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, 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). 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.

Keywords: One Health, biomonitoring, mining, human health, contamination, urban ecosystems, soil, blood

Synopsis: We show how house sparrows can be used to identify and predict levels of lead exposure in nearby children. This has implications for our understanding of shared animal and human health risks in contaminated environments.

Introduction: 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].

Bioindicator or sentinel species can be used to monitor the impacts of environmental pollutants at a population, community, or even ecosystem scale[4, 8]. 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, 9]. The free-ranging wild house sparrow (*Passer domesticus*) is one such species due to its global distribution, close association with humans, and sedentary nature[10, 11]. As a ground forager, sparrows are also directly exposed to surface soil and dust, where many common anthropogenic pollutants accumulate[10]. Studies in Europe[12], North America[13], and Africa[14], 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[15].

These studies have demonstrated the capacity of sparrows to indicate pollution at broad geographic scales, often across urban and rural land uses[12-15]. 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[16]. Globally, exposure to environmental Pb has resulted in adverse health outcomes across a broad range of organisms[17], 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[18]. 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[17]. Children are also most susceptible to the neurological and developmental effects of Pb exposure[17]. 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[19].

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[20, 21]. Mining emissions are the primary source of elevated blood Pb levels in Broken Hill children and there is little evidence to suggest that exposure to contamination from Pb paint or Pb petrol emissions is significant at the population scale[22, 23]. 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[24], this study aimed to provide an integrated assessment of health risks arising from anthropogenic pollution within an urban ecosystem.

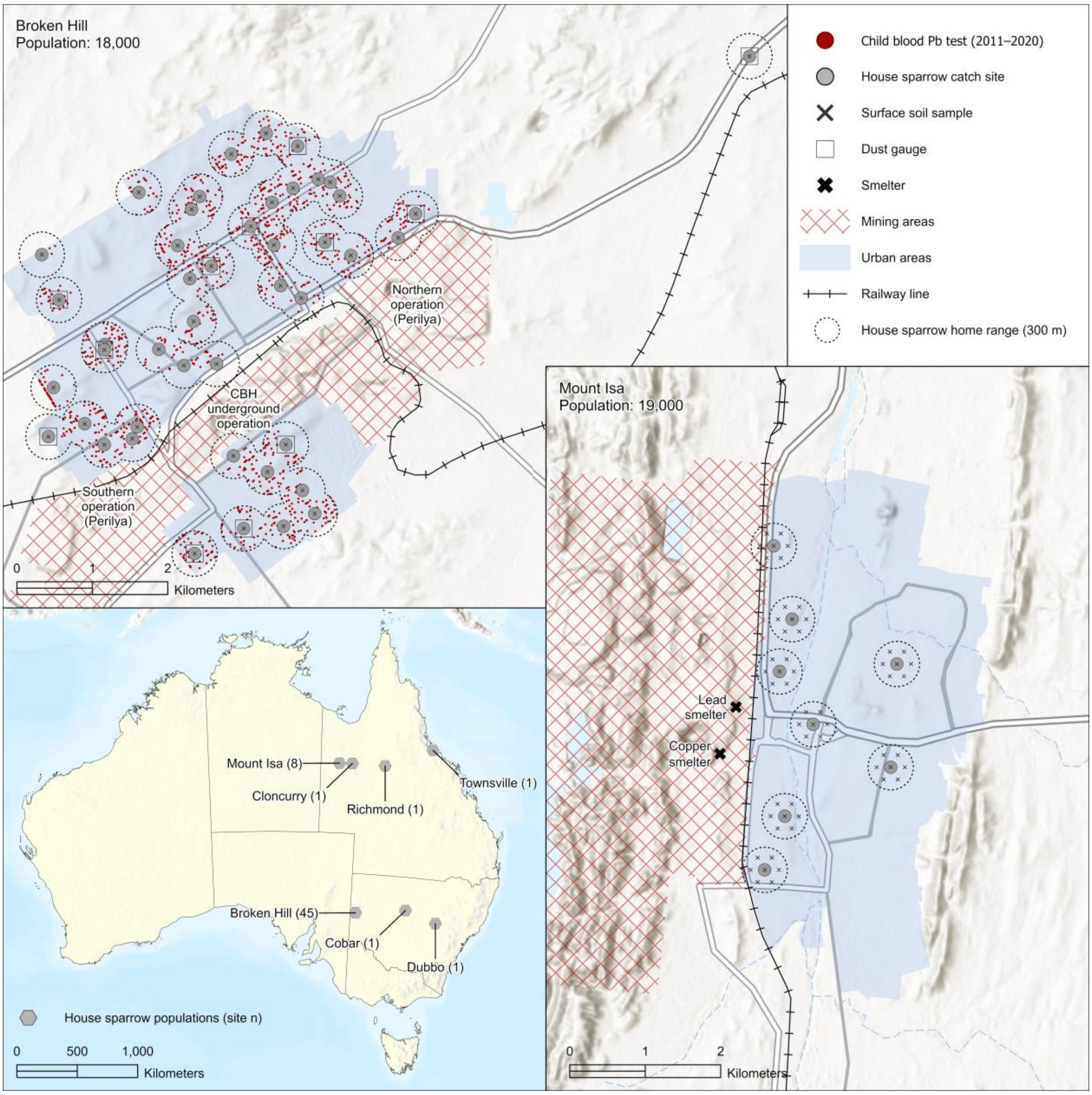

Fig. 1. Map of sparrow sampling sites. Location of sparrow catch sites and associated environmental samples in Broken Hill and Mount Isa. Also shown are locations of relevant infrastructure, urban areas, and sources of Pb contamination, including mining and smelting areas. Dotted lines around each site 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.

Methods:

Biological sampling

Fieldwork was conducted between September and December 2020 in the cities and towns of Broken Hill, Dubbo, and Cobar, located in the state of New South Wales, and in March 2022 in the cities and towns of Mount Isa, Cloncurry, Richmond and Townsville, located in the state of Queensland. 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 = 52) 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[25].

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. Standard operating procedures for the LeadCare Plus Instrument were followed, including calibration of each new test kit sensor lot and repeat analysis of high and low blood Pb controls, which returned Pb concentrations within the acceptable range. 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 and this may lead to an overestimation of child blood Pb levels in some contexts. However, a comparison of results obtained from the LeadCare II instrument with previous data from analyses using inductively coupled plasma mass spectrometry did not indicate a consistent change in blood Pb across the population of screened children[27]. Sparrow blood Pb data obtained from the LeadCare Plus instrument 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 S1). 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 S1).

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 = 52) 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[28]. Concentrations below limits of detection were substituted with a value equivalent to half of this limit (table S2). Reference material Seronorm Trace Elements Whole Blood was used for analytical validation (table S2).

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[29-33] and previous analyses of Broken Hill Pb ore[34-38], and returned values within the range of published data (table S3).

Linear data adjustment

Of the 52 blood samples analysed with ICP-MS, 34 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, 30 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 $r = 0.93$, $p < 0.01$, $n = 30$). However, a Bland-Altman analysis indicated a strong negative bias for blood Pb measured using ASV compared to ICP-MS (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[39-43]. Using established methods[42], we accounted for this underestimation by fitting an ordinary least squares regression to corresponding ASV (independent variable) and ICP-MS (dependent variable) natural-log blood Pb measurements (table S4). Adjustment of the subset of natural-log ASV blood Pb concentrations using the modelled slope and intercept ($\ln(y) = 0.81 \times \ln(x) + 1.30$) improved the correspondence between ASV and ICP-MS measurements following conversion back to a linear scale (fig. S1). This process was repeated 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 (6.2–107.8 µg/dL). Only 6% ($n = 17/304$) of blood Pb measurements fell below the lower limit of detection, with 1% ($n = 3/304$) exceeding the upper limit, suggesting that this method captured the 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[44]. Model endmembers were isolated from median Pb isotopic compositions previously published for samples of Broken Hill Pb ore ($^{206}Pb/^{207}Pb = 1.040$; $^{208}Pb/^{207}Pb = 2.317$)[34-38] and background soil sampled from uncontaminated areas around Broken Hill ($^{206}Pb/^{207}Pb = 1.087$; $^{208}Pb/^{207}Pb = 2.373$)[23]. 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[20] (n = 6)), surface soil (n = 42)[23, 38], house dust (n = 20)[36], sparrow blood (n = 26; this study), and child blood samples (n = 78; excluding one highly anomalous sample ($^{206}Pb/^{207}Pb = 1.102$; $^{208}Pb/^{207}Pb = 2.378$))[23].

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. Address information was geocoded using the Geocoded National Address File for Australia. 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. In addition to controlling potential bias from children who were tested multiple times throughout the year, this also minimised the inclusion of tests from children who had recently moved address, though it does not account for children who moved shortly before their first test of each year. 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. In line with standards for the reporting of epidemiological evidence under the One Health approach[24], additional detail on the selection, sampling, analysis and reporting of human, animal and environmental data is available in references[26, 45].

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 [46]. 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 or 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 ordinary least squares 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[45]. 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). 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[47] and extrapolated to the urban area represented by each site using Thiessen polygons. More sophisticated geospatial modelling methods were not used for this purpose as the intention was to evaluate the transferability of our findings from Broken Hill to a similar environmental context without the support of underlying environmental and human health data.

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.

Ordinary least squares regression was used to model the observed linear relationship between sparrow and child blood Pb. A power regression was used to model the apparent non-linear relationship between soil Pb and sparrow blood Pb with model coefficients optimised using the *scipy.optimize.curve_fit* function in Python 3.9.1. The use of a nonlinear model in this context was supported by findings from Pb dosing studies which indicate a sublinear relationship between blood Pb and dietary Pb[48], though some avian studies also report a linear blood Pb response to Pb dose[49]. Consequently, the relationship modelled here should be interpreted within the limitations of our soil sampling method, particularly with regard to the difficulty of accurately characterising levels of soil Pb contamination associated with the upper range of exposure in wild animals.

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. To determine the minimum number of sites needed to establish a statistically significant relationship between child and sparrow blood Pb concentrations, we conducted a power analysis using Cohen's d as a measure of effect size, which we derived from the observed Pearson correlation coefficients. This analysis was performed to achieve a statistical power of 0.80 and an alpha level of 0.05. 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.

Results and discussion: 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[50]. At Broken Hill, the availability of 30 years (1991–2020) of anonomysed 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)[45]. Nonetheless, data from Mount Isa enabled us to compare our findings from Broken Hill to a context similarly impacted by mining and smelting emissions.

Using literature estimates for the maximum home range of a house sparrow[46] (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 $r = 0.74$, $p < 0.01$, $n = 44$; fig. 2A). This was despite a large difference in the geometric mean blood Pb level of sparrows (25.3 µg/dL, $n = 226$) and nearby children (5.3 µg/dL, $n = 4190$; table S6). In the environmental context of Broken Hill, a sparrow blood Pb of around 20 µg/dL corresponds to a child blood Pb of 5 µg/dL (child blood Pb = 0.07 × sparrow blood Pb + 3.63; fig. 2A; table S7). 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 that is relevant to the assessment and management of Pb exposure risks in urban environments (0.28 km^2), 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 four sites, or approximately 20 sparrows, are needed to establish a statistically significant relationship between the blood Pb of sparrows and children (see Methods).

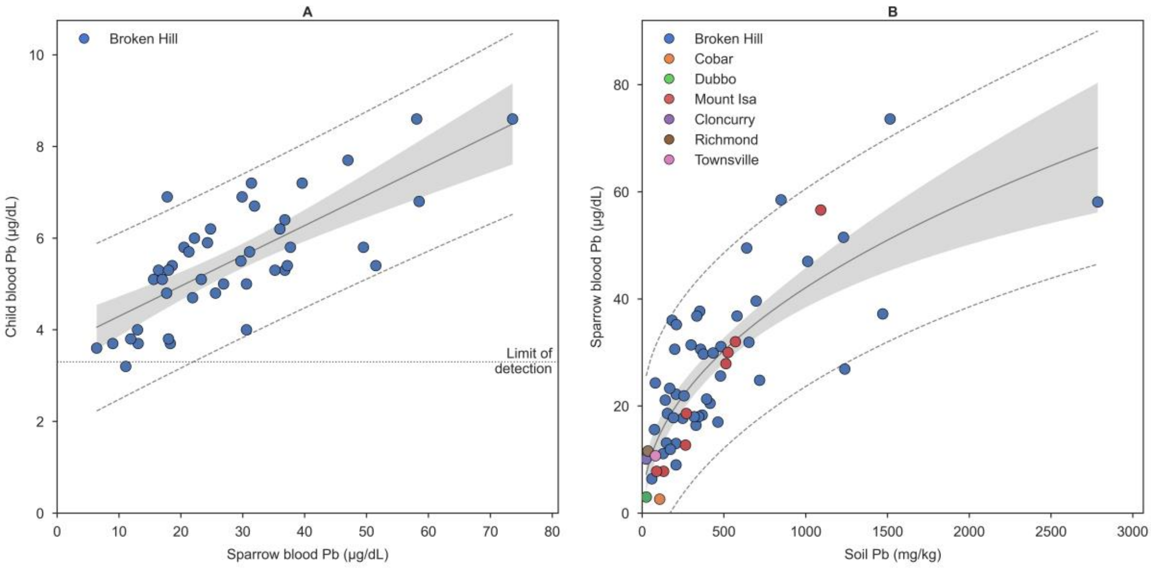

Fig. 2. Co-located blood and soil Pb relationships. (**A**) Relationship between Broken Hill sparrow and child blood Pb concentrations ($n = 44$; child blood Pb = 0.07 × sparrow blood Pb + 3.63; linear regression ± 95% confidence interval ± 95% prediction interval). Points represent geometric mean blood Pb concentration 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 $= 1.62 \times \text{soil Pb}^{0.47}$; power regression ± 95% confidence interval ± 95% prediction interval). Points represent geometric mean soil Pb and sparrow blood Pb concentrations 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[17], 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[50, 51]. 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 $r_s = 0.68$, $p = 0.02$, $n = 12$) and children (Spearman $r_s = 0.65$, $p < 0.03$, $n = 11$). 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 S8), suggesting that child blood Pb might also be comparable between these locations. Accordingly, we applied the linear blood Pb relationship (child blood Pb = 0.07 × sparrow blood Pb + 3.63) 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 ($n = 1014$)[45]. Based on the population of children represented by each of our sites (fig. 3C), we estimated that 24.3% (0.1% $\geq$ 10 µg/dL) of children in Mount Isa would have a blood Pb $\geq$ 5 µg/dL, the human intervention level (fig. 3D; table S9). This sentinel-driven prediction corresponded closely to the 24.0% (3.9% $\geq$ 10 µg/dL) of Mount Isa children measured with a blood Pb $\geq$ 5 µg/dL between 2016–2018[45], and emphasises the broad applicability of this approach for monitoring environmental Pb exposure risks in children.

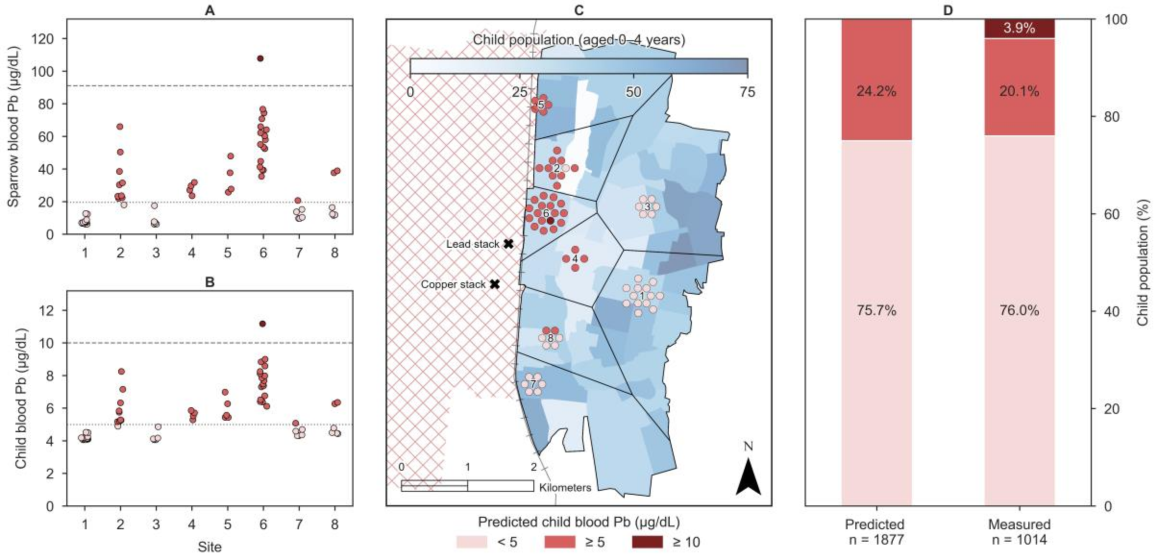

Fig. 3. Predicted distribution of Mount Isa child blood Pb. (**A**) Measured distribution of individual sparrow blood Pb levels at each site in Mount Isa (n = 67). Horizontal lines indicate sparrow blood Pb thresholds at which a nearby child is predicted to have a blood Pb level of ≥ 5 µg/dL (dotted 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[45].

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 = 0.77, $p < 0.01$, 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[50, 51], and the corresponding shifts in human responses to these risks.

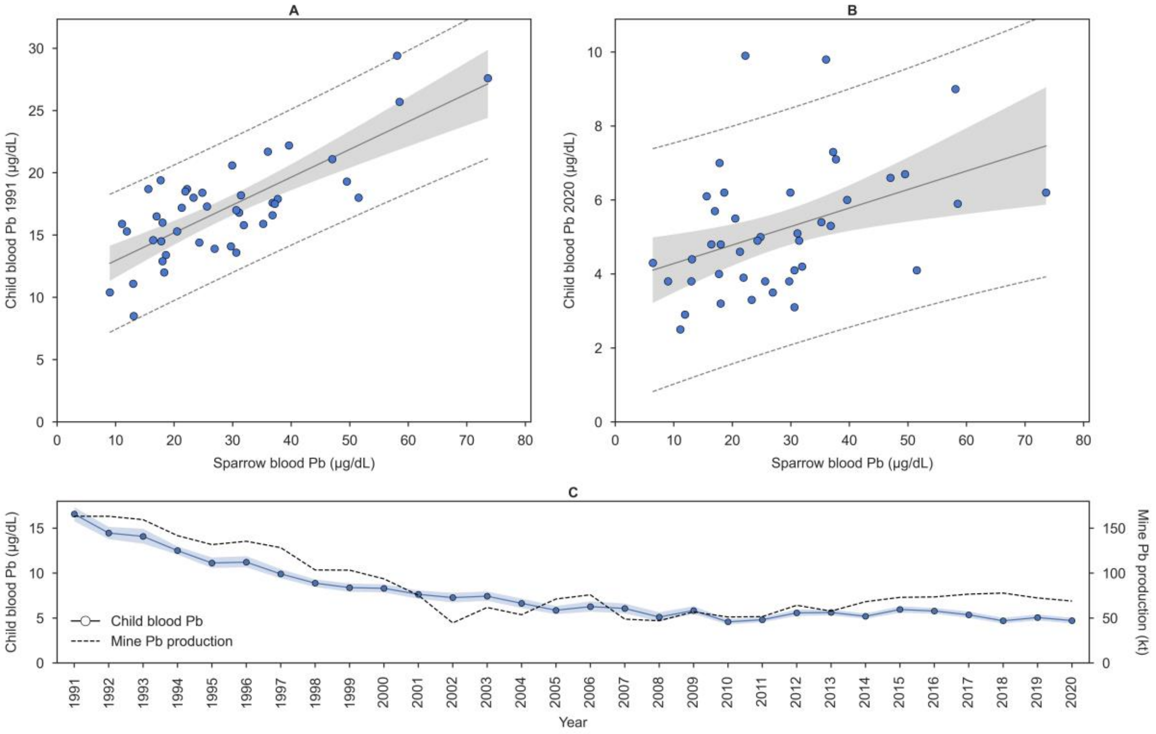

Fig. 4. Relationship between sparrow blood Pb and historical child blood Pb. (**A**, **B**) Comparison of relationship between blood Pb of contemporary sparrows and nearby (< 300 m) children measured in (**A**) 1991 and (**B**) 2020 from each catch site (n = 43; linear regression ± 95% confidence interval ± 95% prediction interval). Points represent geometric mean blood Pb concentrations 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[52].

In 1991, both annual mining Pb production rates[52] (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[50]. 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[50, 51], 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). This highlights the greater agency of humans to modify conditions within their surrounding environment and how this can lead to more variable levels of exposure in humans at an individual and household scale, at least compared to other animals. However, it also shows that despite this variability, wildlife sentinels continue to reflect the aggregate of exposures occuring within human populations over discrete spatial and possibly temporal scales.

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[23]. We found that the distribution of sparrow and child blood Pb isotopic compositions aligned closely with previously published data on surface soil[23, 38], deposited dust (this study and reference[20]), and house dust samples[36], and were more similar in composition to Broken Hill ore Pb (see Methods) than to local samples of uncontaminated soil[23] (fig. 5A; table S10). 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 S10). We also observed declines in the contribution of orebody Pb to these matrices with distance from mining and smelting operations (fig. 5C; table S11). These patterns are consistent with the dispersal, deposition, and mixing of point-source Pb emissions with minor contributions from secondary residential (e.g., paint and petrol; table S10) and geogenic (e.g., weathering and erosion of unmineralised bedrock) Pb sources[22, 23], and their subsequent uptake by sparrows and children.

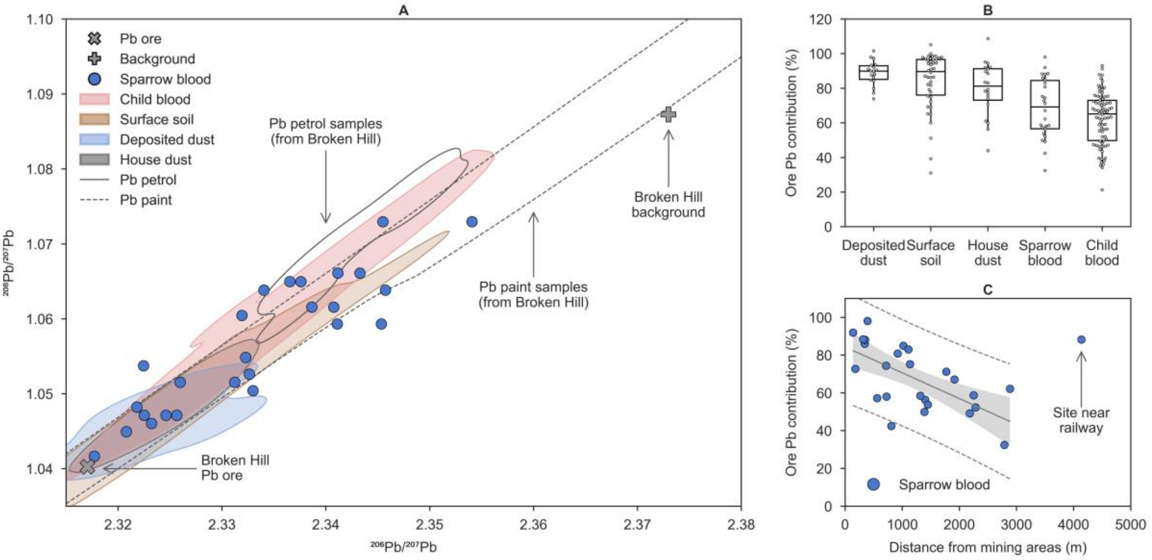

Fig. 5. Environmental and biological Pb isotopic compositions. (**A**) Comparison of Pb isotopic compositions (^{206}Pb/^{207}Pb, ^{208}Pb/^{207}Pb) of Broken Hill Pb ore (median; n = 5), background soil[23] (median; n = 11), sparrow blood (n = 26), child blood[23] (n = 78), surface soil[23, 38] (n = 42), deposited dust (this study and reference[20]; n = 18), house dust[36] (n = 20), and Pb petrol (n = 10) and paint (n = 21) samples from Broken Hill[23] (see Methods; table S10). (**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[38] 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[10]. 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[53]. Soil and indoor dust Pb concentrations are also related in Broken Hill (Spearman $r_s = 0.53$, $p < 0.01$, $n = 62$[36]). This correlation accounts for the overlap between sparrow blood Pb isotopic compositions and those measured in the indoor dust of Broken Hill homes[36] (table S10). 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[10]) and adult sparrows ($p > 0.05$;

table S12), 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 S11), and at regional scales, across towns and cities with and without significant Pb mining and smelting operations (fig. 2B; table S6). 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[54]. This includes mining impacted contexts similar to those investigated here, but also potentially in urban contexts where soil Pb contamination is more strongly linked to other industries, such as Pb acid battery recycling, or the historical and in some cases ongoing use of Pb additives in paint and petrol[19]. 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)[55]. In parts of Asia, the house sparrow is replaced ecologically by its congener, the tree sparrow (*Passer montanus*), which could serve a similar purpose[56].

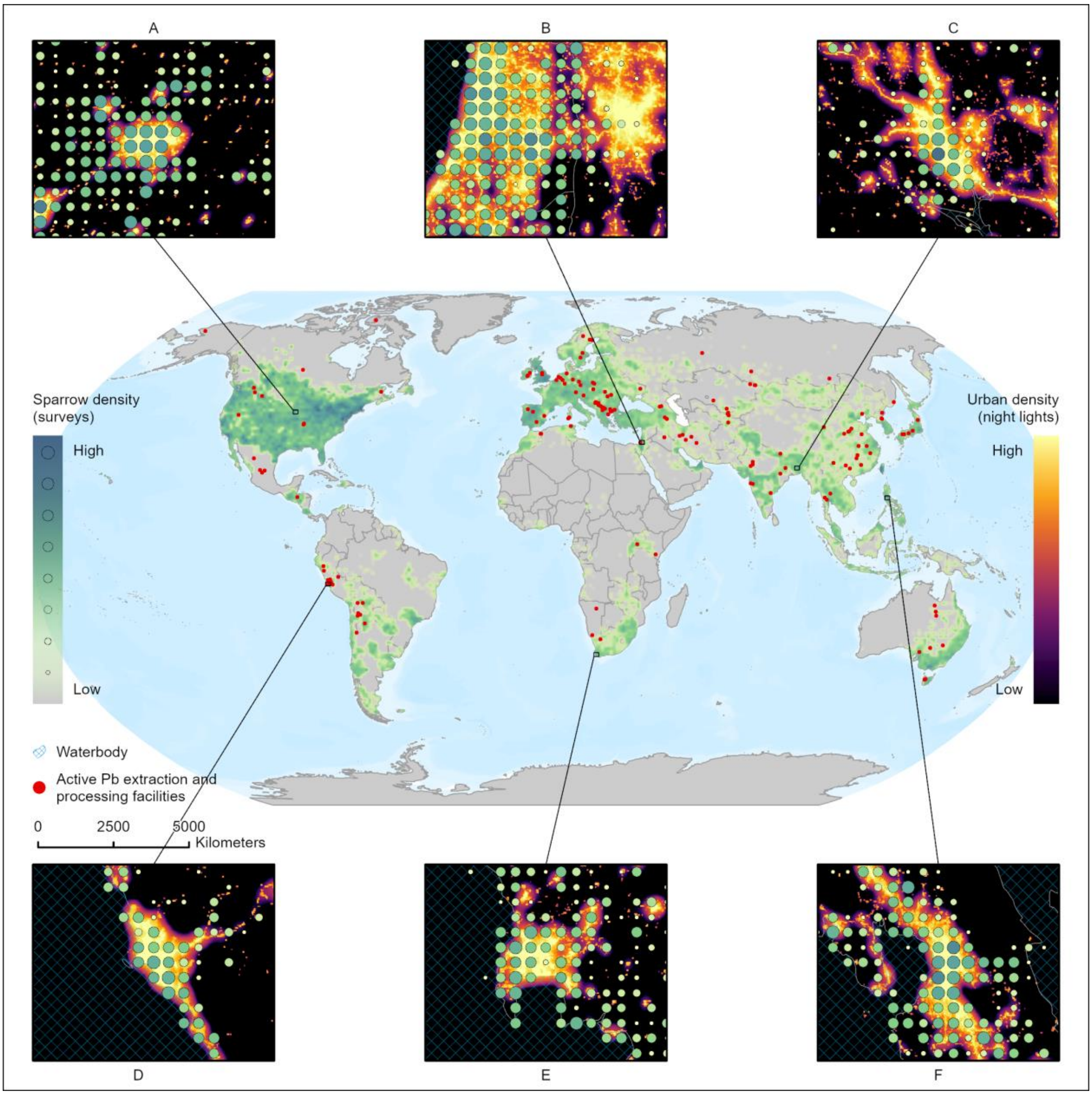

Fig. 6. Global distribution of human commensal sparrow species. Global map shows distribution and relative density of house sparrows (*Passer domesticus*), Italian sparrows (*Passer italiae*), and Spanish sparrows (*Passer hispaniolensis*) and their association with both active Pb extraction and processing facilities and human population centres beyond the Australian context of this study. 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 niche in their absence[56]. Survey data for all species were obtained from eBird, an online database of bird distribution and abundance[57]. 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[58, 59]. 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[60]. The outlined regions represent a limited selection of Pb exposure hotspots relating to a variety of urban Pb sources and where blood Pb levels in children are comparable to those reported

in this study ((**A**) Omaha, United States of America[61]; (**B**) West Bank, Palestine[62]; (**C**) Tungi, Bangladesh[63]; (**D**) Lima, Peru[64]; (**E**) Cape Town, South Africa[65]; (**F**) Manila, Philippines[66]).

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[16]. Inputs of these contaminants are constantly changing, and their measurement in wildlife sentinels such as sparrows can provide an early indication of the risks they pose to human health. This approach is not without limitations, as the sources and pathways of exposure to different contaminants will not always align between human and animal populations[5]. Additionally, while we have shown that this approach can provide a robust indication of exposure risk in human populations, its value in predicting risk amongst individuals and households is more limited. Some of these shortcomings could be overcome through the careful selection of animal sentinels with different ecological characteristics.

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. Soil and air monitoring provide direct insight into levels of these contaminants in the environment, but the use of an effective sentinel animal provides greater awareness of the extent to which these contaminants are biologically available to organisms, including humans, living in that environment[67]. On the other hand, human biomonitoring provides detailed information on exposures occurring at an individual and community level, but is costly, invasive and logistically complex, especially when children are involved[3]. In urban animals, clinical signs of exposure to toxic levels of contamination have provided impetus for interventions targeting related human health risks[6, 7]. This was the case in Broken Hill, where a high incidence of local dogs dying from Pb poisoning provided additional justification for the establishment of the child blood Pb monitoring program. 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. In this way, wildlife sentinels can provide an additional line of evidence to guide and support the establishment of more systematic risk monitoring and management programs.

Just as miners used canaries, we have demonstrated that house sparrows 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[68]. Our corroboration of this idea will help to reduce the growing perception that humans are disconnected from nature[68-70], and promote transformative actions aimed at sustainability across all species.

Supporting information: Supplementary materials include method validation data for pXRF and ICP-MS analyses; summary statistics for linear regression models used for data adjustment and child blood lead predictions; correlation coefficients for relationships between biochemical, geochemical and geographical variables; summary statistics for lead concentrations in sparrow blood, child blood, surface soil, and deposited dust; results for statistical comparisons of lead concentrations based on geographic location and demographics; summary statistics for lead isotopic compositions. Supplementary data include measures of central tendency and variation for lead measurements in sparrows, surface soil, and child blood; individual sparrow blood lead concentrations across all sites; individual surface soil lead concentrations across all sites; dust wipe lead concentrations, loading rates and isotopic compositions sampled from dust deposition gauges; sparrow blood lead isotopic compositions; ICP-MS and LeadCare blood lead measurements from paired sparrow blood samples; and summary geographic information for each catch site.

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Author contributions:

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Investigation: MMG, RT, TH, SCG

Visualization: MMG

Funding acquisition: SCG

Project administration: SCG

Supervision: MPT, SCG

Writing – original draft: MMG

Writing – review & editing: MMG, RT, TH, JPS, MPT, SCG

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 S5 and S6. Data from Mount Isa is freely available from the Queensland Department of Health Disclosure Log 2017–2018 (DOH-DL 17/18-048, p. 133).

References:

1. Landrigan, P. J.; Fuller, R.; Acosta, N. J. R.; Adeyi, O.; Arnold, R.; Basu, N. N.; Baldé, A. B.; Bertollini, R.; Bose-O'Reilly, S.; Boufford, J. I.; Breysse, P. N.; Chiles, T.; Mahidol, C.; Coll-Seck, A. M.; Cropper, M. L.; Fobil, J.; Fuster, V.; Greenstone, M.; Haines, A.; Hanrahan, D.; Hunter, D.; Khare, M.; Krupnick, A.; Lanphear, B.; Lohani, B.; Martin, K.; Mathiasen, K. V.; McTeer, M. A.; Murray, C. J. L.; Ndahimananjara, J. D.; Perera, F.; Potočnik, J.; Preker, A. S.; Ramesh, J.; Rockström, J.; Salinas, C.; Samson, L. D.; Sandilya, K.; Sly, P. D.; Smith, K. R.; Steiner, A.; Stewart, R. B.; Suk, W. A.; van Schayck, O. C. P.; Yadama, G. N.; Yumkella, K.; Zhong, M., The Lancet Commission on pollution and health. *The Lancet* **2018,** *391* (10119), 462-512, doi:10.1016/S0140-6736(17)32345-0.

2. Fuller, R.; Landrigan, P. J.; Balakrishnan, K.; Bathan, G.; Bose-O'Reilly, S.; Brauer, M.; Caravanos, J.; Chiles, T.; Cohen, A.; Corra, L.; Cropper, M.; Ferraro, G.; Hanna, J.; Hanrahan, D.; Hu, H.; Hunter, D.; Janata, G.; Kupka, R.; Lanphear, B.; Lichtveld, M.; Martin, K.; Mustapha, A.; Sanchez-Triana, E.; Sandilya, K.; Schaefli, L.; Shaw, J.; Seddon, J.; Suk, W.; Téllez-Rojo, M. M.; Yan, C., Pollution and health: a progress update. *Lancet Planet. Health* **2022,** *6* (6), e535-e547, doi:10.1016/S2542-5196(22)00090-0.

3. Bocato, M. Z.; Bianchi Ximenez, J. P.; Hoffmann, C.; Barbosa, F., An overview of the current progress, challenges, and prospects of human biomonitoring and exposome studies. *J. Toxicol. Environ. Health Part B Crit. Rev.* **2019,** *22* (5-6), 131-156, doi:10.1080/10937404.2019.1661588.

4. Burger, J., Bioindicators: Types, Development, and Use in Ecological Assessment and Research. *Environmental Bioindicators* **2006,** *1* (1), 22-39, doi:10.1080/15555270590966483.

5. Rabinowitz, P.; Conti, L., Links among human health, animal health, and ecosystem health. *Annual Review of Public Health* **2013,** *34*, 189-204, doi:10.1146/annurev-publhealth-031912-114426.

6. Rabinowitz, P.; Scotch, M.; Conti, L., Human and animal sentinels for shared health risks. *Veterinaria italiana* **2009,** *45* (1), 23-24,

7. Levin, R.; Zilli Vieira, C. L.; Rosenbaum, M. H.; Bischoff, K.; Mordarski, D. C.; Brown, M. J., The urban lead (Pb) burden in humans, animals and the natural environment. *Environ. Res.* **2021,** *193*, doi:10.1016/j.envres.2020.110377.

8. McClelland, S. C.; Durães Ribeiro, R.; Mielke, H. W.; Finkelstein, M. E.; Gonzales, C. R.; Jones, J. A.; Komdeur, J.; Derryberry, E.; Saltzberg, E. B.; Karubian, J., Sub-lethal

exposure to lead is associated with heightened aggression in an urban songbird. *Sci. Total Environ.* **2019,** *654*, 593-603, doi:10.1016/j.scitotenv.2018.11.145.

9. Cai, F.; Calisi, R. M., Seasons and neighborhoods of high lead toxicity in New York City: The feral pigeon as a bioindicator. *Chemosphere* **2016,** *161*, 274-279, doi:10.1016/j.chemosphere.2016.07.002.

10. Anderson, T., *Biology of the Ubiquitous House Sparrow: From Genes to Populations*. Oxford University Press: 2007; p 1-560.

11. Swaileh, K. M.; Sansur, R., Monitoring urban heavy metal pollution using the House Sparrow (Passer domesticus). *Journal of Environmental Monitoring* **2006,** *8* (1), 209-213, doi:10.1039/b510635d.

12. Kekkonen, J.; Hanski, I. K.; Väisänen, R. A.; Brommer, J. E., Levels of heavy metals in House Sparrows (Passer domesticus) from urban and rural habitats of southern Finland. *Ornis Fennica* **2012,** *89* (2), 91-98, doi:10.51812/of.133796.

13. White, J. H.; Heppner, J. J.; Ouyang, J. Q., Increased lead and glucocorticoid concentrations reduce reproductive success in house sparrows along an urban gradient. *Ecological Applications* **2022,** *32* (8), doi:10.1002/eap.2688.

14. Maina, J.; Gerber, R.; Dahms, S.; Baker, N. J.; Greenfield, R., Metal accumulation in house sparrow (Passer domesticus) from Thohoyandou, Limpopo province, South Africa. *African Zoology* **2017,** *52* (1), 43-53, doi:http://dx.doi.org/10.1080/15627020.2017.1293491.

15. Ai, S.; Yang, Y.; Ding, J.; Yang, W.; Bai, X.; Bao, X.; Ji, W.; Zhang, Y., Metal Exposure Risk Assessment for Tree Sparrows at Different Life Stages via Diet from a Polluted Area in Northwestern China. *Environ. Toxicol. Chem.* **2019,** *38* (12), 2785-2796, doi:10.1002/etc.4576.

16. Naidu, R.; Biswas, B.; Willett, I. R.; Cribb, J.; Kumar Singh, B.; Paul Nathanail, C.; Coulon, F.; Semple, K. T.; Jones, K. C.; Barclay, A.; John Aitken, R., Chemical pollution: A growing peril and potential catastrophic risk to humanity. *Environment International* **2021,** *156*, doi:10.1016/j.envint.2021.106616.

17. Wani, A. L.; Ara, A.; Usmani, J. A., Lead toxicity: A review. *Interdisciplinary Toxicology* **2015,** *8* (2), 55-64, doi:10.1515/intox-2015-0009.

18. Entwistle, J. A.; Hursthouse, A. S.; Marinho Reis, P. A.; Stewart, A. G., Metalliferous Mine Dust: Human Health Impacts and the Potential Determinants of Disease in Mining Communities. *Curr. Pollut. Rep.* **2019,** *5* (3), 67-83, doi:10.1007/s40726-019-00108-5.

19. Ericson, B.; Hu, H.; Nash, E.; Ferraro, G.; Sinitsky, J.; Taylor, M. P., Blood lead levels in low-income and middle-income countries: a systematic review. *Lancet Planet. Health* **2021,** *5* (3), e145-e153, doi:10.1016/S2542-5196(20)30278-3.

20. Dong, C.; Taylor, M. P., Applying geochemical signatures of atmospheric dust to distinguish current mine emissions from legacy sources. *Atmospheric Environment* **2017,** *161*, 82-89, doi:10.1016/j.atmosenv.2017.04.024.

21. Mackay, A. K.; Taylor, M. P.; Munksgaard, N. C.; Hudson-Edwards, K. A.; Burn-Nunes, L., Identification of environmental lead sources and pathways in a mining and smelting town: Mount Isa, Australia. *Environ. Pollut.* **2013,** *180*, 304-311, doi:10.1016/j.envpol.2013.05.007.

22. Liu, X.; Taylor, M. P.; Aelion, C. M.; Dong, C., Novel Application of Machine Learning Algorithms and Model-Agnostic Methods to Identify Factors Influencing Childhood Blood Lead Levels. *Environ. Sci. Technol.* **2021,** *55* (19), 13387-13399, doi:10.1021/acs.est.1c01097.

23. Gulson, B. L.; Mizon, K. J.; Law, A. J.; Korsch, M. J.; Davis, J. J.; Howarth, D., Source and pathways of lead in humans from the Broken Hill mining community - an alternative use of exploration methods. *Economic Geology* **1994,** *89* (4), 889-908, doi:10.2113/gsecongeo.89.4.889.

24. Davis, M. F.; Rankin, S. C.; Schurer, J. M.; Cole, S.; Conti, L.; Rabinowitz, P.; Gray, G.; Kahn, L.; Machalaba, C.; Mazet, J.; Pappaioanou, M.; Sargeant, J.; Thompson, A.; Weese, S.; Zinnstag, J., Checklist for One Health Epidemiological Reporting of Evidence (COHERE). *One Health* **2017,** *4*, 14-21, doi:10.1016/j.onehlt.2017.07.001.

25. Fry, K. L.; Wheeler, C. A.; Gillings, M. M.; Flegal, A. R.; Taylor, M. P., Anthropogenic contamination of residential environments from smelter As, Cu and Pb emissions: Implications for human health. *Environ. Pollut.* **2020,** *262*, doi:10.1016/j.envpol.2020.114235.

26. Dong, C.; Taylor, M. P.; Zahran, S., The effect of contemporary mine emissions on children's blood lead levels. *Environment International* **2019,** *122*, 91-103, doi:10.1016/j.envint.2018.09.023.

27. Boreland, F.; Lyle, D.; Brown, A.; Perkins, D., Effectiveness of introducing point of care capillary testing and linking screening with routine appointments for increasing blood lead screening rates of young children: A before-after study. *Arch. Public Health* **2015,** *73* (1), doi:10.1186/s13690-015-0111-y.

28. Scanes, C. G., Chapter 10 - Blood. In *Sturkie's Avian Physiology (Sixth Edition)*, Scanes, C. G., Ed. Academic Press: San Diego, 2015; pp 167-191.

29. Aung, N. N.; Uryu, T.; Yoshinaga, J., Lead Isotopic Compositions of Environmental Certified Reference Materials for an Inter-Laboratory Comparison of Lead Isotope Analysis. *Analytical Sciences* **2004,** *20* (1), 195-198, doi:10.2116/analsci.20.195.

30. Reimann, C.; Smith, D. B.; Woodruff, L. G.; Flem, B., Pb-concentrations and Pb-isotope ratios in soils collected along an east-west transect across the United States. *Appl. Geochem.* **2011,** *26* (9-10), 1623-1631, doi:10.1016/j.apgeochem.2011.04.018.

31. Souto-Oliveira, C. E.; Babinski, M.; Araújo, D. F.; Weiss, D. J.; Ruiz, I. R., Multi-isotope approach of Pb, Cu and Zn in urban aerosols and anthropogenic sources improves tracing of the atmospheric pollutant sources in megacities. *Atmospheric Environment* **2019,** *198*, 427-437, doi:10.1016/j.atmosenv.2018.11.007.

32. Takaoka, M.; Yoshinaga, J.; Tanaka, A., Influence of paint chips on lead concentration in the soil of public playgrounds in Tokyo. *Journal of Environmental Monitoring* **2006,** *8* (3), 393-398, doi:10.1016/j.atmosenv.2018.11.007.

33. Unruh, D. M.; Fey, D. L.; Church, S. E. *Chemical data and lead isotopic compositions of geochemical baseline samples from streambed sediments and smelter slag, lead isotopic compositions in fluvial tailings, and dendrochronology results from the Boulder River watershed, Jefferson County, Montana*; 2331-1258; US Geological Survey: 2000.

34. Chiaradia, M.; Chenhall, B. E.; Depers, A. M.; Gulson, B. L.; Jones, B. G., Identification of historical lead sources in roof dusts and recent lake sediments from an industrialized area: Indications from lead isotopes. *Sci. Total Environ.* **1997,** *205* (2-3), 107-128, doi:10.1016/S0048-9697(97)00199-X.

35. Cooper, J. A.; Reynolds, P. H.; Richards, J. R., Double-spike calibration of the broken hill standard lead. *Earth and Planetary Science Letters* **1969,** *6* (6), 467-478, doi:10.1016/0012-821X(69)90118-6.

36. Gillings, M. M.; Fry, K. L.; Morrison, A. L.; Taylor, M. P., Spatial distribution and composition of mine dispersed trace metals in residential soil and house dust: Implications for exposure assessment and human health. *Environ. Pollut.* **2022,** *293*, doi:10.1016/j.envpol.2021.118462.

37. Townsend, A. T.; Yu, Z.; McGoldrick, P.; Hutton, J. A., Precise lead isotope ratios in Australian galena samples by high resolution inductively coupled plasma mass spectrometry. *Journal of Analytical Atomic Spectrometry* **1998,** *13* (8), 809-813, doi:10.1039/a801397g.

38. Kristensen, L. J.; Taylor, M. P.; Morrison, A. L., Lead and zinc dust depositions from ore trains characterised using lead isotopic compositions. *Environ. Sci. Process. Impacts* **2015,** *17* (3), 631-637, doi:10.1039/c4em00572d.

39. Craighead, D.; Bedrosian, B., Blood lead levels of common ravens with access to big-game offal. *J. Wildl. Manage.* **2008,** *72* (1), 240-245, doi:10.2193/2007-120.

40. González, F.; Camacho, M.; Tiburón, N. P.; Peña, M. Z.; Rueda, L. R.; Luzardo, O. P., Suitability of anodic stripping voltammetry for routine analysis of venous blood from raptors. *Environ. Toxicol. Chem.* **2019**, doi:10.1002/etc.4339.

41. Green, R. E.; Hunt, W. G.; Parish, C. N.; Newton, I., Effectiveness of action to reduce exposure of free-ranging California condors in Arizona and Utah to lead from spent ammunition. *PLoS ONE* **2008,** *3* (12), doi:10.1371/journal.pone.0004022.

42. Herring, G.; Eagles-Smith, C. A.; Bedrosian, B.; Craighead, D.; Domenech, R.; Langner, H. W.; Parish, C. N.; Shreading, A.; Welch, A.; Wolstenholme, R., Critically assessing the utility of portable lead analyzers for wildlife conservation. *Wildl. Soc. Bull.* **2018,** *42* (2), 284-294, doi:10.1002/wsb.892.

43. Langner, H. W.; Domenech, R.; Slabe, V. A.; Sullivan, S. P., Lead and Mercury in Fall Migrant Golden Eagles from Western North America. *Arch. Environ. Contam. Toxicol.* **2015,** *69* (1), doi:10.1007/s00244-015-0139-6.

44. Larsen, M. M.; Blusztajn, J. S.; Andersen, O.; Dahllöf, I., Lead isotopes in marine surface sediments reveal historical use of leaded fuel. *Journal of Environmental Monitoring* **2012,** *14* (11), 2893-2901, doi:10.1039/c2em30579h.

45. Queensland Department of Health *2017/18 Disclosure Log (DOH-DL 17/18-048).* https://www.health.qld.gov.au/__data/assets/pdf_file/0025/733444/dohdl1718048.pdf (accessed 02/03/2023).

46. Vangestel, C.; Braeckman, B. P.; Matheve, H.; Lens, L., Constraints on home range behaviour affect nutritional condition in urban house sparrows (Passer domesticus). *Biological Journal of the Linnean Society* **2010,** *101* (1), 41-50, doi:10.1111/j.1095-8312.2010.01493.x.

47. Australian Bureau of Statistics *Australian Statistical Geography Standard (ASGS).* https://www.abs.gov.au/statistics/statistical-geography/australian-statistical-geography-standard-asgs (accessed 16/02/2023).

48. Casteel, S. W.; Weis, C. P.; Henningsen, G. M.; Brattin, W. J., Estimation of relative bioavailability of lead in soil and soil-like materials using young swine. *Environ. Health Perspect.* **2006,** *114* (8), 1162-1171, doi:10.1289/ehp.8852.

49. Beyer, W. N.; Chen, Y.; Henry, P.; May, T.; Mosby, D.; Rattner, B. A.; Shearn-Bochsler, V. I.; Sprague, D.; Weber, J., Toxicity of Pb-contaminated soil to Japanese quail (Coturnix japonica) and the use of the blood-dietary Pb slope in risk assessment. *Integr. Environ. assess. manage.* **2014,** *10* (1), 22-29, doi:10.1002/ieam.1453.

50. Boreland, F.; Lesjak, M. S.; Lyle, D. M., Managing environmental lead in Broken Hill: a public health success. *New South Wales public health bulletin* **2008,** *19* (9-10), 174-179, doi:10.1071/nb07099.

51. Yang, K.; Cattle, S. R., Effectiveness of cracker dust as a capping material for Pb-rich soil in the mining town of Broken Hill, Australia. *Catena* **2017,** *148*, 81-91, doi:10.1016/j.catena.2016.02.022.

52. Mudd, G. M.; Jowitt, S. M.; Werner, T. T., The world's lead-zinc mineral resources: Scarcity, data, issues and opportunities. *Ore Geology Reviews* **2017,** *80*, 1160-1190, doi:10.1016/j.oregeorev.2016.08.010.

53. Calabrese, E. J.; Stanek, E. J., What proportion of household dust is derived from outdoor soil? *Soil and Sediment Contamination* **1992,** *1* (3), 253-263, doi:10.1080/15320389209383415.

54. Landrigan, P. J.; Fuller, R.; Acosta, N. J.; Adeyi, O.; Arnold, R.; Baldé, A. B.; Bertollini, R.; Bose-O'Reilly, S.; Boufford, J. I.; Breysse, P. N., The Lancet Commission on pollution and health. *The lancet* **2018,** *391* (10119), 462-512, doi:10.1016/S0140-6736(17)32345-0.

55. Clune, A., L.; Falk, H.; Riederer, A., M., Mapping Global Environmental Lead Poisoning in Children. *Journal of Health and Pollution* **2011,** *1* (2), 14-23, doi:10.5696/2156-9614.1.2.14.

56. Sætre, G. P.; Riyahi, S.; Aliabadian, M.; Hermansen, J. S.; Hogner, S.; Olsson, U.; Gonzalez Rojas, M. F.; Sæther, S. A.; Trier, C. N.; Elgvin, T. O., Single origin of human commensalism in the house sparrow. *J. Evol. Biol.* **2012,** *25* (4), 788-796, doi:10.1111/j.1420-9101.2012.02470.x.

57. Sullivan, B. L.; Wood, C. L.; Iliff, M. J.; Bonney, R. E.; Fink, D.; Kelling, S., eBird: A citizen-based bird observation network in the biological sciences. *Biological Conservation* **2009,** *142* (10), 2282-2292, doi:10.1016/j.biocon.2009.05.006.

58. United States Geological Survey *Active Mines and Mineral Processing Plants in the United States in 2003*; United States Geological Survey: Reston, Virginia, 2005.

59. United States Geological Survey *Mineral operations outside the United States*; United States Geological Survey: Reston, Virginia, 2010.

60. Román, M. O.; Wang, Z.; Sun, Q.; Kalb, V.; Miller, S. D.; Molthan, A.; Schultz, L.; Bell, J.; Stokes, E. C.; Pandey, B.; Seto, K. C.; Hall, D.; Oda, T.; Wolfe, R. E.; Lin, G.; Golpayegani, N.; Devadiga, S.; Davidson, C.; Sarkar, S.; Praderas, C.; Schmaltz, J.; Boller, R.; Stevens, J.; Ramos González, O. M.; Padilla, E.; Alonso, J.; Detrés, Y.; Armstrong, R.; Miranda, I.; Conte, Y.; Marrero, N.; MacManus, K.; Esch, T.; Masuoka, E. J., NASA's Black Marble nighttime lights product suite. *Remote Sensing of Environment* **2018,** *210*, 113-143, doi:10.1016/j.rse.2018.03.017.

61. Ye, D.; Brown, J. S.; Umbach, D. M.; Adams, J.; Thayer, W.; Follansbee, M. H.; Kirrane, E. F., Estimating the Effects of Soil Remediation on Children’s Blood Lead near a Former Lead Smelter in Omaha, Nebraska, USA. *Environ. Health Perspect.* **2022,** *130* (3), doi:10.1289/EHP8657.

62. Safi, J.; Fischbein, A.; El Haj, S.; Sansour, R.; Jaghabir, M.; Abu Hashish, M.; Suleiman, H.; Safi, N.; Abu-Hamda, A.; Witt, J. K.; Platkov, E.; Reingold, S.; Alayyan, A.; Berman, T.; Bercovitch, M.; Choudhri, Y.; Richter, E. D., Childhood lead exposure in the Palestinian Authority, Israel, and Jordan: Results from the Middle Eastern Regional Cooperation Project, 1996-2000. *Environ. Health Perspect.* **2006,** *114* (6), 917-922, doi:10.1289/ehp.8339.

63. Mitra, A. K.; Haque, A.; Islam, M.; Bashar, S. A. M. K., Lead poisoning: An alarming public health problem in bangladesh. *International Journal of Environmental Research and Public Health* **2009,** *6* (1), 84-95, doi:10.3390/ijerph6010084.

64. Espinoza, R.; Hernández-Avila, M.; Narciso, J.; Castañaga, C.; Moscoso, S.; Ortiz, G.; Carbajal, L.; Wegner, S.; Noonan, G., Determinants of blood-lead levels in children in Callao and Lima metropolitan area. *Salud Publica de Mexico* **2003,** *45* (SUPPL. 2), S209-S219, doi:10.1590/s0036-36342003000800007.

65. Naicker, N.; Mathee, A.; Barnes, B., A follow-up cross-sectional study of environmental lead exposure in early childhood in urban South Africa. *South African Medical Journal* **2013,** *103* (12), 935-938, doi:10.7196/SAMJ.7157.

66. Suplido, M. L.; Ong, C. N., Lead exposure among small-scale battery recyclers, automobile radiator mechanics, and their children in Manila, the Philippines. *Environ. Res.* **2000,** *82* (3), 231-238, doi:10.1006/enrs.1999.4024.

67. Imagawa, M.; Rushing, M.; Carter, A.; Schott, R.; Berman, J. D., Using blood lead concentrations of wildlife sentinels to identify environmental risk factors of lead exposure for public health and wildlife rehabilitation efforts. *Ecotoxicology* **2023,** *32* (3), 357-369, doi:10.1007/s10646-023-02642-x.

68. Folke, C.; Polasky, S.; Rockström, J.; Galaz, V.; Westley, F.; Lamont, M.; Scheffer, M.; Österblom, H.; Carpenter, S. R.; Chapin, F. S.; Seto, K. C.; Weber, E. U.; Crona, B. I.; Daily, G. C.; Dasgupta, P.; Gaffney, O.; Gordon, L. J.; Hoff, H.; Levin, S. A.; Lubchenco, J.; Steffen, W.; Walker, B. H., Our future in the Anthropocene biosphere. *Ambio* **2021,** *50* (4), 834-869, doi:10.1007/s13280-021-01544-8.

69. Beery, T.; Stahl Olafsson, A.; Gentin, S.; Maurer, M.; Stålhammar, S.; Albert, C.; Bieling, C.; Buijs, A.; Fagerholm, N.; Garcia-Martin, M.; Plieninger, T.; M. Raymond, C., Disconnection from nature: Expanding our understanding of human–nature relations. *People and Nature* **2023,** *5* (2), 470-488, doi:10.1002/pan3.10451.

70. Ives, C. D.; Giusti, M.; Fischer, J.; Abson, D. J.; Klaniecki, K.; Dorninger, C.; Laudan, J.; Barthel, S.; Abernethy, P.; Martín-López, B.; Raymond, C. M.; Kendal, D.; von Wehrden, H., Human–nature connection: a multidisciplinary review. *Current Opinion in Environmental Sustainability* **2017,** *26-27*, 106-113, doi:10.1016/j.cosust.2017.05.005.