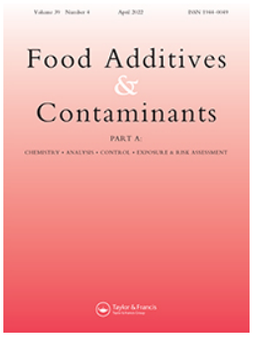

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Human health implications from consuming eggs produced near a derelict metalliferous mine: a case study

Andrea Sartorius[a], Matthew Johnson[b], Scott Young[c], Malcolm Bennett[a], Kerstin Baiker[a], Paul Edwards[d] and Lisa Yon[a]

[a]School of Veterinary Medicine and Science, University of Nottingham, Sutton Bonington, UK; [b]School of Geography, University of Nottingham, Nottingham, UK; [c]School of Biosciences, University of Nottingham, Sutton Bonington, UK; [d]Natural Resources Wales, Cardiff, UK

ABSTRACT

Lead pollution from metalliferous mines can have major environmental and health effects long after the mines have closed. Animals living near derelict mine sites can inadvertently ingest lead-contaminated soils, causing them to accumulate lead and potentially experience significant adverse health effects. Human food products, such as eggs, produced near metalliferous mines may also be contaminated with lead. The focus of this case study was to determine whether free-range chickens living near a derelict lead mine had high lead body burdens, whether they were producing eggs with elevated lead concentrations, and whether these eggs could be hazardous to human health. Soil samples and chicken egg, feather, blood, and bone samples were collected from a small farm near an abandoned metalliferous mine. The soil in and around the chicken pens contained lead concentrations that were elevated above established soil lead baseline concentrations. The lead concentrations in the chicken feather, blood, and bone samples were consistent with lead toxicity and indicated long-term, continuous exposure. Finally, the lead concentrations in the eggs were significantly greater than those found in commercial eggs. Based on previously established lead benchmark dose levels, humans, and in particular, children, could experience adverse health impacts if they routinely consumed these eggs. Environmental lead contamination continues to pose a major health risk for humans, and further research, understanding, and awareness are required to safeguard the public from the risks of consuming food produced near derelict mines.

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Lead; chicken; eggs; legacy pollutants; mining; human health risks

Introduction

Lead is a toxic metal that has significant adverse impacts on human health throughout the world. In 2017, lead exposure was estimated to have caused more than one million deaths and over 24 million disability-adjusted life years (years of life lost due to premature mortality or living with a disability) worldwide (Mathers et al. 2013; Stanaway et al. 2018). The effects of lead exposure are profound, as it can affect multiple organs, including the kidneys, liver, central nervous system, and reproductive system (Tchounwou et al. 2012). Therefore, over the past 40 years, there have been concerted efforts to decrease human lead exposure, primarily through banning or limiting the use of products containing lead, such as lead-based paint, leaded petrol, and lead pipes (Tchounwou et al. 2012). However, since lead is an elemental toxin and does not degrade, historical contamination can continue to pose a threat to human health.

A key route of lead exposure for humans is through the consumption of lead-contaminated food (Tong et al. 2000; Tchounwou et al. 2012). Fruit and vegetables grown in lead-contaminated environments have been found to have correspondingly high lead concentrations (Finster et al. 2004; Feleafel and Mirdad 2013). Similarly, animals reared in lead-polluted environments can ingest lead by drinking contaminated water, consuming contaminated food products, or inadvertently

CONTACT Andrea Sartorius andrea.sartorius@nottingham.ac.uk School of Veterinary Medicine and Science, University of Nottingham, Sutton Bonington Campus, Sutton Bonington LE12 5RD, UK

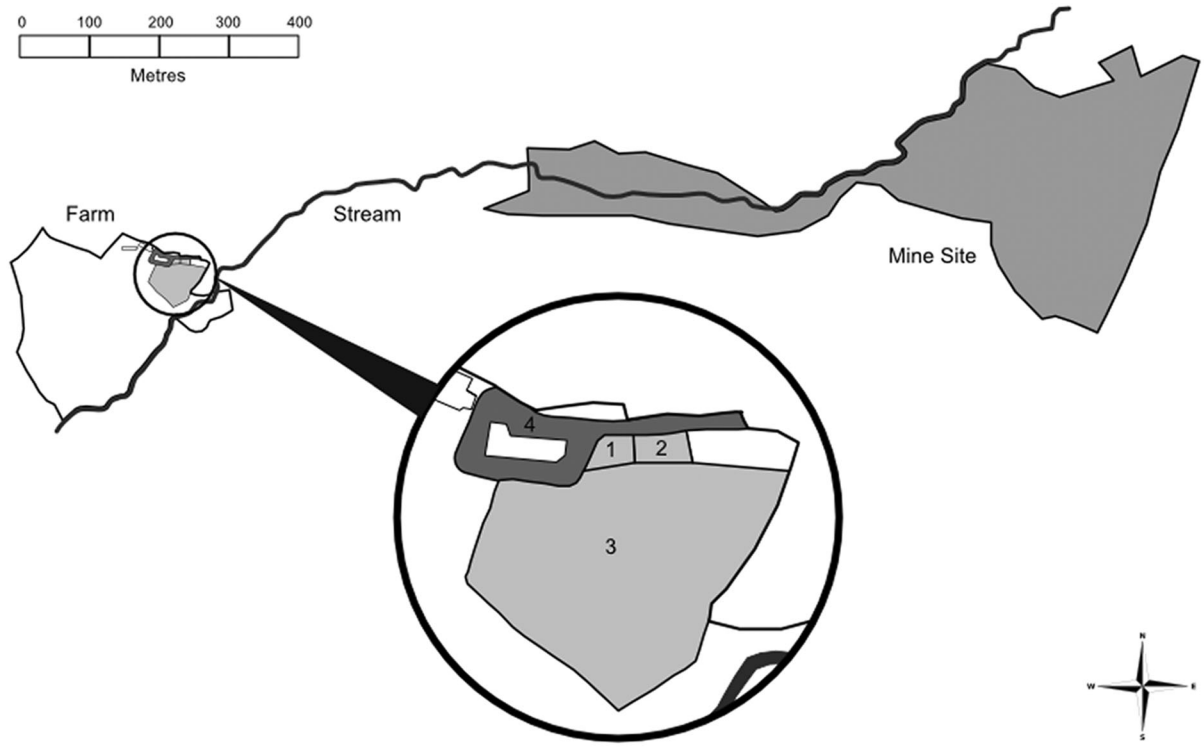

Figure 1. Map of sampling locations. The numbers represent the sampled sites at the farm: Pens 1, 2, and 3 and the gravel track (4).

ingesting contaminated soil (Franson and Pain 2011). In birds and mammals, lead accumulates primarily in the kidney, liver, and bones; high lead exposure, however, can result in lead accumulating across multiple systems, including tissues used for human food products, such as milk or eggs (Trampel et al. 2003; Franson and Pain 2011).

Human exposure to lead through the consumption of domestic chicken (*Gallus gallus domesticus*) eggs is of particular concern, as lead has been known specifically to accumulate in the eggs of lead-exposed chickens (Trampel et al. 2003). A number of studies have examined eggs produced by chickens in urban or semi-urban areas, and found elevated lead concentrations, reflecting the elevated local environmental lead levels (Roegner et al. 2013; Bautista et al. 2014; Spliethoff et al. 2014; Grace and MacFarlane 2016; Leibler et al. 2018; Cowie and Gartrell 2019). However, the few studies that have investigated eggs produced in highly lead-polluted areas have focused on chickens living near currently active sources of pollution, such as working lead smelters (Martins et al. 2010; Zariff et al. 2019). Nevertheless, abandoned lead workings can also serve as significant sources of contamination, as lead concentrations around derelict mines or smelters may remain high for hundreds of years after the operation has ceased (Pyatt et al. 2000; Venkateswarlu et al. 2016). These areas consistently have higher lead concentrations than urban areas, though local residents are not always aware of the contamination or the associated risks (Palmer 2006; Dogaru et al. 2009; Johnson et al. 2012). The aim of this study was therefore to determine whether chickens living near a derelict lead mine accumulate lead within their tissues, whether they produce eggs with elevated lead concentrations, and whether these eggs could be hazardous to human health. This case study focused on eggs produced over a 16-month period by a flock of chickens from a small private farm, located directly downstream from a derelict lead mine.

Materials and methods

Site

All samples were collected from an 8 ha farm in Wales located approximately 0.6 km downstream from an abandoned lead mine (Figure 1). Due to the proximity of the mine, the owner of the farm

requested that their land be investigated for environmental lead contamination.

Eight chickens lived on the farm in October 2018, and were managed under free-range conditions. Two died during the course of this study (one in November 2018 due to predation, another in May 2019 due to unknown causes). Apart from these deaths, all other chickens appeared clinically healthy throughout the study. The chickens were kept within two adjacent pens (Pens 1–2), one of which contained a chicken coop (Pen 2), and they also had regular access to a third, larger pen (Pen 3; Figure 1). All three pens were elevated above a stream flowing from the mine site, so the chickens had no direct access to the stream.

Sample collection

Soil samples were collected from the chickens' three pens, as well as a gravel track adjacent to the pens. The samples were collected using the 'W-transect' method: approximately 10 samples were collected using a stainless steel trowel at roughly equivalent distances within a 'W' shaped pattern across the sampling area. The samples were deposited into a single plastic bag and mixed by hand. Each pen was treated as an individual sampling area. Sampling from the track was restricted to the areas that were directly adjacent to the chicken pens.

Soil samples were also collected from the mine site and from a nearby control site (a protected woodland area) located 3 km from the mine. The control site was chosen to represent a relatively uncontaminated baseline for soil lead concentrations in the immediate region. These samples were collected at approximately 5 m intervals across five 20 m transects distributed across the sampling site. All the samples from a single transect were placed into a plastic bag and mixed by hand. Two distinct areas within the mine site (a mine spoil heap and an adjacent area of flattened mine spoil) were each sampled using the W-transect method.

Six eggs were collected from the farm on four occasions (in October 2018, May 2019, October 2019, and January 2020), and 10 eggs were collected in February 2019. The farm owner collected fresh eggs on the day of collection, and the eggs were kept at 4 °C before analysis.

A total of 12 commercially available eggs, obtained from two different sources, were analysed for comparison purposes. In January 2020, six eggs were purchased from a privately run free-range farm near Sutton Bonington, Leicestershire, UK. In January 2021, six further eggs were purchased from a major supermarket chain; these were commercially produced, free-range eggs from Wales. All eggs were kept at 4 °C before analysis.

Blood and feather samples were collected from the chickens in October 2018. Qualified veterinarians collected blood samples via venous sampling, which they dispensed into 4 mL lithium-heparinised tubes, mixed thoroughly, and stored at 4 °C prior to analysis. One feather from each chicken was carefully clipped close to the skin using stainless steel scissors. Due to sampling difficulties, blood samples were collected from four of the chickens, while feather samples were collected from all eight chickens.

The carcases of the two chickens that died during the study period were opportunistically collected. One carcase was frozen and thawed before dissection (to avoid decay), while the other was stored at 4 °C until dissection. During post mortem dissection, a femur was removed from each chicken for elemental analysis. The bone samples were stored at −20 °C.

Sample processing

The soil samples were air-dried before being sieved to <2 mm with a stainless steel sieve and subsequently ground into fine powder using a Retsch PM 400 planetary ball mill (Retsch, Haan, Germany). Duplicates of each sample were then acid digested using a Teflon-coated graphite hotplate block digester (Analab, Bischeim, France). Approximately 0.4 g of sample, along with 1 mL HNO_3 and 3 mL HCl, were heated on a hotplate block digester at 95 °C. After 2 hours, the samples were allowed to cool to ambient temperature before being dispensed into plastic volumetric flasks. The volume was then made up to 50 mL with Milli-Q water (18.2 MΩ cm; Millipore Corporation, Darmstadt, Germany). The solutions were diluted 1:10 with Milli-Q water prior to elemental analysis by inductively coupled

plasma mass spectrometry (ICP-MS) (Model ICAP-Q; Thermo Fisher Scientific, Bremen, Germany). A certified reference material for lead (NIST 2711 A, Montana soil) was run for quality assurance purposes (Pb recovery was 93.1% of the certified value).

The egg samples were manually separated into shell, yolk, and albumen and weighed before being freeze-dried to a constant mass. The original wet weight and the final dry weight for each egg constituent were recorded. While most yolk and albumen samples were successfully separated upon extraction from the egg, if the samples became mixed, after freeze-drying the yolk and albumen were separated based on their different consistency and colour. Approximately 0.1–0.2 g of each sample, along with 3 mL 70% HNO_3 (Primar Plus^{TM} grade, Thermo Fisher Scientific), 2 mL H_2O_2, and 3 mL Milli-Q water, were digested in a microwave oven (Model Multiwave Pro, Anton Paar) at 140 °C for 30 minutes, following a protocol established by Anton Paar, based on U.S. EPA Method 3051 A (U.S. EPA 2007). After digestion, 7 mL of Milli-Q water was added to the samples. The digestants were diluted 1:10 with Milli-Q water prior to elemental analysis by ICP-MS. Certified reference material for lead in biological samples (BRC-185R Bovine Liver [trace elements]) was run for quality assurance purposes (Pb recovery was 98.8% of the certified values).

The blood samples were homogenised using a roller mixer for 10 min. The blood was diluted 1:20 with 0.1% HNO_3 prior to elemental analysis by ICP-MS. A sample of certified reference material for lead (Seronorm Trace Elements in Whole Blood L-2, Lot 1702825) was also included for quality assurance (Pb concentration = 303 µg L^{-1}).

The feather samples were rinsed with deionised water to remove as much external contamination as possible. Afterwards, they were rinsed with the following solvents in sequence for 15 minutes at a time: deionised water, 0.5% Triton-X, deionised water, acetone, and deionised water. Before each new solvent was added, the previous solvent was poured off and the samples and tubes were briefly rinsed with deionised water. The samples were stirred using a roller mixer during the washing process. After washing was complete, the samples were dried at 60 °C in an oven overnight. The samples were then cut into smaller pieces (~2 cm) using scissors, and were acid digested and analysed using ICP-MS, as previously described for the egg samples.

The chicken bone samples were freeze-dried to a constant mass. After freeze-drying, bone samples were manually cleaned of extraneous soft tissue. The bone samples were then acid digested following the same method as the egg samples (microwave-assisted) prior to elemental analysis by ICP-MS.

Statistical analyses

Lead concentrations were compared between the edible portions (yolk and albumen) of the eggs (wet weight). The edible lead concentration was determined by combining the yolk and albumen concentrations (with adjustment for relative mass).

The limit of detection (LOD) was calculated as 3 times the standard deviation of the lead concentrations of 19 blank samples run alongside the egg samples. The LOD was 0.262 µg L^{-1}, which converted to 0.0227 µg L^{-1} dry weight. Unique LODs for the amount of lead per egg and the wet weight lead concentration were then calculated for the shell, yolk, and albumen portions of the egg using the average wet and dry weights of the relevant component across all eggs sampled. The amount of lead LOD was 0.000140 mg for the shell, 0.000190 mg for the yolk, and 0.000102 mg for albumen, while the wet weight lead concentration LOD was 0.0160 µg L^{-1} for the shell, 0.0113 µg L^{-1} for the yolk, and 0.00276 µg L^{-1}g for albumen. Any sample concentrations or amounts below the LOD were reported as < LOD. For statistical and graphical comparisons, samples with a concentration or amount below the LOD had their concentration substituted with half of the LOD. The limit of quantitation (LOQ) was calculated as 10 times the standard deviation of the 19 blank samples run alongside the egg samples. The LOQ was 0.874 µg L^{-1}, which converted to 0.0757 µg L^{-1} dry weight.

The lead concentrations found in the edible portions of the eggs were compared between the farm and the commercially available eggs, as well as between the farm eggs across the different

collection months, using analysis of variance (ANOVA) in R (R Core Team 2018). Two ANOVAs were used: one comparing the lead concentrations in the farm eggs from each collection month to the two sets of commercially available eggs, and one comparing the lead concentrations in the farm eggs between each collection month. A graph displaying the lead concentrations in the farm and the commercially available eggs across collection months was made in R using the ggplot2 package (Wickham 2016).

Threshold comparisons

The soil lead concentrations were compared to the Normal Background Concentrations (NBCs), which were generated by the British Geological Survey (BGS) to indicate the 'normal levels of contaminants' in different domains (areas defined based on geology and anthropogenic activity) of the UK (Ander et al. 2013). Specifically, the NBC dry weight μg L^{-1} concentrations for the 'Principal' (background) and 'Mineralisation' (mining areas) domains resolved for Wales by the BGS in 2013 were referenced for comparison (Ander et al. 2013).

The amount of lead in the edible portions of the eggs was compared to lead consumption thresholds for known impacts on human health. The European Food Safety Authority (EFSA) determined benchmark dose levels (BMDLs; the lowest 95% confidence limit below the benchmark dose, or dose that is associated with a specific response) for daily lead consumption. These BMDLs focused on the risks of developmental neurotoxicity (intellectual deficits) in children, nephrotoxicity (specifically, chronic kidney disease) and cardiovascular effects (specifically, higher systolic blood pressure) in adults (European Food Safety Authority 2010; Hardy et al. 2017). These BMDLs indicate threshold dietary intake values in μg L^{-1} body weight per day, so the average weight of an adult in England in 2019 (78.6 kg) was used to determine how much lead an adult could consume in a day before exceeding the BMDL (Moody 2019). Due to the large differences in weight across ages during childhood, the threshold for children was calculated for six age brackets (0–1, 2–4, 5–7, 8–10, 11–12, and 13–15 years old), following those determined in the Health Survey for England 2019 (Moody 2019). To compare the egg lead concentrations to the BMDLs, the amount of lead in the edible portions of the eggs was calculated using the measured lead concentrations and the mass of each egg component.

Results

Soil

The three chicken pens (Pens 1–3) and the adjacent gravel track all had elevated soil lead concentrations when compared to the soils from the nearby control site (Table 1). The soil lead concentrations from the farm also exceeded the NBCs for Wales for both the Principal (230 μg L^{-1}) and Mineralisation (280 μg L^{-1}) domains, further indicating that the lead concentrations were elevated above 'normal' levels (Ander et al. 2013). Of the soils sampled at the farm, the highest lead concentration was found in the gravel track, which was similar to the lead concentration in the spoil heap at the nearby mine site (Table 1).

Table 1. Lead concentrations in soil samples.

Site	Lead (μg L^{-1} dw[a])
Mine site	
Spoil heap	23,100 ± 2070
Flattened spoil	11,900 ± 3250
Five transects across the site[b]	6380 ± 1320
Farm	
Pen 1	2030 ± 232
Pen 2	1830 ± 131
Pen 3	885 ± 54.6
Track	23,000 ± 5160
Control site	
Five transects across the site[b]	66.7 ± 16.8

Note. Results are represented as mean ± standard deviation.
[a]Dry weight.
[b]$n = 5$.

Table 2. Lead concentrations within chicken feathers, blood, and bone samples.

Chicken	Feather (μg L^{-1} dw[a])	Blood (μg L^{-1})	Bone (μg L^{-1} dw)
1	35.1		492
2	38.0	4670	42.1
3	19.0		
4	26.0	1020	
5	47.1		
6	27.6	1070	
7	48.7	394	
8	33.6		
Mean	34.4 ± 10.2	1790 ± 1950	267 ± 318

Note. Results are represented as mean ± standard deviation.
[a]Dry weight.

Table 3. Chicken egg lead concentrations (wet weight).

		Farm eggs					Commercially available eggs	
Part of egg		October 2018 ($n = 6$)	February 2019 ($n = 10$)	May 2019 ($n = 6$)	October 2019 ($n = 6$)	January 2020 ($n = 6$)	January 2020 ($n = 6$)	January 2021 ($n = 6$)
Shell	Mean	0.470	0.874	1.15	0.516	0.340	<LOD	0.0361
	SD	0.421	0.395	0.813	0.168	0.0686	NA	0.0689
	Range	0.0884–1.29	0.405–1.74	0.230–2.63	0.391–0.846	0.275–0.452	NA–0.0235	NA–0.177
Yolk	Mean	0.330	0.565	1.30	0.705	0.866	0.0161	0.0207
	SD	0.190	0.314	0.452	0.174	0.386	0.00686	0.0268
	Range	0.128–0.656	0.207–1.11	0.771–1.89	0.499–0.913	0.508–1.58	ND–0.0250	0.00563–0.0717
Albumen	Mean	0.0289	0.00220	<LOD	<LOD	<LOD	<LOD	0.00333
	SD	0.0432	0.00258	NA	NA	NA	NA	0.00302
	Range	ND–0.0948	ND–0.00953	ND–0.0629	ND–ND	ND–0.00727	ND–0.00732	ND–0.00745
Yolk and albumen	Mean	0.179	0.284	0.657	0.353	0.434	0.00922	0.0120
	SD	0.115	0.157	0.224	0.0871	0.193	0.00265	0.0134
	Range	0.0648–0.375	0.104–0.554	0.386–0.947	0.250–0.457	0.255–0.788	0.00647–0.0132	0.00351–0.0366
Overall	Mean	0.276	0.480	0.820	0.408	0.403	0.0102	0.0201
	SD	0.169	0.192	0.278	0.0967	0.121	0.00330	0.0265
	Range	0.0727–0.539	0.208–0.889	0.475–1.19	0.297–0.574	0.290–0.623	0.00699–0.0153	0.00501–0.0712

Notes. All values are in μg L^{-1} wet weight. 'ND' indicates that a concentration was below the detection limit, while < LOD indicates that the overall mean fell under the detection limit.

Feathers, blood, and bones

The lead concentrations found in the feathers, blood, and bones of the chickens were consistently elevated above expected, non-contaminated levels. In fact, the feather lead concentrations exceeded not just those of control chickens but were more than double those found in prior experimental studies where chickens were fed metal-enriched feed [13.8 μg L^{-1} in Zhuang et al. (2014); 11.2 μg L^{-1} in Kim et al. (2020); Table 2]. The blood lead concentrations were similarly elevated above those found in an experimental study [990 μg L^{-1} in Zhuang et al. (2014)] and the standard background concentration of lead in bird blood (200 μg L^{-1}; Franson and Pain 2011; Table 2). Indeed, one of the four chickens sampled had a blood lead concentration that was more than double the acute lead poisoning threshold in chickens (1500 μg L^{-1}; Trampel et al. 2003). Similarly, the lead concentrations found in the bones of the two chickens that died during the course of this study were indicative of 'excessive lead exposure' (above 20 μg L^{-1}), as found by Franson and Pain (2011), and were higher than those recorded during an experimental study where chicks were fed a metal-enriched diet [21.4 μg L^{-1} in Baykov et al. (1996); Table 2].

Eggs

Lead concentrations in the eggs were generally highest in the shells, followed by the yolk, and then the albumen (Table 3). Due to concerns about human health risks from consuming the eggs, this study primarily focused on the lead concentration in the normal dietary components, specifically, the yolk and albumen (the 'edible portion'). The lead concentration in the edible portion of the eggs differed significantly across all collection months and between both commercially available egg groups, with the lead concentrations in the farm eggs noticeably elevated ($F = 16.7$, $df = 6$, $p < 0.001$; Figure 2). The lead concentrations in the edible portions of the eggs from the farm also varied significantly across the different collection months ($F = 7.73$, $df = 4$, $p < 0.001$; Figure 2).

To estimate the human health risks associated with consuming these eggs, the amount of lead within the edible portion of the eggs was compared to the EFSA BMDLs for developmental neurotoxicity in children, and nephrotoxicity and cardiovascular effects in adults (European Food Safety Authority 2010). Children under 8 years old could exceed the developmental neurotoxicity BMDL by eating one to two of the farm eggs per day (Table 4). By comparison, children under 8 years old would have to eat between 9 and 38 of the commercially available eggs tested during this study per day to exceed the BMDL (Table 4). The average adult could exceed the nephrotoxicity BMDL by consuming between two and six of the farm eggs (dependent on the collection month); to exceed the same threshold through eating the commercially available eggs, an adult

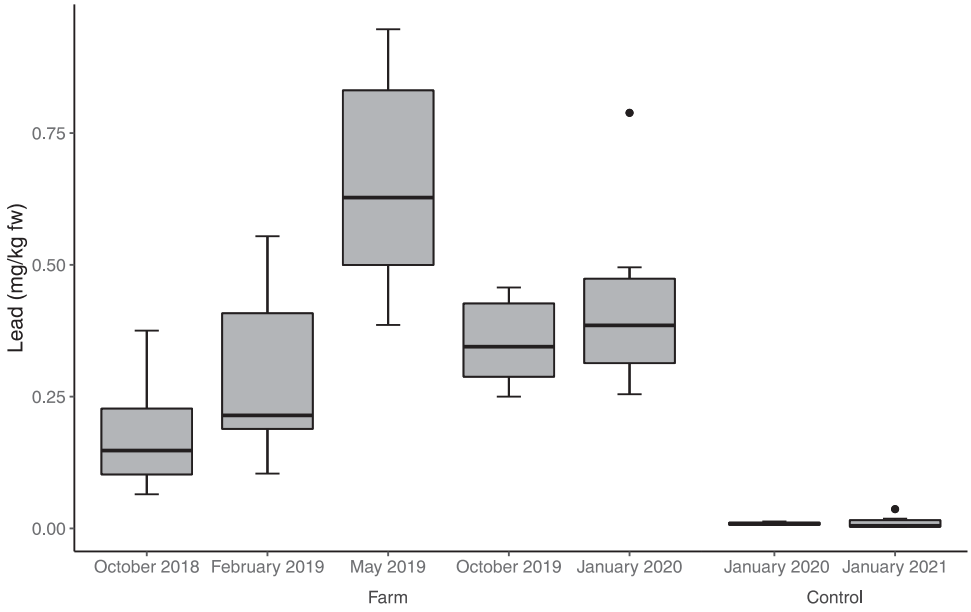

Figure 2. Pb concentrations in edible portions (yolk and albumen) of eggs from the farm and the commercially available eggs across collection months.

Table 4. Number of eggs that can be consumed in 1 day before exceeding EFSA thresholds.

					Farm Eggs					Commercially Available Eggs	
EFSA threshold type	Threshold (μg L^{-1} b.w. per day)	Age	Weight[b] (kg)	Threshold (mg of lead per day)	October 2018 ($n = 6$)	February 2019 ($n = 10$)	May 2019 ($n = 6$)	October 2019 ($n = 6$)	January 2020 ($n = 6$)	January 2020 ($n = 6$)	January 2021 ($n = 6$)
Developmental neurotoxicity BMDL[a,c]	0.00050	0–1 years	9.5	0.00475	0	0	0	0	0	15	9
		2–4 years	16.2	0.00810	1	0	0	0	0	27	16
		5–7 years	22.8	0.0114	1	1	0	0	0	38	22
		8–10 years	34.1	0.0171	2	1	0	1	1	57	33
		11–12 years	47.0	0.0235	3	2	1	1	1	78	46
		13–15 years	59.7	0.0299	4	3	1	2	2	100	59
Nephrotoxicity BMDL[c]	0.00063	Adult	78.6	0.0472	6	5	2	3	3	166	98
Cardiovascular BMDL[c]	0.00150	Adult	78.6	0.118	16	12	5	9	8	395	234

Notes. The number of eggs was rounded down to the nearest whole number. '0' means that eating one egg would exceed the respective EFSA threshold.
[a]Benchmark dose level (the lowest 95% confidence limit below the benchmark dose, or dose that is associated with a specific response).
[b]Average weights based on those recorded in the Health Survey for England 2019 (Moody 2019).
[c]EFSA European Food Safety Authority European Food Safety Authority (2010).

would have to eat almost a hundred eggs per day (Table 4). The cardiovascular BMDL threshold is more than double the nephrotoxicity BMDL, but it could still potentially be exceeded by the daily consumption of more than five of the farm eggs collected in May 2019 (Table 4).

Discussion

Chickens' lead exposure

The chickens in this study were exposed to high concentrations of lead via the lead-contaminated soil in and around their pens. This contaminated soil is likely their primary route of lead exposure, as the chickens were provided with store-bought feed, were given water directly from the mains, and did not have any access to the nearby stream. While mains water can be contaminated with lead, even notably high water lead concentrations (7.8 μg L^{-1}) associated with drinking water contamination events have relatively low lead concentrations compared to those found in the soil during this study (Table 1; Paranthaman and Harrison 2010). While the three chicken pens contained soil with elevated lead concentrations (compared to the soil NBCs), the track

adjacent to the chicken pens had a particularly high lead concentration. The landowner indicated that it was likely that the track had been built using mine spoil, as they stated that this was a common practice in the region. This seems probable, as the lead concentration found in the track strongly resembles the lead concentration found in the mine spoil itself.

When in their pens, the chickens could peck at gravel from the track, part of which ran along the boundaries of their pens. The landowner stated that the chickens favoured using gravel from the track as grit, even preferentially selecting it over oyster shells provided by the landowner. Prior studies investigating the effects of chickens consuming lead-based grit have found high lead concentrations in the birds, and have observed significant negative health effects, including mass mortality in some cases (Salisbury et al. 1958). Lead-contaminated grit is particularly dangerous, as the bird will be continuously exposed to lead as the grit slowly degrades in the gizzard (Salisbury et al. 1958). If the chickens were ingesting gravel from the track to use as grit, this could explain the high lead concentrations found within their feathers, blood, and bones.

The lead concentrations in the chickens' feather, blood, and bone samples were suggestive of severe lead toxicity, and indicated long-term, continuous lead exposure. While lead remains in the blood for a few weeks after an exposure incident, lead is stored in bones and remains sequestered there for years after exposure (Franson and Pain 2011). High lead concentrations in both the blood and bone samples, therefore, suggest that the chickens had been exposed to lead over multiple years, and were still being exposed to lead when the blood samples were collected (in October 2018). This is consistent with the chickens being continuously exposed to lead over years, likely through the soil in their pens and the adjacent gravel track. Despite the high lead concentrations in the feather, blood, and bone samples, symptoms of overt lead toxicity were not observed in the chickens during the course of this study. However, this is common in cases where chickens are exposed to lead, even at high concentrations (Salisbury et al. 1958; Roegner et al. 2013; Bautista et al. 2014; Kim et al. 2020).

Environmental exposure and lead concentrations in eggs

The lead concentrations in the edible portions of the farm eggs varied significantly between sampling events. This could be due to variations in the chickens' lead exposure as a result of management changes throughout the study period. Prior to the beginning of the study, the chickens' owner fed them by placing food directly in a trough. After the first site visit in October 2018, the chickens were instead encouraged to forage for food, with the owner spreading supplementary feed onto the grass and soil within their pens. It is possible that the more foraged diet led to the chickens inadvertently ingesting more lead-contaminated soil and taking up more grit from the nearby contaminated track to aid with digestion (van der Meulen et al. 2008; Grace and MacFarlane 2016; Takasaki and Kobayashi 2020). This could explain the observed increase in egg lead concentrations in February and May 2019 (Figure 2 and Table 3). The owner then decided to move the chickens to an indoor barn with concrete flooring and no outdoor access. After this move, the chickens' egg lead concentrations decreased slightly, though they remained higher than the lead concentrations found in the eggs at the beginning of the study, even after the chickens had been kept in the barn for more than 6 months (Figure 2 and Table 3). It is possible that the chickens were mobilising lead stored in their bones while transferring calcium from bones for eggshell production, and therefore were still producing lead-contaminated eggs, even after their exposure to environmental lead was limited (Bar 2009; Bautista et al. 2014). After January 2020, and the end of this study, the owner returned the chickens to the original pens, so there is no indication as to whether the lead concentrations in the eggs would have continued to decline if the chickens remained in the barn.

Eggs and human health risks

Based on the amount of lead detected in the edible portions of the farm eggs, human adults

consuming between three and seven of these eggs in a day would be at risk of developing chronic kidney disease (European Food Safety Authority 2010). This level of egg consumption is rare for egg-eating adults in the UK, who eat around 5–6 eggs per week (Gibson and Gray 2020). Furthermore, lead exposure would greatly vary depending on which egg components are consumed; a person preferentially eating the albumen from these eggs would be exposed to less lead than someone regularly eating either the yolk or yolk and albumen. However, while following the EFSA thresholds would likely minimise the risk of developing severe adverse health impacts, even low levels of chronic lead exposure have been known to affect adults. Low lead exposure has been linked to various symptoms, including cognitive impairments, mood disorders, and a higher risk of cardiovascular disease (Vorvolakos et al. 2016; Obeng-Gyasi 2020). Because of the extensive effects of exposure to lead at low concentrations, the World Health Organization has stated that 'there is no level of exposure to lead that is known to be without harmful effects' (World Health Organization 2019).

Children are particularly vulnerable to lead's toxic effects. This is partly due to the active development of their organs/systems (in particular, their developing central nervous system), and also due to their higher lead uptake rates: a child's gastrointestinal tract absorbs 50% of consumed lead in food, while an adult's tract only absorbs 10–15% (Tong et al. 2000; Järup 2003). Lead exposure in children has been linked to inhibited growth and impaired physical and neurobehavioral development (Yang et al. 2013; Vorvolakos et al. 2016). In particular, lead can cause lifelong cognitive and behavioural problems, including decreased brain volume, lower IQ scores, inhibited visual brain development, and slower information processing (Tong et al. 2000; Järup 2003; Cecil et al. 2008; Ethier et al. 2012; Boucher et al. 2014; Liu et al. 2014; Karri et al. 2016; Vorvolakos et al. 2016). Based on the EFSA BMDL for children, if a young child regularly ate one to two of the eggs tested in this study, they could become cognitively impaired (measured by a reduction in Full-Scale IQ scores) (European Food Safety Authority 2010). Even low levels of lead exposure in children (indicated by blood lead concentrations from 15 μg L^{-1} down to <5 μg L^{-1}) could lead to a variety of neurocognitive and behavioural impairments, including a lack of attention, increased anxiety, and reduced executive function (the ability to plan and adapt) performance (Chiodo et al. 2004; Roy et al. 2009; Vorvolakos et al. 2016). Lead exposure in children should therefore be minimised as much as possible to avoid lifelong repercussions (Vorvolakos et al. 2016).

Conclusions

Chicken eggs can be a key source of lead exposure for humans. This case study demonstrates that a flock of chickens living near a derelict metal mine can accumulate high concentrations of lead within their bodies and produce lead-contaminated eggs. The presence of lead in chicken eggs is of particular concern because, despite the potentially severe adverse health impacts, lead contamination in eggs is difficult for owners or consumers to detect, as chickens rarely exhibit symptoms of lead toxicity, and lead-contaminated eggs appear normal. Consuming lead-contaminated eggs can have profound negative health effects, especially if the eggs are eaten on a regular basis, and/or if they are eaten by children. As there are potentially hundreds of thousands, if not millions, of abandoned metalliferous mine sites worldwide (United Nations Environment Programme 2001; Venkateswarlu et al. 2016), and over 1,300 in Wales alone (Environment Agency Wales 2002), further studies examining the lead concentrations in eggs produced in similar environments to those in this study are clearly necessary. Better public awareness, additional research, and increased regulations on eggs produced in lead-contaminated areas are necessary to reduce the risk of lead toxicity from the consumption of lead-contaminated eggs.

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ORCID

Andrea Sartorius http://orcid.org/0000-0002-4922-2443
Matthew Johnson http://orcid.org/0000-0003-1336-5490
Scott Young http://orcid.org/0000-0002-3371-7185
Malcolm Bennett http://orcid.org/0000-0002-5490-2910
Kerstin Baiker http://orcid.org/0000-0003-4855-6879
Paul Edwards http://orcid.org/0000-0003-3227-0921
Lisa Yon http://orcid.org/0000-0002-9765-3192

Data availability statement

The data that support the findings of this study are openly available in the Nottingham Research Data Management Repository at https://doi.org/10.17639/nott.7117.

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