An audit of previously remediated sites in Broken Hill

Prepared for Broken Hill Environmental Lead Program by:

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EXECUTIVE SUMMARY

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.

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1. BACKGROUND TO THIS AUDIT

From the mid-1990s through until the mid-2000s, a residential lead (Pb) abatement scheme was carried out in Broken Hill, under the auspices of the Broken Hill Environmental Lead Program (BHELP), and the Child and Family Health Department. This program consisted of both inside and outside interventions, and was made available to residences where a child aged 0-4 years had exceeded the acceptable blood Pb level of the time (>10 μg/dL), regardless of the topsoil Pb concentration around the residence. The focus of this report is solely on the residential yard abatement part of this program. Participation in the abatement program was voluntary, with at least 228 householders/residents electing to have some form of abatement carried out on their residential yards; a list of the addresses of abated residences is given in Appendix 1. The abatement strategies consisted mainly of 'cap and cover' methods, with or without excavation of contaminated topsoil. The capping materials were usually clean garden loam, wood chips, cracker dust or road base, and for most abated residences more than one capping material was used in different parts of the yard.

During the same period of time, several other remediation/abatement programs were carried out in public access areas (footpaths and nature strips, schools, childcare facilities, vacant blocks) around Broken Hill. These remediation strategies also commonly included excavating and topdressing with clean garden loam for refurbished garden beds, or topdressing with cracker dust and/or hardened or loose road base.

While there was some follow-up to the inside residence interventions, there has been no follow-up of the surface soil Pb concentrations of residential yards that underwent some form of abatement during the program (1994–2006), or on the public access areas remediated during the same period. In brief, the effectiveness of abatement in reducing Pb loading (μg/m^2) inside residences varied substantially depending on the initial Pb levels in the houses. Lead loadings in houses with very high initial loadings reduced by up to 80% and the reduction lasted for the 10 months the houses were followed-up after abatement. In contrast, residences with low initial Pb loadings showed no benefit from abatement (probably because often very little was found to do in these houses). The aims of this work are to provide an overview of the residential yard abatement strategies employed (*viz.* the type of materials used and the relative frequency of use), and to assess, by comparison with current day topsoil Pb concentrations, the efficacy of these different abatement strategies in maintaining low topsoil Pb concentrations. The efficacy of abatement on other public access sites (e.g. footpaths and nature strips, schools, childcare centres) was also to be considered.

2. RESEARCH METHODS

2.1. Abatement strategies carried out between 1994 and 2006

Data relating to the extent and type of abatement works carried out on Broken Hill residential yards between 1994 and 2006, and the antecedent topsoil Pb concentrations at the sites and time of abatement, are held in two paper-based sets of files; one held by the Department of Public Works (DPW) and one held by Child and Family Health (CFH). It is understood that at least 228 residential yards underwent abatement under the BHELP program – these are listed in Appendix A. The DPW files are located in a storage facility at the NSW Government Office Block (32 Sulphide St), and were systematically interrogated over a number of days for the purpose of collating antecedent topsoil Pb concentrations, the zones of abatement recommended for residential yards and the eventual abatement strategies carried out in residential yards. As shown in Figure 1, the recommended abatement works for each residential yard were recorded on a hand-drawn map, with different hatchings and colours used to represent different abatement strategies. In most cases, sites of antecedent topsoil Pb testing were also marked on these maps, with measured Pb concentrations listed on the same page or an attached page. Confirmation of the abatement carried out was found in the form of Scope-of-Works files and/or invoices for materials supplied to the relevant property. Abatement records for a total of 75 residences were scrutinised from the DPW files.

The paper-based files held by CFH proved to be elusive for much of the project period, but were eventually located in a ground-floor storage room and a basement storage room of the Child and Family Health Centre at 2 Oxide St, Broken Hill. To further complicate the accessing of relevant data, files documenting the antecedent topsoil Pb concentrations of residential yards and the recommended abatement strategies for those yards, were located in a different room to the Scope-of-Works files documenting the eventual abatement strategies carried out. Abatement records for a total of 17 residences were scrutinised from the CFH files.

Prior to the accessing of data from the CFH Centre, ethics approval was sought from, and given by, the Greater Western Human Research Ethics Committee for scrutinising this data. Ethics approval was sought from, and given by, The University of Sydney Ethics Committee for the conduct of the entire project.

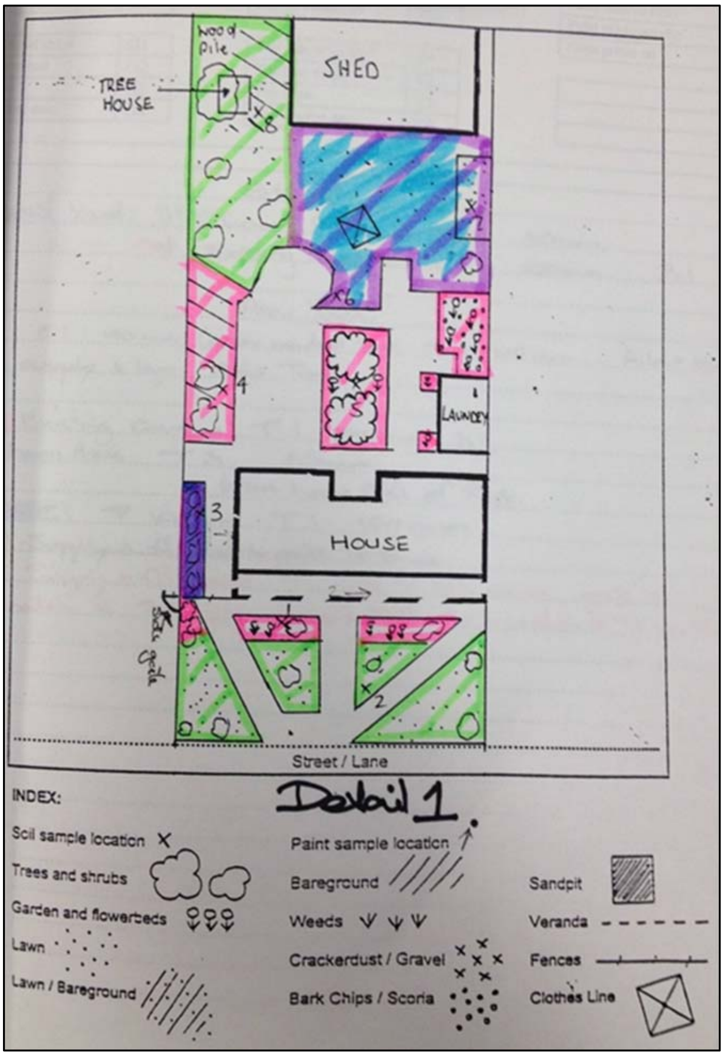


Figure 1. An example of a recommended abatement map for a Broken Hill residential yard, showing different abatement zones and the locations of antecedent topsoil Pb measurements.

2.2. Assessing the long-term efficacy of abatement strategies

During August 2016, a mail-out campaign was carried out to seek the permission of householders to allow the research team to access residential yards to make observations of the condition of abatement zones and to take follow-up measurements of topsoil Pb concentrations – this request was sent to 178 residential properties that underwent yard abatement between 1994 and 2006. All correspondence was accompanied by a Participant Information Statement, as required by the Greater Western and University of Sydney HRECs. Publicity for the follow-up measurements was also garnered by the Chief Investigator having a short article published in the *Barrier Daily Truth* newspaper on September 7th, and a short interview on ABC Radio Broken Hill on September 9th. Flyers were also posted at various locations around Broken Hill to raise awareness of the audit.

By mid-September, when field sampling was scheduled to occur, the research team had received permission from 25 householders/residents to conduct follow-up observations and measurements. The research team identified for sampling a further 4 previously-abated residences that had been abandoned or demolished, and a further 10 vacant blocks or nature strips/garden beds in public access areas that had been abated under other remediation schemes (e.g. the Greening Grants scheme). The 29 residences sampled are indicated in Appendix 1 and the ten public access areas sampled are indicated in Appendix 2.

For each of the 39 residences/properties identified for follow-up, observations of the current condition of abatement works and soil surface Pb measurements were carried out in mid-September, 2016. Where the sites of antecedent topsoil Pb concentration were known and where these were accessible, soil surface measurements of Pb concentration were made using a portable X-ray fluorescence (pXRF) device. At every location the Pb concentration was measured for the surface soil material – in this context, added garden loam and cracker dust were regarded as soil, while wood chips, pebbles and straw mulch were pushed aside to allow measurement to be made of the first soil layer encountered. Each pXRF measurement of an abatement zone was conducted in triplicate (within an area of 1 m^2), and with a measurement time of 90 seconds (30 seconds for each of 3 beams). For completeness, the Pb concentrations of the non-soil capping materials were measured at several locations each. In some cases, the sites of antecedent topsoil Pb measurements were unknown, and so pXRF measurements were made in different representative zones of the yard/vacant block/nature strip/garden bed. All pXRF measurements of residential yards and public access areas are given in Appendix 3.

In order to validate the accuracy of the pXRF in estimating surface soil Pb concentrations, twenty-four soil samples were taken from a variety of yards and sent to the National Measurement Institute (NMI) for estimation of total Pb concentration by ICP-MS following *aqua regia* digestion. The soil samples selected spanned a wide range of pXRF-estimated Pb concentrations and the data are given in Appendix 4. Fourteen of these soil samples were also fractionated to <150 μm and analysed by the pXRF in laboratory mode for Pb concentration (Appendix 5).

To assess statistically if abatement was effective and which strategies were the most effective, a residual maximum likelihood, REML, model was fitted to the change in Pb concentration data (ratio of Antecedent Pb:2016 Pb). This linear mixed model (the REML) was used as it can incorporate the spatial distribution of the sampled soil data. Because of the large number of variations in the exact abatement strategy used, the change in topsoil Pb concentration data was analysed according to eleven amalgamated abatement strategies, as follows;

A. Excavate 100 mm soil, replace with woodchips
B. Excavate 100 or 200 mm soil, replace with garden loam
C. Excavate 75, 100 or 200 mm soil, replace with cracker dust
D. Topdress soil with 50 mm of wood chips
E. Topdress soil with 25 or 50 mm of garden loam
F. Topdress soil with 50 or 75 mm of cracker dust
G. Topdress soil with 75 mm of garden loam
H. Topdress soil with 75 or 100 mm of wood chips
I. Install lawn or topdress with sand
J. Capping of pebbles
K. Excavate 100 mm soil, replace with 50 mm garden loam, 50 mm wood chips

3. RESULTS & DISCUSSION

3.1. Abatement strategies carried out between 1994 and 2006

From the 92 residential properties for which the records of antecedent topsoil Pb concentrations and implemented abatement strategies were available and scrutinised, some 395 individual abatement occurrences have been tabulated according to antecedent topsoil Pb concentration (Table 1), providing a useful ‘snapshot’ of the entire abatement program (~40% of abated properties).

As indicated in Table 1, the two main forms of abatement employed were;

(i) excavation of some depth of soil and replacement to the same depth of a clean material, and
(ii) top-dressing of the soil with some depth of clean material.

The clean materials used were predominantly wood chips, garden loam and cracker dust, although on some properties blue metal (road base), gravel/pebbles and coarse sand was used. There appears to be only a weak correlation between the antecedent topsoil Pb concentration and the abatement strategy used, although garden loam was the most commonly used clean material (46% of occurrences), 100 mm was the most common excavation depth and 50 mm was the most common top-dressing depth. Generally, lawn areas were treated with garden loam or cracker dust, garden beds were finished in wood chips, bare areas and driveways were finished in cracker dust or blue metal, and other areas (e.g. BBQ areas, sand pits) were finished with new materials to match the existing ones. In some cases, existing lawns were only top-dressed to 50 mm depth (irrespective of topsoil Pb concentration) to ensure grass survival.

For most residential yards tested for topsoil Pb, between 4 and 10 locations were tested and the subsequent abatement was often tailored to different sections of the yard (e.g. paths, garden beds, lawn areas). The soil size fraction on which the soil Pb concentrations were measured also varied: the Pb concentration was estimated from the whole soil at 4% of the residential yards tested; from the <2 mm soil fraction at 43% of yards; from the <150 μm soil fraction at 12% of yards; and from the <150 μm and <2 mm soil fractions at 41% of yards.

Figure 2. Examples of the main abatement materials used in Broken Hill; (a) garden loam, (b) cracker dust, (c) wood chips and (d) blue metal/road base.

Table 1. Occurrences of abatement strategies carried out for different levels of antecedent soil Pb in 92 Broken Hill residential yards.

Abatement carried out		Antecedent topsoil Pb concentration (mg/kg)					
Excavation and replacement/ Top-dressing	Material added	0-300	301-1499	1500-2499	2500-5000	>5000	Total occurrences
Excavate and replace 50 mm	Wood chips	0	1	0	0	0	1
	Blue metal	0	3	0	0	0	3
	Garden loam	1	4	0	0	0	5
	Cracker dust	0	4	0	0	0	4
Excavate and replace 100 mm	Wood chips	7	11	4	7	0	29
	Blue metal	0	7	1	1	0	9
	Garden loam	0	17	4	5	0	26
	Cracker dust	2	6	0	0	0	8
	Garden loam + wood chips*	0	1	0	3	1	5
Excavate and replace 150 mm	Blue metal	0	1	0	0	0	1
	Garden loam	1	5	1	2	0	9
	Cracker dust	0	2	2	0	1	5
Excavate and replace 200 mm	Blue metal	0	1	0	1	2	4
	Garden loam	0	0	4	4	0	8
	Cracker dust	0	1	7	0	0	8
	Garden loam + wood chips*	0	2	4	2	0	8
Excavate and replace 300 mm	Garden loam	0	0	4	6	0	10
	Cracker dust	0	0	0	1	0	1
	Cracker dust + blue metal*	0	0	1	1	0	2
Top-dressed 25 mm	Garden loam	2	23	1	1	0	27
	Cracker dust	0	8	2	2	0	12
Top-dressed 50 mm	Wood chips	1	10	0	0	0	11
	Blue metal	1	7	1	2	0	11
	Garden loam	13	24	12	7	0	56
	Cracker dust	3	14	6	3	0	26
Top-dressed 75 mm	Wood chips	2	2	0	0	0	4
	Garden loam	3	9	0	1	0	13
	Cracker dust	1	4	1	0	0	6
Top-dressed 100 mm	Wood chips	0	9	6	5	0	20
	Blue metal	1	4	1	1	0	7
	Garden loam	6	10	6	3	0	25
	Cracker dust	2	6	1	2	0	11
Top-dressed 150 mm	Wood chips	0	0	0	1	0	1
	Blue metal	0	1	0	0	0	1
	Garden loam	0	1	0	1	0	2
Top-dressed 200 mm	Cracker dust	0	0	1	0	0	1
Other	Lawn; 100 mm white rock; 75 mm coarse sand	2	10	3	0	0	15
		48	209	72	62	4	**395**

* In these cases, equal thicknesses of both materials were applied.

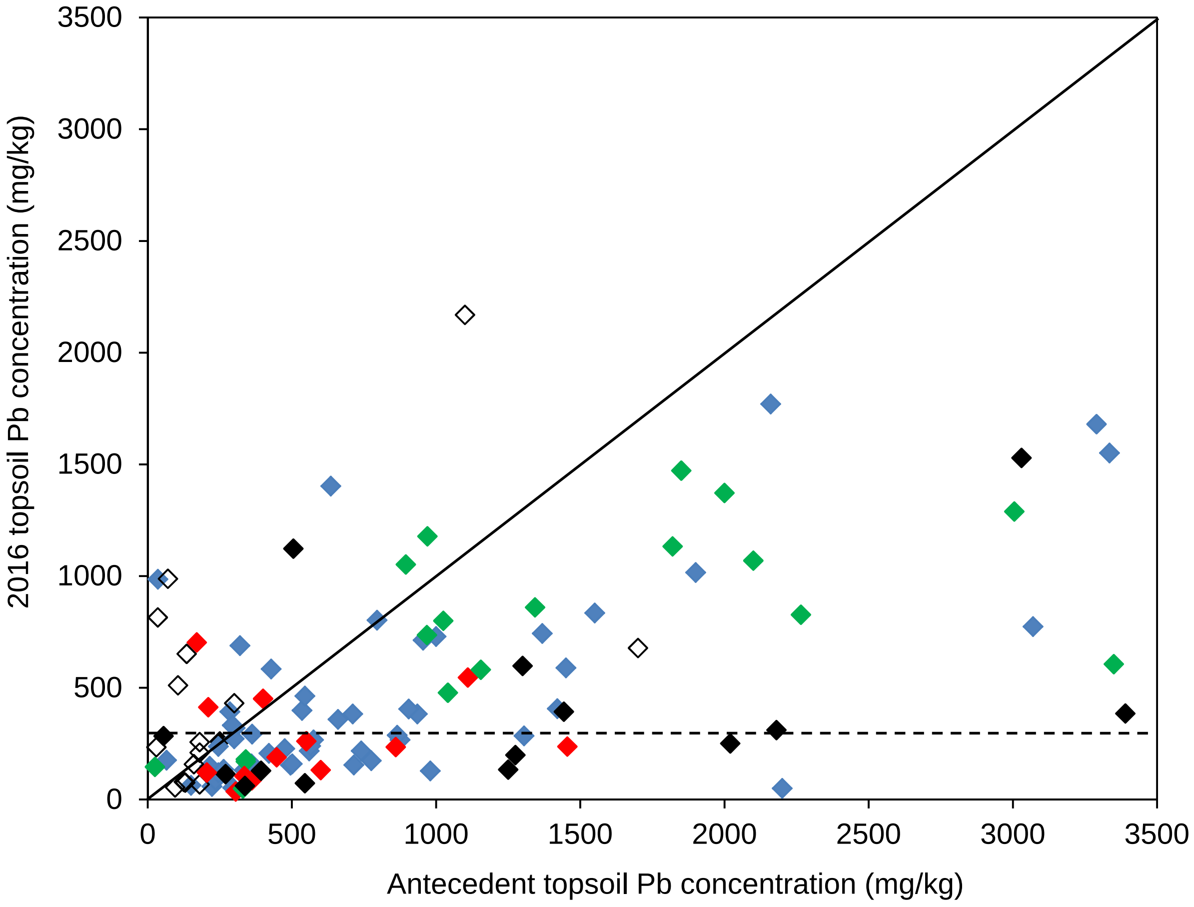
3.2. Assessing the long-term efficacy of abatement strategies

A total of 39 previously-abated residential and public access locations were assessed for current condition and topsoil Pb concentrations, and these were widely spread across both the northern and southern urban areas of Broken Hill (Figure 3). Across these 39 locations, a total of 153 measurements of current topsoil Pb concentrations were obtained, of which 115 could be directly compared to topsoil Pb concentrations measured at the same spot prior to abatement (Appendix 3). For many of the residential yards visited, one or more previously Pb-assessed and/or abated spots were not accessible for follow-up measurements due to paving, concreting or new buildings/infrastructure. For the 10 public access locations assessed, none of the antecedent topsoil Pb concentrations were available, but it is understood that these measurements were made prior to abatement/remediation.

Figure 3. The distribution of previously-abated residences and public access areas re-assessed for topsoil Pb concentrations in 2016.

As shown in Figure 4, which contains the 115 point comparisons for topsoil Pb concentration before abatement and in 2016, it can be broadly stated that the abatement program has been successful in reducing topsoil Pb concentrations. Of the 115 antecedent vs 2016 comparisons, only 27 (~23%) show a higher value of Pb in 2016 than prior to abatement. At least ten of these comparison points had no abatement works carried out after the antecedent topsoil Pb measurement was made. However, if it is assumed that immediately on completion of abatement works at each location the topsoil Pb concentration was below 300 mg/kg (the Health Investigation Limit, HIL, for soil Pb in residential yards; NEPC, 2011), then it can also be seen from Figure 4 and Appendix 3 that a substantial number of locations have undergone partial or substantial re-contamination with Pb. Of the 153 measurements of topsoil Pb in 2016 (Appendix 3), 84 (~55%) show a value of Pb greater than 300 mg/kg. In these instances, the enriched values of topsoil Pb are likely to be due to a combination of ongoing supply of 'new' Pb to the abated surface, mixing of the abatement material with the underlying Pb-rich soil, or the partial or complete removal of the abatement material.

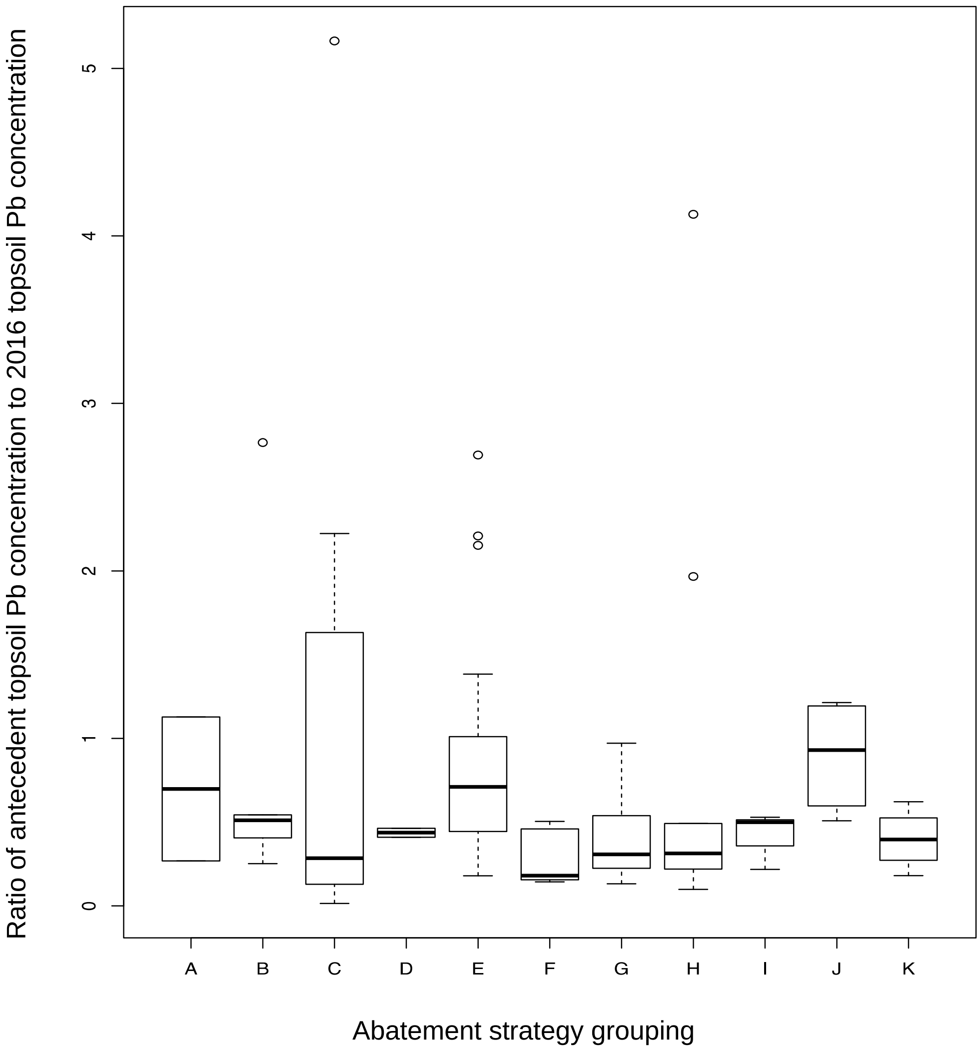
Figure 4. Direct comparisons of antecedent topsoil Pb concentrations at the time of the abatement program with topsoil Pb concentrations at the same locations in 2016. Blue diamonds indicate abatement with garden loam, black diamonds indicate cracker dust, red diamonds indicate wood chips, green diamonds indicate various other abatement strategies and white diamonds indicate no abatement action was taken. The diagonal line is a 1:1 line, while the dashed line represents the HIL for Pb in residential yards (300 mg/kg) (NEPC, 2011).



The spread of abatement strategies across the range of antecedent topsoil Pb concentrations is evident in Figure 4; while wood chips were used primarily in locations where the antecedent Pb concentration was low to moderate, garden loam and cracker dust were used at sites ranging from low antecedent Pb to very high antecedent Pb. Similarly, the ‘other’ abatement strategies were scattered across all antecedent Pb concentrations ranges, while the sites where no abatement action was taken generally corresponded to antecedent Pb values of less than 250 mg/kg.

Applying the REML model to the change in Pb concentration data (antecedent vs 2016 values) for the different groupings of abatement strategies, all of the groups of abatement strategies were found to have significantly decreased the topsoil Pb concentrations. However, as indicated in the boxplots of these ratios of antecedent vs 2016 Pb values (Figure 5), there is no significant difference in how well the various abatement strategies have performed; that is, from this dataset we cannot say that any one abatement strategy is better or worse than the others. Undoubtedly, the different abatement strategies are prone to different types of disturbance, but because of the wide range of locations in which the different strategies were employed, and the very wide ranging antecedent topsoil Pb concentrations across those locations, the change in Pb concentration data does not give a clear guide to abatement strategy efficacy.

Figure 5. Mean ratios of antecedent topsoil Pb concentration to 2016 topsoil Pb concentration for eleven groupings of abatement strategy. A = excavate 100 mm soil, replace with woodchips, B = excavate 100/200 mm soil, replace with garden loam, C = excavate 75/100/200 mm soil, replace with cracker dust, D = topdress 50 mm wood chips, E = topdress 25/50 mm garden loam, F = topdress 50/75 mm cracker dust, G = topdress 75 mm garden loam, H = topdress 75/100 mm wood chips, I = install lawn/topdress with sand, J = pebble/gravel capping, K = excavate 100 mm soil, replace with 50 mm garden loam, 50 mm wood chips.



At a number of locations, the Pb concentration was measured on the surface of intact, non-soil capping materials (road base, gravel, white pebbles, wood chips, straw mulch applied by householders) as well as on the soil surface immediately underlying the capping. As shown in Table 2, where these cappings are in good condition, they are generally very effective in suppressing the ground surface Pb concentration. Of these, white pebbles and gravel gave the most consistently low values of Pb, perhaps because any depositing Pb-rich dust will be washed off the surface of the pebble/gravel and settle on the topsoil beneath. In contrast, wood chips tended to yield slightly higher concentrations of Pb, probably reflecting the greater surface area of the chips that might trap soil/dust particles and the more common mixing of woodchips with the underlying soil. It was observed in a number of the nature strip gardens assessed that the wood chip cappings had become mixed with the underlying soil to varying extents.

Table 2. Surface Pb concentrations of intact, non-soil capping materials compared to the immediately underlying soil surface.

Address	Capping material/underlying soil	Pb concentration (mg/kg)
[redacted] Eyre St	Road base (solid) Soil	185 4183
[redacted] Picton St	Gravel Soil	43 176
[redacted] Cobalt St	Gravel Soil	29 383
[redacted] Blende St	Gravel Soil	103 1052
[redacted] Eyre St	Gravel (limestone) Soil	575 3827
[redacted] Wills Ln	White pebbles Soil	44 393
[redacted] Old South Rd	White pebbles Soil	273 1178
[redacted] Nicholls St	White pebbles Soil	59 1472
[redacted] Crystal St	White pebbles Soil	15 1069
[redacted] Old South Rd	Wood chips Soil	255 2200
[redacted] Piper St	Wood chips Soil	214 827
[redacted] Comstock St	Wood chips Soil	194 594
[redacted] Crystal St	Mulch Soil	1242 1768
[redacted] Chapple St	Mulch Soil	191 702
[redacted] Marks St	Mulch Soil	28 678

3.3. Anthropic, physical and biotic disturbances of abatement surfaces

The partial or substantial re-contamination, or enrichment, of many previously abated sites with Pb suggests that there are one or more processes operating to gradually reduce the efficacy of the prior abatement. From observations during the field sampling campaign, we think it likely that the main Pb re-contamination or enrichment processes can be broadly categorised into *anthropic*, *physical* and *biotic* processes.

Anthropic processes

Through conversations with various householders, it became clear that in many cases previously-abated surfaces had been disturbed, altered or completely obliterated/covered by changes to the amenity of the yards. In some cases, abated surfaces had been paved, concreted or built on, rendering them obsolete, while in other cases applied garden loam had been mixed with the underlying Pb-rich soil, and applied wood chips had been moved or mixed into the underlying soil. This issue appears to be more acute in those properties near to the Line of Lode, where natural soil Pb concentrations are already high. Presumably, changing house ownership and a loss of knowledge of previous abatement will have exacerbated this situation at various locations. Another anthropic process that may have affected abated surfaces located near to the Line of Lode is that of Pb-rich dust emission. Fugitive dust from mining works, traffic along the Line of Lode itself and from the railway precinct is likely to have been deposited across adjoining areas, acting to gradually replenish surface Pb stocks. At several of the properties near the Line of Lode (Old South Rd, Crystal St, Piper St, Eyre St), topsoil Pb concentrations were almost always in excess of 300 mg/kg regardless of how intact previous abatement works appeared to be. As an example of this, at [redacted] Crystal St, a front garden inside a 2 m-high wall on Crystal St has had a synthetic matting laid down and a thin veneer of soil applied over the top (Figure 7) – while this soil contains less than the 1900 mg Pb /kg at this spot pre-abatement, its current Pb concentration of 1016 mg/kg (Appendix 3) suggests accretion of Pb-rich dust.

Figure 7. Pb-rich soil overlying a synthetic textile/fabric in the front yard of [redacted] Crystal St.

Physical processes

Water and wind erosion are two physical, surficial processes that have clearly had an impact on some previously-abated surfaces in Broken Hill. The householder at [redacted] Wills St reported that the original abatement capping of wood chips had completely washed away during a heavy rain, while at a number of the vacant blocks along Eyre St there was clear evidence of rill erosion breaking up the pre-existing abatement surfaces of road base and cracker dust. In the case of [redacted] Eyre St (Figure 8a), the intact road base had a surface Pb concentration of 185 mg/kg, whereas patches of exposed soil had a Pb concentration of 4183 mg/kg. The vacant block at [redacted] South Rd Lane also shows considerable evidence of water erosion, with plumes of Pb-rich reddish sediment clearly evident across the lane surface (Figure 8b). These plumes of sediment contained more than 3000 mg Pb/kg, whereas the laneway gutter sediment contained only 700 mg Pb/kg.

Figure 8. Examples of eroding surfaces exposing or transporting Pb-rich soil and sediment. (a) is at [redacted] Eyre St, and (b) is at [redacted] South Rd Lane.

Biotic processes

A prominent feature of a number of cracker-dusted localities in particular, was the presence of small ants' nests of different colour to the cracker dust surface on which they were built. This *bioturbation* process was prominent in the cracker dusted nature strips outside both [redacted] Morish St (Figure 9a) and [redacted] Crystal St (Figure 9b). At [redacted] Morish St, the Pb concentration on top of the cracker dust was 134 mg/kg (Appendix 3), whereas the Pb concentration of the reddish ants' nest was 1375 mg/kg. Similarly, at [redacted] Crystal St, the Pb concentration on top of the cracker dust was 650 mg/kg (Appendix 3), whereas the Pb concentration of the reddish ants' nest was 2840 mg/kg, the light red ants' nest was 1327 mg/kg and the greyish ants' nest was 693 mg/kg. These data very clearly show that with greater proportions of subsurface soil brought to the surface, the greater the 'recycling' of Pb to the surface.

A further observation about ants' nests was that they were most conspicuous on cracker dust surfaces; it is likely that they also exist in many garden loam abatement surfaces as well, but on wood chips, pebbles and gravel surfaces the microtopography was generally too rough to allow ants' nests to be built easily.

Figure 9. Point-scale re-contamination of cracker dust surfaces through bioturbation, with capped, Pb-rich soil brought to the surface for ant nest building. (a) is at [redacted] Morish St and (b) is at [redacted] Crystal St, and values for individual nests and cracker dust are Pb concentrations in mg/kg.

4. CONCLUSIONS

- At least 228 residential yards underwent some form of abatement in the period 1994-2006.
- A wide range of abatement strategies were employed, including excavation and/or top-dressing to various depths with clean garden loam, cracker dust, wood chips, road base, pebbles and coarse sand. Garden loam was the most commonly used clean material, 100 mm was the most common excavation depth and 50 mm was the most common top-dressing depth.
- For the previously abated residential yards observed and measured, the majority of abated sites had less topsoil Pb in 2016 than immediately prior to abatement, but more than half of the sites assessed had topsoil Pb concentrations exceeding 300 mg/kg, suggesting considerable re-contamination or enrichment with Pb since abatement.
- For the number of measurements made in this study, no particular abatement strategy was found to be significantly more effective in suppressing topsoil Pb concentration than the others.
- A combination of anthropic, physical and biotic processes are believed to be responsible for the higher-than-background Pb concentrations measured on some abatement surfaces.
- Many of the abatement surfaces examined appear to need some level of rejuvenation, although there are still many other abatement surfaces that appear to be in good condition and are continuing to be effective.

5. REFERENCE

National Environment Protection Council (NEPC) 2011. Guideline on Investigation Levels for Soil and Groundwater. Available at:
http://www.scew.gov.au/sites/www.scew.gov.au/files/resources/93ae0e77-e697-e494-656f-afaaf9fb4277/files/schedule-b1-guideline-investigation-levels-soil-and-groundwater-sep10.pdf

6. APPENDICES

Appendix 1. A listing of residential addresses that underwent yard abatement 1994–2006.

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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Appendix 2. A listing of previously-abated public access locations re-visited and measured for Pb concentration in 2016.

Address	Landuse	Nature of abatement	Notes
[redacted]	Garden bed on Sulphide St nature strip	Garden loam, plants	Next to the Wesley Uniting Church
[redacted]	Garden bed on Oxide St nature strip	Garden loam, plants	Next to a private residence
[redacted]	Garden bed on nature strip	Garden loam, plants	At the front of Railway Town Public School
[redacted]	Vacant, unused block	Capping soil	Moderately sloping, rocky, badly eroding
[redacted]	Garden bed on nature strip	Garden loam, plants	Next to Alma Public School
[redacted]	Disused block – previously a playground	Crushed limestone capping	Backs onto mining lease area
[redacted]	Unused blocks	Road base	Road base in good condition; only a little erosion
[redacted]	Unused blocks	Road base	Disturbed site with evidence of water erosion
[redacted]	Unused block	Crushed limestone capping	Next to Rockwell St, backs onto mining lease area
[redacted]	Garden bed on nature strip	Garden loam, plants	At the front of Rainbow Pre-School

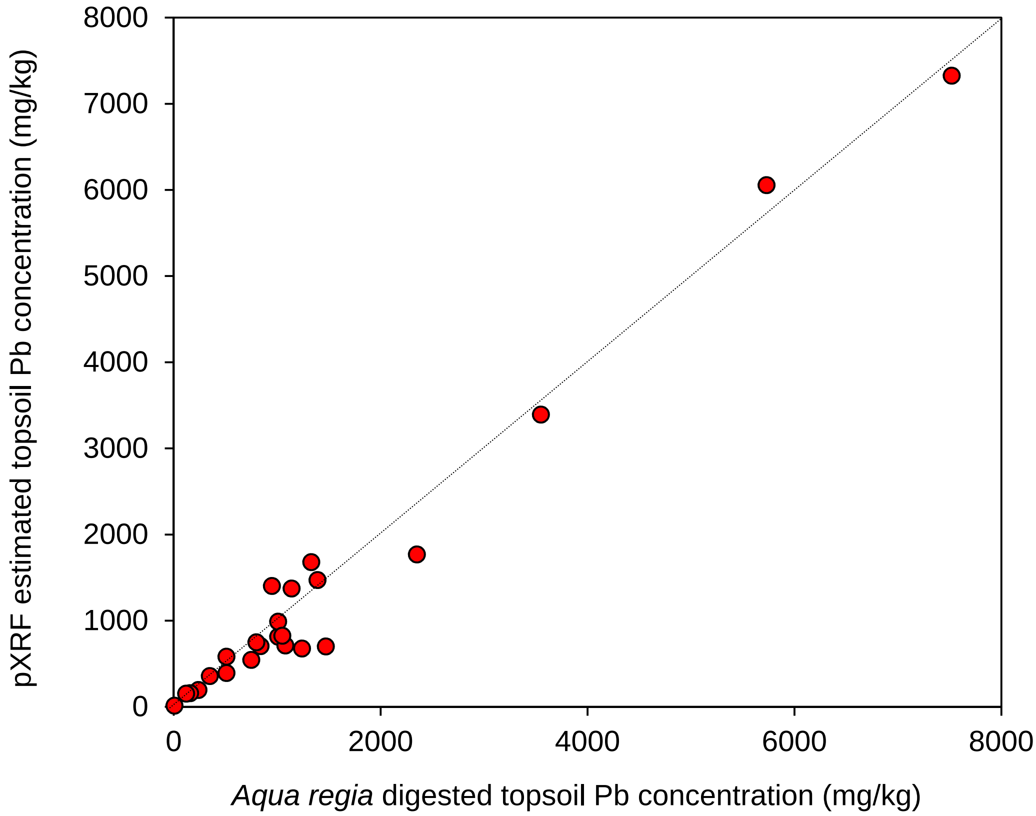
Appendix 3. Topsoil Pb measurements made in 2016 and change in Pb concentrations since abatement, where calculable.

Address	Abatement zone	Antecedent Pb conc. (mg/kg)	2016 Pb conc. (mg/kg)	Absolute change (mg/kg)	Proportional change (%)
[redacted]	Rear yard – cracker dust	55	284	229	416
	Rear yard – cracker dust	250	260	10	4
	LS yard – cracker dust	505	1123	618	122
	RS yard – loam	35	986	951	2717
	Front yard – loam	635	1403	768	121
	Front yard – loam	3335	1551	-1784	-53
[redacted]	Rear yard – no action	70	988	918	1312
	Rear yard RHS – loam	1550	835	-715	-46
	Rear yard RHS – loam	955	713	-242	-25
	Rear yard – loam	1000	730	-270	-27
	LS yard – white gravel	2000	1372	-628	-31
	LS yard – white gravel	895	1052	157	18
[redacted]	Front yard – wood chips	550	261	-289	-53
	Front yard – loam	740	218	-522	-71
	LS yard – wood chips	1455	237	-1218	-84
	LS yard – wood chips	1110	546	-564	-51
	Rear yard – loam, turf	1305	285	-1020	-78
	Rear yard – wood chips	305	36	-269	-88
	Rear yard – wood chips	860	235	-625	-73
[redacted]	Front yard – wood chips	170	703	533	313
	Front yard – wood chips	210	413	203	97
	Rear yard – cracker dust	1275	199	-1076	-84
[redacted]	Front yard – loam, turf	2200	50	-2150	-98
[redacted]	RS yard – loam	575	267	-308	-54
	Rear LS yard – no action	105	511	406	387
	Rear yard – loam	935	383	-552	-59
[redacted]	Front yard LS – loam	1420	407	-1013	-71
	Front yard RS – loam	2160	1770	-390	-18
	Front yard LS – cracker dust	3030	1529	-1501	-50
[redacted]	LS yard – wood chips	4250	982	-3268	-77
	Rear yard – white pebbles	2100	1069	-1031	-49
	LS yard – no action	300	431	131	44
	LS yard – no action	1100	2169	1069	97
	Front yard lawn	–	705	–	–
	Front yard – loam, textile	1900	1016	-884	-47
[redacted]	Front LS – loam, w.chips	3350	606	-2744	-82
	Nature strip – cracker dust	–	650	–	–
[redacted]	Front yard – loam	–	504	–	–
	Rear yard – cracker dust	1300	598	-702	-54
	Rear yard – cracker dust	–	749	–	–
[redacted]	Rear yard – cracker dust	1443	393	-1050	-73
	Rear yard lawn – loam	–	399	–	–
	Rear yard – loam	711	383	-328	-46
	Front yard – loam, pebbles	968	736	-232	-24
	Front yard – loam, pebbles	1041	478	-563	-54
[redacted]	Front lawn – no action	30	234	204	679
	Front garden – no action	1700	678	-1022	-60
	Rear yard – loam	875	267	-608	-69
	Rear yard – loam	865	288	-577	-67

[redacted]	Front drive – blue metal	330	49	-281	-85
	Rear yard – no action	125	79	-46	-37
	Rear yard – no action	180	68	-112	-62
	Rear yard – cracker dust	545	73	-472	-87
[redacted]	Front yard – no action	130	76	-54	-41
	Front garden – no action	160	158	-2	-1
	Driveway – cracker dust	270	114	-156	-58
	Rear yard – loam	775	174	-601	-78
	Rear yard – loam	334	131	-203	-61
[redacted]	Front garden – no action	–	197	–	–
	Lawn – loam	560	218	-342	-61
	Rear yard – no action	180	210	30	17
	LS garden bed – wood chips	600	132	-468	-78
	LS garden bed – wood chips	447	189	-258	-58
[redacted]	Rear yard – coarse sand	340	180	-160	-47
	Rear garden – no action	35	815	780	2229
	Rear yard – coarse sand	340	170	-170	-50
	LS garden bed – loam	1450	589	-861	-59
	Front garden – no action	135	652	517	383
	Front yard LS – loam	795	803	8	1
	Front footpath – cracker dust	1250	134	-1116	-89
[redacted]	Front RS garden – pebbles	1850	1472	-378	-20
	RS yard – loam 4 yrs ago	1025	800	-225	-22
	RS yard – loam 4 yrs ago	1155	581	-574	-50
	RS yard – loam 4 yrs ago	1343	860	-483	-36
[redacted]	Front yard RS – loam, lawn	3290	1680	-1610	-49
	Front yard – loam, w.chips	–	2200	–	–
	RS yard – cracker dust	3390	385	-3005	-89
	Rear yard – cracker dust	2180	311	-1869	-86
	Rear yard LS – loam	3070	774	-2296	-75
	Rear garden path – pebbles	970	1178	208	21
[redacted]	Rear yard sandpit – sand	25	146	121	483
	Rear yard – loam	905	405	-500	-55
	Front yard – loam	65	176	111	170
[redacted]	Front yard LS – loam, chips	1820	1133	-687	-38
	Front yard RS – loam, chips	3005	1289	-1716	-57
	LS yard – loam, wood chips	2265	827	-1438	-63
	Rear yard – cracker dust	2020	251	-1769	-88
	Rear yard lawn – loam	535	399	-136	-25
	Rear garden – loam	1368	743	-625	-46
[redacted]	Front yard LS – loam	428	584	156	36
	Rear yard – loam	303	320	17	6
	Rear yard – loam	320	689	369	115
[redacted]	Front garden – wood chips	–	408	–	–
	Rear yard – loam	660	359	-301	-46
	Rear yard – wood chips	400	451	51	13
[redacted]	Front garden – loam	150	64	-86	-57
	Nature strip – loam	295	53	-242	-82
	Nature strip – loam	223	59	-164	-74
[redacted]	LS yard – wood chips	335	105	-230	-69
	Rear yard LS – loam	235	87	-148	-63
	RS yard – loam	420	207	-213	-51
	Rear yard – loam	245	120	-125	-52
	Front yard RS – wood chips	205	121	-84	-41
	Front yard LS – loam	215	149	-66	-31

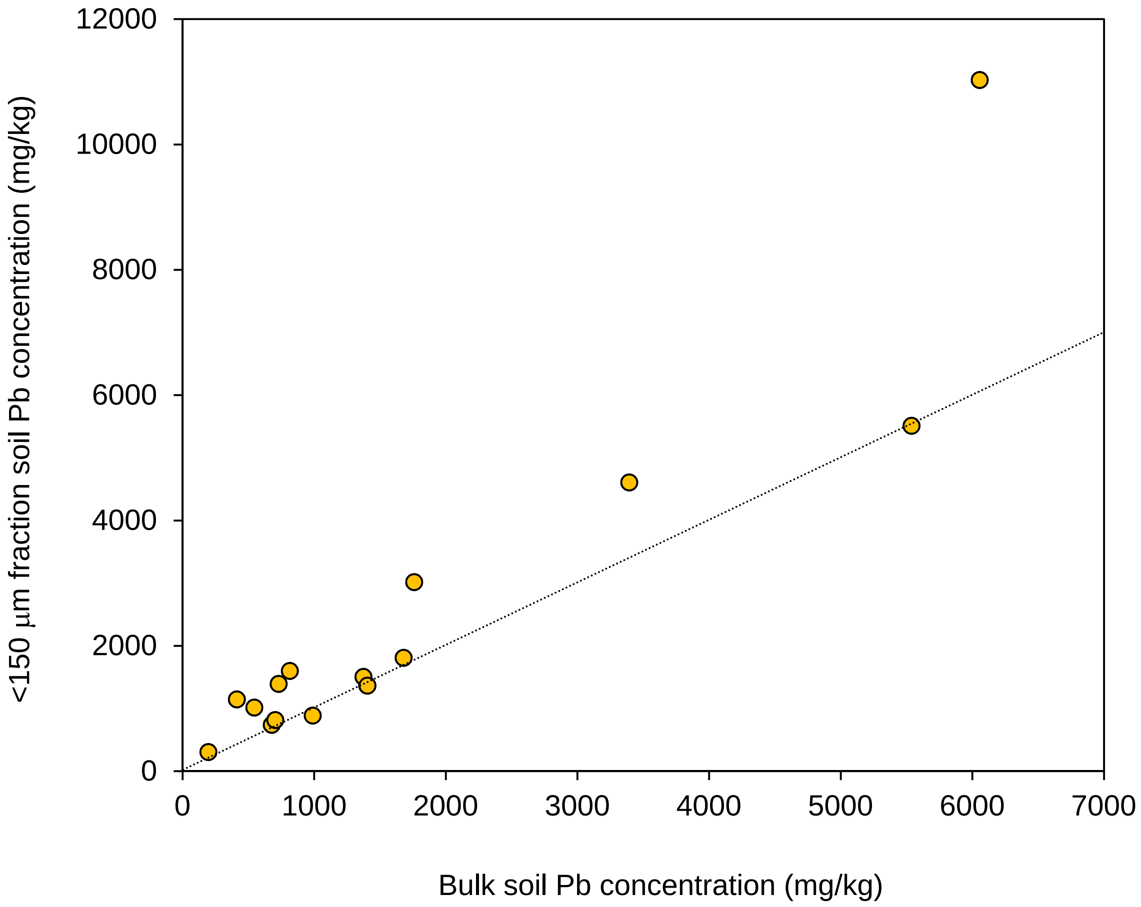
	Front yard LS – loam	263	135	-128	-49
[redacted]	Front garden – bark chips	361	86	-275	-76
	Rear yard LS – lawn	565	240	-325	-58
	Under carport – cracker dust	337	61	-276	-82
	Rear yard – cracker dust	393	129	-264	-67
[redacted]	Front yard – no action	180	257	77	43
	Rear yard – loam	545	463	-82	-15
	Rear yard RS – loam	360	160	-200	-56
	Rear yard RS – loam	362	293	-69	-19
[redacted]	Front garden LS – no action	–	393	–	–
	Front garden bed – no action	–	145	–	–
	Rear yard lawn – loam	300	272	-28	-9
	Rear garden bed – loam	285	393	108	38
	Rear garden bed – loam	293	332	39	13
[redacted]	Front yard – cracker dust	–	133	–	–
	Front garden bed – w.chips	–	357	–	–
	Rear yard – cracker dust	–	105	–	–
	Rear yard – cracker d., loam	–	277	–	–
	Rear yard – lawn	–	343	–	–
[redacted]	Rear yard – loam	495	154	-341	-69
	Rear yard LS – loam	475	228	-247	-52
	Rear yard RS – loam	980	128	-852	-87
	Driveway – no action	95	54	-41	-43
	Front garden – loam	715	155	-560	-78
	Front lawn – loam	245	238	-7	-3
	Front lawn – loam	501	160	-341	-68
[redacted]	Garden bed – loam, w.chips	–	99	–	–
	Original nature strip soil	–	1054	–	–
[redacted]	Garden bed – loam, mulch	–	118	–	–
	Footpath soil – cracker dust	–	129	–	–
[redacted]	Garden bed – loam	–	146	–	–
	Soil between garden beds	–	174	–	–
[redacted]	Runoff plume across lane	–	3216	–	–
	Front of block – loam/clay	–	6056	–	–
	Centre of block – loam/clay	–	7327	–	–
	Gutter of lane	–	708	–	–
[redacted]	Garden bed – loam, w.chips	–	594	–	–
	Garden bed – loam, w.chips	–	748	–	–
[redacted]	Front of block – limestone	–	1052	–	–
	Rear of block – limestone	–	1316	–	–
[redacted]	Rear of block – road base	–	185	–	–
	Rear of block – bare soil	–	4183	–	–
[redacted]	RS block – gravel, sandy soil	–	465	–	–
	Centre of block – pale sand	–	5258	–	–
	Centre of block – red clay	–	2666	–	–
[redacted]	Exposed underlying soil	–	3827	–	–
	Volunteer veg. – limestone	–	538	–	–
[redacted]	Garden bed – loam, w.chips	–	918	–	–
	Soil at front LS of block	–	675	–	–

Appendix 4. Comparison data for the pXRF-estimated and *aqua regia*-digested, ICP-MS measured topsoil Pb concentrations. The dashed line is the 1:1 line.



These comparative data show that the pXRF performed very well in the field, predicting Pb concentration values very closely to those estimated by *aqua regia* digestion and ICP-MS analysis in the laboratory. There is some discrepancy in the values for those samples with between 1000 and 2000 mg/kg, but the sample analysed in the laboratory was taken from a larger surface area than the target soil scanned by the pXRF in the field.

Appendix 5. A comparison of topsoil Pb concentration measured by pXRF in the field with topsoil Pb concentration in the <150 μm size fraction, measured by pXRF in the laboratory mode. The dashed line represents the 1:1 line.



This data confirms that, as is often the case, the finer fraction of the soil tends to contain more Pb than the coarser soil material. For some of the residential yards that underwent abatement, the antecedent Pb concentrations for both the bulk soil and the <150 μm fraction were measured, with the latter fraction usually containing more Pb than the bulk soil.