An assessment of legacy soil Pb contamination of ten public parks in Broken Hill

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Eveleigh NSW 2015

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EXECUTIVE SUMMARY

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.

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1. BACKGROUND TO THIS STUDY

Previous research has demonstrated that topsoil within 1.0 km of the Line of Lode is usually enriched in lead (Pb) due to a combination of; (i) Pb-rich soil parent material, (ii) ongoing accessions of Pb-rich dust from mining works, and (iii) anthropic sources such as leaded petrol emissions and Pb-rich paint. In recognition of this, considerable capping of earthen footpaths with Pb-free cracker dust has been carried out in recent decades, while a residential yard abatement program between 1994 and 2006 also involved substantial capping and covering of Pb-contaminated topsoil. Some public parks in Broken Hill have been refurbished in recent years, with Pb-free turf swards laid down, but the topsoil Pb contamination status of others have yet to be assessed. Anecdotally, it has been suggested that established trees in parks may be acting as dust traps, due to observations of high topsoil Pb concentrations underneath tree canopies, but this may also reflect the difficulty of soil remediation under trees.

In this research, the topsoil Pb concentrations across ten public parks will be assessed, and recommendations made on the requirement for soil abatement in those parks. The ten parks to be assessed, shown on Figure 1, are;

(1) Duke of Cornwall Park
(2) Patton St Park
(3) Alma Oval
(4) Kintore Reserve
(5) Sturt Park
(6) North Family Play Centre
(7) Picton Sports Ground
(8) O'Neil Park
(9) Memorial Oval
(10) Jubilee Oval

The role of tree canopies in capturing Pb-rich dust at these parks will also be examined.

Figure 1. The locations of the ten public parks in Broken Hill assessed for topsoil Pb concentration.

2. RESEARCH METHODS

2.1. Sampling design and measurements of Pb

2.1.1. Sampling design

For each of the 10 parks and ovals investigated, a stratified random sampling design was created in Rstudio. A grid was prepared for each park, and a sampling point randomly allocated within each grid cell (approximately 1340 m^2), giving a sampling density of 8 sampling points per hectare for the first field trip. This design was repeated for the second field trip, but measurements from the first field trip were used to help inform the new sampling density - parks/oval with higher Pb concentrations were allocated extra sample points. The final sampling densities, ignoring some samples taken under the canopies of large trees, ranged from 12 points per hectare for O'Neil Park up to 33 points per hectare for Patton St Park, with an average of 16 sample points per hectare across all parks and ovals. This design was chosen as many of the parks are irregular in shape and have hard, man-made surfaces that cannot be included in this monitoring project, e.g. large areas of concrete paths, skateboarding areas and bandstands. Sampling points that fell on a hard, man-made surface were moved to the nearest site of accessible topsoil. In some cases, where there was a high level of homogeneity in the surface condition and topsoil Pb concentration (e.g. in well-maintained, thickly turfed playing fields), some allocated sampling points were not visited.

The sampling points were visited during one of two week-long sampling campaigns in May, 2017. All sample points were located using a hand-held global positioning system (GPS). During the first sampling campaign approximately half of the allocated sampling points for each park were visited, allowing for the sampling design to be optimised for the second field trip; in particular, further sampling points were incorporated into the design for sections of parks that were apparent Pb hotspots or where there was large variance in Pb concentrations, and trees with large canopies were identified for intensive topsoil Pb measurement to assess the effect of those canopies on dust capture and Pb accumulation. In total, over the two weeks of sampling, 567 topsoil locations were assessed for Pb concentration.

2.1.2. Field and laboratory measurements of Pb

At each allocated sampling point, an estimate of the topsoil Pb concentration was made using an Olympus portable X-ray fluorescence (pXRF) device. An average of three readings within a 0.5 m radius of the allocated point was used to estimate the Pb concentration; the pXRF was used in the *Soil* mode, and each measurement had a total analysis time of at least 20 seconds. The soil surface or soil-like surface (i.e. cracker dust, gravel) was assessed for Pb concentration at each point; where a continuous grass thatch or mulch cover was in place, these were temporarily removed to allow access of the pXRF's X-ray beam to the soil. In some cases, the Pb concentrations of the non-soil covering materials were also measured.

Extra sample points were allocated in the vicinity of trees in Patton St Park, Kintore Reserve, Duke of Cornwall Park and Sturt Park. Trees selected for these extra sample locations were chosen to be away from busy roads and of similar, broad canopy structure. At each tree, pXRF measurements of topsoil Pb concentration were made, in four different directions, close to the base of the trunk of the tree, half-way from the trunk to the edge of the canopy ("mid-canopy"), at the outer edge of the canopy, and just beyond the edge of the canopy.

At twenty-eight allocated sampling points, topsoil (<2 cm depth) samples were collected for laboratory analysis of Pb concentration to validate the field measurements obtained with the pXRF. The samples were taken from sites with a range of pXRF-estimated Pb concentrations and with a range of ground covers. All samples were air-dried and sieved to less than 2 mm, sub-sampled and sent to the National Measurement Institute (NMI) for *aqua regia* digestion and analysis for Pb concentration using ICP-MS. The remaining soil sub-samples were size fractionated to <100 µm, with this 'dust-sized' fraction then analysed for Pb concentration using the pXRF in the laboratory set-up.

2.2. Modelling and mapping techniques for topsoil Pb concentrations

The topsoil Pb concentration data for the ten Broken Hill parks is presented in two ways in this report; (i) as blob plots of field measured Pb concentrations overlaying satellite imagery of each park (Figures 2–11), and (ii) kriged maps of Pb concentration modelled for the entirety of each park (Figures 14–23). The kriged maps were derived from a 'global' model of topsoil Pb distribution, a key component of which is the ground cover types of each park.

2.2.1. Ground cover classes

All sections of all ten parks were allocated to one of eleven ground cover classes (Table 1) – these classes include a variety of mineral and organic surfaces, and exclude anthropic surfaces such as concrete footpaths and playground soft-fall matting.

In the case of both the 'Cracker dust' and 'Worn cracker dust' classes, and the 'Roadbase/gravel' and 'Worn roadbase/gravel' classes, the worn condition was indicated by the presence of patches of reddish soil appearing in the blue-grey coloured cracker dust or roadbase. Similarly, the 'Worn mulched surface' class included patches of soil between accumulations of mulch material. The classes 'Under grass/turf' and 'Playing field', while similar, were distinguished on the basis that many of the playing surfaces had clearly been cultivated with relatively little diversity in grass species, whereas grass cover in other recreational parks was generally less thick and was comprised of a greater mix of grass species. Photographs of example ground cover types are shown in Figure 2.

Table 1. The eleven ground cover classes used to categorise sections of Broken Hill parks and ovals.

Ground cover class	*n*
Bare soil	50
Cracker dust	30
Worn cracker dust	46
Roadbase/gravel	7
Worn roadbase/gravel	14
Under grass/turf	128
Under patchy grass/turf	20
Unimproved shrubs and grasses 25-75%	77
Playing field	93
Mulched surface	27
Worn mulched surface	25

As shown in Table 1, the most prominent ground cover classes sampled were soils under grass/turf and soils under playing field grass, which together accounted for approximately 42% of the sampled points.

2.2.2. Mapping of topsoil Pb concentrations

A map of each park/oval was produced in ArcGIS, showing the location of each measurement site, and a coloured 'blob' indicating the average topsoil Pb concentration (within a range) at that site.

2.2.3. 'Global' modelling

To allow the generation of continuous maps of topsoil Pb concentration for all ten parks and ovals, a 'global model' was generated to predict Pb concentration onto a grid spacing of 1 m. An exponential model was used to simultaneously predict Pb concentration for all ten parks and ovals, using Ground cover class, distance to the Line of Lode (LoL), and the averaged topsoil Pb concentrations measured with the pXRF, as parameters. The modelled values of Pb concentration (on the 1 m grid spacing) were then interpolated across all parks and ovals by kriging.

Figure 2. Examples of nine of the eleven ground cover classes for Broken Hill parks.

3. RESULTS & DISCUSSION

3.1. Topsoil Pb concentrations estimated in each of the ten public parks

Following is a broad summary of the size of the ten parks investigated, the number of sampling points in each park, the shortest direct distance to the Line of Lode from the park, the mean topsoil Pb concentration of each park and the number of sample points in each park where the HIL for recreational public spaces (600 mg/kg) (NEPM, 2013) was exceeded (Table 2).

Over the following pages, each park or oval will be considered separately and in more detail.

Table 2. A summary of topsoil Pb concentrations in ten Broken Hill parks and ovals.

Park	Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
Duke of Cornwall	0.79	33	339	2	0.77
Patton St Park	1.24	52	947	36	0.86
Alma Oval	3.05	41	485	11	1.15
Kintore Reserve	1.31	25	363	5	0.60
Sturt Park	4.13	90	463	24	0.80
Centre for Community	0.45	14	829	8	
North Family P.C.	1.67	26	121	0	2.20
Picton Sports Ground	4.03	49	156	0	2.30
O'Neil Park	11.11	120	647	55	1.08
Soccer field		*13*	*130*	*0*	
Soccer field perimeter		*17*	*777*	*13*	
Norm Fox		*39*	*585*	*7*	
Bike track area		*51*	*789*	*35*	
Memorial Oval	5.82	68	176	2	1.81
Jubilee Oval	3.66	49	311	6	0.99
Totals	37.26	567	–	149	–

3.1.1. Duke of Cornwall Park

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
0.79	33	339	2	0.77

The Duke of Cornwall Park covers a relatively small area, and includes two tennis courts, a playground area covered in a thick layer of woodchips, a small grassed playing field and garden beds with well-established trees. Refurbishment of this park was undertaken approximately 1-2 years before this sampling campaign. The mean topsoil Pb concentration of the 33 sampling points was relatively low at 339 mg/kg. Measurements of Pb concentration taken on top of woodchips and grass surfaces returned a mean value of 89 mg/kg. Two higher Pb readings (1050 and 750 mg/kg) were obtained from around the base of established trees, where bare soil was exposed. Overall, exposure to soil is expected be low in this park, given the good covering of woodchips and grass.

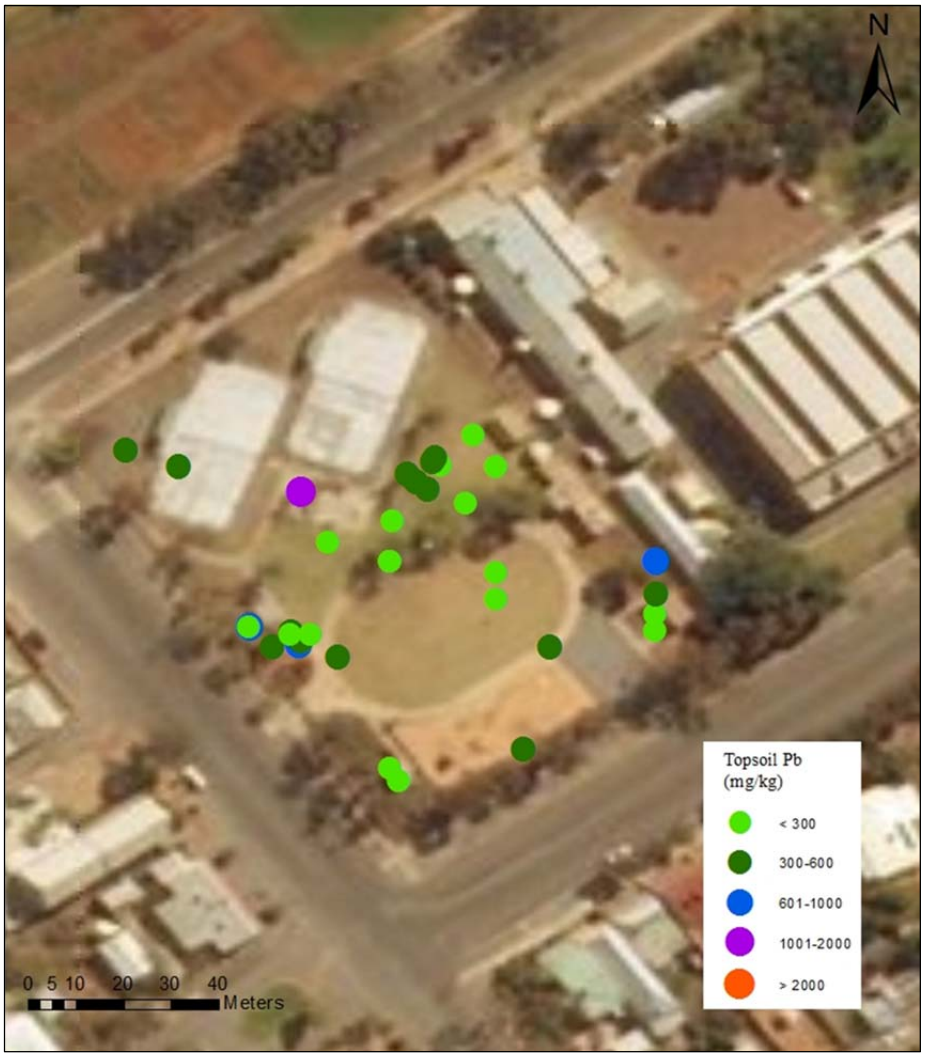


Figure 2. Topsoil Pb concentrations estimated for the Duke of Cornwall Park and surrounds.

3.1.2. Patton St Park

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
1.24	52	947	36	0.86

The Patton Street Park complex consists of a separate small playground in the southwestern section, a dog park area in the northeastern section (that is separately fenced), a lawn area in the northwestern corner and mulched bush areas. The small playground has a thick layer of woodchips as a soft-fall material, and also a thick layer of woodchips surrounding the designated play equipment area. The dog park is a simple grassed area with established trees around the perimeter; the groundcover is approximately 90%. The lawn area of the park also has a groundcover of approximately 90%. The mulched bush areas show patches of thick mulch (more than 5 cm thick), as well as patches of worn mulch where much of the soil is re-exposed.

Patton St Park has a high mean topsoil Pb concentration, with more than half of the measurement sites exceeding the HIL for recreational public spaces (600 mg/kg) (NEPM, 2013). This is particularly the case for sites with exposed soil. Woodchip surfaces in Patton St Park also yielded the highest Pb concentrations of non-soil surfaces in this study (mean of 267 mg/kg Pb).

Figure 3. Topsoil Pb concentrations estimated for Patton St Park.

3.1.3. Alma Oval

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
3.05	41	485	11	1.15

Alma Oval consists of a well-grassed playing field surrounded by spectator viewing areas. At the northwestern and southeastern ends of the block, which both receive substantial vehicular and pedestrian traffic, the surface is covered mainly in cracker dust. Where there is worn cracker dust, Pb readings are often higher than 600 mg/kg, especially at the southeastern end of the block. This southeastern end also appears to be the lowest point, with signs of water runoff down to the enclosing wall. The playing field itself shows the smallest topsoil Pb levels. As the grass coverage on this field is 100% and well maintained, access to the soil is unlikely in any event. Estimates of Pb concentration taken from the top of the grass characteristically show levels less than 40 mg/kg.

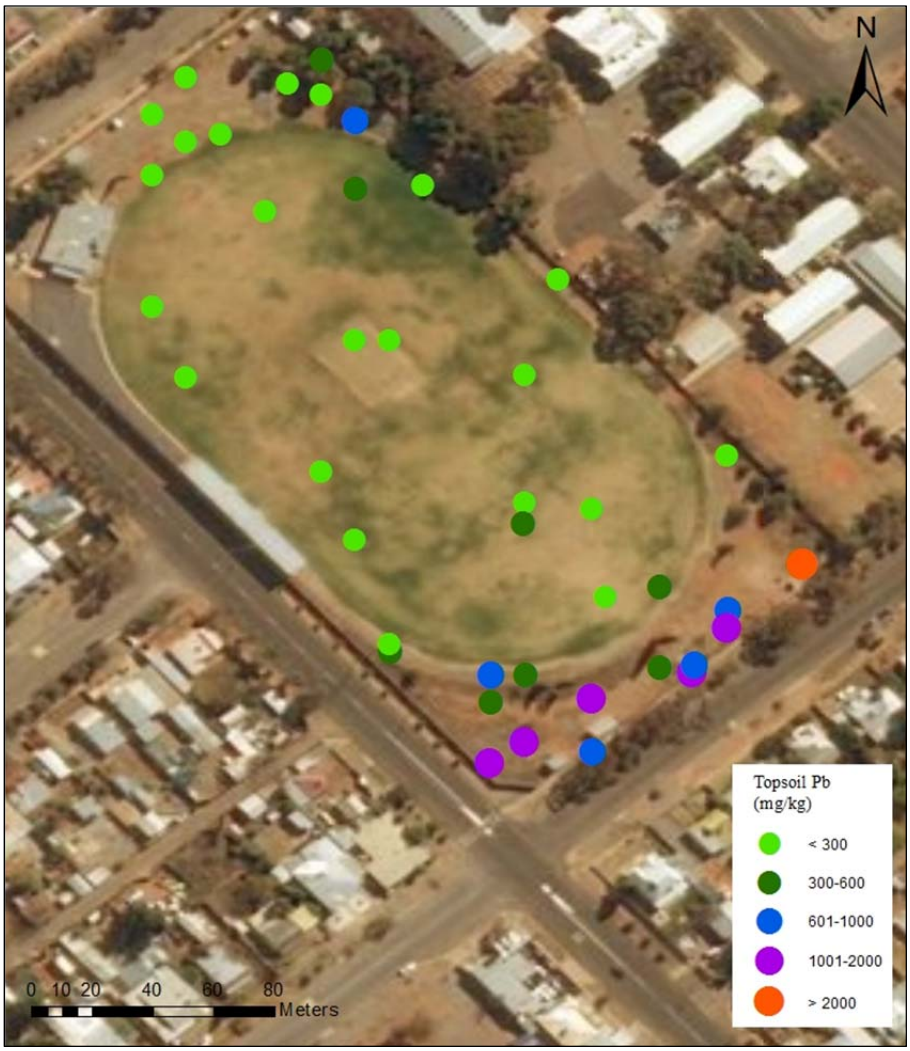


Figure 4. Topsoil Pb concentrations estimated for Alma Oval and surrounds.

3.1.4. Kintore Reserve

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
1.31	25	363	5	0.60

Kintore Reserve consists of a fenced-off area with a cracker dust and soil surface, a completely cracker-dusted car park area with historic mining equipment, and the grassed Lions Picnic Reserve at the eastern end. The picnic reserve also contains areas of well-mulched native plant garden and concrete paths. The cracker dusted surfaces on the western two-thirds of the Reserve show only a few patches of thinning.

Overall, Kintore Reserve topsoil has a relatively low mean Pb concentration, but where the soil has been re-exposed through the wearing of cracker dust, Pb concentrations are higher (600–1000 mg/kg). The Lions Picnic Reserve was refurbished approximately 10-15 yrs ago, is well maintained and has few bare soil patches; subsequently, the topsoil Pb concentrations in this part of the Reserve are less than 600 mg/kg.

On the western side of the Reserve, some Pb slag rocks are on display. pXRF analysis of these ‘rocks’ revealed Pb concentrations of 3000–5000 mg/kg.

Figure 5. Topsoil Pb concentrations estimated for Kintore Reserve.

3.1.5. Sturt Park

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
4.13	90	463	24	0.80
Centre for Community	14	829	8	0.80

Sturt Park is well-grassed and maintained. It contains areas of different uses, including a playground, a skate park, a rose garden and extensive, grassed parkland. In the northwestern corner of the block, the land has been reshaped into a gentle slope with good grass coverage after the removal of the town swimming pool.

Overall, Sturt Park has a relatively low mean topsoil Pb concentration which falls under the HIL for recreational public spaces. While more than a quarter of the measurements exceeded 600 mg/kg Pb, many of these were for soil under the grass covering and therefore highly unlikely to be in contact with the community whilst ever the grass cover is maintained. The bare soil around the bases of some trees also displayed some higher Pb concentrations.

The three clusters of points evident in Figure 6 below (north of park, centre of park, southeast of park), represent three trees that were assessed for canopy effects on topsoil Pb concentrations. These results will be discussed further later in this report.

Figure 6. Topsoil Pb concentrations estimated for Sturt Park.

Centre for Community

The Centre for Community is a small, fenced enclave in the southern section of Sturt Park. This centre has very little exposed soil, as most of the surface is covered by two lawn bowls rinks comprised of artificial grass and fine sand. For some years, these rinks have not been used for lawn bowls, but for community market events held once or twice a month. The estimates of 'topsoil Pb' for this centre have been separated from those of the surrounding Sturt Park, because of the difference in surface material and landuse.

All estimates of Pb concentration on the artificial grass surface were greater than 600 mg/kg, while the few estimates of Pb concentration on the cracker dust and garden bed surfaces were all below 600 mg/kg. Sandy soil from the artificial grass was collected and size-fractionated (to <100 µm) to determine if the dust-sized fraction contains a greater Pb concentration than the 'bulk soil' in the artificial grass. It is understood that past manufacturing processes for artificial grass used Pb as a constituent, and so this may be also be contributing to the high Pb concentrations measured at the Centre for Community. The dust-fraction Pb concentrations are dealt with later in this report.

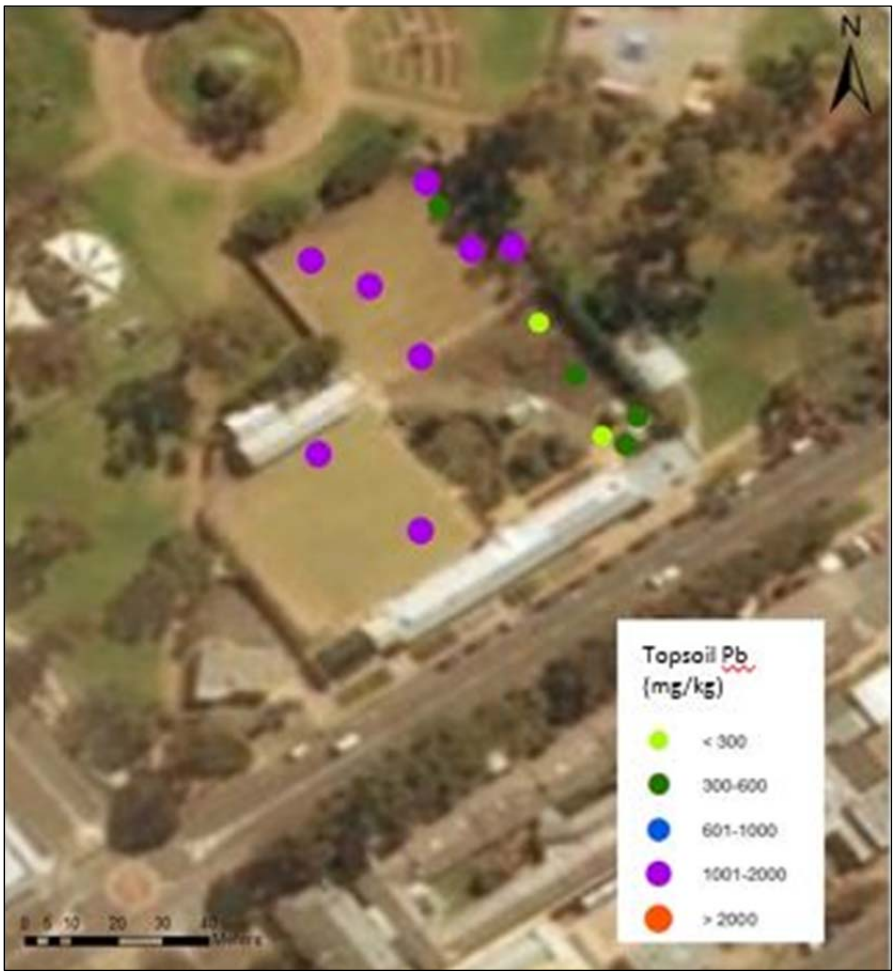


Figure 6a. Topsoil Pb concentrations estimated for the Centre for Community.

3.1.6. North Family Play Centre

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
1.67	26	121	0	2.20

The North Family Play Centre is a well-grassed park area at the northern extremity of the Broken Hill urban area. The centre includes a low-lying water catchment area at the eastern end, a picnic area and small playground, and grassed areas with scattered trees. At the western end of the centre is a stand of established trees with substantial mulch cover.

The mean topsoil Pb concentration for this centre is low, with no measurements exceeding 300 mg/kg Pb. Many measurements of topsoil Pb concentration were similar to the regional background level (~30 mg/kg).

Figure 7. Topsoil Pb concentrations estimated for the North Family Play Centre.

3.1.7. Picton Sports Ground

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
4.03	49	156	0	2.30

Picton Sports Ground consists of a large, well-maintained playing field, surrounded on most sides by areas of unimproved shrubs and grasses, giving groundcover of between 20 and 60%. There is a small fenced playground in the eastern corner of the block, with a thick layer of woodchips as a soft-fall material. The childcare facility in the northern corner of the block was not assessed.

The playing field shows the lowest topsoil Pb readings, but the surrounding areas also have low topsoil Pb concentrations. None of the 45 measurement points returned a Pb concentration exceeding the HIL for recreational public spaces (600 mg/kg Pb) (NEPM, 2013).

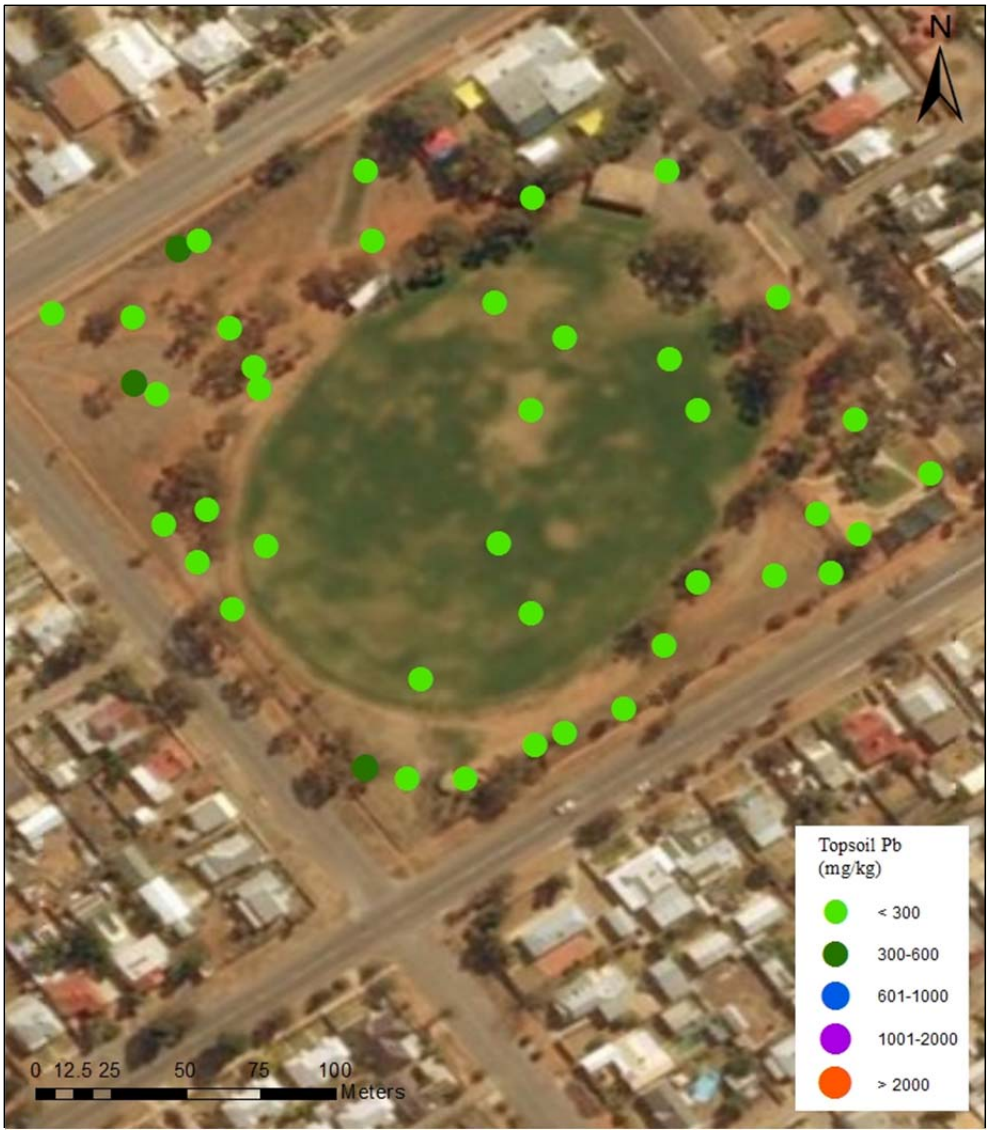


Figure 8. Topsoil Pb concentrations estimated for Picton Sports Ground and surrounds.

3.1.8. O'Neil Park

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
11.11	120	647	55	1.08
Soccer fields	*13*	*130*	*0*	
Soccer field perimeter	*17*	*777*	*13*	
Norm Fox	*39*	*585*	*7*	
Bike track	*51*	*789*	*35*	

O'Neil Park is a large complex consisting of three separate areas used for different activities; (i) two adjoining soccer fields, (ii) the Norm Fox playing field, and (iii) a bike track area.

The soccer fields: located in the east of the complex, these are only used for scheduled soccer training and matches, and are closed to the general public at all other times. The soccer fields are well maintained and are surrounded to the north, east and south by thin strips of vegetation comprising well-established shrubs and trees. The vegetated buffers to the north and east of the soccer fields are raised earthen banks up to 2 m high and are somewhat steeply sloping away from the fields. There is evidence of tracks through these vegetated slopes, leaving exposed, erodible soil.

Topsoil Pb concentrations on the soccer fields are generally low, averaging 130 mg Pb/kg. The mulched surfaces surrounding the fields have a mean Pb concentration of 292 mg/kg. In contrast, soil of the surrounding vegetated embankments has a mean Pb concentration of 777 mg/kg.

Norm Fox playing field: located in the south of the complex, this field is used for various sports and provides an open area for the community. The playing field is well maintained and supports a turf ground cover of close to 100%. The playing field itself shows topsoil Pb concentrations varying from 72 to 1325 mg/kg, while higher concentrations (up to 1603 mg/kg) are located off the playing field, around the outside vegetated areas. Measurements made along the strip of sparse vegetation and exposed soil along the southern edge of Norm Fox returned the highest Pb concentrations.

Bike Track area: located in the north of the complex, this area consists of a BMX-style bike track through a grove of shrubs, grasses and trees. Ground coverage of this vegetation is generally good. To the south and west of this vegetated area is a flat area of exposed soils of different colours, cracker dust and sparse vegetation. There appears to have been some contouring of this area for water management. The cracker dusted areas are used for extra car parking at times. The exposed soils show many inclusions of small black 'rocks' that were identified as mining slag (due to very high Pb concentrations, >1500 mg/kg). These inclusions are likely to be at least partially the cause of the relatively high soil Pb concentrations in this area.

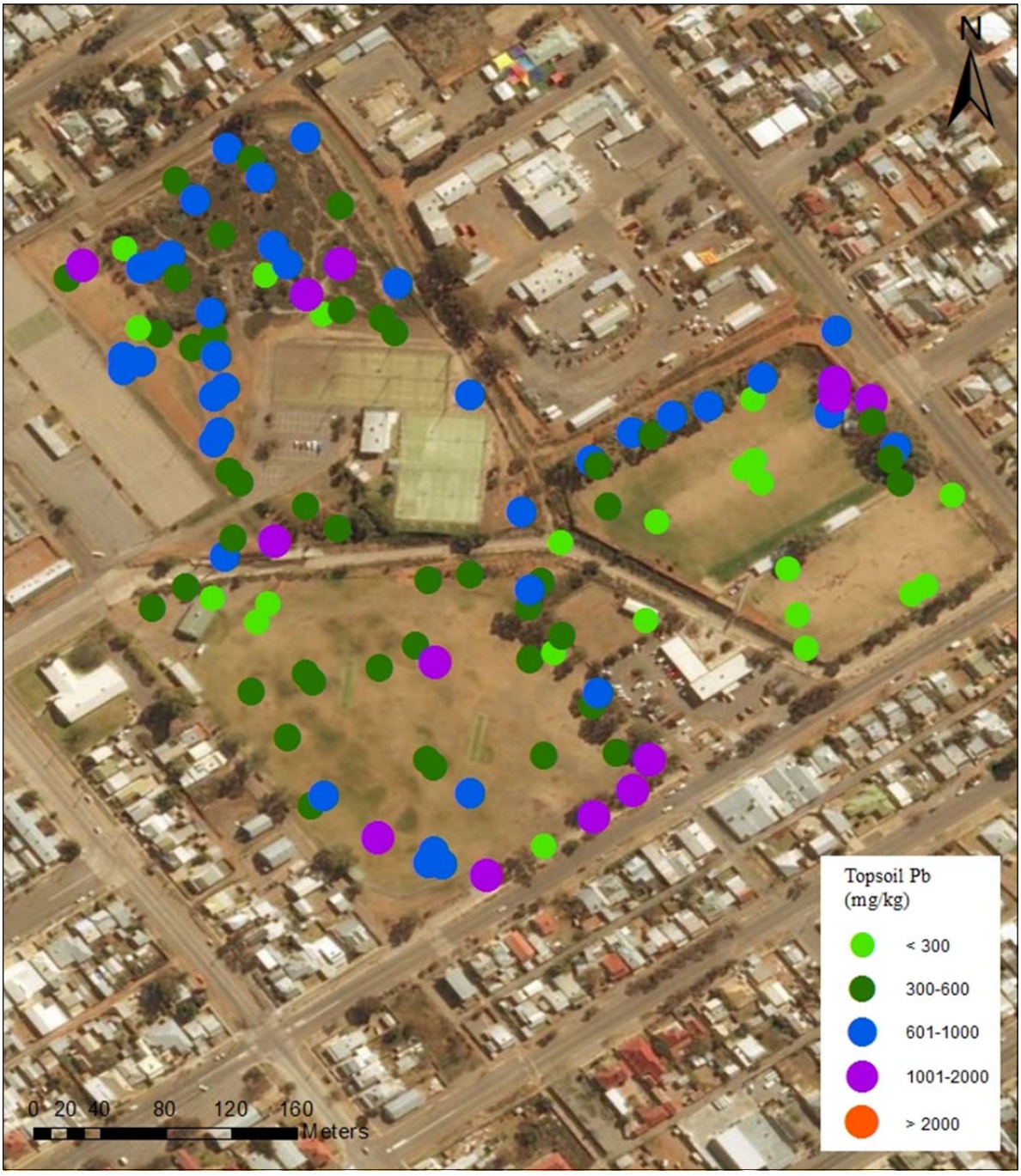


Figure 9. Topsoil Pb concentrations estimated for the O'Neil Park complex, with the soccer fields to the east, Norm Fox playing field to the south and the bike track area to the north.

3.1.9. Memorial Oval

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
5.82	68	176	2	1.81

Memorial Oval is a gated sports field, comprising a grassed oval and cracker-dusted trotting track around the perimeter of the oval. The oval and track are surrounded by a combination of concreted and gravelled driveways, cracker-dusted parking areas, tiered viewing platforms comprised of a combination of cracker dust/gravel and soil, and a gentle hill up to the south covered in small shrubs and grasses.

The mean topsoil Pb concentration around Memorial Park is low, with only two points exceeding 600 mg Pb/kg. These two points are located along the southern fence line in an unused scrub area that has no obvious footpaths.

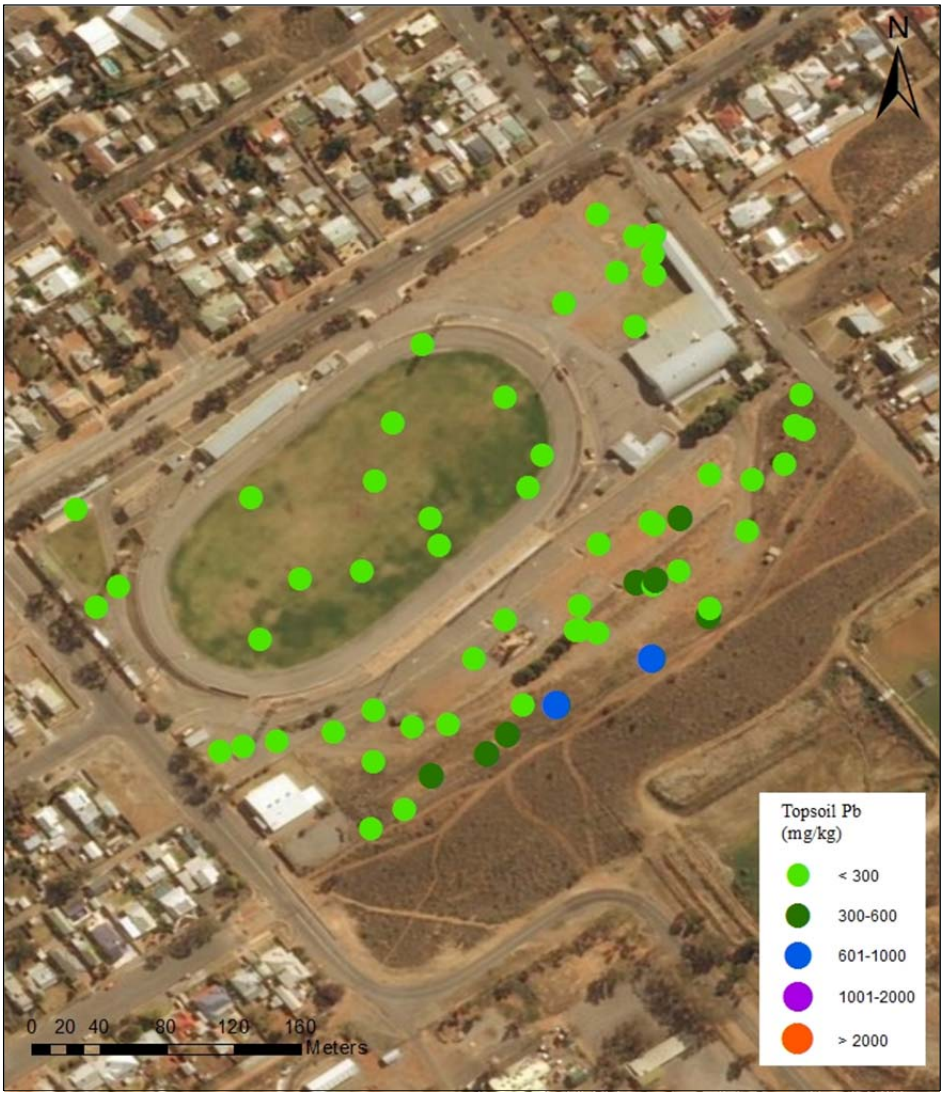


Figure 10. Topsoil Pb concentrations estimated for Memorial Oval and surrounds.

3.1.10. Jubilee Oval

Area (ha)	Topsoil measurement points (*n*)	Mean topsoil Pb concentration (mg/kg)	No. topsoils >600 mg/kg Pb	Distance to Line of Lode (km)
3.66	49	311	8	0.99

Jubilee Oval is a locked, gated park only accessible for sporting events and scheduled team practice sessions. It consists of a large, well-grassed playing field with a cracker dusted/gravel entrance and surrounding track. The back of the oval to the northeast drops down into a small area of dense shrubs and grasses.

All of the measurements of topsoil Pb concentration on the playing field and surrounding cracker-dusted areas were less than 600 mg/kg, and generally less than 300 mg/kg. However, several large topsoil Pb concentrations were measured in the area of scrub to the northeast of the oval.

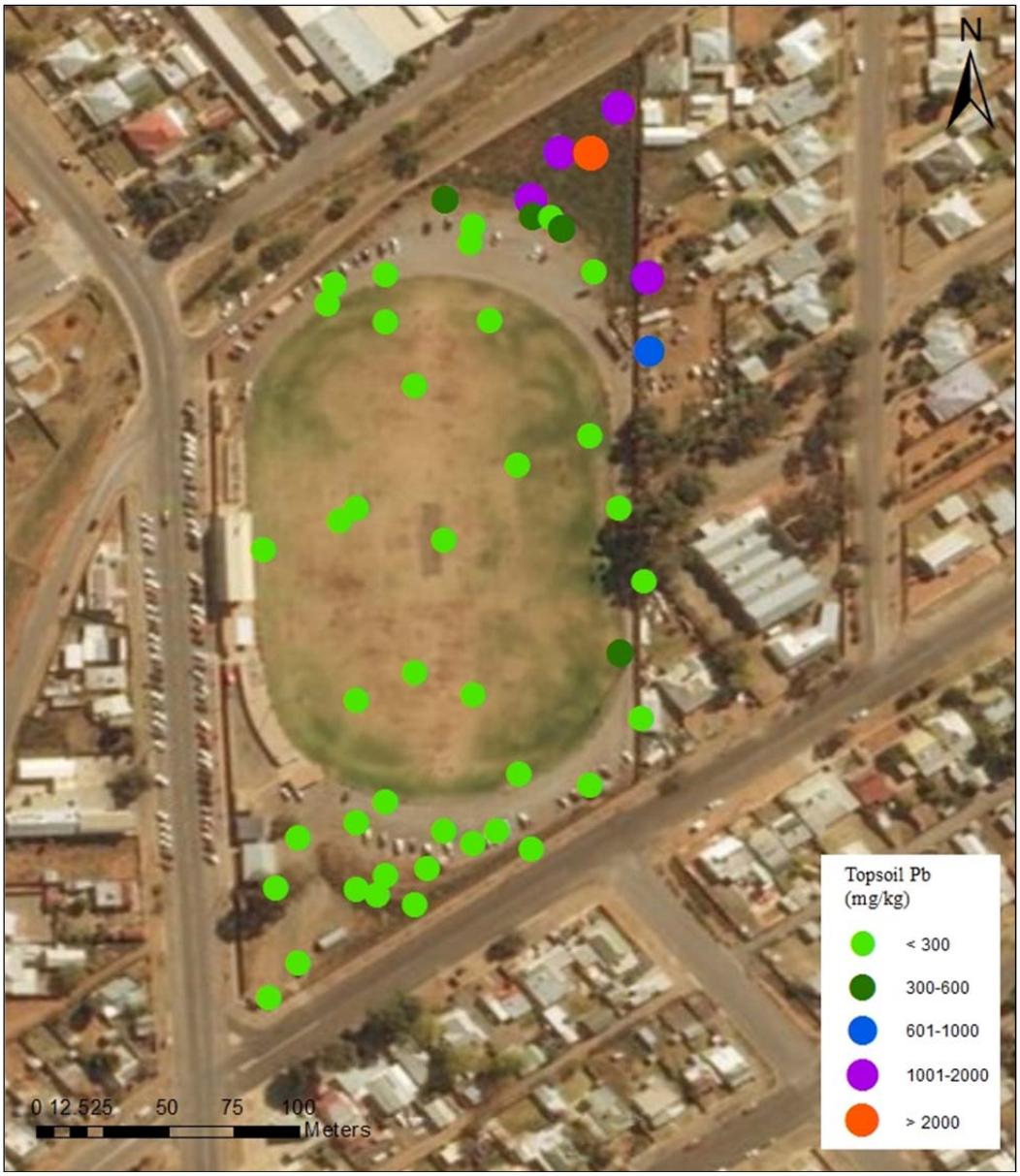


Figure 11. Topsoil Pb concentrations estimated for Jubilee Oval and surrounds.

3.2. Non-soil surface Pb concentrations in public parks and Pb concentrations of the bulk soil and dust-sized particle size fractions

3.2.1. Non-soil surface Pb concentrations

Although the topsoil surfaces of the various parks and ovals were the main targets of this monitoring project, estimates were also made of the Pb concentrations of various non-soil surface materials in different parks, as small children will likely come into contact with such materials. Measurements of Pb concentrations of these non-soil surface materials were made in the same manner as soil surfaces, *viz.* through the use of a pXRF device, in triplicate.

Table 3. Non-soil surface Pb concentrations from different Broken Hill parks and ovals.

Park	Non-soil surface	Mean Pb concentrations (mg/kg)
Duke of Cornwall Park	Woodchips	172, 108, 11, 165, 22, 18, 157
	Grass	56
Patton St Park	Mulch	187, 186, 236, 120, 186, 548, 772, 1157
Alma Oval	Playing field grass	127, 50, 37, 30
Sturt Park	Grass	132, 58, 123
Centre for Community	Artificial grass with sand	1525, 1031, 1102, 1254, 1765, 1420
North Family Play Centre	Mulch	81
	Grass	35
Picton Sports Ground	Playing field grass	46, 21
O'Neil Park	Playing field grass	54, 21, 52
	Mulch	293, 197
Memorial Oval	Playing field grass	55, 77, 46
Jubilee Oval	Playing field grass	46, 31

With the exception of the artificial grass bowling rinks at the Centre for Community and two mulch samples in Patton St Park, all non-soil surfaces were found to have Pb concentrations below the HIL limit of 600 mg/kg, regardless of the proximity of the Line of Lode. Playing field grass, in particular, yielded consistently low Pb concentrations, which probably reflects the benefit of top-dressing with clean mineral material from time-to-time. The high Pb concentrations in the artificial grass bowling rinks at the Centre for Community are considered in the following section.

3.2.2. Bulk soil and dust-sized fraction Pb concentrations

The majority of dust particles that are transported significant distances in air are 100 µm or finer. To assess the likely contribution of Pb-rich dust to topsoil Pb concentrations, the Pb concentrations of both the bulk soil and the <100 µm fraction of that soil, were assessed for twenty eight samples from Broken Hill parks and ovals.

In Figure 12, it is evident that some, but not all, of the topsoil samples have higher concentrations of Pb in the dust-sized fraction than in the bulk soil – a slim majority of points lie above the 1:1 line. Of these points above the 1:1 line, two samples (orange markers in Figure 12) have noticably larger Pb concentrations in the dust-sized fraction, suggesting a significant contribution of dust to the Pb loading in those soils. These samples, from left to right on Figure 12, were taken from Alma Oval and Sturt Park.

In the case of the red-coloured marker on Figure 12, this sample was collected from the Centre for Community bowls rink, where the 'soil' consists of sand in an artificial grass matrix. This data point represents the relationship between the <100 µm fraction Pb concentration and the 100-2000 µm

fraction Pb concentration, and shows a very pronounced accumulation of Pb in the finer fraction. The only possible sources of new mineral material to these rinks would be dust and perhaps soil brought in on tyres of vehicles accessing the rinks for monthly markets. There is no water run-on to these rinks. Given the proximity of this location to the Line of Lode, it is likely that these artificial grass bowling rinks have been acting as passive Pb-rich dust traps since installation.

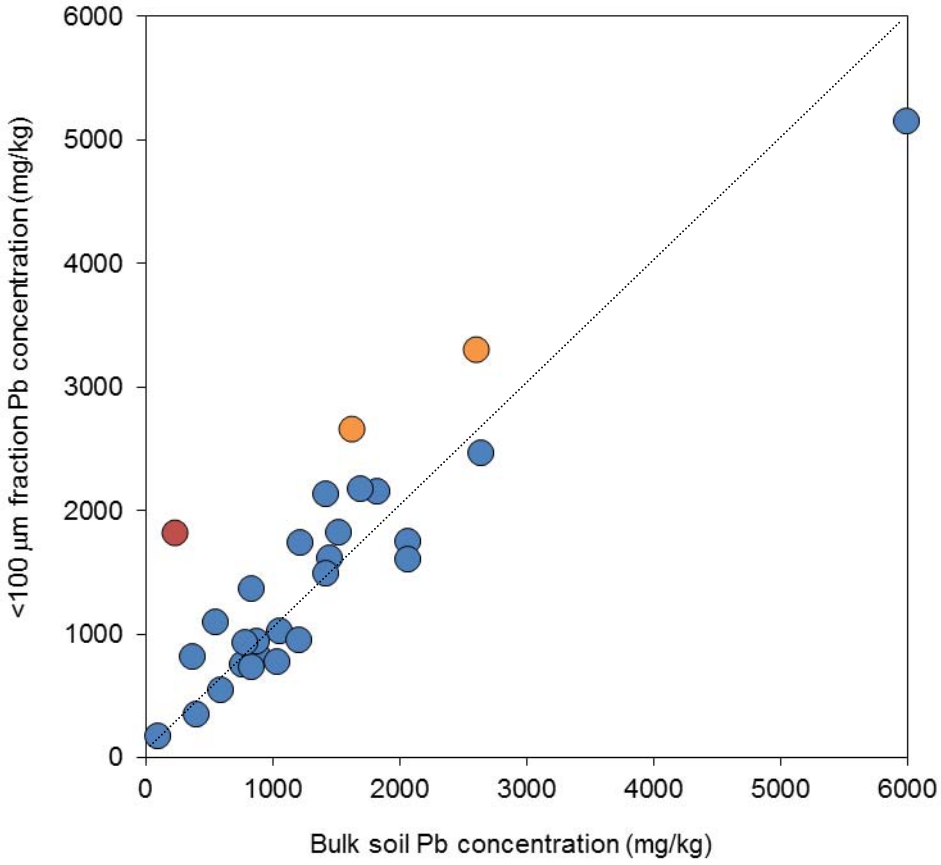


Figure 12. The relationship between Pb concentration in the bulk soil (<2 mm, air-dried) and Pb concentration in the dust-sized (<100 µm) fraction of the soil, for 28 topsoil samples taken from Broken Hill parks and ovals. The two samples represented by orange-coloured markers are noticably enriched in Pb in the dust-sized fraction. The sample represented by the red-coloured marker is from the Centre for Community bowling rink and this data point reflects the relationship between the <100 µm fraction Pb concentration and the 100-2000 µm fraction Pb concentration.

3.3. Estimated topsoil Pb concentrations across all public parks using a global model

The kriged (interpolated) maps of topsoil Pb concentration for all ten parks and ovals, derived from the global prediction model, are shown in Figure 13. The global model provided a good fit with the raw data, giving a correlation (r^2 value) of 0.78. Distance to the Line of Lode and ground cover class were significant parameters in the global model.

Figure 13 clearly shows the importance of both proximity to the Line of Lode and park/oval ground cover, to the predicted topsoil Pb concentration. The parks and ovals furthest from the Line of Lode have the lowest predicted topsoil Pb concentrations, while for those parks and ovals within about 1 km of the Line of Lode, ground cover becomes the main determinant of predicted topsoil Pb concentration.

Figures 14-23 that follow show the interpolated maps for each park and oval individually.

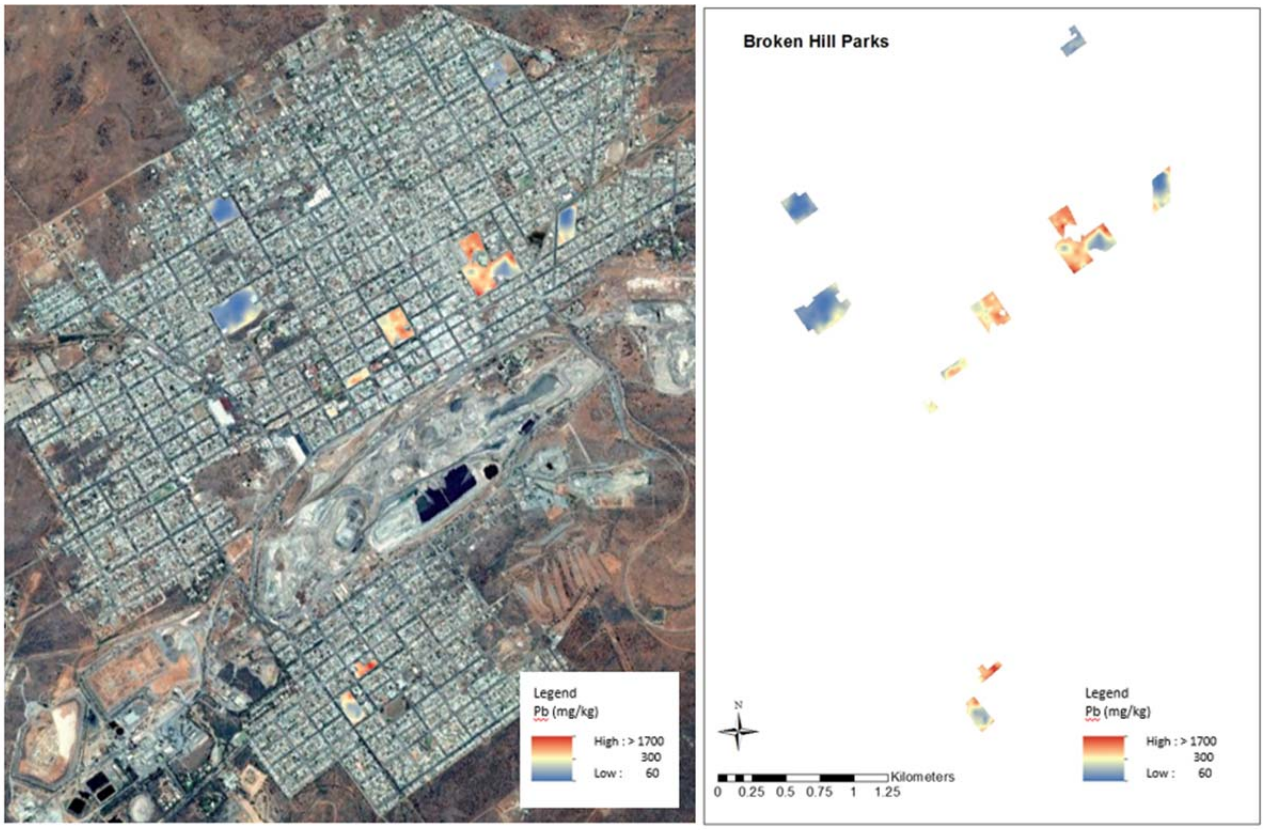


Figure 13. Global model predictions of topsoil Pb concentration, mapped for the ten Broken Hill parks and ovals.

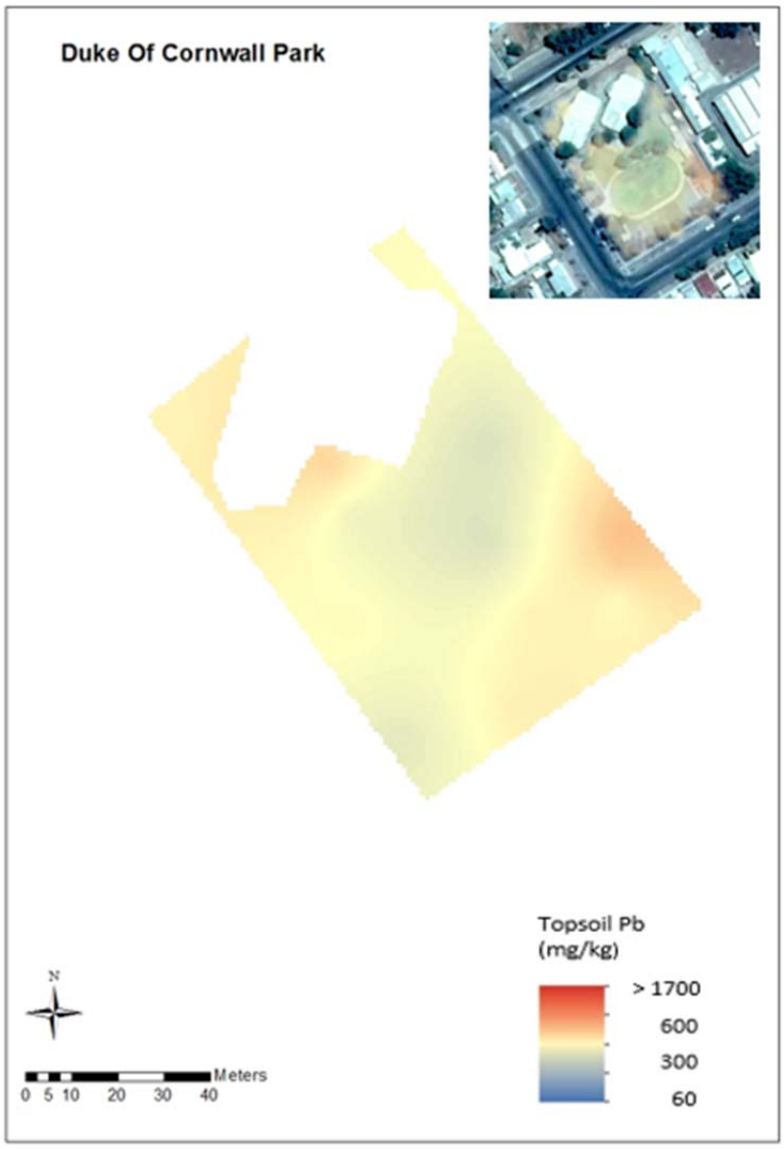


Figure 14. Global model predictions of topsoil Pb concentration, mapped for the Duke of Cornwall Park.

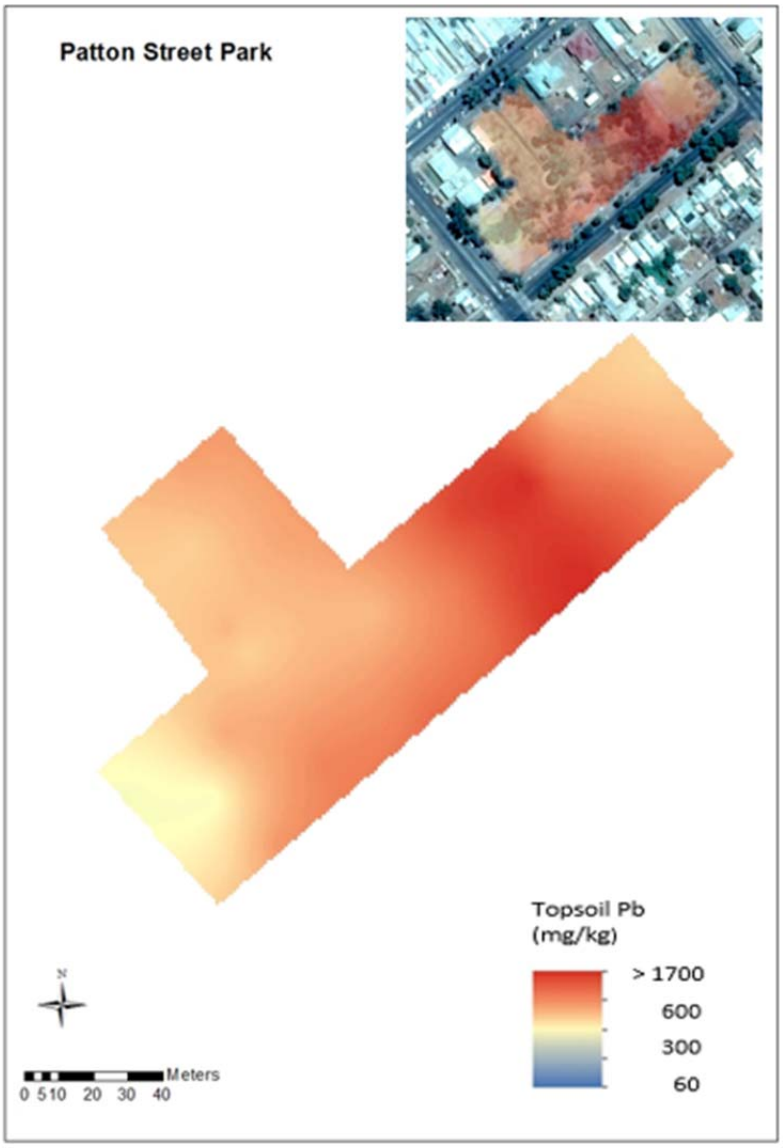


Figure 15. Global model predictions of topsoil Pb concentration, mapped for the Patton St Park.

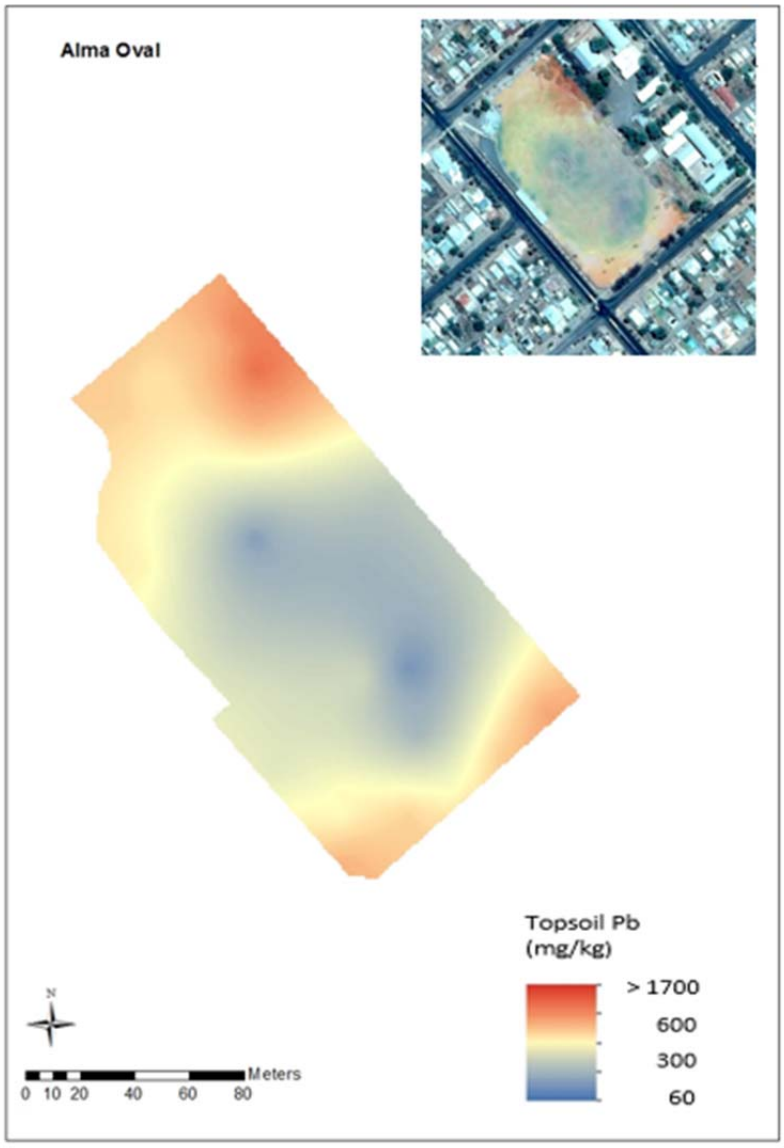


Figure 16. Global model predictions of topsoil Pb concentration, mapped for Alma Oval.

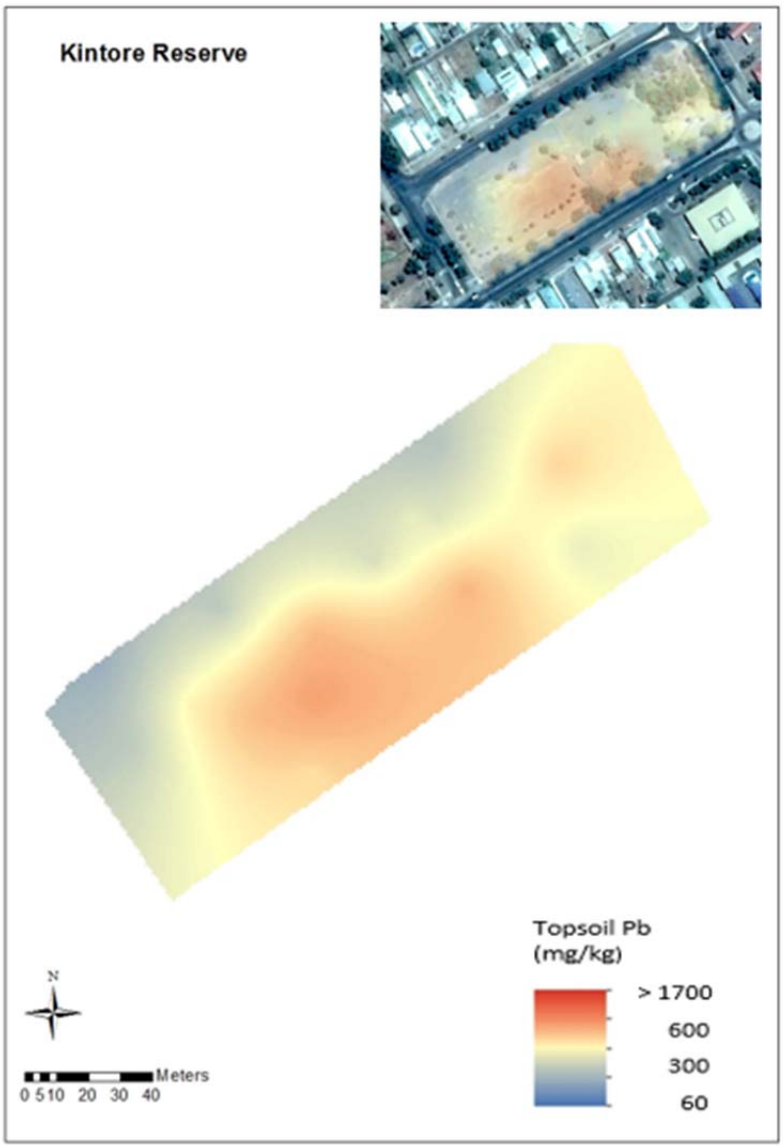


Figure 17. Global model predictions of topsoil Pb concentration, mapped for the Kintore Reserve.

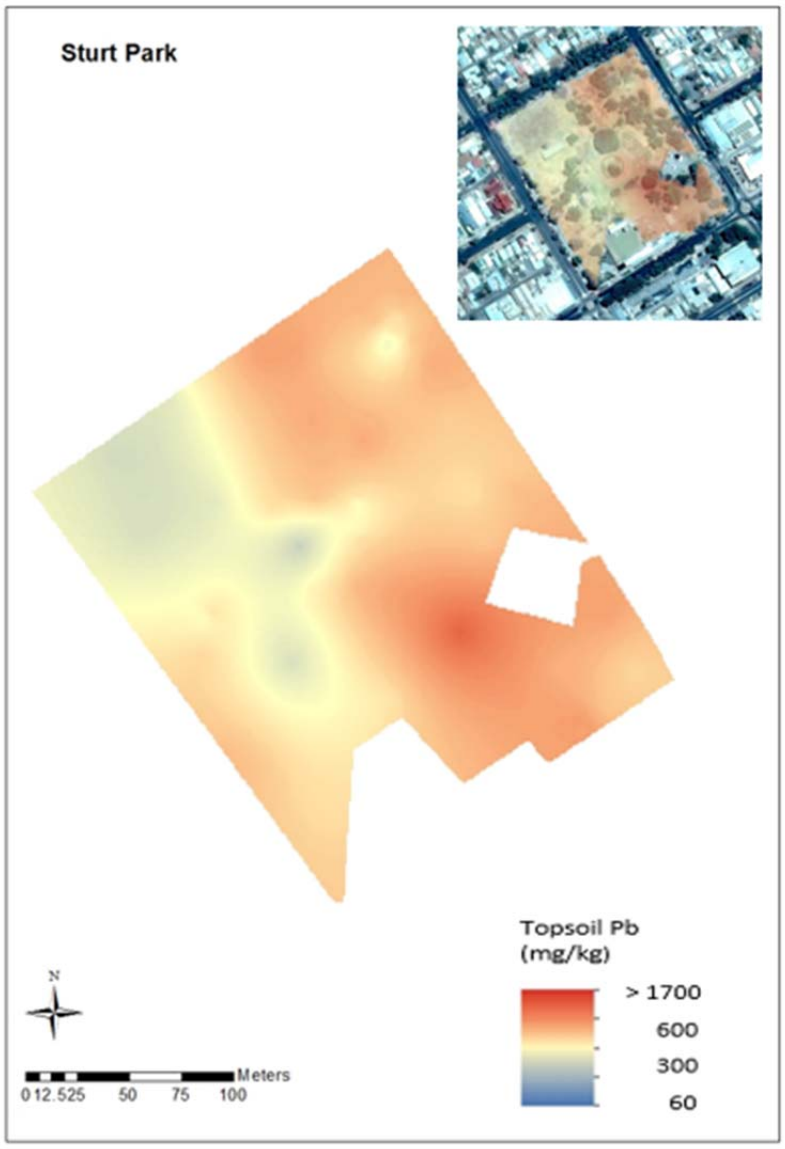


Figure 18. Global model predictions of topsoil Pb concentration, mapped for Sturt Park.

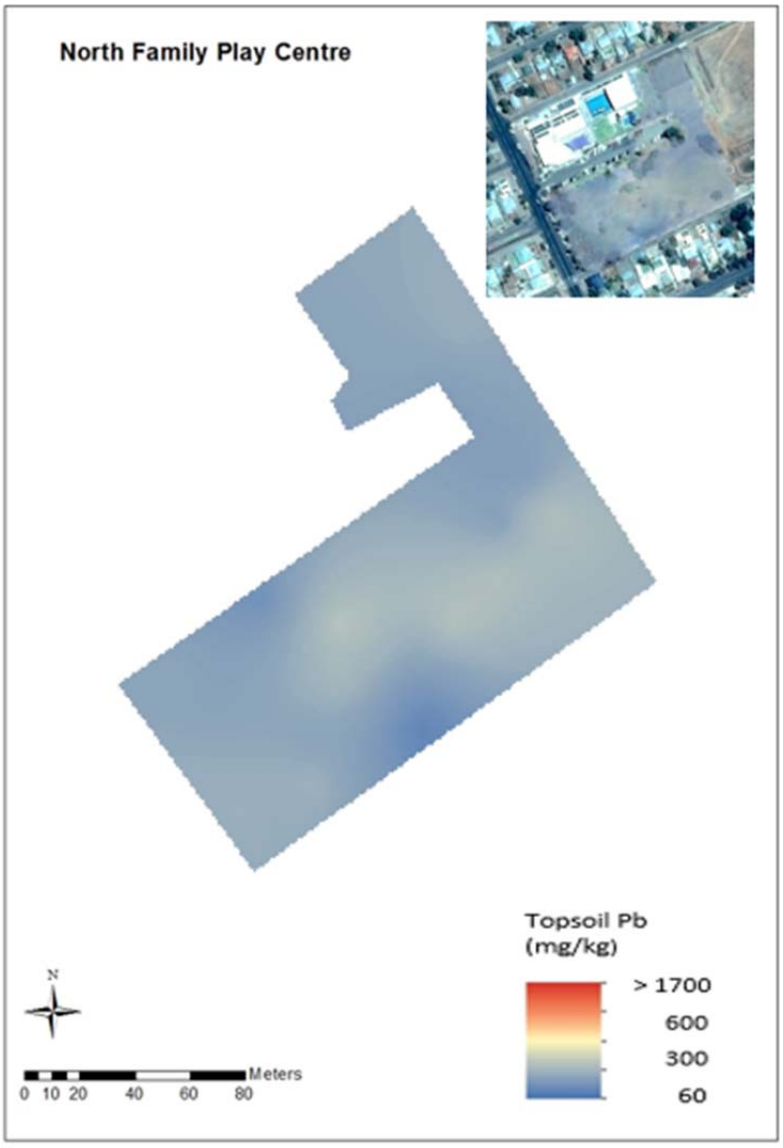


Figure 19. Global model predictions of topsoil Pb concentration, mapped for the North Family Play Centre.

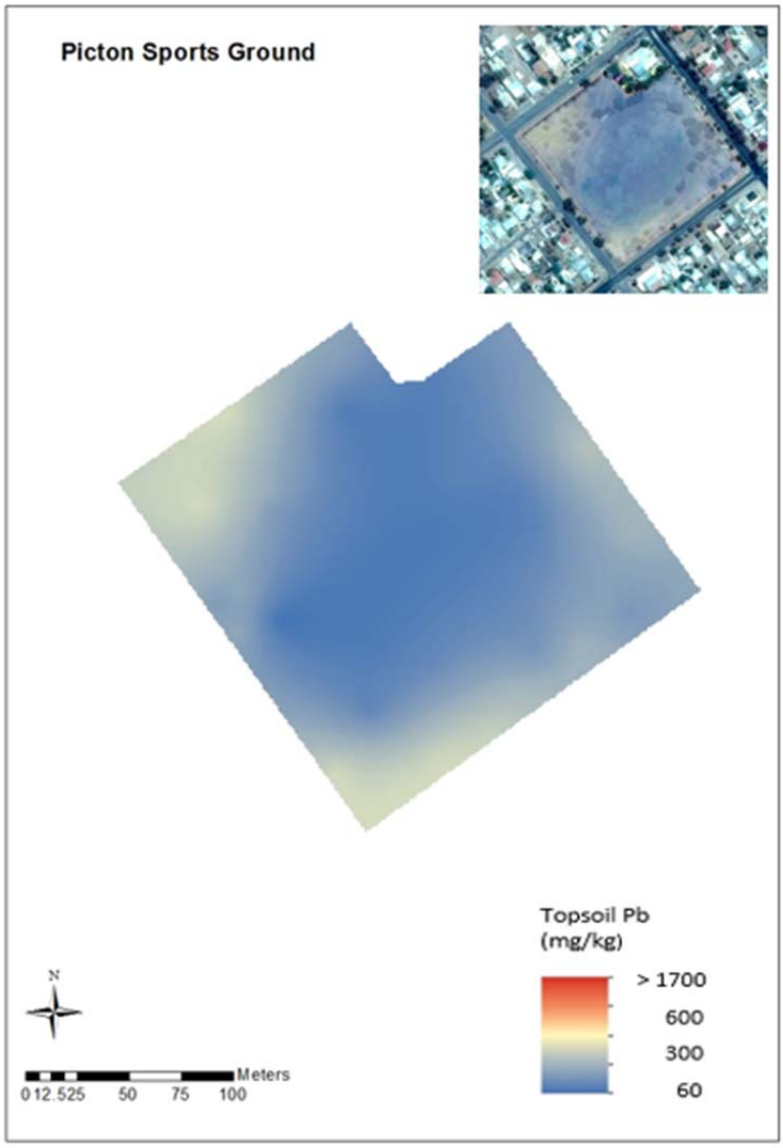


Figure 20. Global model predictions of topsoil Pb concentration, mapped for the Picton Sports Ground.

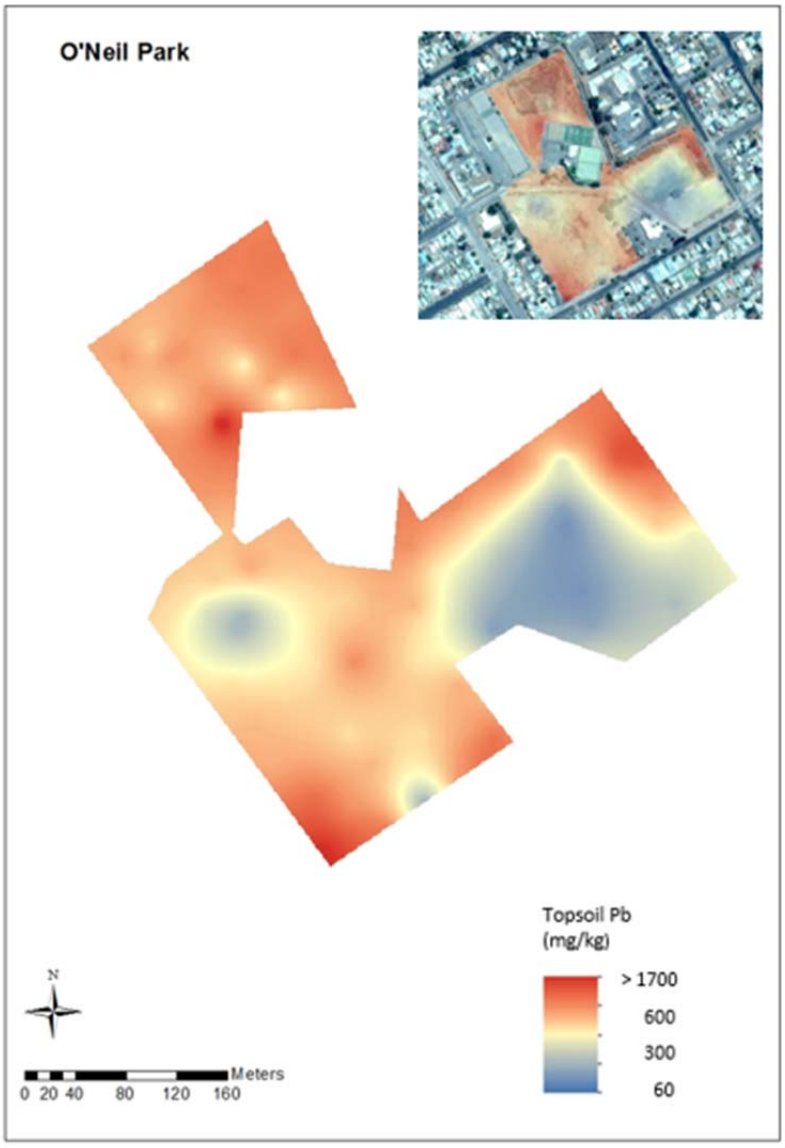


Figure 21. Global model predictions of topsoil Pb concentration, mapped for O'Neil Park.

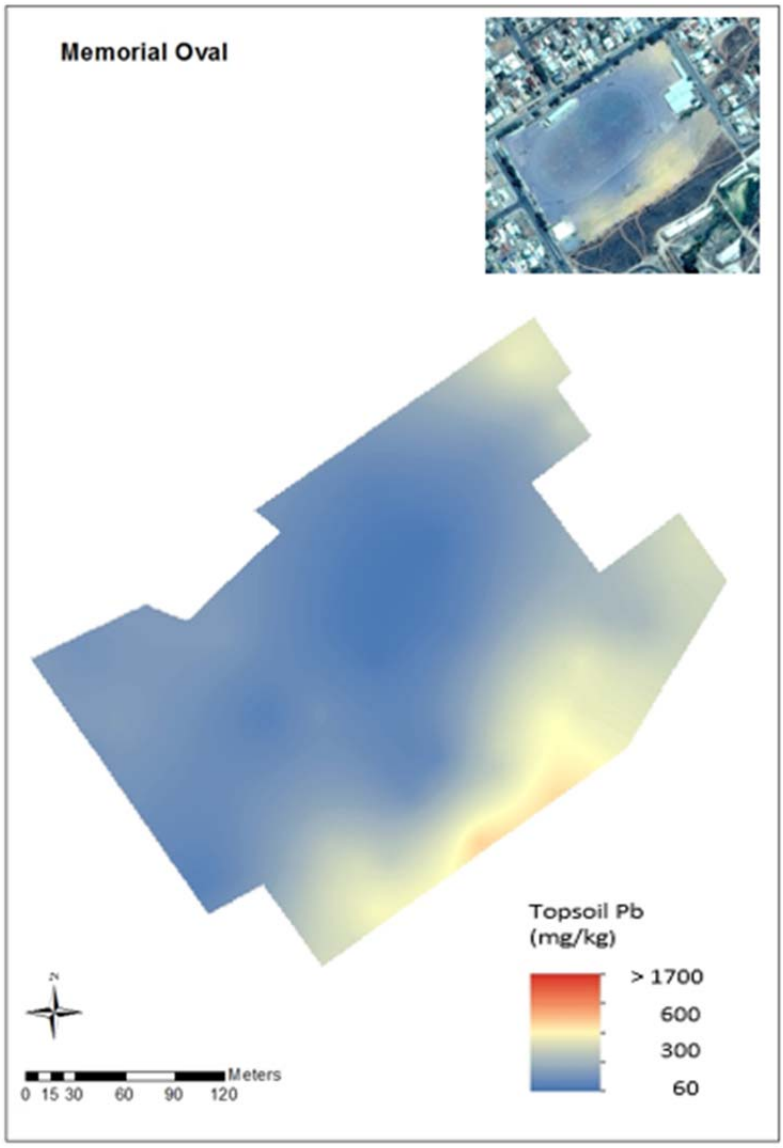


Figure 22. Global model predictions of topsoil Pb concentration, mapped for Memorial Oval.

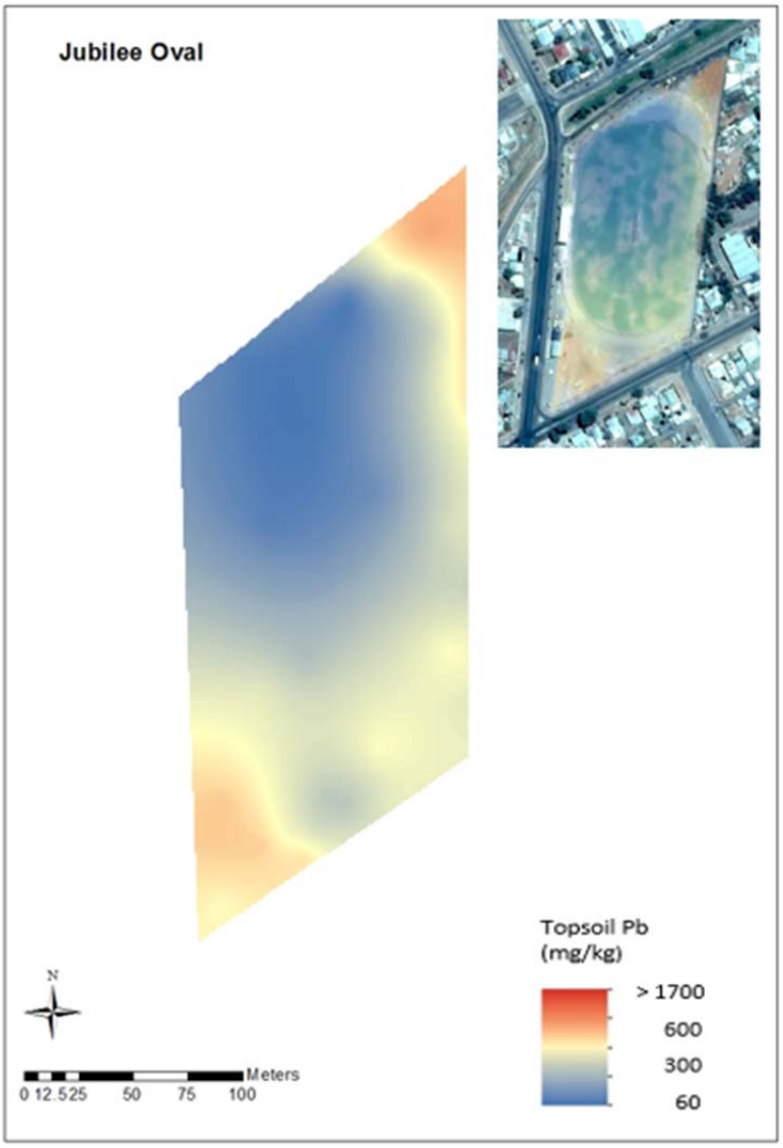


Figure 23. Global model predictions of topsoil Pb concentration, mapped for Jubilee Oval.

3.4. Investigating tree canopy effects on Pb distribution

The possible role of leaf canopies influencing soil Pb concentrations under and around trees was investigated, as there has been anecdotal evidence to suggest that topsoil Pb concentrations under trees are often higher than those of surrounding areas. This may be due to the canopies collecting Pb-rich dust that is then washed to the ground-surface during rainfall events. It was assumed that if trees canopies were acting as dust traps (with dust enriched in Pb), then the maximum accumulation of Pb should be under the centre of the tree where the canopy is thickest, and that the accumulation of Pb would decrease markedly outside the perimeter of the canopy.

The topsoil Pb concentrations under eight large-canopied trees in Sturt Park, Kintore Reserve, Duke of Cornwall Park and Patton St Park were measured, and no clear trends emerged to suggest a Pb-accumulation effect under such trees. Examining all of the under-canopy topsoil Pb concentration data together, it is evident that there is no significant difference in topsoil Pb concentration with increasing distance outwards (under the canopy) from the near the base of the tree trunk (Figure 24). There is also no significant difference in topsoil Pb concentration between sites just outside the canopy and those underneath the canopy. Similarly, there were no significant trends in topsoil Pb concentrations under tree canopies when each tree site was analysed separately (statistics not shown).

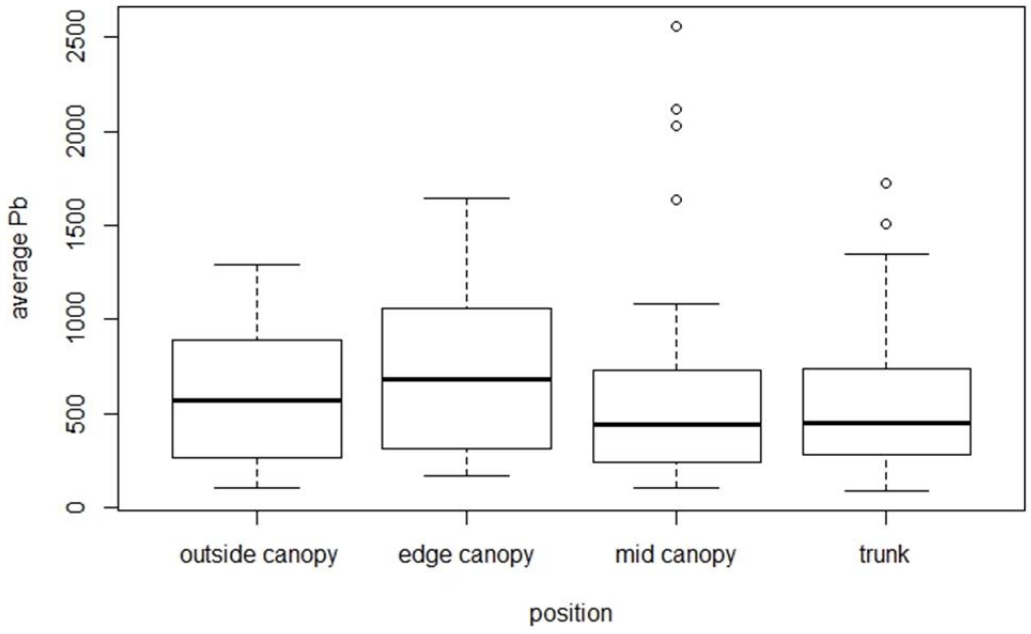


Figure 24. The relationship between distance from a tree's trunk and topsoil Pb concentration, based on data collected from under five large-canopied trees in parks of Broken Hill.

As the underlying topsoil of only eight trees was considered in this study, it is not possible to definitively assess the effect of tree canopies on dust capture and topsoil Pb accumulation in Broken Hill parks. There are a number of factors that may have influenced the data collected, including the distance of the trees to the nearest road, the ground covering under the trees, the size and canopy structure of the trees (species of trees), the amount of organic matter (debris) beneath the trees, and the distance to the Line of Lode.

Nevertheless, this dataset provided no strong evidence of a Pb accumulation effect under the canopies. Because turf does not readily grow under tree canopies, the observed higher Pb concentrations under trees compared to nearby grassed areas (in past studies) may simply reflect the difference between the original topsoil and a more recently renovated grassed surface.

4. CONCLUSIONS AND RECOMMENDATIONS

- In the ten Broken Hill parks and ovals investigated in this study, there is a strong correlation between topsoil Pb concentration and both distance to the Line of Lode and the type of ground cover present.
- The most distant sites from the Line of Lode, the North Family Play Centre, Picton Sports Ground and Memorial Oval, are all characterised by topsoil Pb concentrations well below the HIL of 600 mg/kg, and have little need for abatement.
- For the other seven parks and ovals, which are all within 1 km of the Line of Lode, the need for abatement is governed by the type and quality of the ground cover present.
- The well-maintained turf playing surfaces of Jubilee Oval, Alma Oval and the soccer fields at O'Neil Park, are all characterised by low topsoil Pb concentrations.
- Similarly, in areas where layers of cracker dust and roadbase/gravel form an intact soil-like surface, such as in parts of the Duke of Cornwall Park, Kintore Reserve and Alma Oval, Pb concentrations are generally low.
- In areas of parks where cracker dust/roadbase/gravel coverage is worn or patchy, and soil patches are evident, topsoil Pb concentrations tend to be higher, often exceeding the HIL for recreational areas. Similarly, areas of bare soil and areas of unimproved, patchy grass cover tend to exhibit moderate to high topsoil Pb concentrations.
- There is no strong evidence to suggest that well-established trees with large canopies are acting as Pb-rich dust traps, but in parks near to the Line of Lode, bare areas of soil adjacent to tree trunks are commonly enriched in Pb.
- The Pb concentrations of the dust-sized fractions of selected Broken Hill park topsoils are generally equivalent to, or slightly higher than, the Pb concentrations of the bulk soil samples, suggesting that dust accessions have played a minor to moderate role in affecting the Pb loading of these soils.

Taking into account these conclusions, a summarising table of the need for abatement in the ten parks and ovals of Broken Hill considered in this study, follows (Table 4).

Table 4. Recommended priority areas of parks and ovals for abatement.

Park	Priority for abatement	Priority areas for abatement
Duke of Cornwall Park	Low	Around bases of established trees where soil is exposed
Patton St Park	High	The bush areas in the centre of the park where soil is exposed, particularly near the fenced dog park
Alma Oval	Medium	The southeastern end of the block, inside the stone wall; possibly the northeastern corner of the block
Kintore Reserve	Medium	The centre of the reserve where the cracker dust surface is worn
Sturt Park	Medium	Around bases of established trees and where soil is exposed in the northeastern half of the park; the Centre for Community bowling rinks
North Family Play Centre	Low	Not applicable
Picton Sports Ground	Low	Not applicable
O'Neil Park	High	Areas of worn cracker dust in the bike track area; the vegetated earthen banks adjoining the soccer fields; the southern roadside strip of Norm Fox oval and parts of the oval surface
Memorial Oval	Low	Not applicable to the Oval complex – the adjoining area to the south is possibly contaminated
Jubilee Oval	Low	Northeastern area of native scrub

Examining the abatement options for the two parks of highest abatement priority, Patton St Park and the O'Neil Park complex, a variety of options may need to be considered. At Patton St Park, top-dressing with clean soil and/or mulch may be necessary for the area adjacent to the dog park. Next to the soccer fields at O'Neil Park, the surrounding sloped, earthen banks with mature trees and shrubs have been left relatively untouched and the original soil is high in Pb concentration. Ensuring this area has adequate mulch to cover the soil may need some earthworks to stop the mulch being eroded and re-exposing the soil. The same considerations are needed for the southern embankment of the Norm Fox oval. The Norm Fox playing oval has patches exceeding 600 mg Pb/kg, and so would benefit from a top-dressing of clean loam. The bike track area of the O'Neil Park complex is perhaps the most problematic to abate, given its particular usage. Mulching or cracker-dusting the scrub area used by bike-riders would reduce its amenity for that purpose, as would fencing it off. The car-park adjacent to the scrub area requires a fresh capping of cracker dust or roadbase.

At Alma Oval, refurbishment of the southeastern end of the block with a thick layer of cracker dust would appear to be a prudent strategy, although the drainage of the area may need to be considered to avoid erosion of the abated surface.

At Kintore Reserve, the central area of the reserve has worn cracker dust and some exposed soil – addition of a thick layer of cracker dust across this area looks to be the most appropriate abatement measure.

At Sturt Park, there are some areas of concern scattered throughout the northeastern half of the park. These areas of concern are a combination of bare patches in the grass, and the bare areas around the trunks of some large, established tress. Ensuring continuous grass coverage and adequate mulch around the bases of trees would appear to be an appropriate abatement approach. The artificial grass bowling rinks at the Centre for Community are high in fine-grained Pb (in the fine sand in the artificial grass), but the risk of this material coming into contact with small children is not high, given the infrequent use of the area. The removal of this fine sand and its replacement with clean, fine sand is perhaps a mid-term priority if the bowling rinks are to remain at this location.

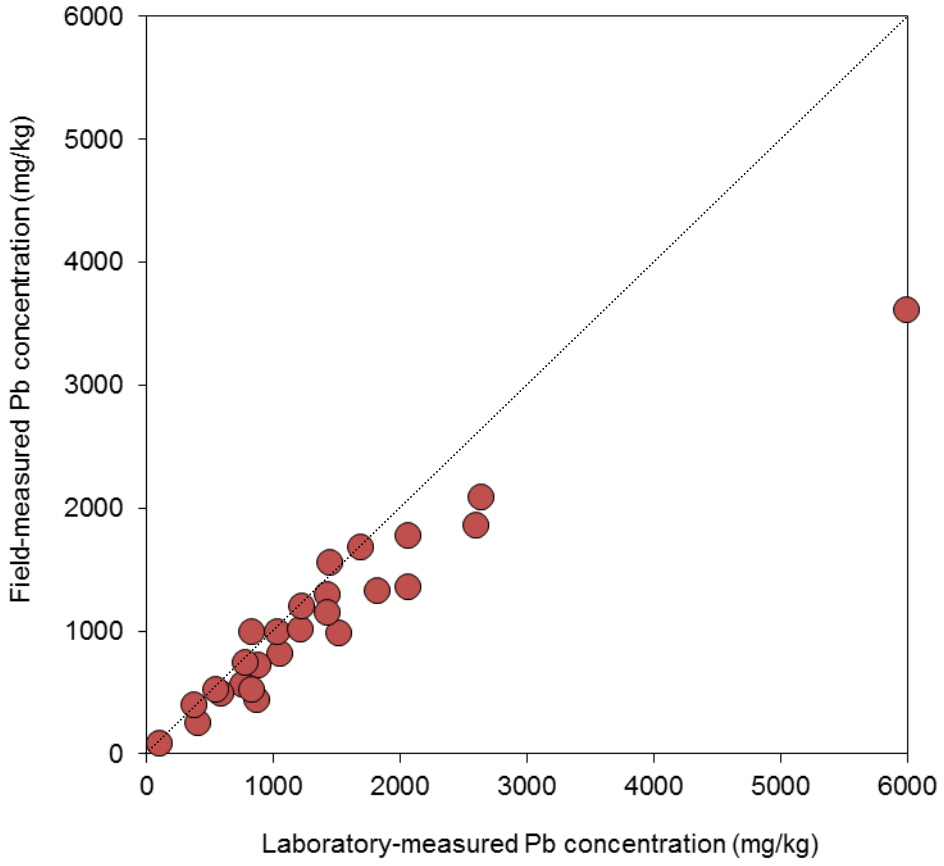
5. REFERENCE

National Environment Protection Measure (NEPM) 2013. *National Environment Protection Measure 1999 Schedule B1 - Guideline on Investigation Levels for Soil and Groundwater.* Australia: Federal Register of Legislative Instruments.

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. APPENDIX

Appendix 1. Comparison data for the (field) pXRF-estimated and (laboratory) *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 well in the field, predicting Pb concentration values close to those estimated by *aqua regia* digestion and ICP-MS analysis in the laboratory. This is particularly the case for samples containing less than 1500 mg Pb/kg.

However, there is a general trend of the pXRF estimating slightly lower Pb concentrations in the field than the laboratory digestion and analysis – the majority of points are below the 1:1 line in the Appendix 1 figure. This trend becomes increasingly prominent with large Pb concentration samples. Reasons for this discrepancy include the attenuating effect of soil moisture (less Pb is estimated for moist field soil than dry soil used in laboratory analysis), and the more heterogeneous soil surface area that the pXRF scans in the field.

For the purpose of this monitoring study, though, the strong positive correlation between field and laboratory-based estimates of Pb concentration gives confidence that contaminated areas are being identified.