Title: House sparrows as sentinels of childhood lead exposure

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Abstract: Our understanding of connections between human and animal health has advanced substantially since the canary was introduced as a sentinel of toxic conditions in coal mines. Nonetheless, development of wildlife sentinels for monitoring human exposure to toxins has been limited. Here, we capitalised on a three-decade long child blood lead monitoring program (> 20,000 measurements), to demonstrate that the globally ubiquitous and human commensal house sparrow (*Passer domesticus*) can be used as a sentinel of human health risks in urban environments impacted by lead mining. We show that sparrows are a viable proxy for the measurement of blood lead levels in children at a neighbourhood scale (0.28 km^2), and could be used to monitor changes in lead exposure risks over time. In support of the generalisability of this approach, the blood lead relationship established in our focal mining city enabled us to accurately predict elevated blood lead levels in children from another mining city using only sparrows from the second location. Using lead concentrations and isotopic compositions from environmental and biological matrices, we identified shared sources and pathways of lead exposure in sparrows and children, with strong links to contamination from local mining emissions. Our findings show how human commensal species can be used to identify and predict human health risks over time and space. Moreover, they affirm the emerging paradigm that humans and animals share these risks, and highlight the true ecological cost of contaminated environments.

Main Text: Morbidity and mortality patterns in humans are inextricably linked to environmental contamination (1), with pollution responsible for an estimated nine million premature deaths annually (2). Effective action against global pollution requires more effective monitoring, and greater public awareness of the links between contaminated environments and human health (2). However, monitoring contaminant exposures in human populations, especially during childhood, is costly and raises significant logistical and ethical issues (3).

Organisms that are sensitive to pollutants have long been recognized as useful indicators of environments detrimental to human health (4). However, links between exposure as measured in these organisms, and impacts on human populations are difficult to establish due to the disparate pathways and scales over which these exposures occur (5). Given these complexities, it is not surprising that research on animal sentinels tends to focus on the direct transfer of contaminants through food chains (6), even though links between human and animal health are not solely confined to food chain interactions (7).

This knowledge gap highlights the growing need to escape the silos within which we compartmentalise our understanding of the human, animal and environmental health domains. The One Health Initiative (8), which seeks to unite human and veterinary health along with the environmental sciences, identifies the crux of the problem. By separating these domains, we limit our understanding of interconnections between the natural systems which underlie our health, and the health of the organisms around us.

Bioindicator species can be used to monitor the impacts of environmental pollutants at a population, community, or even ecosystem scale (9). However, those with most utility for understanding the effects of pollution on human health are likely to be commensal, sedentary (non-migratory) species that share our environment (5, 10). The free-ranging wild house sparrow (*Passer domesticus*) is one such species due to its global distribution, close association with humans, and sedentary nature (11, 12). Studies in Europe (13), North America (14), and Africa (15), have linked changes in biomarkers of exposure and effect to sparrow populations inhabiting different environments with varying levels of contamination, and similarly, for the congeneric tree sparrow *Passer montanus* in Asia (16).

These studies have demonstrated the capacity of sparrows to indicate pollution at broad geographic scales, often across urban and rural land uses. However, public health interventions benefit from information at a finer spatial scale, where it can inform the management of human health risks in the same areas where sentinel species such as sparrows are sampled. For instance, the use of canaries in coal mines was an effective warning system because it provided a spatially and temporally biologically relevant indication of underground air quality for nearby miners.

Lead (Pb) is one of the oldest and most ubiquitous contaminants of the Anthropocene (17). Globally, exposure to environmental Pb has resulted in adverse health outcomes across a broad range of organisms (7, 18), and is estimated to cause around 900,000 premature human deaths annually (2). While Pb emissions have declined in many areas due to the replacement of Pb additives in fuel, Pb contamination remains widespread across urban environments globally, and poses a particular hazard to humans living around active mining and smelting facilities (19). Within these areas, children are disproportionately exposed to Pb in soil, dust and water, due to behaviours such as crawling and frequent hand to mouth contact (18). Children are also most susceptible to the neurological and developmental effects of Pb exposure (18). There is a global need to identify areas where children are at greatest risk of exposure to environmental Pb contamination, such that it can be managed through remediation or avoidance (20).

This study investigates the relationship between environmental Pb contamination and Pb exposure in house sparrows and children inhabiting the remote Australian mining cities of Broken Hill in western New South Wales, and Mount Isa in northeast Queensland (fig. 1). In both cities, prolonged Pb ore extraction, processing and transport activities have polluted surrounding urban areas with atmospheric emissions, creating soil Pb contamination gradients which decline away from mining operations (21, 22). To benchmark blood Pb levels in sparrows from these mining cities, we also sampled populations from 5 additional sites in towns and cities representing ‘background’ levels of Pb from urban areas unaffected by Pb mining and smelting operations (fig. 1). By drawing on quantitative and spatially overlapping human, animal and environmental data (23), this study aimed to provide an integrated assessment of health risks arising from anthropogenic pollution within an urban ecosystem.

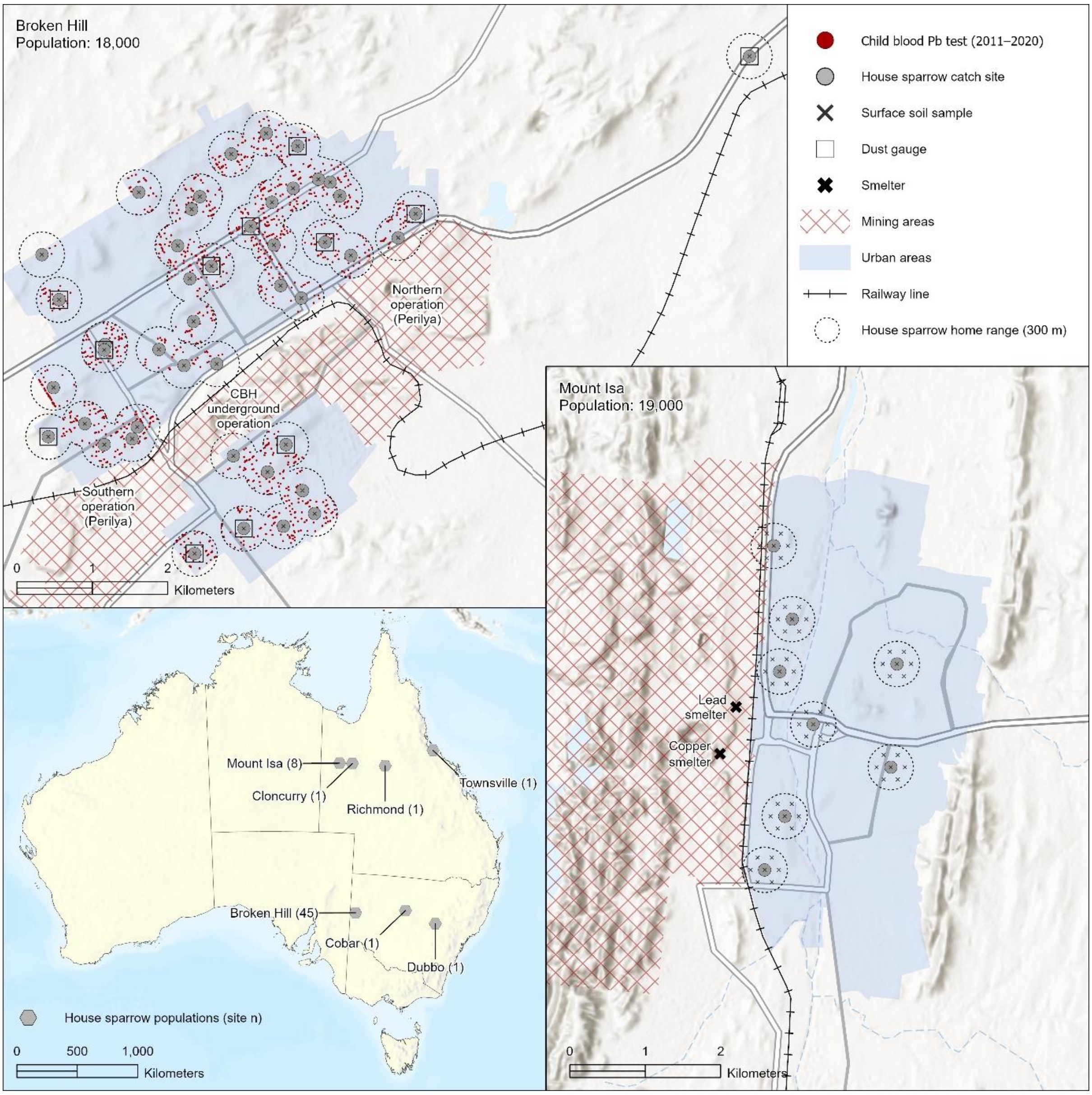

Fig. 1. Map of sparrow sampling sites. Location of sparrow catch sites and associated environmental samples in Broken Hill and Mount Isa. Also shown are locations of relevant infrastructure, urban areas, and sources of Pb contamination, including mining and smelting areas. Dotted lines around each site designate the estimated home range (300 m radius) of sparrows captured from that location. For Broken Hill, red points indicate the approximate distribution of blood Pb measurements from children living within the home range of one or more sparrow catch sites. Regional map shows location of all towns and cities where sparrows were sampled.

Our comparison of Pb exposure in sparrows and children leveraged data from extensive human biomonitoring programs established in response to elevated blood Pb levels in local children (24). At Broken Hill, the availability of 30 years (1991–2020) of anonymysed blood Pb data geolocated to the home address of tested children enabled us to spatially join and compare the distribution of blood Pb levels in children and sparrows over different time intervals. At Mount Isa, geolocated address information was not available, and child blood Pb levels were reported as categorical ranges (< 5 µg/dL, ≥ 5 µg/dL, ≥ 10 µg/dL) (25). Nonetheless, data from Mount Isa enabled us to compare our findings from Broken Hill to a context similarly impacted by mining and smelting emissions. In line with standards for the reporting of epidemiological evidence under the One Health approach (23), additional detail on the selection, sampling, analysis and reporting of human, animal and environmental data is provided in the Methods and references (25, 26).

Using literature estimates for the maximum home range of a house sparrow (27) (300 m radius around each catch site = 0.28 km^2), we spatially linked blood Pb measured in sparrows in 2020 to the co-located population of Broken Hill children (fig. 1). In linking this data, we used the preceding decade (2011–2020) of blood Pb measurements from children aged 1–4 years, as child blood Pb levels in Broken Hill have remained relatively stable over this period. We identified a spatially robust relationship between geometric mean blood Pb in sparrows and nearby (< 300 m) children at each catch site (Pearson $r = 0.73$, $p < 0.01$, $n = 44$; fig. 2A). This was despite a large difference in the geometric mean blood Pb level of sparrows (20 µg/dL, $n = 226$) and nearby children (5 µg/dL, $n = 4190$; table S1). In the environmental context of Broken Hill, a sparrow blood Pb of around 17 µg/dL corresponds to a child blood Pb of 5 µg/dL (child blood Pb = 0.06 × sparrow blood Pb + 3.98; fig. 2A; table S2). This is the human blood Pb intervention level at which further investigation of an individual's risk of Pb exposure is recommended. Importantly, we have established this relationship at a scale (0.28 km^2) that is relevant to the assessment and management of Pb exposure risks in urban environments, and have done so using measurements from a relatively small cohort of sparrows ($n = 226$). While these findings are based on a high density of sites ($n = 44$), a power analysis indicates that as few as five sites, or approximately 25 sparrows, are needed to establish a statistically significant relationship between the blood Pb of sparrows and children (see Methods).

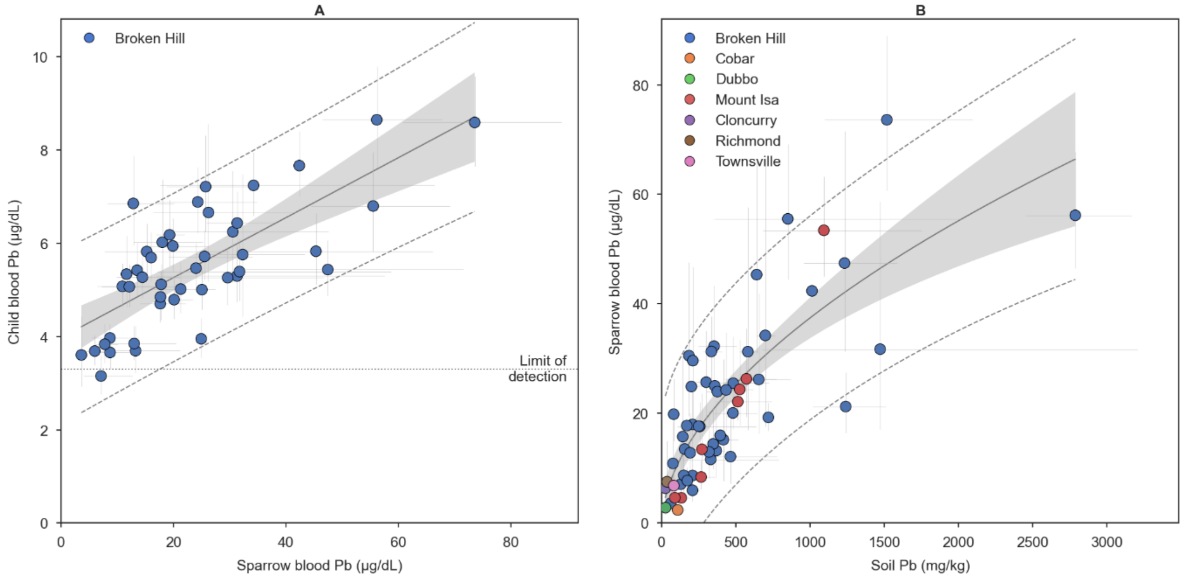

Fig. 2. Co-located blood and soil Pb relationships. (**A**) Relationship between Broken Hill sparrow and child blood Pb concentrations (n = 44; child blood Pb = 0.06 × sparrow blood Pb + 3.98; linear regression ± 95% confidence interval ± 95% prediction interval). Points represent geometric mean blood Pb concentration (± 95% confidence interval where sample n ≥ 3) of sparrows and nearby (< 300 m) children for each catch site. Dotted line indicates the lower limit of detection of the LeadCare II blood Pb analyser (3.3 µg/dL) used for the majority of blood Pb screening in Broken Hill between 2011–2020 (26). (**B**) Relationship between soil Pb and sparrow blood Pb concentrations (n = 58; sparrow blood Pb = 0.52 × soil $\text{Pb}^{0.61}$; power regression ± 95% confidence interval ± 95% prediction interval). Points represent geometric mean soil Pb and sparrow blood Pb concentrations (± 95% confidence interval where sample n ≥ 3) for each site, with colour designating the regional location of that site.

Geometric mean soil Pb concentrations were strongly related to sparrow blood Pb across all the sites included in this study (Spearman $r_s = 0.78$, $p < 0.01$, $n = 58$; fig. 2B). This relationship was stronger than that observed between soil Pb and nearby (< 300 m) child blood Pb measurements in Broken Hill (Spearman $r_s = 0.50$, $p < 0.01$, $n = 44$). Here, our findings reflect differences in the geographic scales over which environmental Pb exposure typically occurs in sparrows and children. Children are primarily exposed to Pb within and around the home (18), and are therefore more susceptible to localised heterogeneity in soil Pb contamination, such as that arising from the targeted remediation of homes and public spaces (24, 28). As such, in many mining and smelting impacted urban areas, airborne Pb is considered a stronger predictor of child blood Pb levels than soil Pb (26). Accordingly, we observed a similar relationship between Pb deposition rates and blood Pb in sparrows (Spearman $r_s = 0.67$, $p = 0.02$, $n = 12$) and children (Spearman $r_s = 0.67$, $p < 0.02$, $n = 11$). Sparrows, on the other hand, are typically active over a larger geographic area than children, and are therefore less sensitive to local variability in soil Pb contamination. The strong relationship between sparrow blood Pb and soil Pb affirms this (fig. 2B), and suggests that the measurement of sparrows can cut through much of the geochemical noise inherent in contaminated urban environments.

A powerful test of whether sentinel species can be used to monitor health risks in human populations is to explore if the blood Pb relationship established between sparrows and children in Broken Hill (fig. 2A) can be used to predict blood Pb levels in a new location. Mount Isa provided a relevant Pb mining context in which to test the generalisability of our findings, as median sparrow blood Pb and soil Pb from this location was not significantly different to our data from Broken Hill ($p > 0.05$; table S3), suggesting that child blood Pb might also be comparable between these locations. Accordingly, we applied the linear blood Pb relationship (child blood Pb = 0.06 × sparrow blood Pb + 3.98) established in Broken Hill to blood Pb measurements from Mount Isa sparrows ($n = 67$) to predict the distribution of blood Pb levels in nearby Mount Isa children (fig. 3A–B). We compared our predictions to the most recently available (2016–2018) and demographically consistent (children aged 0–4 years) data from Mount Isa ($n = 1014$) (25). Based on the population of children represented by each of our sites (fig. 3C), we estimated that 24.3% (0.1% ≥ 10 µg/dL) of children in Mount Isa would have a blood Pb ≥ 5 µg/dL, the human intervention level (fig. 3D; table S4). This sentinel-driven prediction corresponded closely to the 24.0% (3.9% ≥ 10 µg/dL) of Mount Isa children measured with a blood Pb ≥ 5 µg/dL between 2016–2018 (25), and emphasises the broad applicability of this approach for monitoring environmental Pb exposure risks in children.

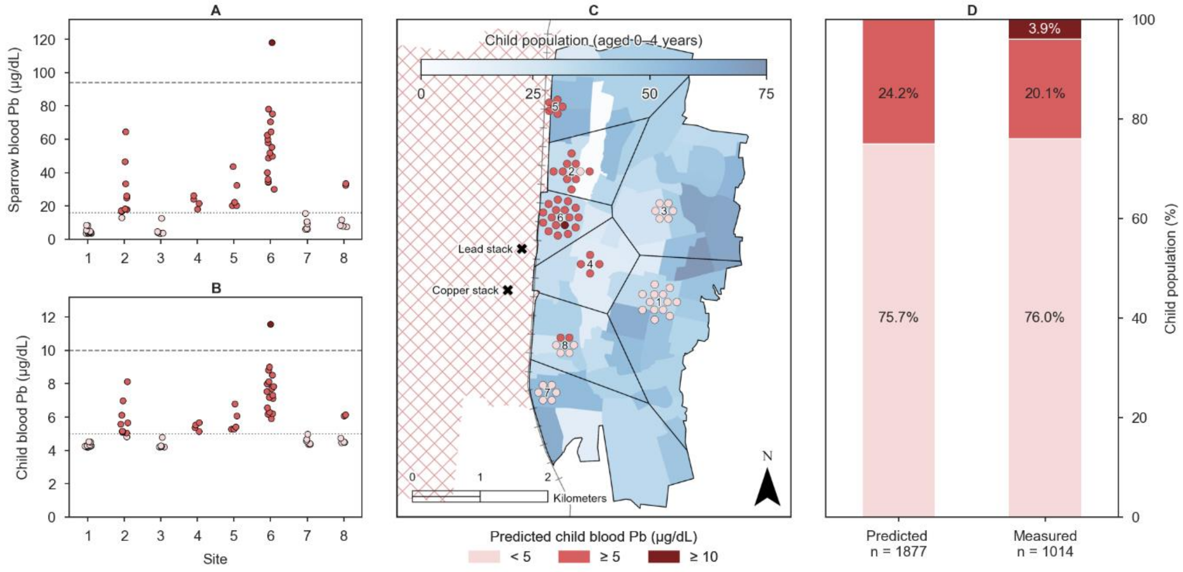

Fig. 3. Predicted distribution of Mount Isa child blood Pb. (**A**) Measured distribution of individual sparrow blood Pb levels at each site in Mount Isa (n = 67). Horizontal lines indicate sparrow blood Pb thresholds at which a nearby child is predicted to have a blood Pb level of ≥ 5 µg/dL (dotted line) or ≥ 10 µg/dL (dashed line) based on data from Broken Hill. (**B**) Predicted distribution of child blood Pb levels ≥ 5 µg/dL (dotted line) or ≥ 10 µg/dL (dashed line) at each Mount Isa site based on measured distribution of sparrow blood Pb levels at that site. (**C**) Map of predicted child blood Pb levels around sites in Mount Isa. Thiessen polygons are used to designate the population of Mount Isa children represented by each site. (**D**) Percentage of children in Mount Isa estimated to have a blood Pb level ≥ 5 µg/dL or ≥ 10 µg/dL, compared to measured exceedances of these same thresholds between 2016–2018 (25).

We do not expect the relationship between blood Pb in sparrows and children to be the same in all environmental contexts, especially where the sources and pathways of Pb exposure are different. Indeed, comparison of historical blood Pb data from Broken Hill suggests that, even within the same city, the relationship between Pb exposure in sparrows and children has changed over time. When we compared our blood Pb measurements from sparrows to historical child blood Pb data, we found the strongest relationships in the earliest years of child blood Pb screening. For example, contemporary sparrow blood Pb levels were more strongly associated with blood Pb measured in children from 1991 (Pearson $r = 0.79$, $p < 0.01$, $n = 43$; fig. 4A) — the first year of systematic blood Pb screening in Broken Hill — than any other individual year for which data were available (e.g., fig. 4B; table S5). We cannot definitively ascertain the reasons for this decoupling without more temporally explicit sparrow blood Pb data. Nonetheless, it is likely driven by changes in environmental conditions contributing to Pb exposure risks over time (24, 28), and the corresponding shifts in human responses to these risks.

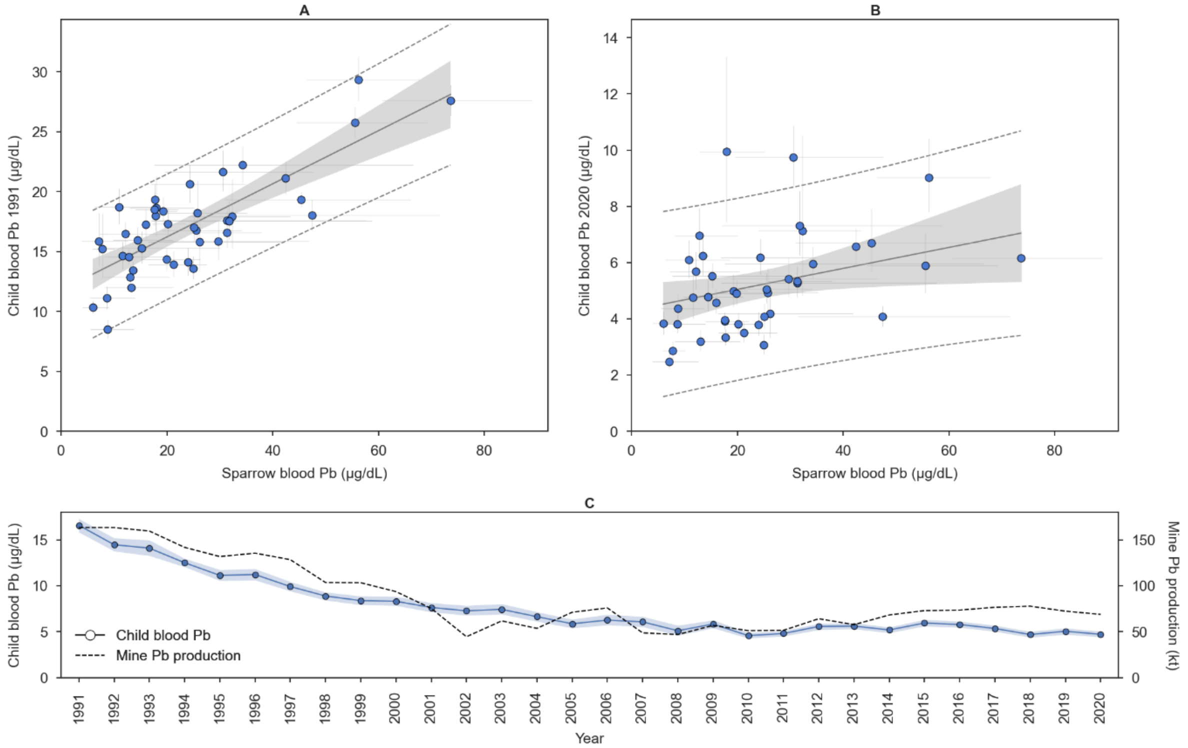

Fig. 4. Relationship between sparrow blood Pb and historical child blood Pb. (**A**, **B**) Comparison of relationship between blood Pb of contemporary sparrows and nearby (< 300 m) children measured in 1991 (**A**) and 2020 (**B**) from each catch site (n = 43; linear regression ± 95% confidence interval ± 95% prediction interval). Points represent geometric mean blood Pb concentrations (± 95% confidence interval where sample n ≥ 3) of sparrows and nearby (< 300 m) children for each catch site. (**C**) Comparison of annual geometric mean child blood Pb concentrations (± 95% confidence interval) and Pb production from Broken Hill mines. Mine Pb production data between 1991–2012 is based on previously published data, with values from 2013–2020 derived from unpublished estimates of Pb production from the same author (29).

In 1991, both annual mining Pb production rates (29) (a robust proxy for atmospheric Pb emissions (26)) and child blood Pb levels were higher than any other year in the following three decades (fig. 4C). At this time, environmental and social interventions targeting Pb contamination and exposure risks within the community were also in their infancy (24). Consequently, Pb exposures in children were occuring in an environmental context characterised by elevated Pb emissions and largely unmitigated Pb contamination in soil and dust. Blood Pb levels in sparrows are closely linked to the distribution of Pb contamination in soil reservoirs (fig. 2B), and therefore correlate strongly with child blood Pb levels from this period. Conversely, as Pb production, Pb emissions, and child blood Pb concentrations have declined over time (fig. 4C; table S5), and interventions targeting Pb contamination, such as the remediation of residential areas (24, 28), have grown more widespread, the home environment of many children has become increasingly decoupled from the prevailing distribution of Pb contamination in Broken Hill. This is reflected by an increase in the relative variability of child blood Pb concentrations over time, and a corresponding decline in the strength of the blood Pb relationship between sparrows and children (table S5). Though this decoupling highlights the greater agency of humans to modify conditions within their surrounding environment, it also shows how wildlife sentinels have the potential to validate, and even quantify, the effectiveness of human responses to Pb contamination through remediation and other inteventions. Sparrows, unlike humans, are largely unbiased sentinels of environmental Pb exposure risks.

To investigate similarities between sources and pathways of Pb exposure in sparrows and children, we compared sparrow blood Pb isotopic compositions (^{206}Pb/^{207}Pb, ^{208}Pb/^{207}Pb) with those previously reported for children measured in the early years of blood Pb screening in Broken Hill (30). We found that the distribution of sparrow and child blood Pb isotopic compositions aligned closely with previously published data on surface soil (30, 31), deposited dust (this study and reference (21)), and house dust samples (32), and were more similar in composition to Broken Hill ore Pb (see Methods) than to local samples of uncontaminated soil (30) (fig. 5A; table S6). Using these data, we estimated the contribution of Broken Hill ore Pb to the environmental and biological matrices included in this study. We found the highest median contribution of ore Pb in deposited dust (90%), followed by surface soil (90%), house dust (81%), sparrow blood (69%) and child blood (65%) (fig. 5B; table S6). We also observed declines in the contribution of orebody Pb to these matrices with distance from mining and smelting operations (fig. 5C; table S7). These patterns reflect the dispersal, deposition, and mixing of point-source Pb emissions with secondary contributions from residential (e.g., paint and petrol; table S6) and geogenic (e.g., weathering and erosion of unmineralised bedrock) Pb sources, and their subsequent uptake by sparrows and children.

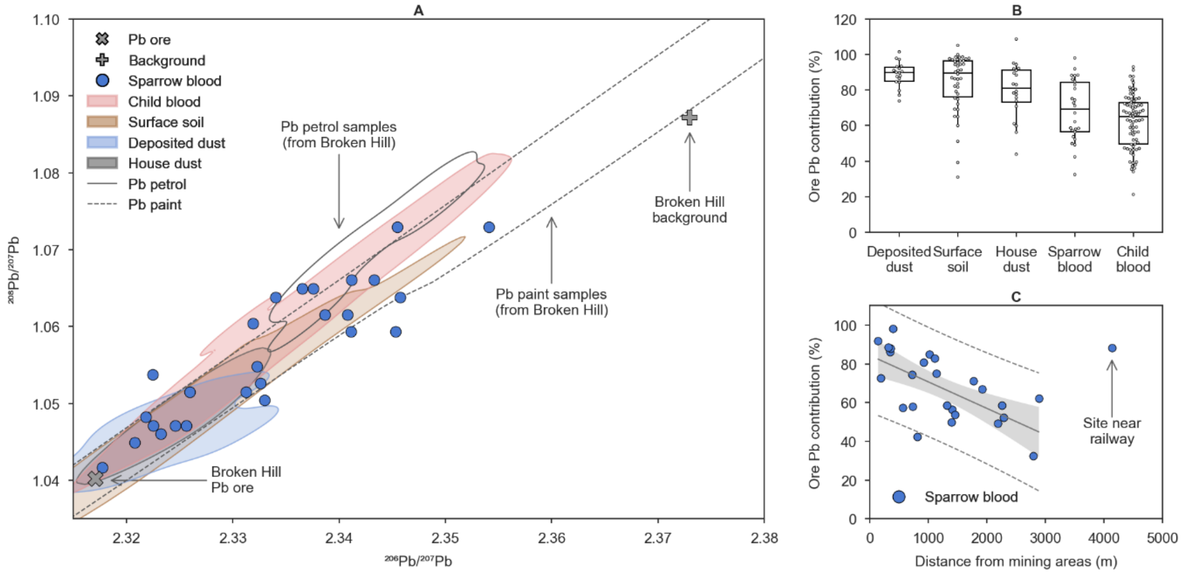

Fig. 5. Environmental and biological Pb isotopic compositions. (**A**) Comparison of Pb isotopic compositions (^{206}Pb/^{207}Pb, ^{208}Pb/^{207}Pb) of Broken Hill Pb ore (median; n = 5), background soil (30) (median; n = 11), sparrow blood (n = 26), child blood (30) (n = 78), surface soil (30, 31) (n = 42), deposited dust (this study and reference (21); n = 18), house dust (32) (n = 20), and Pb petrol (n = 10) and paint (n = 21) samples from Broken Hill (30) (see Methods; table S6). (**B**) Estimated contribution of Broken Hill Pb ore to the Pb isotopic compositions of environmental and biological samples included in this study. Boxplots summarise the 5th, 25th, 50th, 75th and 95th percentiles of the dataset with distribution of individual points also shown. (**C**) Estimated contribution of Broken Hill orebody Pb to sparrow blood Pb isotopic compositions with respect to distance from mining areas (linear regression ± 95% confidence intervals ± 95% prediction intervals). One site located along a railway previously used for the transport of Pb ore concentrate (31) was excluded from the linear regression model.

While inhalation of aerosolised Pb undoubtedly occurs in this species, soil ingestion is likely the primary pathway of Pb uptake in sparrows due to their proclivity for ground foraging and ingestion of grit (11). This is supported by the strong association detected between co-located soil Pb and sparrow blood Pb across all the catch sites included in this study (Spearman r_s = 0.78, $p < 0.01$, n = 58). While we acknowledge that indoor dust may represent a more important source of Pb uptaken by children, a significant proportion of indoor dust originates from nearby soil reservoirs (33). Soil and indoor dust Pb concentrations are also related in Broken Hill (Spearman r_s = 0.53, $p < 0.01$, n = 62 (32)). This correlation accounts for the overlap between sparrow blood Pb isotopic compositions and those measured in the indoor dust of Broken Hill homes (32) (table S6). Furthermore, sparrows are likely exposed to Pb in nesting cavities, where sources and pathways of Pb ingress would likely be more analogous to those contributing to the contamination of indoor environments. We did not identify a significant difference between the median blood Pb concentration of juvenile (< 4 months old (11)) and adult sparrows ($p > 0.05$; table S8), which indicates that blood Pb levels in these younger birds are a consequence of exposure occurring within, or shortly after leaving the nest.

In this study, we observed significant spatial variability in sparrow blood Pb concentrations across local scales, with distance from Pb emissions sources (table S7), and at regional scales, across towns and cities with and without significant Pb mining and smelting operations (fig. 2B; table S1). On a global scale, Pb contamination is widespread and there are hundreds, if not thousands of contexts in which soil Pb levels are equivalent to Broken Hill and Mount Isa (1). We suggest that due to their extensive distribution and close association with people, the human commensal sparrow provides an opportunity to rapidly and efficiently assess risks to children from Pb in the environment (fig. 6). For example, in Europe, Africa, and North and South America, significant Pb contamination and child blood Pb hotspots are associated with high density human and sparrow populations (fig. 6A–F) (34). In parts of Asia, the highly commensal house sparrow is replaced ecologically by its congener, the tree sparrow (*Passer montanus*), which could serve a similar purpose (35).

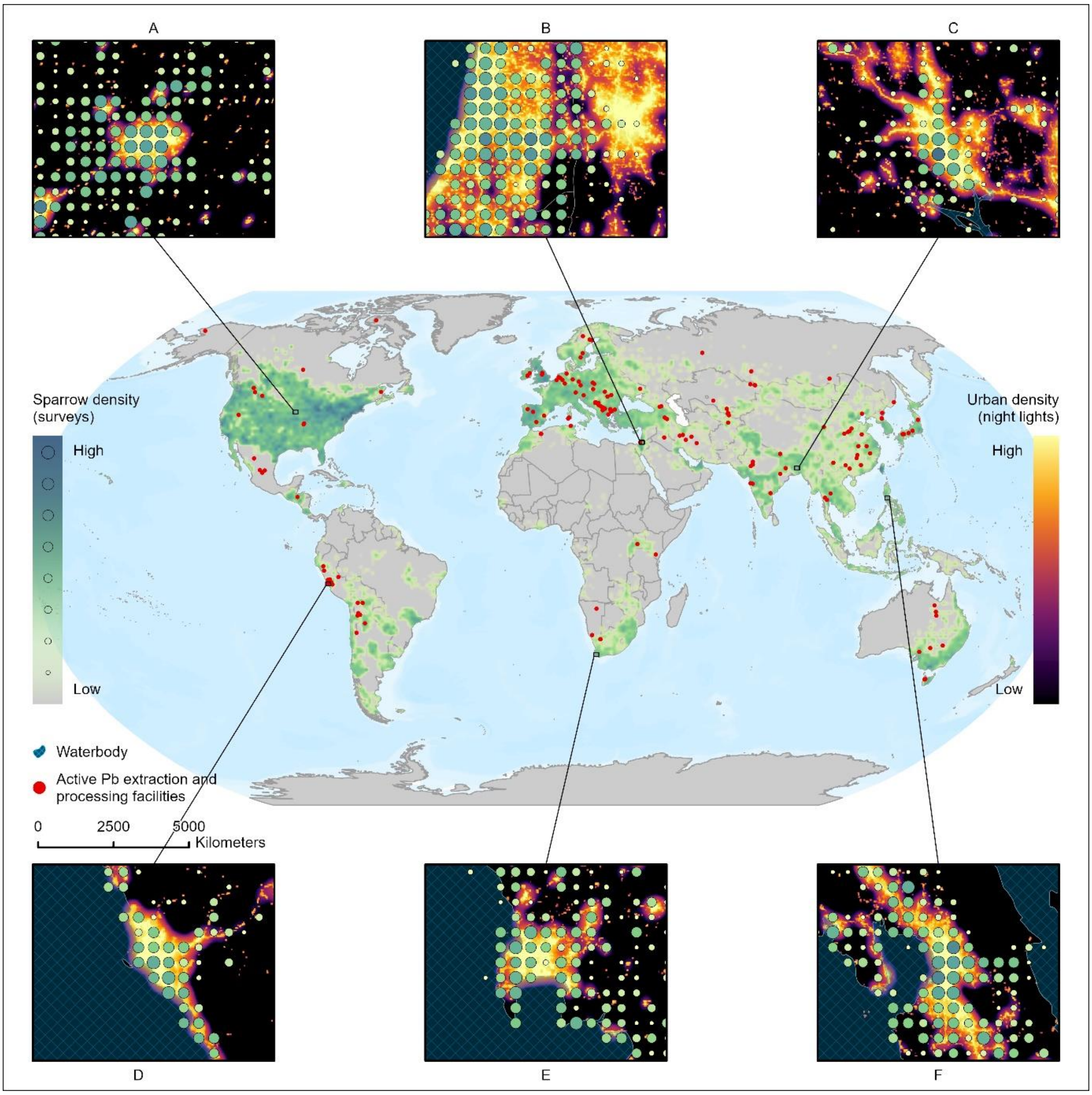

Fig. 6. Global distribution of human commensal sparrow species. Global map shows distribution and relative density of house sparrows (*Passer domesticus*), Italian sparrows (*Passer italiae*), and Spanish sparrows (*Passer hispaniolensis*). Eurasian tree sparrows (*Passer montanus*) are included in regions where the aforementioned species are not present, as this species is known to fulfill a similar human commensal niche in their absence (35). Survey data for all species were obtained from eBird, an online database of bird distribution and abundance (59). The relative density of sparrows (bilinearly resampled as 100 km^2 grid cells) is estimated based on counts of surveys from 2013–2022 that included one or more individual of the selected species. Locations of recently active Pb extraction and processing facilities are also shown (60, 61). Inset (a–f) maps show the relative density of sparrows (centroids of 10 km^2 grid cells) relative to urbanised areas indicated by remotely sensed nocturnal visible light emissions (62). The outlined regions represent a limited selection of Pb exposure hotspots where blood Pb levels in children are comparable to those reported in this study ((**A**) Omaha, United States of America (63); (**B**) West Bank, Palestine (64); (**C**) Tungi, Bangladesh (65); (**D**) Lima, Peru (66); (**E**) Cape Town, South Africa (67); (**F**) Manila, Philippines (68)).

While Pb contamination remains a pervasive and globally relevant health risk, human populated areas are hotspots for a far more complex range of potentially toxic elements and chemical compounds (17). Inputs of these contaminants are constantly changing, and their measurement in wildlife sentinels such as sparrows will provide an early indication of the risks they pose to human health. This is not without limitations, as the sources and pathways of exposure to different contaminants will not always align between human and animal populations (5). The biological half-life of a contaminant is also important. Blood Pb, for example, has a half-life of around 40 days in humans (18), and so blood Pb levels are generally representative of chronic exposures occuring over a similar timeframe. Contaminants with a long biological half-life in blood, such as cadmium (Cd) (36) or perfluoroalkyl and polyfluoralkyl substances (PFAS) (37) may therefore be more suitable targets for a non-destructive approach to biomonitoring human health risks using animal blood samples.

Finally, we are not suggesting that the use of wildlife sentinels could or should supplant established environmental and epidemiological approaches to monitoring contaminant exposures in humans. In urban animals, clinical signs of exposure to toxic levels of contamination have often provided impetus for the more systematic monitoring and management of related human health risks (6, 7). This was the case in Broken Hill, where a high incidence of local dogs dying from Pb poisoning contributed to the establishment of the child blood Pb monitoring program in 1991 (38). Here, we have shown that even at sublethal and subtoxic levels, contaminant exposures measured in animals cohabiting human populated areas should be considered in light of their potential implications for human health. Furthermore, while direct soil and air monitoring can undoubtedly provide insight into the levels of contamination in the environment, the use of an effective sentinel animal provides greater awareness of the extent to which the contamination is biologically available to organisms, including humans, living in that environment (39).

Just as miners used canaries, we have demonstrated that house sparrows, a human commensal and sedentary species, are effective predictive sentinels for Pb exposure risks in children. We have shown how sparrows, and potentially similar species, could be used as a monitoring tool to prevent deleterious health outcomes associated with exposure to Pb during the early stages of development. Our study provides robust evidence for the main tenet of the One Health approach; that human, animal and environmental health are tightly intertwined (40). Our corroboration of this idea will help to reduce the growing perception that humans are disconnected from nature (40-42), and promote transformative actions aimed at sustainability across all species.

Materials and Methods

Biological sampling

Fieldwork was conducted between September and December 2020 in Broken Hill, Dubbo, and Cobar, and in March 2022 in Mount Isa, Cloncurry, Richmond and Townsville. Sampling was authorised by the Macquarie University Animal Ethics Committee (AEC #2020/011). House sparrows were caught with mist nets. Captured birds were identified for sex and age, and banded. Blood was sampled onsite through the brachial vein of each bird using 75 µL Livingstone Microhematocrit Capillary Tubes. A 50 µL blood sample was taken and stored in tubes containing a dilute solution of HCL specifically for the quantification of blood Pb concentrations using a Meridian Bioscience LeadCare Plus blood Pb analyser. At each site, an average of 5 individuals were sampled for this purpose for a total of 304 birds. Where permitted by blood flow, another 50 µL blood sample was taken and stored in 1.5 mL Eppendorf Tubes for the additional analysis of blood Pb concentrations (n = 62) and Pb isotopic compositions (n = 26) using inductively coupled plasma mass spectrometry (ICP-MS).

Environmental sampling

To link sparrow blood Pb levels to environmental Pb contamination, we sampled surface soil at each catch site. Soil samples were collected in triplicate (n = 3) from the upper 2 cm of the soil profile at locations approximately 1 m equidistant. Samples were collected as near to the catching location as possible. Clean fill and imported soil was avoided. In Mount Isa, Cloncurry, Richmond and Townsville, additional soil samples (n = 6) were collected at evenly distributed locations within about 100 m of the catch site. This was done to improve the characterisation of environmental Pb contamination around each site. In total, 240 soil samples were collected from 58 sites.

Deposited dust was collected using dust deposition gauges installed at 12 of the Broken Hill catch sites. Dust gauges consisted of a 30 by 30 cm acrylic sheet mounted 1 m off the ground in an open area. After an average of 10 days, a 15 by 15 cm dust wipe (Ghost Wipe) was used to sample deposited dust from the dust gauge surface using established methods (43).

Anodic stripping voltammetry (ASV)

Most sparrow blood samples (n = 304) were analysed using a point-of-care Meridian Bioscience LeadCare Plus blood Pb analyser with a detection range of 1.9–65.0 µg/dL. This instrument uses anodic stripping voltammetry (ASV) to measure the Pb concentration of a whole blood sample mixed with a dilute solution of HCl. In line with typical reporting practices for child blood Pb screening data in Broken Hill (26), sparrow blood Pb measurements outside the detection limits of this instrument are reported as equivalent to these limits. Since 2009, a similar point-of-care instrument, the Meridian Bioscience LeadCare II blood Pb analyser, has been used for most child blood Pb screening in Broken Hill (26). The LeadCare II instrument has a narrower detection range (3.3–65.0 µg/dL) than the LeadCare Plus instrument. Sparrow blood Pb data was validated with inductively coupled plasma mass spectrometry (ICP-MS) of paired blood samples taken from the same sparrow, as detailed below.

Portable X-ray fluorescence (pXRF)

Soil samples were analysed with an Olympus Vanta portable X-ray fluorescence spectrometer (pXRF) fitted with a 50 kV tungsten (W) anode tube. Soil samples were dried and sieved to < 250 µm. Approximately 10 g of soil was transferred to sample cups for pXRF analysis. Cupped samples were analysed using the proprietary soil mode for a total test time of 60 s with 20 s per measurement condition (Beams I–III, 15–50 kV). Values are reported in mg/kg. Concentrations below instrument limits of detection are substituted with a value equivalent to half of this limit (table S9). Standard pXRF operating procedures including the measurement of National Institute of Standards and Technology (NIST) Standard Reference Materials (SRM) 2709a (San Joaquin Soil; n = 20) and 2711a (Montana II soil; n = 20; table S9).

Inductively coupled plasma mass spectrometry (ICP-MS)

Dust wipes (n = 12) and a subset of sparrow blood samples were sent for analysis of Pb concentrations (n = 62) and Pb isotopic compositions (n = 26) using an Agilent 7900 Q-ICP-MS at the National Measurement Institute, New South Wales, Australia. Concentrations initially reported in mg/kg were converted to µg/dL assuming a avian blood density of 1.05 g/mL (44). Concentrations below limits of detection were substituted with a value equivalent to half of this limit (table S10). Reference material Seronorm Trace Elements Whole Blood was used for analytical validation (table S10).

For the analysis of Pb isotopic compositions, between 3–4 blood samples from sites in Broken Hill were combined to ensure sufficient sample volume for analysis. Sample digest solutions were analysed with samples bracketed by concentration matched NIST SRM 981 (common Pb isotopic standard). Raw counts were corrected for blanks and potential isobaric interference, and then corrected for mass discrimination and instrument drift using the mean of NIST SRM 981 measurements. Instrument performance was assessed relative to NIST 2709a (45-49) and previous analyses of Broken Hill Pb ore (31, 32, 50-52), and returned values within the range of published data (table S11).

Linear data adjustment

Of the 62 blood samples analysed with ICP-MS, 44 could be matched to corresponding ASV blood Pb measurements. One sample was excluded due to potential contamination during field sampling (i.e., returned an anomalously high Pb concentration with respect to both its paired sample and corresponding samples from the same location). Of the remaining samples, 38 returned Pb concentrations within the limits of detection for either analytical method and so could be directly compared. The Pb concentrations of paired house sparrow blood samples measured using ASV and ICP-MS were strongly correlated (Pearson $r = 0.90$, $p < 0.01$, $n = 38$). However, a Bland-Altman analysis indicated a strong negative bias for blood Pb measured using ASV compared to ICP-MS (mean of differences ± 95% confidence interval = −15.03 ± 27.23 µg/dL; fig. S1).

Previous studies of Pb exposure in avian species have reported comparative underestimations of blood Pb concentrations when comparing ASV measurements to those of more analytically robust laboratory methods (53-56). To account for the systematic underestimation of blood Pb measured using ASV, a linear regression model (y-intercept = 0) was fitted for corresponding ASV (independent variable) and ICP-MS (dependent variable) blood Pb measurements (table S12). Adjustment of the subset of ASV blood Pb concentrations using the calculated conversion factor ($y = 1.8115x$) improved the correspondence between ASV and ICP-MS measurements (mean of differences ± 95% confidence interval = −1.79 ± 21.31 µg/dL; fig. S1). The conversion factor ($y = 1.8115x$) based on paired blood samples was therefore applied to adjust the full dataset of ASV blood Pb concentrations ($n = 304$). The upper and lower limits of detection for the LeadCare Plus instrument used in this study (1.9–65.0 µg/dL) were adjusted accordingly (3.44–117.75 µg/dL). Only 1% ($n = 3/304$) of blood Pb measurements exceeded this upper limit, suggesting that this method captured the upper range of blood Pb levels amongst the studied populations. Unpaired blood samples analysed with ICP-MS ($n = 18$) were incorporated into the adjusted ASV dataset ($n = 304$), bringing the total number of sparrows for which a blood Pb measurement was available to 322.

Source attribution modelling

A vector based model was used to estimate the proportion of house sparrow blood and deposited dust Pb isotopic compositions attributable to Broken Hill Pb ore(57). Model endmembers were isolated from median Pb isotopic compositions previously published for samples of Broken Hill Pb ore (^{206}Pb/^{207}Pb = 1.040; ^{208}Pb/^{207}Pb = 2.317)(31, 32, 50-52) and background soil sampled from uncontaminated areas around Broken Hill (^{206}Pb/^{207}Pb = 1.087; ^{208}Pb/^{207}Pb = 2.373) (30). We applied the model to data from this study and previously published data on Pb isotopic compositions from deposited dust (n = 18; this study (n = 12) and reference (21) (n = 6)), surface soil (n = 42) (30, 31), house dust (n = 20) (32), sparrow blood (n = 26; this study), and child blood samples (n = 78; excluding one highly anomalous sample (^{206}Pb/^{207}Pb = 1.102; ^{208}Pb/^{207}Pb = 2.378)) (30).

Child blood lead data

The availability of geolocated child blood Pb screening data from Broken Hill enabled comparison of blood Pb levels in sparrows and nearby children. Access to child blood Pb data was approved following ethics assessment by NSW Greater Western Human Research Ethics Committee (#2020/ETH01783) and in concurrence with Macquarie University's Human Research Ethics Committee. The NSW Greater Western Human Research Ethics Committee granted a waiver of the usual requirement for the consent of the individual to the use of their health information in a research project. Data from children aged 1–4 years that were tested in the years 2011–2020 were included, as the blood Pb of Broken Hill children has remained relatively stable over this period (table S5). Data from children under 1 year of age were excluded as there was no systematic testing of children in this age group between 2013–2016. If a child was tested more than once throughout the year, only the first test result for that year was included. Using the same criteria, we also compared sparrow and child blood Pb in each individual year for which child blood Pb screening data was available (1991–2020). We did this to explore how changes in Pb exposure risks in Broken Hill have influenced the relationship between historical child blood Pb levels and those of contemporary sparrows.

Geolocated child blood Pb measurements from Broken Hill were spatially joined to sparrow catch sites using a 300 m fixed radius around each site. The 300 m radius was based on the largest reported home range of a house sparrow measured using radio telemetric tracking (27). Between 2011–2020, a total of 4190 unique child blood Pb measurements that met the aforementioned inclusion criteria were spatially joined to one or more sites. The number of unique measurements joined to one ore more sites for individual years between 1991–2020 are reported in table S5.

To determine the generalisability of the blood Pb relationship established between sparrows and children in Broken Hill, we used the linear regression model from this location to predict child blood Pb levels in Mount Isa. To improve the granularity of this prediction, we applied the model to individual sparrow blood Pb measurements from Mount Isa, and predicted the corresponding distribution of blood Pb in nearby children. In validating our predictions, we used the most recently available child blood Pb data from Mount Isa, which was collected between 2016–2018 and included 1014 measurements from children between the ages of 0–4 years (25). Geolocated address information was not available for Mount Isa data, and measured blood Pb data were reported categorically as concentration ranges (< 5 µg/dL, ≥ 5 µg/dL, ≥ 10 µg/dL). Consequently, the number of children predicted to have a blood Pb level within one of these concentration ranges was calculated based on the population of children (aged 0–4 years) living within the urban area represented by each site. Population data (2016) was obtained from Australian Bureau of Statistics Statistical Area Level 1 geographic boundaries (58) and extrapolated to the urban area represented by each site using Thiessen polygons.

Statistical and spatial analyses

Statistical and spatial analyses were conducted using ArcGIS Pro 3.0.1 and Python 3.9.1. Concentrations of Pb measured in biological and environmental matrices were non-normally distributed and were therefore summarised for each site using the geometric mean. Geometric mean Pb concentrations in sparrow blood, child blood, and soil from each site, along with coefficients of variation and sample counts are reported in data S1. Pearson or Spearman correlation coefficients were used to determine associations between biochemical, geochemical and geographical variables depending on their linearity and the presence of outliers. The Mann-Whitney U test was used to identify differences in soil and blood Pb concentrations depending on location, and the age and sex of sparrows. The distance of each site from mining areas was calculated from the nearest outer boundary of mining operations as defined by Australian Statistical Geography Standard Mesh Blocks (58).

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Investigation: MMG, RT, TH, SCG

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Writing – original draft: MMG

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Competing Interests: Mark Patrick Taylor has undertaken work for and received funding from the Broken Hill Environmental Lead Program of the NSW Environment Protection Authority (EPA). He has received funding for lead and other trace metal related work from the Australian Federal Government. He has also prepared commissioned reports and provided expert advice on environmental contamination and human health for a range of bodies, including the Australian Building Codes Board (lead in plumbing fittings and materials), lawyers, governments, union agencies, and private companies. He has also served as an expert in plaintiff cases of childhood lead poisoning relating to Mount Isa, Queensland and Kabwe, Zambia. No other authors declare a competing interest.

Data and materials availability: Data supporting the findings of this study are available within the paper and its Supplementary Materials (specifically, data S1–S7). Child blood Pb data from Broken Hill are not openly available due to reasons of personal privacy, though are summarised in tables S1 and S5. Data from Mount Isa is freely available from the Queensland Department of Health Disclosure Log 2017–2018 (DOH-DL 17/18-048, p. 133).

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Supplementary Materials for

House sparrows as sentinels of childhood lead exposure

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The PDF file includes:

Fig. S1

Tables S1 to S12

References (53 to 68)

Other Supplementary Materials for this manuscript include the following:

Data S1 to S7

Fig. S1.

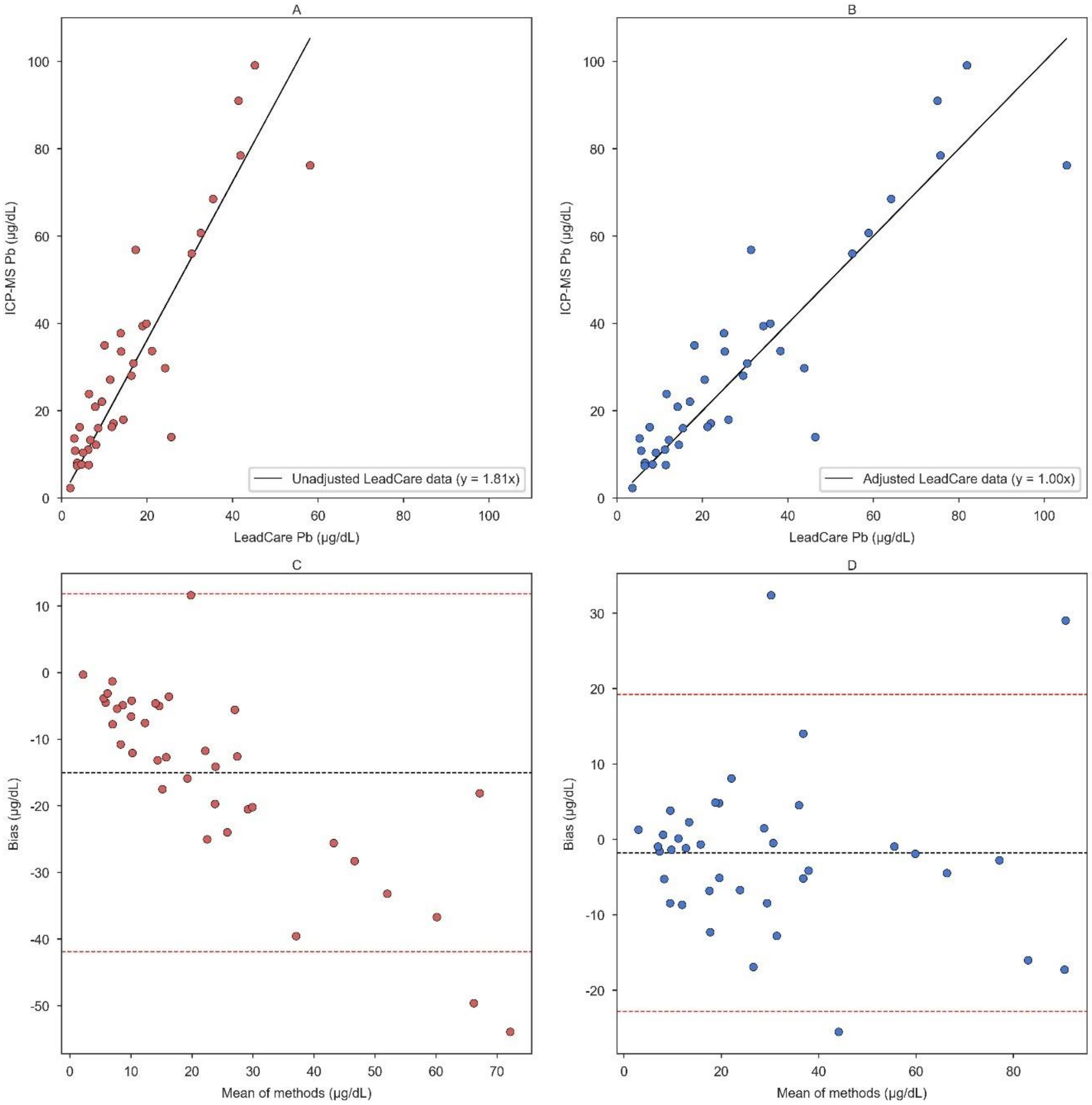

Fig. S1. (**A**) Linear regression model (intercept = 0) for paired LeadCare and ICP-MS measurements of sparrow blood Pb (n = 30) used to adjust LeadCare data. (**B**) Linear regression model (intercept = 0) for paired LeadCare and ICP-MS measurements of sparrow blood Pb following linear adjustment of LeadCare data. (**C**) and (**D**) Bland-Altman plot describing analytical agreement between ICP-MS and LeadCare measurements of blood Pb concentrations before (**C**) and after (**D**) adjustment of LeadCare data.

Table S1.

	Sparrow blood Pb (µg/dL)			Child blood Pb (µg/dL)
	Broken Hill	**Mount Isa**	**Other locations**	**Broken Hill**
Min	3	3	2	1.00
25th percentile	12	6	2	3.00
Median	21	18	5	5.00
75th percentile	37	35	7	8.20
Max	118	118	109	65.00
Mean	27	26	9	6.67
SD	23	24	20	5.45
Upper 95% CI	30	32	16	6.84
Lower 95% CI	24	20	2	6.50
Geometric mean	20	16	5	5.28
Count	226	67	29	4190

	Surface soil Pb (mg/kg)			Dust Pb (µg/m^2/day)
	Broken Hill	**Mount Isa**	**Other locations**	**Broken Hill**
Min	57	54	8	5
25th percentile	187	181	24	60
Median	339	354	39	81
75th percentile	603	598	72	133
Max	3214	3341	371	175
Mean	510	500	61	91
SD	556	561	66	57
Upper 95% CI	604	630	84	123
Lower 95% CI	416	370	38	59
Geometric mean	345	329	43	65
Count	135	72	33	12

Table S1. Summary statistics for Pb concentrations in sparrow blood, child blood (2011–2020), surface soil, and deposited dust across Broken Hill and Mount Isa. Other locations (Cobar, Dubbo, Cloncurry, Richmond, Townsville) are combined.

Table S2.

Slope (± SE)	0.06 (± 0.01)	**Intercept (± SE)**	3.98 (± 0.25)
Coefficient (r^2)	0.54	**Y-estimate SE**	0.88
F statistic	49.33	**DF**	42.00
Regression sum of squares (SST)	38.54	**Residual sum of squares (RSS)**	32.81

Table S2. Statistics for ordinary least squares regression calculated between geometric mean sparrow blood Pb (independent variable) and child blood Pb (dependent variable) at each catch site.

Table S3.

Variable	Group 1	Group 2	Group 1 (n)	Group 2 (n)	U Statistic	P-value
Blood Pb	Broken Hill	Mount Isa	226	67	8384	0.1822
Blood Pb	Broken Hill	Other locations	226	29	5833	< 0.0001
Blood Pb	Mount Isa	Other locations	67	29	1573	< 0.0001
Soil Pb	Broken Hill	Mount Isa	135	72	4898	0.9272
Soil Pb	Broken Hill	Other locations	135	33	4287	< 0.0001
Soil Pb	Mount Isa	Other locations	72	33	2255	< 0.0001

Table S3. Results of Mann-Whitney U test comparing median soil and blood Pb across the studied locations.

Table S4.

Site	Sparrow blood Pb (n)	Sparrow blood Pb (µg/dL)[a]	Predicted child blood Pb (µg/dL)	Predicted population < 5 µg/dL	Predicted population 5–9 µg/dL	Predicted population ≥ 10 µg/dL	Total population[b]
1	13	4.59	4.26	502	0	0	502
2	10	24.35	5.44	21	84	0	105
3	6	4.62	4.26	550	0	0	550
4	4	22.11	5.31	0	68	0	68
5	5	26.28	5.56	0	208	0	208
6	17	53.35	7.18	0	36	2	38
7	6	8.39	4.48	229	0	0	229
8	6	13.43	4.79	118	59	0	177

[a] *Geometric mean*

[b] *Estimated number of children living closest to each site.*

	Total < 5 µg/dL	Total 5–9 µg/dL	Total ≥ 10 µg/dL	Total
Predicted	1420	455	2	1877
Measured	771	204	39	1014

	% < 5 µg/dL	% 5–9 µg/dL	% ≥ 10 µg/dL
Predicted	75.7	24.2	0.1
Measured	76.0	20.1	3.9

Table S4. Summary data for output of linear regression model (child blood Pb = 0.06 × sparrow blood Pb + 3.98) used to predict child blood Pb levels in Mount Isa using blood Pb measurements from individual Mount Isa sparrows (n = 67). Predictions are extrapolated to the total population of Mount Isa children and are reported as percentages within the blood Pb concentration ranges of < 5 µg/dL, 5–9 µg/dL or ≥ 10 µg/dL. Results are benchmarked against reported exceedances of these same concentrations amongst Mount Isa children measured between 2016–2017(*25*).

Table S5.

Year	Pearson r	P-value	Sites (n)	Tests (n) (female/male)	Child blood Pb (µg/dL)	GCV (%)	Mined Pb (tonnes)
1991	0.7862	< 0.0001	43	466 (205/261)	16.57	64.68	163303
1992	0.6210	< 0.0001	43	449 (215/234)	14.47	65.97	163249
1993	0.5519	0.0002	43	327 (147/180)	14.09	74.55	159502
1994	0.6047	< 0.0001	43	567 (252/315)	12.51	57.84	141747
1995	0.7245	< 0.0001	43	454 (199/255)	11.13	72.59	131726
1996	0.6525	< 0.0001	43	338 (152/186)	11.22	71.53	135447
1997	0.5691	0.0001	43	410 (177/233)	9.91	69.97	128396
1998	0.6069	< 0.0001	42	447 (198/249)	8.89	71.43	103524
1999	0.6220	< 0.0001	43	408 (185/223)	8.38	77.18	103323
2000	0.4703	0.0017	43	375 (196/179)	8.31	73.48	93642
2001	0.5306	0.0003	44	341 (167/174)	7.64	82.47	75424
2002	0.5886	< 0.0001	44	333 (148/185)	7.28	96.96	44620
2003	0.5975	< 0.0001	43	298 (137/161)	7.43	92.26	61800
2004	0.3750	0.0100	42	303 (128/175)	6.64	101.09	53700
2005	0.3309	0.0323	43	325 (146/179)	5.87	107.72	71200
2006	0.4945	0.0009	42	254 (107/147)	6.27	110.33	75900
2007	0.5575	0.0001	43	265 (112/153)	6.07	109.52	48800
2008	0.4321	0.0050	41	209 (112/97)	5.11	113.90	47000
2009	0.2020	0.2050	42	224 (111/113)	5.83	75.13	56900
2010	0.4352	0.0040	43	239 (127/112)	4.58	70.23	51200
2011	0.6320	< 0.0001	43	331 (161/170)	4.81	75.02	51600
2012	0.7055	< 0.0001	43	401 (192/209)	5.58	91.30	64187
2013	0.6355	< 0.0001	44	435 (219/216)	5.62	88.88	57730
2014	0.4520	0.0026	43	444 (213/231)	5.20	83.12	68248
2015	0.5919	< 0.0001	44	418 (212/206)	5.95	83.62	73022
2016	0.5648	0.0001	44	450 (223/227)	5.79	83.80	73557
2017	0.5403	0.0002	44	465 (218/247)	5.36	100.95	76612
2018	0.4251	0.0045	44	387 (186/201)	4.70	98.17	77799
2019	0.5258	0.0003	42	433 (214/219)	5.06	105.21	72381
2020	0.4182	0.0053	43	426 (213/213)	4.72	101.45	68923

Table S5. Pearson correlation coefficients for the relationship between sparrow blood Pb and child blood Pb for each individual year of child blood Pb screening in Broken Hill included in this study (1991–2020). For each year, the total number of unique child blood Pb tests joined to one or more sites, the geometric mean child blood Pb, the geometric coefficient of variation (GCV) of child blood Pb, and the total annual production of Pb in Broken Hill are provided. Data from 1991–2012 is based on published estimates, with data from 2013 – 2020 unpublished estimates from the same author*(29).*

Table S6.

	Sparrow blood Pb (this study)			**Child blood Pb** (*30*)		
	^{206}Pb/^{207}Pb	**^{208}Pb/^{207}Pb**	**Ore Pb %**	**^{206}Pb/^{207}Pb**	**^{206}Pb/^{207}Pb**	**^{208}Pb/^{207}Pb**
Min	1.0417	2.3177	32	1.0443	2.3203	21
Median	1.0571	2.3328	69	1.0598	2.3341	65
Max	1.0730	2.3541	98	1.1019	2.3781	93
Mean	1.0567	2.3334	69	1.0613	2.3360	62
SD	0.0089	0.0095	17	0.0093	0.0089	15
Count	26	26	26	78	78	78
	Deposited dust Pb (this study)			**Deposited dust Pb (published data)** (*21*)		
	^{206}Pb/^{207}Pb	**^{208}Pb/^{207}Pb**	**Ore Pb %**	**^{206}Pb/^{207}Pb**	**^{208}Pb/^{207}Pb**	**Ore Pb %**
Min	1.0406	2.3153	74	1.0410	2.3190	85
Median	1.0444	2.3220	91	1.0465	2.3230	88
Max	1.0526	2.3323	102	1.0480	2.3260	97
Mean	1.0456	2.3234	89	1.0457	2.3230	89
SD	0.0036	0.0054	8	0.0025	0.0028	4
Count	12	12	12	6	6	6
	Surface soil (*30, 31*)			**House dust** (*32*)		
	^{206}Pb/^{207}Pb	**^{208}Pb/^{207}Pb**	**Ore Pb %**	**^{206}Pb/^{207}Pb**	**^{208}Pb/^{207}Pb**	**Ore Pb %**
Min	1.0380	2.3140	31	1.0373	2.3112	44
Median	1.0458	2.3223	90	1.0477	2.3274	81
Max	1.0787	2.3520	105	1.1111	2.3944	109
Mean	1.0484	2.3254	84	1.0526	2.3303	80
SD	0.0088	0.0088	17	0.0153	0.0169	16
Count	42	42	42	20	20	20
	Broken Hill ore Pb (*31, 32, 58-60*)			**Background soil Pb** (*30*)		
	^{206}Pb/^{207}Pb	**^{208}Pb/^{207}Pb**		**^{206}Pb/^{207}Pb**	**^{208}Pb/^{207}Pb**	
Min	1.0390	2.3102		1.0422	2.3190	
Median	1.0403	2.3170		1.0873	2.3730	
Max	1.0428	2.3253		1.1957	2.6317	
Mean	1.0405	2.3178		1.1024	2.4192	
SD	0.0014	0.0057		0.0597	0.1116	
Count	5	5		11	11	
	Broken Hill Pb paint (*30*)			**Broken Hill Pb petrol** (*30*)		
	^{206}Pb/^{207}Pb	**^{208}Pb/^{207}Pb**	**Ore Pb %**	**^{206}Pb/^{207}Pb**	**^{208}Pb/^{207}Pb**	**Ore Pb %**
Min	1.0396	2.3173	5	1.0613	2.3372	35
Median	1.0572	2.3346	92	1.0685	2.3403	52
Max	1.1496	2.4303	116	1.0770	2.3497	61
Mean	1.0714	2.3494	68	1.0701	2.3423	48
SD	0.0343	0.0359	36	0.0051	0.0044	8
Count	21	21	21	10	10	10

Table S6. Summary statistics for Pb isotopic compositions (^{206}Pb/^{207}Pb; ^{208}Pb/^{207}Pb) and estimated contribution of Broken Hill ore Pb in different environmental and biological matrices included in this study. Includes previously published data and data first reported in this study.

Table S7.

Variable A	**Variable B**	**Spearman r_s**	**P-value**	**Sites (n)**
Distance	**Soil Pb**	-0.6669	< 0.0001	53
Distance	**Dust Pb**	-0.8811	0.0002	12
Distance	**Deposited dust Pb (ore Pb %)**	-0.7400	0.0059	12
Distance	**Sparrow blood Pb**	-0.6491	< 0.0001	53
Distance	**Sparrow blood Pb (ore Pb %)**	-0.6166	< 0.0001	29
Distance	**Child blood Pb**	-0.7435	< 0.0001	44

Table S7. Spearman correlation coefficients for relationship between distance from mining areas and Pb concentrations measured in various environmental and biological matrices included in this study.

Table S8.

Variable	Group 1	Group 2	Group 1 (n)	Group 2 (n)	U Statistic	P-value
Blood Pb	Adult	Juvenile	227	81	8776	0.5440
Blood Pb	Female	Male	122	145	9896	0.0948

Table S8. Results of Mann-Whitney U test comparing median blood Pb between adult and juvenile, and male and female sparrows.

Table S9.

	Pb
Limit of detection (mg/kg)	5
Silicate blank (mg/kg)	< 5
NIST 2711a	
Certified value (mg/kg)	1400
Mean recovery (%)	95
Mean RSD (%)	1
NIST 2709a	
Certified value (mg/kg)	17
Mean recovery (%)	93
Mean RSD (%)	7
Soil duplicates	
Duplicate A mean recovery (%)	100
Duplicate B mean recovery (%)	100
Duplicate mean RSD (%)	2

Table S9. Quality assurance and quality control data for Vanta VMW pXRF analyses of Pb concentrations from sieved (< 250 µm) and cupped surface soil samples. Mean recoveries and mean RSDs are reported for silicate blank (n = 15), NIST 2711a (n = 15) and NIST 2709a (n = 15) analyses. Mean recoveries and mean RSD are also reported for duplicate A (n = 25; sample kept stationary with respect to pXRF analysis window between measurements) and B (n = 25; sample moved with respect to pXRF analysis window between measurements) analyses.

Table S10.

	Sparrow blood Pb	Dust wipe Pb
Limit of reporting (mg/kg)	0.05	0.05
Blank (mg/kg)	< 0.05	< 0.05
Control recovery (%)	104 (± 7)[a]	97
Matrix spike recovery (%)	97 (± 3)[a]	101
Duplicates (n)	4	1

[a] *Mean (± SD)*

Table S10. Quality assurance and control data for ICP-MS analyses of Pb concentrations in sparrow blood and dust wipes. Reference material Seronorm™ Trace Elements Whole Blood was used for analytical validation of Pb concentrations in sparrow blood. Recovery data for deposited dust wipe Pb and house sparrow blood Pb are reported separately.

Table S11.

	NIST 2709a (n = 3)			**Broken Hill ore (n = 3)**		
	$^{204}Pb/^{206}Pb$	**$^{207}Pb/^{206}Pb$**	**$^{208}Pb/^{206}Pb$**	**$^{204}Pb/^{206}Pb$**	**$^{207}Pb/^{206}Pb$**	**$^{208}Pb/^{206}Pb$**
Published mean	0.0524	0.8210	2.0400	0.0625	0.9620	2.2260
Measured mean	0.0523	0.8205	2.0415	0.0626	0.9605	2.2345
Measured SD	0.0004	0.0015	0.0029	0.0002	0.0026	0.0079
Mean RSD (%)	0.20	0.04	0.05	0.11	0.11	0.27
Mean recovery (%)	99.71	99.94	100.07	100.16	99.84	100.38

Table S11. Method validation data for ICP-MS analysis of Pb isotopic compositions. Instrument performance was assessed relative to previously published Pb isotopic compositions for NIST 2709a (*53-57*) and Broken Hill ore Pb (*31, 32, 58-60*).

Table S12.

Slope (± SE)	1.8115 (± 0.08)	**Intercept (± SE)**	0 (± 0)[a]
Coefficient (r^2)	0.93	**Y-estimate (SE)**	11.02
F statistic	481	**DF**	37
Regression sum of squares (SST)	55980	**Residual sum of squares (RSS)**	4494

[a] *Intercept set to 0*

Table S12. Summary statistics for ordinary least squares regression equation calculated for the relationship between the Pb concentration of paired blood samples analysed with LeadCare (independent variable) and ICP-MS (dependent variable).

Data S1. Geometric means (GM), geometric coefficients of variation (GCV) and sample counts for Pb measurements in sparrows, surface soil, and child blood (2011 – 2020) from catch sites across the study locations.

Data S2. Individual sparrow blood Pb concentrations across all sites included in this study (n = 322). Where recorded, the sex (Male/Female/Unknown) and age (Adult/Juvenile/Unknown) of each sparrow are provided. Sites are from Broken Hill (BH), Cobar (CB), Dubbo (DB), Mount Isa (MI), Cloncurry (CC), Richmond (RM) and Townsville (TV). This dataset includes blood Pb measurements analysed using ASV (n = 304) and subsequently adjusted using data from paired blood samples analysed with ICP-MS (n = 38). Unpaired ICP-MS measurements are also included (n = 18).

Data S3. Individual surface soil Pb concentrations across all sites included in this study (n = 240). Sites are from Broken Hill (BH), Cobar (CB), Dubbo (DB), Mount Isa (MI), Cloncurry (CC), Richmond (RM) and Townsville (TV). All soil samples are sieved to < 250 µm, cupped and analysed using pXRF.

Data S4. Dust wipe Pb concentrations (µg/sample) and deposited dust Pb loading rates (µg/m^2/day) sampled from dust deposition gauges in Broken Hill. Associated Pb isotopic compositions (^{206}Pb/^{207}Pb, ^{208}Pb/^{207}Pb) and estimated contribution of Broken Hill ore Pb(*65*) are provided for each sample. The period of days indicates the number of days the dust gauge was left to collect deposited dust before being sampled with a dust wipe.

Data S5. Broken Hill Sparrow blood Pb isotopic compositions (^{206}Pb/^{207}Pb, ^{208}Pb/^{207}Pb) and estimated contribution of Broken Hill ore Pb (*65*). Combined blood sample count indicates number of samples combined to ensure sufficient sample volume for ICP-MS analysis of Pb isotopic compositions.

Data S6. ICP-MS and LeadCare blood Pb measurements from paired sparrow blood samples before and after LeadCare data adjustment.

Data S7. Summary geographic information for each catch site. Distance (m) from mining areas is calculated from the nearest outer boundary of mining operations as defined by Australian Statistical Geography Standard Mesh Blocks (*66*).