmarks for arsenic, cadmium and lead. Lead isotopic compositions (206Pb/207Pb, 208Pb/207Pb) of surface dust wipes from the playgrounds revealed the source of lead contamination to be indistinct from the local Broken Hill ore body. The data suggest frequent, cumulative and ongoing mine-derived dust metal contamination poses a serious risk of harm to children.

Thompson, A. J., W. M. Hamlet and J. Thomas. 1893. Report of board appointed to inquire on the prevalence and prevention of lead poisoning at the Broken Hill Silver-Lead Mines to the Honourable Minister for Mines and Agriculture. New South Wales Legislative Assembly. Accessed 25th February 2019 at https://wellcomecollection.org/works/e6gda4kk.

Thompson, A. J., W. M. Hamlet and J. Thompson. 1892. Lead poisoning in silver lead mines in New South Wales. Public Health **5**: 374-375.

Tong, S., P. Baghurst, A. McMichael, M. Sawyer and J. Mudge. 1996. Lifetime exposure to environmental lead and children's intelligence at 11-13 years: the Port Pirie cohort study. Bmj **312**(7046): 1569-1575.

> Objective: To examine the association between environmental exposure to lead and children's intelligence at age 11-13 years, and to assess the implications of exposure in the first seven years of life for later childhood development. Design: Prospective cohort study. Subjects: 375 children born in or around the lead smelting town of Port Pirie, Australia, between 1979 and 1982. Main outcome measure: Children's intelligence quotient (IQ) measured at 11-13 years of age. Results: IQ was inversely associated with both antenatal and postnatal blood lead concentrations. Verbal, performance, and full scale IQ were inversely related to blood lead concentration with no apparent threshold. Multivariate analyses indicated that after adjustment for a wide range of confounders, the postnatal blood lead concentrations (particularly within the age range 15 months to 7 years) exhibited inverse associations with IQ. Strong associations with IQ were observed for lifetime average blood lead concentrations at various ages. The expected mean full scale IQ declined by 3.0 points (95% confidence interval 0.07 to 5.93) for an increase in lifetime average blood lead concentration from 0.48 to 0.96 mumol/l (10 to 20 micrograms/dl). Conclusion: Exposure to environmental lead during the first seven years of life is associated with cognitive deficits that seem to persist into later childhood.

U.S. Army Corps of Engineers. 2008. Tar Creek Superfund Site Property Buy-Out and Relocations in Picher, Cardin, and Hockerville, Ottawa County, Oklahoma. US Army Tulsa District.

> The purpose of this EA is to evaluate the environmental impacts and consequences of transfer and use of Federal funds for property buy-out, permanent relocation of residents and businesses, and demolitions within the Tar Creek Relocation Zone. The Corps of Engineers proposes to amend the existing grant to DEQ to include buy-out and permanent relocation of residents and businesses within the Tar Creek Relocation Zone as additional uses of the Federal funding, in accordance with

the authorization of WRDA 2007, and to provide additional funds for the purposes specified in the grant should such funds be appropriated. The action is needed to assist the State of Oklahoma in addressing lead exposure and other environmental problems by relocating residences and businesses located in the Tar Creek Relocation Zone out of an area experiencing negative health and environmental effects associated with past mining operations.

USEPA. 2017. United States Code. Title 42 - THE PUBLIC HEALTH AND WELFARE. CHAPTER 63 - LEAD-BASED PAINT POISONING PREVENTION.

The Secretary shall require the inspection of all intact and nonintact interior and exterior painted surfaces of housing subject to this section for lead-based paint using an approved x-ray fluorescence analyzer, atomic absorption spectroscopy, or comparable approved sampling or testing technique. A certified inspector or laboratory shall certify in writing the precise results of the inspection. If the results equal or exceed a level of 1.0 milligrams per centimeter squared or 0.5 percent by weight, the results shall be provided to any potential purchaser or tenant of the housing. The Secretary shall periodically review and reduce the level below 1.0 milligram per centimeter squared or 0.5 percent by weight to the extent that reliable technology makes feasible the detection of a lower level and medical evidence supports the imposition of a lower level.

USEPA. 2018. About the Integrated Systems Toxicology Division (ISTD) of EPA's National Health and Environmental Effects Research Laboratory. Accessed 25th February 2020 at https://www.epa.gov/aboutepa/about-integrated-systems-toxicology-division-istd-epas-national-health-and-environmental.

Van Alphen, M. 1991. The history of smelting and ore dressing in Broken Hill and the potential for mine derived lead contamination in Broken Hill, M. van Alphen.

von Lindern, I., S. Spalinger, V. Petroysan and M. von Braun. 2003. Assessing remedial effectiveness through the blood lead: soil/dust lead relationship at the Bunker Hill Superfund Site in the Silver Valley of Idaho. Science of The Total Environment **303**(1-2): 139-170.

The 21 square mile Bunker Hill Superfund Site in northern Idaho includes several thousand acres of contaminated hillsides and floodplain, a 365-acre abandoned lead/zinc smelter and is home to more than 7000 people in 5 residential communities. Childhood lead poisoning was epidemic in the 1970s with >75% of children exceeding 40 μg/dl blood lead. Health response activities have been ongoing for three decades. In 1991, a blood lead goal of 95% of children with levels less than 10 μg/dl was adopted. The cleanup strategy, based on biokinetic pathways models, was to reduce house dust lead exposure through elimination of soil-borne sources. An interim health intervention program, that included monitoring blood lead and exposures levels, was instituted to reduce exposures through parental education during the cleanup. In 1989 and 2001, 56% and 3% of children, respectively, exceeded the blood lead criteria. More than 4000 paired blood lead/environmental exposure observations were collected during this period. Several analyses of these data were accomplished. Slope factors derived for the relationship between blood lead, soil and dust concentrations are age-dependent and similar to literature reported values. Repeat measures analysis assessing year to year changes found that the remediation effort (without intervention) had approximately a 7.5 μg/dl effect in reducing a 2-year-old child's mean blood lead level over the course of the last ten years. Those receiving intervention had an additional 2–15 μg/dl decrease. Structural equations models indicate that from 40 to 50% of the blood lead absorbed from soils and dusts is through house dust with approximately 30% directly from community-wide soils and 30% from the home yard and immediate neighborhood. Both mean blood lead levels and percent of children to exceed 10 μg/dl have paralleled soil/dust lead intake rates estimated from the pathways model. Application of the IEUBK model for lead indicates that recommended USEPA default parameters overestimate mean blood lead levels, although the magnitude of over-prediction is diminished in recent years. Application of the site-specific model, using the soil and dust partitions suggested in the pathways model and an effective bioavailability of 18%, accurately predicts mean blood lead levels and percent of children to exceed 10 μg/dl throughout the 11-year cleanup period. This reduced response rate application of the IEUBK is consistent with the analysis used to originally develop the cleanup criteria and indicates the blood lead goal will be achieved.

Von Lindern, I. H., S. M. Spalinger, B. N. Bero, V. Petrosyan and M. C. Von Braun. 2003. The influence of soil remediation on lead in house dust. Science of The Total Environment **303**(1-2): 59-78.

Lead in house dust has long been recognized as a principal source of excess lead absorption among children at the Bunker Hill Superfund Site (BHSS) in northern Idaho. House dust lead concentration from homeowner's vacuum cleaner bags has been monitored since the epidemic of childhood lead poisoning in 1974. Geometric mean house dust lead concentrations decreased from >10 000 mg/kg in 1974 to approximately 4000 mg/kg in 1975, in response to air pollution control initiatives at the defective primary lead smelter. After smelter closure, 1983 mean dust lead concentrations were near 3000 mg/kg and were most dependent on soil sources. Following emergency soil removals from public areas and roadsides and fugitive dust control efforts in the mid-1980s, house dust lead decreased by approximately 40–60% to 1200–1500 mg/kg. In 1992, a cleanup goal of 500 mg/kg dust lead community average, with no individual home exceeding 1000 mg/kg, was adopted. This goal was to be achieved by a combination of contaminated soil removals and fugitive dust control efforts throughout the 21 square mile BHSS. Continual reductions in house dust lead concentrations have been noted throughout the residential area soil cleanup. Geometric mean house dust lead concentrations averaged approximately 500–600 mg/kg from 1996 to 1999 and dropped below 500 mg/kg in 2000. Analysis of these data indicates that approximately 20% of the variance in dust lead concentrations is attributed to yard, neighborhood, and community soil lead concentrations. Since 1996, dust lead concentrations and dust and lead loading rates have also been measured by dust mats placed at entryways into the homes. Neighborhood soil lead concentrations, household hygiene, the number of adults living in the home, and the number of hours a child spends outdoors in summer explain approximately 26% of the variance in mat dust lead loading rates. It is estimated that post-remedial house dust lead concentrations will stabilize at 400–500 mg/kg, as compared to approximately 200 mg/kg in socio-economically similar background communities; the difference possibly attributed to residual soil concentrations (3–6 times background), recontamination of rights-of-way, tracking of non-residential mining district soils and dusts, fugitive dusts associated with the remediation, and residual structural or carpet dusts.

Webster, A. 2004. The structural evolution of the Broken Hill Pb-Zn-Ag deposit. New South Wales, Australia: PhD Thesis, University of Tasmania.

Broken Hill Type lead-zinc-silver deposits (BHT) are a sought after style of mineralisation because of their simple metallurgy and high metal grades. The purpose of this research project is to gain a deeper understanding of the complex BHT style of mineralisation through a comprehensive re-examination of the structure and stratigraphy of the 300 million tonne, multiply deformed and metamorphosed, type example, located at Broken Hill, in far western New South Wales, Australia. This study used the techniques of structural analysis of high-grade gneiss terrains and exploited 119 years of geological data collected during the mining exploitation and exploration of the Broken Hill (BH) mining field. The gneissic sulphide-silicatecarbonate rocks of the BH ore environment lend themselves well to such structural studies because of their mineralogical diversity, coarse grain-size and because of the presence of distinctive and persistent marker units. The result is a deposit-scale stratigraphic and structural model of this complex mineralised system, which allows an unparalleled view of the 'anatomy' of this giant deposit.

WHO. 2018. Lead poisoning and health. World Health Organization. Accessed 25th February 2020 at http://www.who.int/en/news-room/fact-sheets/detail/lead-poisoning-and-health.

Wilson, G. 2010. Rasp Project Preferred Project Report. Accessed 25th February 2020 at http://www.cbhresources.com.au/files/3913/3747/8536/response-to-submissions-PPR.pdf.

Woodward-Clyde. 1993. Evaluation of environmental lead at Broken Hill. Prepared for Environment Protection Authority. Report No. 3328. Sydney, NSW.

Woodward, O. H. 1952. A Review of the Broken Hill Lead-silver-zinc Industry, Australasian Institute of Mining and Metallurgy.

Yan, K., Z. Dong, R. Naidu, Y. Liu, Y. Li, A. Wijayawardena, P. Sanderson, H. Li and L. Q. Ma. 2019. Comparison of in vitro models in a mice model and investigation of the changes in Pb speciation during Pb bioavailability assessments. J Hazard Mater: 121744.

> In this study, the predominant Pb minerals prior to and after Pb relative bioavailability (Pb-RBA) and Pb bioaccessibility (Pb-BAc) tests were identified using SEM (scanning electron microscopy), XANES (X-ray absorption near edge structure) and XRD (X-ray diffraction). The correlations between in vitro Pb-BAc (using the UBM (Unified BARGE Method) and RBALP (Relative BioAccessibility Leaching Procedure) models) and in vivo Pb-RBA (using endpoints of kidney and liver in an mice model) were determined. The results demonstrated that both RBALP and UBM (gastric phase) reliably indicate Pb-RBA (Pb-RBA). However, raising the solid:liquid ratio of the gastric phase of UBM is necessary to determine Pb-BAc if the soils contain total Pb >10,000 mg/kg. The comparison of Pb minerals prior to and after in vitro extractions demonstrated that the relatively soluble forms of Pb (PbSO4, PbO2 and MgO Pb) start to dissolve than other forms of Pb minerals, suggesting there was no difference in Pb2+ release between chemical-based (RBALP) and physiologically-based (UBM) models. The identification of the Pb minerals of Pb5(PO4)3Cl and organically-complexed Pb in mice excreta demonstrated that a portion of Pb2+ combined with food and humic acid to generate organically-complexed Pb in mice excreta, and that Pb5(PO4)3Cl is not bioavailable.

Yang, K. and S. R. Cattle. 2015. Bioaccessibility of lead in urban soil of Broken Hill, Australia: a study based on in vitro digestion and the IEUBK model. Science of The Total Environment **538**: 922-933.

> This study was conducted to investigate lead (Pb) bioaccessibility in urban soil and to assess health risk to children in the city of Broken Hill, Australia, which was established around one of the world's largest lead–zinc–silver mines. Fifty-three topsoil (0–0.1 m) and 50 subsoil (0.3–0.5 m) samples were collected from earthen footpaths, nature strips, parks or vacant land throughout the urban area. The soil samples were analysed for total Pb concentration, Pb bioaccessibility and Pb mineral phases, together with important soil physicochemical properties known to influence Pb bioaccessibility. Lead bioaccessibility ranged from 24% to 89% in topsoil and from 16% to 100% in subsoil, exhibiting a generally decreasing pattern with increasing distance from the orebody. Lead bioaccessibility was strongly positively related to total Pb concentration in both the topsoil and subsoil. In subsoil, a moderate negative correlation existed between Pb bioaccessibility and soil pH, while a moderate positive correlation existed between Pb bioaccessibility and soil organic matter (OM) content. In contrast, only a weak positive correlation existed between Pb bioaccessibility and OM content in topsoil. The presence of different Pb mineral phases also appeared to have caused variation in soil Pb bioaccessibility, with galena (PbS)-rich samples tending to exhibit lower Pb bioaccessibility. The prediction of blood lead (PbB) levels in Broken Hill children aged 1–4 years using the IEUBK model well matched the measured data from a recent PbB screening, suggesting a high risk of childhood chronic low-level Pb exposure (PbB levels > 5 μg/dL) in Broken Hill, especially in the vicinity of the orebody. Future Pb abatement programs in Broken Hill should utilise the IEUBK model to establish target soil Pb values in an effort to achieve particular child PbB outcomes.

Yang, K. and S. R. Cattle. 2015. Bioaccessibility of lead in urban soil of Broken Hill, Australia: A study based on in vitro digestion and the IEUBK model. Science of the Total Environment **538**: 922-933.

Yang, K. and S. R. Cattle. 2016. Contemporary sources and levels of heavy metal contamination in urban soil of Broken Hill, Australia after ad hoc land remediation. International Journal of Mining, Reclamation and Environment **32**(1): 18-34.

> This study used GIS-based and multivariate statistical approach to identify sources of Cr, Mn, Ni, Pb and Zn in urban soil surrounding a large Pb-Zn-Ag orebody. The results show that Mn-Pb-Zn-rich dust originating from the orebody and associated mining works has acted as an important

contaminating source of topsoil metals. In contrast, Cr and Ni appear to be sourced naturally from weathering of parent materials. The calculation of contamination indices reflects a high level of Pb and Zn contamination in topsoil near the orebody and a moderate level of Mn contamination, while topsoil contamination with Cr and Ni is negligible.

Yang, K. and S. R. Cattle. 2017. Effectiveness of cracker dust as a capping material for Pb-rich soil in the mining town of Broken Hill, Australia. Catena **148**: 81-91.

Lead (Pb)-poor ‘cracker dust’, commonly used in kerb and gutter construction, has been installed on top of Pb-rich soil surfaces in Broken Hill over the last few decades, with the aim of reducing the risk of human exposure to Pb particulates. In this study, topsoil (0–0.1 m) and subsoil (0.3–0.5 m) samples were collected along rays spanning all parts of the Broken Hill urban area to investigate the effectiveness of remediation with cracker dust. Total Pb concentrations in the fine earth fraction (< 2 mm) of topsoil and subsoil samples and the dust-sized fraction (< 100 μm) of topsoil samples were measured. Undisturbed subsoil Pb concentrations are high near the ‘Line of Lode’ (LoL) orebody, especially on its southern flank, but are similar to background Pb concentrations at locations more than 0.8 km from the LoL. Topsoil Pb concentrations at locations near the LoL are very high, but tend to decrease rapidly with increasing distance from the LoL. At most sampled locations the topsoil is significantly enriched in Pb relative to the subsoil, while Pb concentrations in the dust-sized fraction of topsoils are generally twice as high as those in the fine earth fraction of topsoils. Notably, where cracker dust has been applied, most topsoil Pb concentrations are significantly lower, indicating that remediation with cracker dust has been generally effective. Although contemporary dust deposits in Broken Hill can be very rich in Pb, the relatively small amounts of dust deposited ensure that Pb accretion from fugitive dust deposition is a very gradual process; undisturbed cracker dust should have a ‘clean lifespan’ of at least 100 years. However, a small number of cracker dusted sites are found to have Pb-enriched surfaces, suggesting that the efficacy of cracker dust is curtailed where fluvial transport of Pb-rich sediment and/or mixing of the applied cracker dust with the underlying Pb-rich soil occurs.

Zhou, X., M. P. Taylor, P. J. Davies and S. Prasad. 2018. Identifying sources of environmental contamination in European honey bees (Apis mellifera) using trace elements and lead isotopic compositions. Environ Sci Technol **52**(3): 991-1001.

Trace element concentrations (As, Mn, Pb, and Zn) and Pb isotopic compositions were analyzed in honey bees, wax, and honey along with co-located soil and dust samples from Sydney metropolitan and Broken Hill, Australia. Compared with the other trace elements, Pearson correlations show that Pb concentrations in soil and dust had the strongest relationship to corresponding values in honey bees and their products. Dust Pb was not only highly correlated to corresponding soil values ($r = 0.806$, $p = 0.005$), it was the strongest predictor of Pb concentrations in honey bees, wax, and honey ($p = 0.001$, 0.007, 0.017, respectively). Lead isotopic compositions (206Pb/207Pb and 208Pb/207Pb) showed that honey bees and their products from Broken Hill were nearly identical (95–98%) to the composition of the local ore body. Samples of honey bees and their products collected from background sites adjacent to national parks in Sydney had Pb isotopic compositions (206Pb/207Pb = 1.138–1.159, 208Pb/207Pb = 2.417–2.435) corresponding to local geogenic values (206Pb/207Pb = 1.123–1.176, 208Pb/207Pb = 2.413–2.500). By contrast, honey bees and their products from Sydney metropolitan (206Pb/207Pb = 1.081–1.126, 208Pb/207Pb = 2.352–2.408) were similar to aerosols measured during the period of leaded petrol use (206Pb/207Pb = 1.067–1.148, 208Pb/207Pb = 2.341–2.410). These measurements show Pb concentrations and its isotopic compositions of honey bees, and their products can be used to trace both legacy and contemporary environmental contamination, particularly where sources are well documented. Moreover, this study demonstrates that legacy Pb emissions continue to be remobilized in dust, contaminating both food and ecological systems.

Zuraimi, M. S., G. J. Nilsson and R. J. Magee. 2011. Removing indoor particles using portable air cleaners: Implications for residential infection transmission. Building and Environment **46**(12): 2512-2519.

Reducing indoor exposure to influenza particles can be an important strategy to manage residential infections. Many portable air cleaning (PAC) technologies are currently employed in residential

environments but very little research has been performed to evaluate and compare their performance in terms of particle removal associated with influenza. This study evaluates the effectiveness of portable air cleaners at removing airborne NaCl particles as an analogue to the influenza virus and applies the results to an IAQ mass balance model to evaluate the performance in controlling residential exposures and mitigating infection risks. Various devices representing different PAC technologies were tested using a pull down particle challenge in a full scale stainless steel chamber. Particle generation and measurement were conducted using a 6-jet atomizer and a paired aerodynamic particle sizer (APS)-scanning mobility particle sizer (SMPS), respectively. PAC incorporating HEPA filtration, electrostatic precipitation, ion generation and electret filtration were tested. We found that particle exposures released during a cough or sneeze event in a typical Quebec City residential room in Canada can significantly be reduced using HEPA, electrostatic precipitation and electret filtration PACs when compared with a situation where no PAC is being used. Modelling analysis demonstrates that the use of these PACs can mitigate the risks of influenza infection via airborne route for a caregiver or a spouse sharing the same room. The implications of this study are significant considering low ventilation rates of Quebec City residences.

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