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Effectiveness of cracker dust as a capping material for Pb-rich soil in the mining town of Broken Hill, Australia

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A B S T R A C T

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

1. Introduction

The Australia's largest Pb–zinc (Zn)–silver (Ag) mine is located in Broken Hill. The orebody, known as the 'Line of Lode', was discovered in the 1880s and both open pit and underground mining have occurred ever since. Between 1885 and 1898, *in situ* smelting of Pb and Zn was also conducted in Broken Hill (Solomon, 1988). As discussed by Lyle et al. (2006), 'lead poisoning was evident amongst the early miners and their families', but was regarded as an occupational hazard. By the 1990s, however, the effects of Pb had re-emerged as a public health issue due to various studies documenting the relationship between the blood Pb (PbB) of children and their intellectual development. A survey of Broken Hill children aged 1–4 years in 1991 revealed that more than 20% of these children had PbB levels exceeding the 'level of concern' at that time (25 μg Pb/dL) (Lyle et al., 2006). Numerous investigations into the various sources of Pb in the Broken Hill environment followed, so that an effective Pb management programme could be implemented to minimise the detrimental effects of the metal (Lyle et al., 2001). Recent reports indicate that, as a result of the Pb management programme put into place, the percentage of Broken Hill children aged 1–4 years with PbB levels below the current National Health and Medical Research Council (NHMRC) guideline level of 10 μg Pb/dL has steadily increased from 13.6% in 1991 to 79.8% in 2012 (Lesjak et al., 2013).

One of the first studies in Broken Hill to investigate the link between topsoil Pb concentrations and children's PbB levels was that of Phillips and Hall (1994). They took soil samples from residences around the city and looked for correlations between soil and children's PbB. In so doing, they created a map of average topsoil Pb concentrations, dividing the town into 25 zones. At much the same time, the Broken Hill City Council (BHCC) also sampled and analysed topsoils from footpaths of every city block, leading to the production of a similar district map of topsoil Pb concentrations (Boreland et al., 2002). Both of these surveys indicated that, not surprisingly, high topsoil Pb concentrations created a halo pattern around the LoL, with average values of up to 3500 ppm in areas of South Broken Hill within several blocks of the LoL, and average values of around 1500 ppm in areas of Northern Broken Hill near the LoL. Beyond about 1 km either north or south of the LoL, average topsoil Pb concentrations fell back to 300–600 ppm, while at the northern and

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eastern extremities of Northern Broken Hill, typical values of topsoil Pb were 30–100 ppm. A subsequent unpublished soil survey of Broken Hill by Ghabach (2012), focussing on earthen footpaths and parks, confirmed and reinforced this general pattern of topsoil Pb concentration.

As identified by a number of other studies, however, there are various anthropogenic processes which will have altered the spatial distribution of topsoil Pb in Broken Hill over time. These include the deposition of Pb-rich dust from mining activity, the emission of Pb-rich particulates from smelting activity, the emission of Pb-rich particulates derived from leaded petrol and the incorporation of Pb-based paint flakes into residential topsoil. Gulson et al. (1994, 1995) used Pb isotope ratios to demonstrate that most soil Pb in Broken Hill was sourced from the orebody, but that leaded petrol and Pb-based paint also contributed to the Pb loads of dust, soil, and human blood. Dusts and the dust-sized fraction of soils were found to be particularly enriched in Pb (Gulson et al., 1995), suggesting that mine dust was at least partly responsible for the Pb-load of some soils. The smelting operations in Broken Hill of the late 1800s are likely to have resulted in substantial airborne transport and deposition of Pb-rich material to downwind locations; the findings of Cartwright et al. (1976), who investigated Pb contamination around a smelter at Port Pirie in South Australia, indicated pronounced fallout of Pb-rich particulates up to 15 km from the smelter. Numerous studies on the atmospheric transport and deposition of Pb-containing dust to soil have shown that once introduced into soil, Pb contaminants tend to accumulate in the upper 5 cm of the receiving soil because the leaching risk for Pb in soil is very low under most natural conditions (United Nations Environment Programme (UNEP), 2010; Patinha et al., 2012). Therefore, topsoil often acts as an important sink for anthropogenic or deposited Pb, while Pb in subsoil can be regarded as that sourced from the soil parent material.

Not all anthropogenic processes affecting topsoil Pb concentrations will result in Pb enrichment. The replacement of topsoil in residential gardens and in public parkland, and various remedial strategies may also have decreased topsoil Pb in some parts of Broken Hill. Over the last decade in particular, an extensive Pb management programme, funded by the state government and supported by local government initiatives, has been conducted, involving topsoil replacement in parks and topsoil capping along earthen footpaths and nature strips. The capping of footpaths and nature strips, done at the time of kerbing and guttering, or during targeted campaigns to remediate streets with known high topsoil Pb concentrations, has usually involved the application of a 5–10 cm thick layer of 'cracker dust'.

Cracker dust is a by-product of crushing blue metal from a range of volcanic rocks, including granite and basalt, to create aggregates for concrete and for landscaping of paths and driveways. It consists of small (<10 mm) fragments of rock and a finer dust-sized fraction. In the Broken Hill district, the sole source of cracker dust used by the BHCC has been a quarry operation near the LoL, where an outcrop of the quartzo-feldspathic Potosi Gneiss has been exploited. This gneiss is commonly comprised of quartz, feldspars and biotite, with abundant inclusions of garnet and occasionally sillimanite (Brown, 1983). The typical Pb concentration of cracker dust produced from this gneiss is around 15 ppm, which is substantially below the National Environment Protection Council (NEPC) Health Investigation Level (HIL) for soil Pb (300 ppm) in residential gardens (NEPC, 2013). The bimodality of the cracker dust particle size allows the material to pack stably as a gravelly, Pb-free capping layer over the pre-existing topsoil. Since the 1940s, cracker dust has been used in Broken Hill as a backfill material when kerbs and gutters have been installed, although most of the present-day kerbs and gutters were installed in the 1960s, 1970s, and 1980s. The most recent installation of a cracker dust capping layer, as a deliberate remedial measure rather than as a by-product of kerbing and guttering, was completed between 2005 and 2006, one block either side of the LoL, as an initiative of the Broken Hill Environmental Lead Centre.

Soil Pb abatement schemes usually do not include the excavation of large quantities of contaminated land due to the cost and disruption to the environment (Harvey et al., 2015). Instead, the 'cap and cover' approach is commonly used around the world as a cost-effective strategy for remediating Pb-contaminated urban environments. For example, the soil Lead Abatement Strategy (LAS) programme in Boolaroo, New South Wales, Australia, surrounding the Pasminco Cockle Creek Smelter, included a provision for the removal of highly contaminated topsoil (>2500 ppm Pb), but was dominated by cap and cover procedures for less contaminated topsoil using materials such as clean soil, mulch, and grass (Harvey et al., 2015). In this LAS, depths of added clean soil ranged from 2.5 to 5 cm, depending on the level of Pb contamination of the pre-existing topsoil (Harvey et al., 2015). Likewise, in the Coeur d'Alene River basin, Idaho, the United States, barriers, such as asphalt pavement, clean gravel or soil, and turf, were installed on top of Pb-contaminated soil surfaces to reduce Pb exposures (Committee on Superfund Site Assessment and Remediation in the Coeur d'Alene River Basin, 2005). The effectiveness of such cap and cover approaches can be influenced significantly by the nature of the capping material and how well the capping layer is maintained. For example, Wang et al. (1990) demonstrated that cadmium (Cd) concentration in Pak Choy decreased with increasing depth of clean soil replacement layer of Cd-contaminated agricultural soil in Shanghai suburbs, China.

In Broken Hill, cracker dust application can be regarded as a 'cap and cover' style of Pb abatement without using clean soil, mulch or grass; the arid climate of the region severely limits the efficacy of vegetative barriers such as turf grass. This site-specific capping along earthen footpaths and nature strips around Broken Hill follows a similar principle to the installation of asphalt pavement as a barrier to reduce the potential for Pb exposure.

Given that previous studies of the topsoil Pb distribution in Broken Hill have specifically disregarded capping layers of cracker dust, the actual land surface Pb concentrations, especially near the LoL where the bulk of the remedial works have taken place, are not well characterised. Similarly, due to the potential for ongoing Pb enrichment of cracker-dusted topsoil through the various anthropogenic processes discussed above, the efficacy and longevity of cracker dust application as a remediation strategy is not well understood. The aims of this study, therefore, are to (a) investigate the spatial distribution of Pb in soil both affected and unaffected by the application of cracker dust, and (b) evaluate the effectiveness of Pb-rich topsoil remediation with cracker dust.

2. Material and methods

2.1. Study area

Broken Hill is an isolated mining city in the far west of New South Wales, which is dominated by a hot and dry desert climate. The average annual minimum and maximum temperatures are 11.9 and 24.3 °C, respectively, and the average annual rainfall is 260 mm (Bureau of Meteorology, 2015). Although Broken Hill is located at the edge of the vast Western Plains of New South Wales, the city marks the southern end of the Barrier Range, a low range of hills extending more than 100 km to the north. The Barrier Range is comprised of uplifted Precambrian and Palaeozoic metamorphics and metasediments belonging to the Willyama Supergroup (Brown, 1983; Gibson, 1999). Soils of the region vary in thickness according to landscape position, but the bedrock is generally covered by a veneer of alluvial, colluvial and sometimes residual sediments (Gibson, 1999). Around the city of Broken Hill, soil profiles are almost ubiquitously red in colour, vary in thickness from less than 0.2 m to in excess of 1.0 m, are weakly structured or apedal and