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Evaluation and assessment of the efficacy of an abatement strategy in a former lead smelter community, Boolaroo, Australia

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Abstract 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

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widespread lead contamination was inadequate for mitigating current and future risk of lead exposures.

Keywords Boolaroo · Lead exposure · Lead Abatement Strategy · Remediation evaluation · Smelter

Introduction

Lead mining and smelting operations have been linked to widespread environmental contamination and elevated blood lead levels in children in Australia (Cartwright et al. 1977; Gulson et al. 2004; Martley et al. 2004; McMichael et al. 1985; Morrison 2003; Taylor et al. 2014a). Dispersal of toxic metals from smelter stack and fugitive emissions across urban environments and subsequent accumulation in home environments presents a major potential exposure pathway which is a significant contributor to elevated blood lead concentrations (Boreland and Lyle 2006; Csavina et al. 2014; Graziano et al. 1990; Landrigan et al. 1976; Mielke et al. 2011; Taylor et al. 2013; Yankel et al. 1977; Zahran et al. 2014). The harmful human health impacts of environmental lead exposure are well documented and include severe neurological deficits in young children, even at low levels of exposure (Canfield et al. 2003, Lanphear et al. 2000, 2005; Mielke et al. 2013).

Internationally, the research literature is replete with techniques aimed at reducing the concentration of lead in soils without the need to excavate large quantities of contaminated land. These techniques range from the application of ethylenediaminetetraacetic acid (EDTA) to surface soils as an immobilisation agent to the addition of animal and vegetable by-products including mussel shells, wine-processing sludge and bio-char (Ahmad et al. 2012; Bolan et al. 2014; Jez and Lestan 2015). These techniques result in variable success, depending on a range of physical and environmental conditions including soil matrix, soil infiltration capacity and the spatial extent of the technique application (Bolan et al. 2014). In contrast to topical applications, the complete removal of contaminated soils is a strategy that has occurred predominantly in locations affected by smelter lead emissions (e.g. US EPA 2012). While comprehensive removal of soil is often effective at eliminating the contaminated soil from the environment, this approach requires a significantly greater cost outlay and is more disruptive to the environment than other methods. With the increasing global acknowledgement of environmental lead contamination, including significant issues in China, Europe, Nigeria and the USA (e.g. Aschengrau et al. 1994; Blacksmith Institute 2011; Farrell et al. 1998; Li et al. 2015, Lillo et al. 2015; Mielke et al. 2011), there is a need to develop successful cost-effective strategies for remediating lead-contaminated environments. Despite the widespread nature of environmental lead contamination in Australia, examples of successful large-scale schemes to clean up such contamination are surprisingly rare. In the light of this knowledge gap, this study examines the efficacy of an approach approved by the NSW Environment Protection Authority (*inter alia* other government departments) for reducing the risk associated with significant atmospheric lead deposition in soils.

Lead Abatement Strategy (LAS) for Pasminco Cockle Creek Smelter

Work to reduce the human exposure hazard from lead-contaminated soils surrounding the former Pasminco Cockle Creek Smelter (PCCS) commenced in 2007, following closure of the smelter in 2003, with work completed in 2013. The Pasminco Cockle Creek Smelter (PCCS) was situated within the urban area of Boolaroo on the New South Wales (NSW), Central Coast, approximately 140 km north from Sydney and 20 km from the regional city of Newcastle, Australia (Fig. 1). The PCCS operated on the Boolaroo site from 1897 as Sulphide Corporation Ltd, with intermittent operation during 1922–1961 and then full-scale operation until the closure of Pasminco Cockle Creek Smelter Pty Ltd in 2003 (Dames and Moore 1994a, b). In 1994, the smelter was producing approximately 80,000 t of zinc, 32,000 t of lead, 500 t of cadmium and 180,000 t of sulphuric acid, generated from gases captured during smelting of the Broken Hill galena (PbS) ore (Dames and Moore 1994b).

The PCCS has a long history of environmental contamination with studies in the 1980s revealing metal contamination of northern Lake Macquarie and surrounding suburbs (Batley 1987; Galvin 1992; Roy and Crawford 1984). Combined with atmospheric emissions resulting in soil lead contamination (Fig. 2),

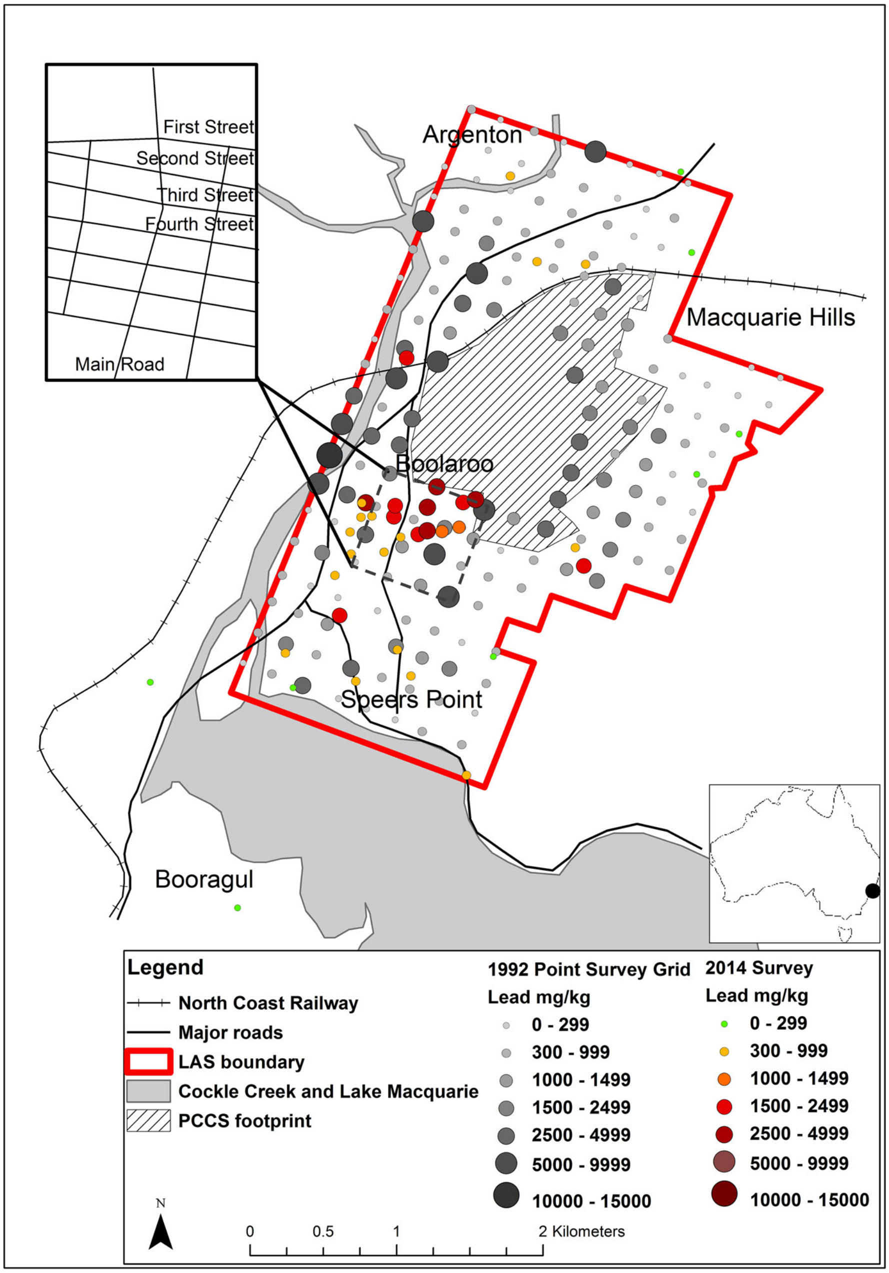

Fig. 1 Soil lead concentrations from Boolaroo, NSW, Australia, in the <180-µm fraction superimposed on the 1992 point survey grid soil lead data. Contemporary soil lead concentrations are greatest proximal to the PCCS

a significant other source of environmental lead exposure arose from the highly bio-accessible (54 % bio-accessible) smelter slag that was distributed widely as backyard fill throughout the suburbs surrounding the PCCS (Morrison and Gulson 2007). Batley (1992) concluded that "*most of the heavy metals present in the slag are in readily bio-available forms. It is likely that ingested slag reaching the gut would readily release lead, zinc, cadmium and copper, and this could have toxic consequences*" (p. 5).

Environmental lead contamination resulting from PCCS emissions in Boolaroo contributed to elevated blood lead levels in children living in the town (Galvin 1992). Multiple studies of soil lead–blood lead relationships show clearly that higher soil lead values are associated with elevated blood lead levels in young

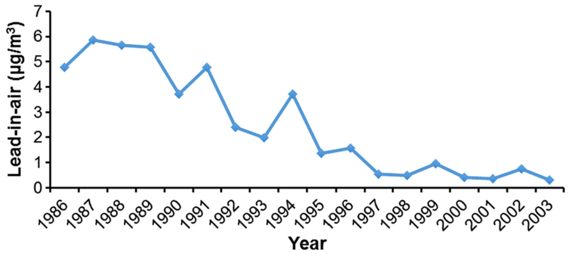

Fig. 2 Average annual atmospheric lead concentrations—First Street, Boolaroo, NSW

children (Bickel 2010; Zahran et al. 2009). Various historical studies have shown that children exposed to the lead emissions of the PCCS had elevated blood lead concentrations above accepted guidelines, the most recent of which was 10 µg/dL but which has now been reduced to 5 µg/dL with the ultimate aim to have no detectable blood lead concentration (Dalton and Bates 2005; Galvin 1992; Morrison 2003; Ouw and Bisby 1976). Following multiple attempts to "clean up" the suburbs surrounding the smelter, including a property buy-back scheme in 1992 where homes were cleaned and then leased, 37 % of tested children 0–5 years of age presented a blood lead concentration exceeding 10 µg/dL in 2002 (Gulson et al. 2004; Hunter Health 2003; Morrison 2003). Dalton and Bates (2005) demonstrated a decline in population blood lead concentrations post-closure of the PCCS (17 % of children 0–5 years >10 µg/dL) with a further reduction in 2006 to 7 % of children ($n = 171$) (Hunter New England Population Health 2006). In mid-2015, 12 % of children and pregnant women tested ($n = 72$) returned a blood lead concentration above what the NSW Health, Hunter New England Local Health District deemed a low reading (3.3 µg/dL), with no samples above 5 µg/dL (NSW Health Health 2015a).

The LAS was initiated with the intention of finding "*a suitable and workable solution to managing the lead fallout levels from soils in the community surrounding the former PCCS smelter*" (Pasminco 2007). The explicit goal of the LAS was "*to reduce the current potential exposure for residents of the nominated properties that could arise from previous lead dust deposition such that the exposure levels from lead dust deposition after the LAS has been completed are within acceptable limits during everyday living*" (Zines 2007, p. 5). It is unfortunate that this goal was never tested following completion of the urban abatement programme in 2013.

Nominated properties were set out in the 1995 conditions of consent for the upgrade of the PCCS and included "*those being likely to be affected by lead dust from the smelter operations*" (Zines 2007, p. 5). Nominated properties fell within the LAS grid constructed by incorporating soil data from the 1992 soil lead survey, blood lead data and contour mapping (Supplementary Data 1; Fig. 1). Participation of nominated properties in the LAS scheme was "opt-in"; landowners were offered participation via written communication over a one-month period. Properties were abated according to the thresholds set out by LAS (Table 1, Zines 2007). Those who did not respond to or declined this invitation received no abatement (Zines 2007). Parkland, open space, schools and other high-use community areas were not included in the LAS because it was deemed as per similar work conducted in Port Pirie that "*older children, adolescents and non-occupationally exposed adults exhibit near normal blood levels unless significantly exposed during early life*" (Maynard et al. 2006). It is unclear how many properties were actually involved in the LAS as participant numbers are inconsistent in different official documents (Ferrier Hodgson 2013, 2015; Lake Macquarie City Council 2013). According to the document issued by Lake Macquarie City Council (2013), approximately 750 properties recorded soil lead concentrations above 300 mg/kg and were therefore eligible for abatement. This figure of impacted residences, however, is confused by a 2014 communication from the NSW Environmental Protection Authority to MP Taylor in which Ferrier Hodgson confirmed that "*437 participants received results above 300 ppm [mg/kg] and were advised of the recommended abatement works*" (pers. comm. Coffey, EPA, 2014). It is worth noting that of the 1238 properties that the Administrator Ferrier Hodgson identified as elected participants, 783 (63 %) received only education materials. These properties were deemed to have soil less than 300 ppm [mg/kg] (341 properties—category 1, Table 1) or sufficient grass/mulch covering with soils between 300 and 1000 ppm [mg/kg] (282 properties, category 2, Table 1) or a mixture of category 1 and category 2 (Table 1) with sufficient grass/mulch covering (160 properties).

Table 1 Lead abatement protocol utilised by Ferrier Hodgson for the Boolaroo abatement following environmental lead contamination by smelting at the Pasminco Cockle Creek smelter

Measured lead concentration	Abatement strategy action
<300 mg/kg	No lead abatement action
300–1000 mg/kg	Option a: if grass covered, then barrier exists and no further action necessary
	Option b: if not covered by grass but can be, then till and apply turf maintaining practical ground levels for particular site
	Option c: when in shady spot with low grass cover, add 25 mm topsoil and mulch cover
1000–1500 mg/kg	Option a: for already grassed areas, add additional 25 mm of topsoil
	Option b: if not covered by grass but can be, add 25 mm of topsoil and apply turf maintaining practical ground levels for particular site
	Option c: when in shady spot with low grass cover add 40 mm topsoil and mulch cover
1500–2500 mg/kg	Option a: for already grassed areas, add additional 50 mm of topsoil as barrier
	Option b: if not covered by grass but can be, then add 50 mm of topsoil and apply turf
	Option c: when in shady spot with low grass cover, excavate 50 mm of topsoil and mulch cover
2500–5000 mg/kg	Option a: for already grassed areas, excavate 50 mm of topsoil and replace with 50 mm of new topsoil as barrier—replace grass cover (if suitable lead content) or otherwise apply new turf
	Option b: if not covered by grass but can be, then excavate 50 mm of topsoil and then replace with 50 mm of new topsoil and apply new turf
	Option c: when in shady spot with low grass cover, excavate 50 mm of topsoil and then replace with 50 mm of new topsoil and mulch cover
>5000 mg/kg	Investigate soil profile vertically to determine level of excavation required (expect 100 mm maximum) and then excavate, reinstate with new topsoil and apply new turf, maintaining practical levels for particular site or mulch as above

Methods and materials

Field methods

Soil and vacuum dust samples were collected from abated and non-abated residential properties within and outside of the LAS grid in August 2014. The abatement status of each property was withheld from the researchers until after the results had been obtained. Soils were also collected from open spaces and parklands (community areas). Surface soil samples were taken from a depth 0–2 cm following the protocols in the Australian Standard for sampling soils that are potentially lead contaminated (Australian Standard AS4874-2000, 2000).

Each residential property was sampled in three locations, front yard soils, back yard soils and a vacuum dust sample (Supplementary Data S2 and S3). Vacuum dust was sampled to characterise the contemporary exposure within the home and was collected where available directly from the household's vacuum bag or canister. Domestic vacuum samples are a suitable means of sampling lead dust and are comparable to a range of other methods including high-volume sampling (Colt et al. 2008; Deziel et al. 2014; Gulson et al. 1995). In order to characterise soil lead concentrations in front and back yards as a whole, an aggregate of five samples were collected each from the front and back of the property. Soils collected from open spaces and parklands were similarly averaged across the site by collecting up to five samples at each location. In addition, a Government Information (Public Access) Act 2009 (NSW) (GIPA) application was submitted by Newcastle Herald (Fairfax Media Ltd) to the Lake Macquarie Council to access the Pasminco soil assessment data that were used to determine the abatement actions on individual property titles. This yielded data from 8 properties that we had sampled as part of our study, enabling assessment of pre- and post-abatement soil lead levels.

Laboratory methods

Soil samples were oven dried at 60 °C and then sieved to <180 μm. The <180-μm fraction was selected as the PCCS's primary environmental contamination was from fine particulate emissions from smelter stacks, making finer soil and dust fractions the most significant health exposure pathway. In order to understand the effect of sieving to <180 μm on soil metal concentrations compared to the more conventional <2 mm fraction, a subset ($n = 6$) of soil samples was subdivided into the two fractions and analysed (Supplementary Data S4). Dust samples were sieved to <2 mm to remove large particulate debris. Sieving to <180 μm was not possible because of insufficient sample volume once all the coarse and non-particulate matter had been removed (hair, paper, etc.). These protocols are consistent with those defined in the Australian *National Environment Protection (Assessment of Site Contamination) Measure 1999* (NEPM 2013), which states at s 4.2.4.3: "*Unless impracticable or not recommended for a specific method, the sample portion for analysis should be of a size to pass a 2.0 mm aperture sieve*".

Soil ($n = 75$; front yards, back yards, open spaces, sports fields, playgrounds, schools and 2 mm fractions) and dust ($n = 17$) samples were analysed at the National Measurement Institute (NMI), Sydney. Approximately 0.5 g of dust or soil was digested in 3 mL concentrated, trace metal grade HNO_3 and 3 mL HCl. Elements commonly detected in smelting environments, antimony, arsenic, cadmium, lead and zinc concentrations were determined using a Perkin Elmer Elan DRC II Inductively Couple Plasma Mass Spectrometer (ICP-MS). Three procedural laboratory blanks returned concentrations below limit of reporting (LOR) of <0.5 mg/kg for all elements. Recovery rates of two NMI standard reference materials, AGAL-10 (river sediment) and AGAL-12 (bio-soil), for all elements were between 92 and 114 %. Duplicate analyses for the samples returned relative per cent difference (RPD) of <20 %.

Vacuum dust samples ($n = 17$) were also analysed to estimate their bio-accessible lead concentration by digesting 2 g of sample in 50 mL 1 M HCl and tumbling for 1 h. This procedure was selected due to its simplicity and effectiveness in mimicking the internal environment of the human intestinal tract. Procedural laboratory blanks returned average concentrations < 0.5 mg/kg for bio-accessible lead. Spike recovery rates for dusts were 103 %. Duplicate analyses for bio-accessibility in dust returned a RPD of 11 %.

Statistical analysis on the various sample media was performed using the Web-based statistical application developed by Stangroom (2014).

Results and discussion

All analysed concentrations are presented in the Supplementary Data (S2–S5). Data were divided into properties that received physical treatment in terms of soil removal or the addition of clean soils over existing contaminated soils and those properties that received no treatment (under the LAS). Due to privacy restrictions, the specific properties are not noted in the Supplementary Data. Mann–Whitney U tests showed that for all metals, the combined soil (<180 μm) and vacuum bag samples (<2 mm) were not statistically different between the treatments (calculated p values >0.05). Similarly, comparison of front yard and back yard soil samples between the treatment types showed no statistical difference for any of the metals, indicating abatement had not resulted in any material difference in soil metal values. Comparison of the six paired <180-μm and <2 mm soil fractions show a mean RPD of 27 % (Supplementary Data S4), indicating that lead concentrations are similar throughout the two size fractions.

It is worth noting that there are procedural differences in the sampling analysis protocols undertaken by Ferrier Hodgson (Zines 2007) versus those used in our study. The Ferrier Hodgson approach collected five soils from across the property and used the average value to determine the category for abatement (Table 1). In addition, Ferrier Hodgson collected soils from the top 5 cm of soil as opposed to the approach relied upon here (top 0–2 cm of soil), which parallels the recommended method for sampling potentially lead-contaminated soils (Australian Standard AS4874-2000, 2000).

Residential properties

All residential sites, with the exception of site 17, exceeded the NEPM 1999 (2013) health investigation level for domestic residences (HIL-A) of 300 mg/kg for at least one location on the property (Fig. 1, Supplementary Data S2). Antimony, arsenic, cadmium and zinc also exceeded their respective NEPM 1999 (2013) HIL-A guideline values thrice, once, eight times and once, respectively. As these elements do not appear as dominant contaminants in this environment, they have been included for completeness of the data set and have not been further extensively analysed. A Mann–Whitney U test for lead of all individual soil samples from front and back yards showed there was no significant difference in front yard soils compared to back yard soils (z score = −0.10, p value = 0.96). Soil lead concentrations in the back yards (mean = 1180 mg/kg, max = 3410 mg/kg) do not statistically differ from soil lead concentrations in front yards (mean = 1310 mg/kg, max = 4230 mg/kg) (Fig. 3).

Residential surface soil lead presents a significant health exposure risk to children (Filippelli et al. 2005; Zahran et al. 2014). Exterior soil can continually contribute lead to the internal home environment when seasonally driven decreased moisture content and increased re-suspension causes the re-distributing of finer soil fraction into the home (Hunt et al. 2006). Outdoor playtime is often restricted by parents to the "safe" backyard environment (Holt et al. 2009; Veitch et al. 2006) where children are often free to dig and play in or around soil, resulting in the ingestion of soil and dust, especially for children under 5 who display frequent hand-to-mouth behaviours (Mielke et al. 2011). The soils in the Boolaroo residential environment still contain lead levels that have the potential to pose a significant risk of harm; therefore, it is difficult to conclude that objective of the LAS to reduce human exposure to environmental lead contamination has been achieved (Zines 2007, p. 5).

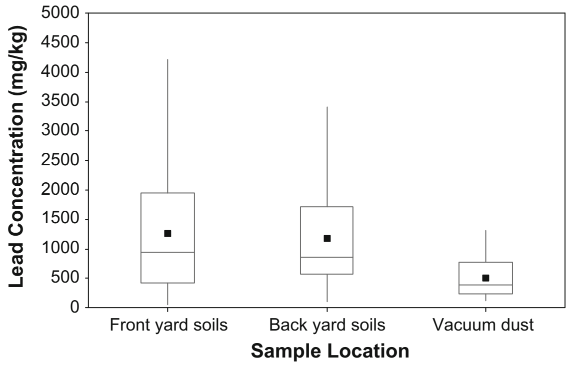

Fig. 3 Distribution of lead concentrations in soils and dust collected from front yards, back yards and household vacuum cleaner dust in Boolaroo. Mean concentrations are similar across each sampling area

Publically accessible areas

In addition to residential properties, soil samples (n = 32) were collected from a range of other specified land uses across Boolaroo and its immediate surrounds. This land is categorised here as open space (including roadside verges, parklands and vacant blocks) had a mean lead concentration of 778 mg/kg lead (median = 620 mg/kg) (Table 2).

For these samples, the NEPM 1999 (2013) health investigation level Recreational C guideline (i.e. public open space such as parks, playgrounds, playing fields, secondary schools and roadside verges) for lead in soils (600 mg/kg) was exceeded in 13 of 23 samples. No other element exceeded the relevant Australian soil guidelines.

Sports fields are considered separately to open space even though they are also subject to Recreational C soil metal guidelines because children are more likely to interact with exposed soil surfaces. The data from sports field sampling show environmental lead levels exceed guidelines with a mean lead concentration of 5130 mg/kg (median = 1275 mg/kg) (Table 2). The pattern of elevated soil metal concentrations is also reflected in playground and school soils (Table 2), which have a mean lead value of 812 mg/kg (median = 920 mg/kg) compared to the NEPM 1999 (2013) HIL-A value of 300 mg/kg. The HIL-A guideline includes children's day care centres, preschools and primary schools.

The non-residential community areas reveal a consistent pattern of lead-contaminated soil, with values ranging from 99 mg/kg to 17,500 mg/kg with a mean of 1330 mg/kg (median = 640 mg/kg) (Supplementary Data S5). The sports ground from where the sample containing 17,500 mg/kg of lead was taken had been filled with slag from the former PCCS, which is known to be rich in multiple metals (Morrison 2003) and also highly bio-accessible (Batley 1992; Morrison and Gulson 2007). Sites more distal to the former PCCS footprint contain lower soil lead concentrations (Figs. 1, 4), which parallels soil data collected during the operational phase of the smelter (Galvin 1992; Willmore et al. 2006).

Community areas including parks, playgrounds, schools and open spaces were not included in the LAS. This study investigated community areas excluded by the LAS to comprehensively delineate the lead-exposure risk across Boolaroo. The data show that a

Table 2 Statistical data for open space (roadside verges, parklands vacant blocks), sports fields and playgrounds/schools samples

Sampling area		Antimony	Arsenic	Cadmium	Lead	Zinc
Open space (mg/kg), $n = 23$	Mean	2.2	17.7	11.9	778	1146
	Median	2.2	14.0	9.2	620	950
	SD	1.5	10.6	10.8	622	741
	Min	0.0	5.0	0.7	99.0	250
	Max	5.0	39.0	37.0	2040	2590
Sports fields (mg/kg), $n = 4$	Mean	12.7	67.3	8.9	5130	9930
	Median	4.2	28.5	6.1	1275	4205
	SD	19.0	88.9	8.3	8275	13,458
	Min	1.5	12.0	2.5	470	1410
	Max	41.0	200	21.0	17,500	29,900
Playgrounds/schools (mg/kg), $n = 5$	Mean	3.1	35.8	9.7	812	1936
	Median	3.7	18.0	9.9	920	1330
	SD	2.7	53.1	8.0	723	2388
	Min	0.0	4.5	1.7	100	220
	Max	6.6	130	20.0	1830	6090

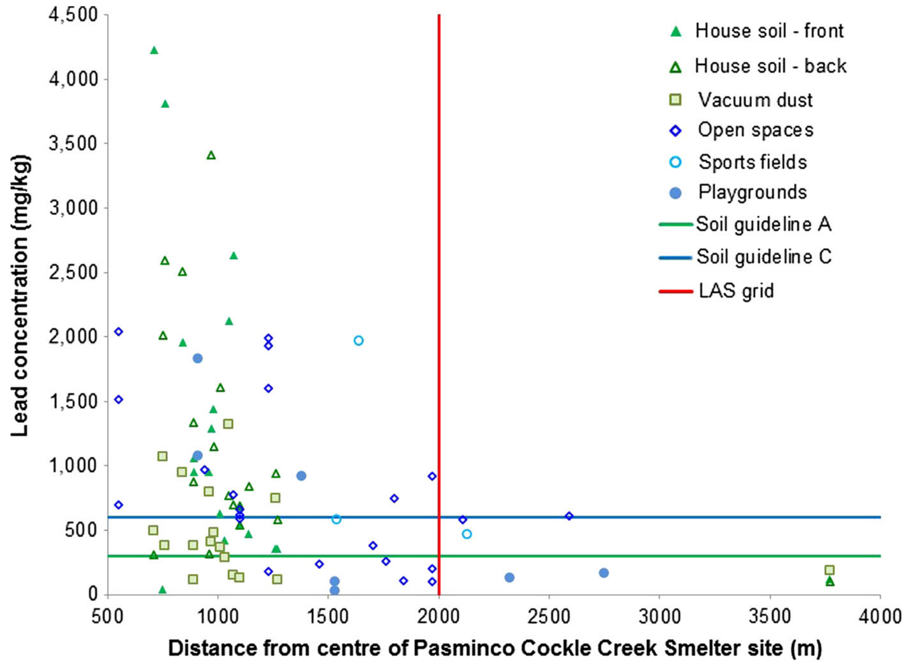

Fig. 4 Soil and dust lead concentrations from Boolaroo homes and community areas plotted against distance from the centroid of the PCCS site, illustrating a decrease in contamination with distance from the former smelter

number of community areas contain lead concentrations unacceptable for regular community use. Lead contamination of child play areas is not uncommon, particularly in industrial towns (Haugland et al. 2008; Mielke et al. 2011; Taylor et al. 2013, 2014b). Playground equipment has been identified as a pathway for lead exposure in children where dust deposited on the equipment collects on the hands of playing children (Taylor et al. 2013, 2014b). Although playing sports on grass-covered sporting fields would limit lead exposure to players, there is a reasonable risk that grass will be degraded during play or seasonally, increasing the risk of exposure to lead-contaminated soils (Carr et al. 2008). High total lead concentrations and the well-established bio-accessibility of lead in community areas around Boolaroo (Kim et al. 2009) strongly suggest that unacceptably elevated environmental lead contamination is more prevalent than that was addressed by the LAS.

Residential vacuum dust

Vacuum dust indicates a contemporary exposure pathway with sites containing very high concentrations of lead; one site returned a total extractable lead concentration of 1320 mg/kg (vacuum dust mean = 495 mg/kg, median = 380 mg/kg, $n = 17$) (Supplementary Data S3). Properties in close proximity to the former PCCS generally contain higher concentrations of vacuum dust lead (Fig. 4), which is not surprising given that smelter atmospheric emissions were a significant source of contaminated dust (Morrison 2003). Lead bio-accessibility of household vacuum dust ($n = 17$) was also elevated (mean = 92 %, median = 90 %). Total extractable lead and bio-accessible lead concentrations in household vacuum dusts were also strongly correlated ($r = 0.97, p < 0.00001$). While these relationships may be an artefact of the extraction methods, these values are in agreement with those reported recently by Kim et al. (2009) in a separate assessment of bio-accessibility and phyto-availability of smelter-contaminated soils from the Boolaroo area and also concur with Morrison and Gulson (2007).

The Bunker Hill Superfund Site in Idaho, USA, was subject to a similar clean-up as Boolaroo to reduce lead in the environment (von Lindern et al. 2003b). At Bunker Hill, lead in household dust was sourced predominately from soil lead contamination around this site. Relevantly, research shows that up to 40 % of the dust inside houses is sourced from soil surrounding the home, which is then carried inside on shoes (Dixon et al. 2006, Hunt et al. 1992; 2006, Murgueytio et al. 1998, Stanek and Calabrese 1995). An estimated 40–50 % of a child's elevated blood lead level in the Bunker Hill Superfund Site area was attributed to household dusts (von Lindern et al. 2003a, b).

Assessment of effective management strategies

It is evident that despite the Boolaroo LAS, high concentrations of lead in the living environment in Boolaroo persist. One of the most apparent failures of the LAS approach is the absence of post-abatement soil analysis in order to measure the efficacy of the programme. Post-abatement assessment is fundamental to evaluate the work to reduce environmental metals exposures, and such an assessment would have revealed that the nominated properties approach used by the LAS did not achieve its goal. The strategies employed by the LAS of shallow soil capping, mulching or grass covering are insufficient to mitigate the risk of lead exposure in the long term. Management of high-risk lead-exposure sites in New Orleans, USA, involved laying a brightly coloured water permeable layer over exposed contaminated soils and capping with a minimum of 15 cm of certified clean fill (Mielke et al. 2011). This procedure placed a physical and visual barrier between the contemporary users of the site and the contaminated soil layer. Similar abatement strategies were adopted in Boston, USA, where 15 cm of soil was removed and a geotextile barrier was put in place and then capped with a minimum of 20 cm of clean soil and grass (Aschengrau et al. 1994). The Baltimore Lead in Soil Project adopted the protocol of removing the top 15 cm of soil and replacing it with clean fill (Farrell et al. 1998). In Zamfara State, Nigeria, which has been identified as one of the biggest lead poisoning incidents in history, a clean-up protocol similar to that of Boston and Baltimore was applied. Soils with lead concentrations above 1000 mg/kg were removed and replaced with clean (<100 mg/kg lead) soil, and soils between 400 and 1000 mg/kg lead were capped with 8-cm hard packed clean (<100 mg/kg lead) soil (Blacksmith Institute 2011). Despite significant financial constrictions, the protocol applied in Zamfara State, combined with community awareness and education, is estimated to have reduced environmental lead ingestion by 98 % (Blacksmith Institute 2011).

One Australian location where environmental lead contamination clean-up and exposure reduction were successful was at the coastal town of Esperance in Western Australia, which was the site of extensive contamination arising from wind-blown dust distribution from the lead ore shipping ports in 2007 (Gulson et al. 2009). After extensive soil removal (a minimum of 20 cm depth and to achieve concentrations below 300 mg/kg) and hard surface cleaning, the town was deemed to have successfully recovered from the incident and declared lead free (Government of Western Australia 2011).

In another recent example, soils around the still operational Hayden-Winkleman smelter in Arizona, USA, were remediated where values exceeded 23 mg/kg arsenic, 400 mg/kg lead and 9300 mg/kg copper (US EPA 2012). The agreement between the US EPA and the smelter company, ASARCO, required that soil clean-up was to be completed to these concentrations or to a depth of four feet (1.2 m). The US EPA undertook soil sampling and analysis to verify effectiveness of clean-up at the base of excavated areas. Where soil concentrations still exceeded clean-up standards at a depth of four feet (1.2 m), a coloured barrier was laid at the base to alert anyone digging at this depth that the soil was still contaminated. Remediated properties were back-filled with clean soil and re-landscaped to its original condition.

These abatement strategies were effective clean-up methods because either they completely removed contaminated soil or a thick physical barrier was used to limit contact between contaminated soil and the human environment, reducing the opportunity for exposure to high concentrations of lead in soil. In order to apply the same rigorous, world's best practice approach to the lead-contaminated soil clean-up in Boolaroo, i.e. total removal of the potential lead-exposure risks from children, as was conducted in Boston (15 cm of contaminated soil), it will require approximately 234,000 m^3 of soil to be removed (calculated by determining the exposed soil surface area on each property within the LAS boundary).

Evaluating the success of the LAS through monitoring blood lead concentrations

Elevated blood lead levels in mining and smelting communities are often attributed to additional environmental sources including leaded petrol and paint (Gulson et al. 1996). Prior work examining blood lead source apportionment at Boolaroo illustrates that these additional sources contribute little to blood lead levels at Boolaroo (Gulson et al. 2004). Further, the elemental correlations between concentrations of soil antimony and lead ($r = 0.86$, $p < 0.00001$) and cadmium and lead ($r = 0.87$, $p < 0.00001$) demonstrate a single smelter point source and not one derived from former lead petrol emission or old lead paint. Unsurprisingly, similar arguments have often been promulgated in lead mining and smelting towns as part of an institutional approach to downplaying risk (Taylor et al. 2011, 2015; Sullivan 2014). Regardless of the contributions of these additional sources, residential soils in Boolaroo remain a modifiable lead-exposure risk, with the quality of the soil far below that reasonably expected for a contemporary living environment.

A dedicated assessment programme of blood lead concentrations in the community surrounding the PCCS had not been carried out since 2006, although continued NSW population health surveillance data revealed a continued declining blood lead concentration trend (NSW Health 2014). No specific blood lead assessment was conducted post-LAS to quantify the efficacy of the work although "*the mechanisms to test whether abatement or remediation has been successful in the case of lead contamination in soil is to assess the level of lead in blood*" (pers. comm. Coffey, NSW EPA 2014). Following the release of provisional results and conclusions from this study to the NSW Government in late 2014, the NSW EPA determined that it was necessary to establish an expert work group to evaluate the effectiveness of the LAS and other remediation activities relating to lead contamination arising from the former Pasminco lead smelter located at Boolaroo, NSW (NSW EPA 2015). The assessment includes the new blood lead surveillance programme targeted at children under 5 years of age from the Boolaroo community, initiated in 2015 (NSW Health 2015b).

Lessons from the LAS

There is a growing need to develop effective contaminated site rehabilitation approaches (Trasande and Liu 2011). Central to all clean-up efforts is the need to protect vulnerable populations, predominantly children. Given the near universal acceptance that there is no safe exposure limit for lead, it would be prudent to consider strategies to mitigate risks permanently, which provide a margin of safety in soil concentrations and avoid approaches that rely on self-protection and education strategies, which have been shown to be ineffective (Yeoh et al. 2012). The current analysis and evaluation of the LAS offer important lessons for future contaminated site clean-up attempts. It is evident that the approach applied by the LAS was insufficient for effective clean-up due to two primary reasons:

1. The LAS did not capture the full extent of the contamination problem in Boolaroo. The data show that environmental lead contamination is more widespread and pervasive than the localised works in residential front and back yards. Multiple exclusions of the LAS scheme including public spaces and schools have resulted in significant lead contamination sinks remaining within the urban environment. Failure to also consider the migration of contaminated soil and dust around the urban environment and provide a clean-up strategy that prevents future re-entrainment and contamination has resulted in an unacceptable legacy in Boolaroo.
2. There was no post-LAS assessment to determine the effectiveness of the strategy. This study shows significant environmental lead contamination persists following completion of the LAS. If a post-LAS assessment had been conducted, it would have been apparent that the approach adopted by the LAS was not appropriate for the residential setting.

Given that the extent of environmental contamination and associated health impacts is increasing on a global scale, it has been argued that there is an intergenerational health pandemic (Adeola 2012; Edelstein 2004; Grandjean and Landrigan 2014, Hardoy et al. 2013). Even applying the precautionary principle as a minimum standard, it is clear that we should not place communities at risk of long-term illness and disease as a result of failed or insubstantial environmental rehabilitation initiatives. The embodied costs to society (socially and economically) far outweigh the costs of proper, permanent and effective intervention (Grandjean et al. 2012; Pichery et al. 2011; Trasande and Liu 2011).

Conclusion

This study demonstrates that despite the implementation of the LAS, elevated and unacceptable lead contamination surrounding the former PCCS site remains. Lead-contaminated soils in residential properties within the LAS zone have not been adequately abated to achieve lead concentrations below the soil guideline levels. The examples of international environmental clean-up approaches presented in this study illustrate the shortfalls of the LAS "cap and cover" approach. The data in this study, when compared to the expectations of current approaches and environmental standards, lead us to conclude that the goal of the LAS to reduce the lead contamination to concentrations that are within "*acceptable limits for everyday living*" has not been achieved, particularly when benchmarked against world's current best practice (Zines 2007, p. 5).

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