Heliyon 8 (2022) e10014

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

European mammal exposure to lead from ammunition and fishing weight sources

Louise Chiverton[a,*], Ruth Cromie[b], Richard Kock[a]

[a] The Royal Veterinary College, London, NW1 0TU, UK
[b] Wildfowl & Wetlands Trust, Slimbridge, Gloucestershire, GL2 7BT, UK

ARTICLE INFO

Keywords:
Lead
Ammunition
Fishing weights
Risk assessment
Source-pathway-receptors
European mammals

ABSTRACT

Ammunition and fishing weight usage is the greatest largely unregulated contributor of lead (Pb) deposition to the European environment. While the range of negative impacts of Pb exposure to humans and avian wildlife are relatively well documented, little is known about risks to wild mammals despite recent scientific interest and publications. A qualitative risk assessment of the potential Source-Pathway-Receptor linkages for European mammal exposure was conducted, based on literature reviews and existing evidence and discussions with experts from the fields of wild mammal feeding ecology, behaviour and health.

The assessment identified 11 pathways for mammal exposure to Pb, with all 243 European species likely to be potentially exposed via one or more of these. All species were identified as potentially exposed via ingestion of water with elevated Pb from degraded ammunition/fishing weights. Ingestion of vegetation with elevated Pb from degraded ammunition/fishing weights potentially exposed many species (158), 78% of which had a potentially high risk of exposure when feeding in areas of high Pb deposition. Ingestion of retained ammunition in previously shot prey and/or discarded kill/gut piles with embedded ammunition was another significant pathway, contributing to predatory and scavenging carnivorous mammal exposure where an individual exposure event would be expected to be high.

The mechanisms by which Pb from ammunition and fishing weight sources are moved up trophic levels and 'transferred' from areas of high deposition into wider food chains e.g. via water, flying invertebrates and herbivores being subsequently preyed upon requires further investigation.

In conclusion, there are multiple and diverse Source-Pathway-Receptors linkages for European mammal exposures to Pb and evidence of exposure, from Europe and elsewhere, exists for some herbivores, carnivores, omnivores and insectivores. Both fatal but more likely non-fatal chronic and acute exposures may be expected to occur in wild European mammalian species, including those in poor conservation status.

1. Introduction

Lead (Pb) is a toxic heavy metal which, on ingestion, inhalation or other absorption, negatively impacts the neurological development and functioning of a range of vertebrates (Fuchs et al., 2021). In recognition of there being in effect no safe level of Pb exposure, international coordination and introduction of policy, has led to global Pb releases being controlled and drastically reduced (Stroud, 2015). However, the toxic substance continues to be released to the environment, largely unregulated, in metallic form as shotgun pellets, bullets, and fishing weights. The European Chemicals Agency (ECHA) estimates that 97,000 tonnes of ammunition and fishing weights are deposited in terrestrial environments in the European Union countries annually (ECHA 2021).

Game hunting and sports shooting are widespread across Europe, providing income and recreation, and a food source in particular for hunting families and other game eaters. Pb ammunition has been used since the invention of firearms; the malleable metal favoured for its ballistic qualities and lethality (ECHA, 2021). Ammunition, and in particular bullets, fragment on impact and scatter Pb particles including nanoparticles through tissues, elevating tissue Pb concentrations (Kollander et al., 2017) thus providing dietary exposure to lead for game meat consumers (Green and Pain, 2019).

* Corresponding author.
E-mail address: louchiv@gmail.com (L. Chiverton).

https://doi.org/10.1016/j.heliyon.2022.e10014
Received 2 January 2022; Received in revised form 10 April 2022; Accepted 15 July 2022

For wildlife, there is an extensive body of literature on the impacts of Pb exposures from ammunition and fishing weight sources for avian species (Mateo, 2009; Ganz et al., 2018; Grade et al., 2019; Pain et al., 2019). Regulation to restrict Pb shot use in wetland habitats was adopted across the EU in January 2021, in response to high levels of mortality and morbidity in waterbirds in Europe (European Commission, 2021). Avian species feeding in terrestrial habitats are exposed to lead ammunition, including predators and scavengers, which consume lead ammunition embedded in the prey and carrion they consume (Monclús et al., 2020).

As a follow on from the restriction of lead shot in wetlands, and to protect human, wildlife, livestock and environmental health, a restriction proposal in the EU is currently under development, with interested parties providing evidence and being consulted in relation to the restriction of Pb ammunition and fishing weights from all outdoor hunting, sport shooting and fishing settings. Various knowledge gaps remain including the likelihood of exposures to wildlife other than birds.

Mammals are an important part of European biodiversity, performing various ecosystem services (Lacher et al., 2019) and holding intrinsic value for humans. Their presence at a variety of trophic levels marks them as excellent bioindicators for environmental health. However, the toxic effects of Pb from ammunition and fishing weight sources in wild mammals are sparsely studied in this taxon. It is known that lead poisoning of domestic mammals occurs, such as that of cattle following ingestion of foodstuffs contaminated by Pb shot from shooting ranges (Frape and Pringle, 1984; Rice et al., 1987; Payne and Livesey, 2010; Payne et al., 2013) indicating that wild herbivores may be similarly exposed. Lead poisoning in captive wild mammals has been reported following consumption of lead-shot meat (North et al., 2015; Hivert et al., 2018). In wild settings, this has been reported in cougars (*Puma concolor*) with post-mortem procedures and radiographs identifying metallic particulate Pb within the gastrointestinal (GI) tract (Burco et al., 2012). Pb may circulate in blood or be stored within kidney or bone tissue, the latter leading to endogenous exposure during times of high bone resorption (particularly during pregnancy) (Fuchs et al., 2021). Biologically incorporated Pb can be traced to its source isotopically, however this methodology is challenged by the diversity of chemical fingerprints and Pb recycling (Arrondo et al., 2020). The aim of the study is to add to the body of literature surrounding the fate of the anthropogenically

Table 1. Potential pathways for mammal exposure from Pb from ammunition and fishing weight sources. The colours in the number and name columns correspond throughout the paper (Agency for Toxic Substances and Disease Registry (ATSDR), 2020; Comino et al., 2011; Jacks et al., 2001; Mateo et al., 2011; Peralta-Videa et al., 2009; Vallverdú-Coll et al., 2015).

Number	Pathway Name	Description
1	Direct ingestion from environment (shot/bullet/fishing weight)	Consumption of whole or fragmented spent ammunition and fishing weights directly from the environment (not embedded in prey).
2	Soil with elevated Pb from degraded shot/bullets/fishing weight	Spent ammunition collects on the ground after shooting and will degrade through weathering processes over time. Physical transformation speed depends on factors such as the soil type, pH, precipitation, and vegetation (ATSDR, 2020).
3	Vegetation with elevated Pb from degraded shot/bullets/fishing weight	Degradation through oxidation to PbO_2 increases the availability of metallic Pb to vegetation (ATSDR, 2020). Pb is taken in through the roots; some species have root to stem/leaf transference capabilities but is mostly stored in subterranean growth (Peralta-Videa et al., 2009; Comino et al., 2011).
4	Water with elevated Pb from degraded shot/bullets/fishing weight	Degradation of metallic Pb in water is slow (Jacks et al., 2001) but waterways can become contaminated through run off from high deposition sites (Mariussen et al., 2017).
5	Invertebrate prey with elevated Pb from degraded shot/bullets/fishing weight	Ingestion of matter with increased Pb concentration may elevate the tissue Pb levels of invertebrates. Mammals which consume these invertebrates are exposed via indirect consumption of degraded ammunition.
6	Vertebrate prey with elevated Pb from degraded shot/bullets/fishing weight	Prey may have been exposed via degraded ammunition in their diet or direct ingestion of spent ammunition particulate which dissolves and is incorporated with blood or tissues. This includes matter such as bird and fish eggs; where mothers have been exposed and so produce eggs and offspring with elevated Pb levels (Vallverdú-Coll et al., 2015; Pain et al., 2019).
7	Ingestion of live prey with embedded ammunition	Unsuccessful shooting incidents leave animals with embedded particulate ammunition. As one example, 68% of live mallards (*Anas platyrhynchos*) in The Netherlands are estimated to contain embedded shot (Pain et al., 2015) which is then available for ingestion by predatory species who are likely to target weaker, wounded animals when hunting.
8	Ingestion of discarded kill/gut piles with embedded ammunition	Viscera from large game is discarded during field dressing and kills are not always collected. This is available for consumption by a wide range of scavenging species, exposing them to the Pb fragments which scatters through the tissue on impact.
9	Ingestion of prey which has ammunition particulate in gastrointestinal (GI) tract	Avian species with a gizzard which ingest shot, or other species which graze or consume soil may accidentally ingest ammunition particulate while foraging. Particulate may be ingested by a predator if it has been consumed recently and therefore not yet passed through the digestive tract.
10	Retained ammunition from wound solubilized into tissue	Unsuccessful shooting incidents leave ammunition embedded in the tissue to be solubilized and absorbed into the blood and tissue or to be stored in bones (Mateo et al., 2011).
11	Ingestion of fishing weight particulate in prey	Most common in species which live or forage in aquatic ecosystems. Prey may consume fishing weights accidentally and be present in the digestive tract of prey species when consumed by a predator.

released Pb and determine the risk of exposure to Pb from ammunition and fishing weight sources for European mammals. Given the known toxicity of Pb at almost any level, a risk-based approach is recommended.

2. Methodology

2.1. Risk question

The risk question guiding this qualitative assessment was: *What is the likelihood that European mammals will be exposed to Pb from ammunition and fishing weight sources?*

2.2. Data collection

The potential exposure pathways are described in Table 1. These were identified through an initial literature review and confirmed by professionals working in wildlife health, toxicology, and ecology industries.

A list of mammal species present in Europe was compiled using the IUCN Red List Database, European Commission's European Red list, and the European Environment Agency's “Nature Information System” (EUNIS). Conservation status (European and EU), population trend, EU presence and feeding strategy were reported by cross-checking each species through the three databases system, with the most current data being used for this study. Species were included if they had a known presence in any of the 50 countries west of the Ural mountain range and river system in Russia and Kazakhstan (National Geographic Society, 2012). Species were considered present in the European Union if there were reports of established populations in any of the 27 member states (EU, 2021). Population trends reported are those from the whole European region.

Feeding strategy data were collected using the habitat and ecology section of European Red list data (European Environment Agency, 2018) and literature reviews on Google Scholar when data were sparse. To mitigate confirmation bias, literature reviews were standardized by using the scientific species name followed by “diet”, “feeding ecology” or “prey” to establish preferences and strategy for each species. Where no data were available, feeding strategy data were extrapolated from similar species. The research was collated within an MS Excel spreadsheet, with each species scored dependent on the “likelihood of exposure” to Pb ammunition or fishing weights from their feeding strategy.

2.3. Potential exposure pathways

Exposure may arise from direct consumption of metallic particulate from the environment, consumption of particulate Pb within prey or from ingested material with elevated elemental Pb originating from ammunition/fishing weight sources. These are described in Table 1.

2.4. Likelihood of exposure

Exposure scores were based on the perceived possibility of ammunition (degraded or particulate) exposure in areas of high and low ammunition deposition accounting for both likelihood (including a likelihood of spatial overlap with areas with shooting or fishing activities) and frequency of exposure.

High deposition areas were defined as places which are consistently used for hunting or sport shooting activity such as shooting ranges, clay pigeon shoot sites, annual culling sites or game shooting reserves. Low deposition areas were defined as areas where shooting (or fishing) occurs on an irregular basis such as forests with low intensity shooting, or one-off/infrequent pest management events.

Exposure scores reflect feeding ecology, dietary preferences and frequency as reported in current literature. Rationale for scores was outlined in the comments columns. Scores were based on a 5-point system (0–4) as described in Table 2. Where exposure routes scored 1 in high deposition areas, this remained un-changed for low deposition areas, as the risk of exposure would only be non-existent in areas where no ammunition was released.

Table 2. Description and examples of likelihood scores given for European mammal species for each identified pathway.

Score	Description
0	**Never exposed/no evidence for exposure** *Mammal never consumes the food source/food source never exposed. e.g. Lagomorphs do not consume vertebrate prey*
1	**Very unlikely; exposure may only occur in specific circumstances** *Mammal not recorded to consume food source, limited evidence to suggest exposure. Pathway is tenuous but plausible. e.g. Lagomorphs or squirrels consuming lead shot – it wouldn't be intentionally sought out but might be nibbled and possibly consumed.*
2	**Possible; some evidence for exposure, dependent on species preferences** *Food source may or may not become exposed; mammal may or may not be exposed due to feeding preferences. e.g. Omnivorous species have a wide dietary niche; exposure is possible if they are feeding on exposed source.*
3	**Likely; evidence for exposure exists, dependent on frequency of exposure** Exposure pathway has been confirmed in species or species with similar feeding ecology, or experimentally. Wild mammal exposure dependent on intake frequency. *e.g. Ruminants accidently ingest soil at varying rates when grazing; if ammunition is present on pasture, some species are likely to suck-up particulates.*
4	**Highly likely; supported by case studies and peer-reviewed papers.** *Exposure pathway confirmed in species or species with similar feeding ecology. e.g. Shrews (Family: Soricidae) consume large volumes of earthworms, which readily accumulate Pb in body tissue. Shrews have a high risk of exposure from ingestion of invertebrate prey with elevated body Pb in areas of high lead deposition.*

Per pathway, considering the magnitude of exposure (in effect dose), a qualitative assessment was made of the likelihood of an individual exposure event being high to differentiate between exposure to small quantities of Pb e.g. within water in one drinking event (Pathway 4) vs consumption of particulate Pb in a gut pile (Pathway 8).

2.5. Expert contribution

Experts were contacted and invited to contribute their expertise to the qualitative assessment during the drafting stage. Experts were chosen due to their expertise in mammal ecology and behavior, ecotoxicology or previous experience with Pb pollution in European wildlife. All were given access to an early draft of the assessment and a summary of current Pb exposure knowledge before being asked to contribute their opinion based on their own experience with Pb ammunition and mammal feeding ecology. Their insights were discussed, and alterations were made to the risk assessment as required.

Ethical clearance for the interviews with these professionals was approved by the Royal Veterinary College (RVC) Social Sciences Research Ethical Review Board (URN SR2021-0136). Expert consent to participate was provided by replying to an email stating their willingness to contribute. Some experts replied with a signed consent form.

3. Results

Full qualitative risk assessment was undertaken of potential pathways for exposure to Pb from ammunition and fishing weight sources for 243 European mammal species. Key evidence from the literature for affected taxa is summarised in Table 3, along with the purported exposure pathways for each species. Figure 1 is an illustrated flow diagram, depicting the exposure pathways from shooting activity only. The coloured arrows are indicative of the route of exposure, corresponding with the colours in the tables.

Proposed pathways were evaluated against published Pb exposure studies and species feeding ecology. The number of species predicted to be at risk of exposure based on current literature and feeding ecology are presented in Table 4, along with the number of threatened species exposed via each pathway and percentage of exposed species with high exposure risk (score = 4). High exposure risk relates only to areas of high deposition as no species had a high exposure risk from any pathway in

Table 3. A Summary of evidence for mammal exposure to Pb from ammunition and fishing weight sources and the pathways by which they have been exposed.

Feeding strategy	Species	Evidence (main research findings)	Reference	Exposure pathway
Herbivore	Cattle (*Bos taurus*)	*Cattle grazing in vicinity of clay pigeon range found with Pb fragments retained in forestomach* *Plant Pb uptake is dependent on factors such as tolerance and soil physiochemical properties. Where soils have become contaminated from shooting activities, grazing livestock and wild animals may become poisoned or introduce Pb to the food chain.*	Payne et al. (2013) Dinake et al. (2021)	1, 2 and 3
	White-tailed deer (*Odocoileus virginianus*)	*Pb fragments in abomasum of deer linked to sub-clinical elevated kidney Pb concentration.*	Lewis et al. (2001)	1
	Eastern cottontail (*Sylvilagus floridanus*)	*Herbivorous small mammals feeding on vegetation which has accumulated Pb have elevated risk of toxicosis.*	Bennett et al. (2007)	3
	European hare (*Lepus europaeus*)	*23% of hares studied had multiple injuries from previous non-fatal shootings, spreading Pb pellet fragments through the entire body.*	Stankevičiūtė et al. (2013)	10
Carnivore	Cougar (*Puma concolor*)	*Free ranging cougars are known to gorge on prey/scavenged carcasses and therefore if carcass contains fragments of ammunition, cougars are likely to ingest large volume of Pb in a single sitting.*	Burco et al. (2012).	7, 8 and 9
	Harbour Seal (*Phoca vitulina*)	*Marine mammals reported with toxicosis resulting in death after ingestion of a single Pb fishing sinker attached to fish prey.*	Zabka et al. (2006)	11
Omnivore	Brown bear (*Ursus arctos*)	*Bears could be exposed when hunting wild ungulates; only a small part of diet and dependent on geographic location* *In Quebec, scavenging mammals predicted to be present with similar fluctuating blood Pb levels as avian species throughout the hunting season.* *Ammunition could not be confirmed as source of Pb exposure to large carnivores in the greater Yellowstone ecosystem. Grizzly bears had elevated blood Pb levels, but these did not correlate with shooting seasons.* *Pb concentration in blood of suckling cubs found to correlate with mother's blood and milk concentrations. Original source of Pb is un-confirmed however ammunition predicted as major contributing factor.*	Lazarus et al. (2020) Legagneux et al. (2014) Rogers et al. (2012) Fuchs et al. (2021)	6, 7, 8 and 9 Possibly 2, 3 and 11
	Grey Wolf (*Canis lupus*)	*Wolves whose territory overlaps with high density deer hunting site may have greater exposure risk due to increased Pb in viscera piles.*	Kelly et al. (2021)	8
	Bank vole (*Myodes glareolus*)	*Elevated Pb levels of herbivorous small mammals at abandoned shooting range indicative of ammunition's mobility through the food chain once degraded.* *Significant portion of metallic Pb from high deposition sites is bioavailable in soil, entering the trophic network through edaphic organisms.*	Ma (1989) Migliorini et al. (2004)	2, 3 and 5
	Grey Squirrel (*Sciurus carolinensis*)	*Squirrels consistently found with highest liver and kidney Pb levels; suggesting that initial poisoning case was not isolated and Pb toxicosis could threaten mammal populations foraging within the vicinity of shooting ranges*	Lewis et al. (2001)	1 and 3
Insectivore	Shrews (Family: Soricidae)	*Metallic Pb from ammunition is available to readily enter food chains after conversion to chemical form (Pb^{2+}) in sandy and acidic soils.* *Soil habitat function affected as high concentrations of Pb deposited at shooting ranges caused adverse effects on terrestrial invertebrates and is indicative of a high retention capacity of Pb in soils.* *Earthworms have greater exposure than other edaphic species due to direct ingestion of soil particles and contaminants.* *High deposition of ammunition at shooting range facilities linked to elevated risk from consumption of earthworms (which bioaccumulate Pb from soil)*	Ma (1989) Rodríguez-Seijo et al. (2017) Bennett et al. (2007)	2, 3 and 5

areas of low deposition, noting however that individual exposure events (in effect dose) in areas of both high or low Pb deposition may be high.

Table 5 attempts to draw together an illustrative summary of the species or species groups at risk per pathway combining likelihood of exposure and magnitude of exposure event.

4. Discussion

European mammal exposure to Pb from ammunition and fishing weight sources is sparsely studied in current literature. The potential pathways for mammal exposure are both numerous and interlinked, and due to the interspecies variation in feeding ecology, are likely not all covered in this study. Overall the assessment indicates that movement of Pb from the shooter or fisher into the wider environment and thereon different receptors, mammals in this case but likely other taxa too, is perhaps more extensive and insidious than previously thought.

There are undoubted complexities in attempting to determine exposure risk and dose of exposure when considering so many species in so many habitats with different levels of Pb contamination. However, results from high deposition areas found all European mammals have a risk of potential exposure to Pb from ammunition/fishing weight sources from at least one of the eleven described pathways. Attention should be focused on the degraded ammunition pathways, as ingestion of elevated Pb in vegetation (Pathway 3) water (Pathway 4) and invertebrate prey (Pathway 5) were found to potentially expose the most species across a range of taxa. In terms of magnitude of exposure event as well as likelihood of exposure risk, ingestion of particulate Pb directly from the environment (Pathway 1) and in prey and gut piles with embedded ammunition (Pathways 7 and 8) will also be further explored.

It is likely that for mammals most exposures are sub-lethal, and this study does not assess thresholds for clinical toxicosis presentation. The World Organisation for Animal Health (WOAH) states that blood concentrations >0.35 ppm and liver/kidney concentrations of ≥6–10 ppm (wet weight) are indicative of subclinical intoxication in vertebrates (Gieger and Furmaga, 2020); Pb concentrations above these baseline figures suggest above-background-level exposure.

4.1. Pathway 1 - Direct ingestion from environment (shot/bullet/fishing weight)

Grazing deer (rather than browsing) which are numerous and common in Europe would be expected to ingest some particulate Pb when feeding in areas of high Pb shot deposition outside of the hours or events in which the shot is deposited. Lewis et al. (2001) describes such exposure in white-tailed deer (*Odocoileus virginianus*) at a North American shooting range. Similarly, exposures might be expected for granivorous species of small mammal. Pb dust and fragments at or near to shooting ranges would increase this likelihood in those high deposition areas (Chrastný et al., 2010).

4.2. Pathway 3 – Vegetation with elevated Pb from degraded ammunition/fishing weights

This pathway potentially exposed 158 species (65%), 78% of which had a high risk of exposure when feeding in areas of high Pb deposition. Trophic contamination from degraded Pb has the potential to impact a majority of species within an ecosystem. However, those with narrow diet diversity and small territories are most likely to suffer if their habitat overlaps with a high deposition site. Extreme cases of bone disintegration in waterbuck (*Kobus ellipsiprymnus defassa*) were associated with heavy metal contamination of soil and forage in Lake Nakuru National Park, Kenya (Jumba et al., 2007), and the accumulation of Pb in some toxin-tolerant plant species (Fahr et al., 2013) implies that even historic sites of high deposition could be causative of herbivore toxicosis.

Large volumes of Pb being used for sports shooting, 77,000 tonnes per year in the EU (ECHA, 2021), indicates that Pb concentrates in shooting ranges (Sehube et al., 2017; ECHA, 2021) which provides conditions for herbivorous mammal exposure. Evidence of wild mammals with elevated Pb levels from vegetation contaminated by ammunition/fishing weights exists (Ma, 1989; Bennett et al., 2007) but is limited. However, this assessment demonstrates the potential for dietary exposure when foraging in high deposition sites. 96.6% of adsorbed Pb was found to accumulate in root tips in the plants studied by Wierzbicka and Antosiewicz (1993), inhibiting plant growth and exposing subterranean herbivores such as hamsters (Family: Cricetidae), porcupines (*Hystrix cristata*) and moles (Family: Talpidae) to the toxin. Herbivorous mammals require a high daily intake to meet their metabolic energy requirements; mammals such as rabbits (*Oryctolagus cuniculus*) consume around 6% of their body weight in forage daily (Armstrong, 1996). Data from Sneddon et al. (2009) found ryegrass (*Lolium perenne*) from shooting range fields to contain 38.4 mg/kg of Pb suggesting that rabbits could be exposed to 3.84mg of Pb each day (assuming a 0.1kg dry weight intake for a 1.5kg animal). As bioavailability of Pb from soil - vegetation - mammals is thought to be proportional to the concentration of the initial contamination (Angelova et al., 2010), continued dietary exposure in herbivores such as rabbits will likely lead to chronic toxicosis. Greater research investment is required to discover the extent to which grazers are exposed in Europe as increased Pb concentrations in these primary consumers could lead to the exposure of their predators and offspring.

4.3. Pathway 4 – water with elevated Pb from degraded ammunition/fishing weights

100% of assessed species were predicted to be exposed where water is contaminated with degraded Pb although no species had high risk of exposure. Species at highest risk were semi-aquatic mammals such as otters (*Lutra lutra*) and beavers (*Castor fiber*) which habituate riverbanks and are reliant on waterways for food. Despite reports of contamination of surface water from shooting ranges (Kajander and Parri 2014; ECHA, 2021), there are relatively few reports of water systems becoming contaminated solely from fishing weight deposition. Mariussen et al. (2017) found where water was contaminated by shooting range run-off, fish suffered the worst effects. Mammals in the area were not studied. European otter populations have historically been limited by anthropogenic use of orgnochlorine pesticides and the species is known to be

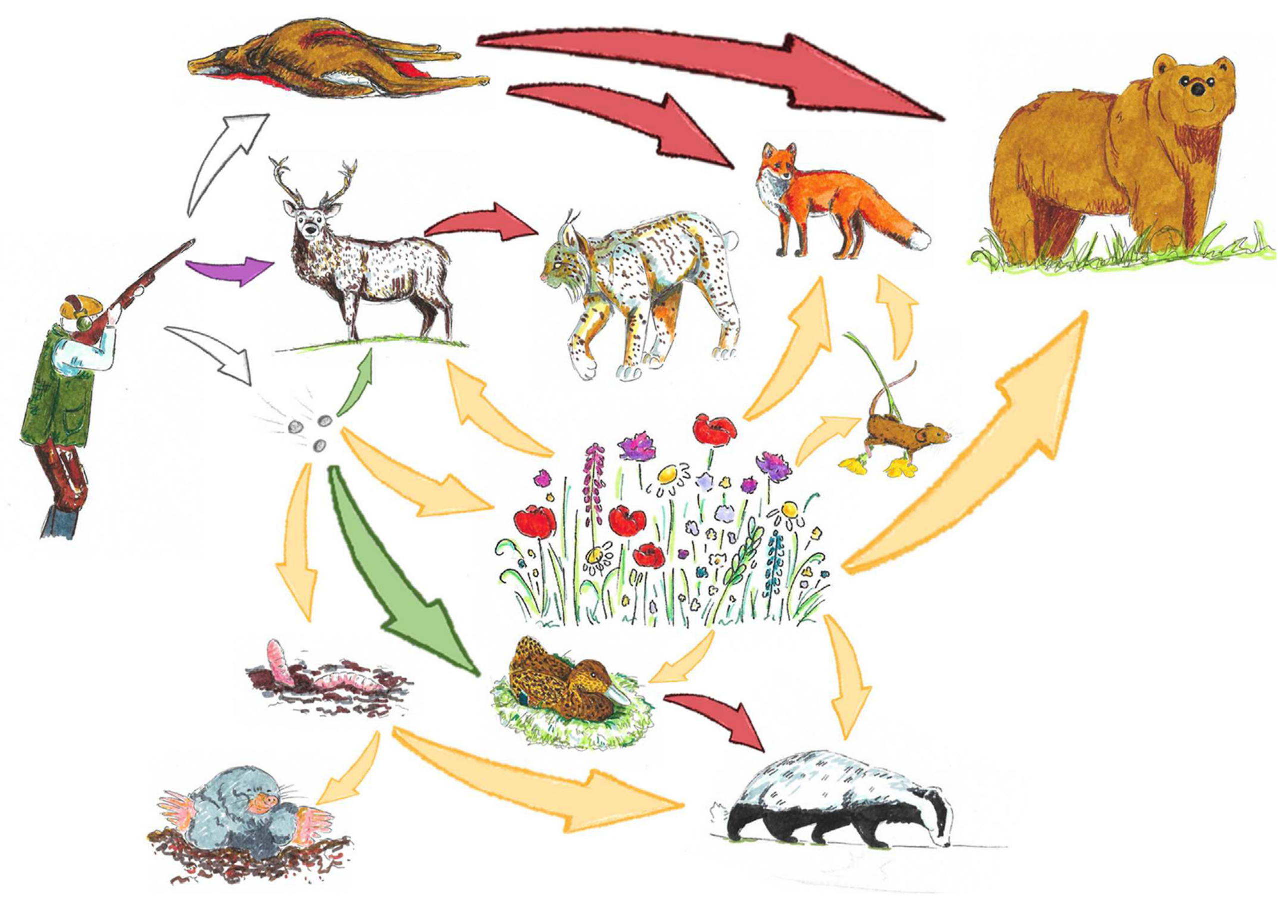

Figure 1. Flow diagram summarizing the fate of Pb ammunition after release from shooting activity for European mammals. Red arrow: exposure via ingestion of embedded ammunition in prey. Yellow arrow: exposure via ingestion of degraded Pb in diets. Green arrow: exposure via direct ingestion of particulate ammunition. Purple arrow: exposure via retained ammunition from non-fatal shot. Arrow size is not indicative of exposure. This diagram is not exhaustive of all potential exposure routes but highlights key risk pathways within a European system.

Table 4. Total number of European species exposed, proportion of exposed species with highest risk of exposure and number of exposed threatened species (IUCN conservation status of near threatened, vulnerable, endangered, or critically endangered at European level) and qualitative assessment of likelihood of an individual exposure event being high. Values are based on areas with high Pb deposition. Score = 4 indicate high likelihood of exposure.

Pathway	Total number of European species with exposure risk (%) N=243	*Number of threatened species with exposure risk (%)*	Total number of species with score = 4 (%)	*Number of threatened species with score = 4 (%)*	*Likelihood of individual exposure event being high (+, ++, +++)***
1 Direct ingestion from environment (shot/bullet/fishing weight)*	**81 (33.3%)**	*8 (9.9%)*	0 (0%)	*0 (0%)*	*+++*
2 Soil with elevated Pb from degraded shot/bullets/fishing weight	85 (35%)	*9 (10.5%)*	0 (0%)	*0 (0%)*	*+*
3 Vegetation with elevated Pb from degraded shot/bullets/fishing weight*	**158 (65%)**	*22 (13.9%)*	**123 (77.8%)**	*18 (14.6%)*	*+*
4 Water with elevated Pb from degraded shot/bullets/fishing weight	**243 (100%)**	*49 (20.2%)*	0 (0%)	*0 (0%)*	*+*
5 Invertebrate prey with elevated Pb from degraded shot/bullets/fishing weight	125 (51.4%)	*29 (23.2%)*	88 (70.4%)	*24 (27.2%)*	*+*
6 Vertebrate prey with elevated Pb from degraded shot/bullets/fishing weight	62 (25.5%)	*9 (14.5%)*	31 (50%)	*6 (19.4%)*	*+*
7 Ingestion of live prey with embedded ammunition	35 (14.4%)	*6 (17.1%)*	10 (28.6%)	*2 (20%)*	*+++*
8 Ingestion of discarded kill/gut piles with embedded ammunition	23 (9.5%)	*3 (13%)*	18 (78.3%)	*3 (16.7%)*	*+++*
9 Ingestion of prey which has ammunition particulate in gastrointestinal (GI) tract	40 (16.4%)	*6 (15%)*	10 (25%)	*2 (20%)*	*++*
10 Retained ammunition from wound solubilized into tissue	40 (16.4%)	*6 (15%)*	0 (0%)	*0 (0%)*	*++*
11 Ingestion of fishing weight particulate in prey	32 (13.1%)	*6 (18.8%)*	3 (9.4%)	*3 (100%)*	*++*

*Consumption of lead particles or dust on vegetation from shooting ranges (Chrastný et al 2010) arguably sits within or between Pathways 1 and 3.
**+ = low likelihood of high individual exposure event, ++ = medium likelihood of high individual exposure event, +++ = high likelihood of high individual exposure event.

sensitive to pollutants within the food chain (Mason and Macdonald, 1993; Lemarchand et al., 2011). Therefore, while ingestion of water with elevated Pb does not seem to present a high risk to mammals here, further research of mammals living downstream of shooting facilities would be beneficial.

4.4. Pathways 5 - Invertebrate prey with elevated Pb from degraded ammunition/fishing weights

Of the 125 invertebrate-eating mammals in Europe, 70.4% have a high risk of Pb exposure from this dietary source if feeding in areas of high deposition. 58% of global animal biomass constitutes arthropods, molluscs, and annelids (Bar-On et al., 2018). If exposed to pollutants, invertebrates can rapidly contaminate ecosystems, due to their crucial role within food webs and in providing ecosystem services (Morley et al., 2014). Detritivores and their coleoptera predators bioaccumulate soluble Pb from shooting range soils, demonstrating that Pb from ammunition can enter the trophic network (Migliorini et al., 2004). Earthworms are particularly capable of bioaccumulating Pb at a rate higher than many other edaphic species, introducing degraded ammunition to food chains which would otherwise remain uncontaminated (Bennett et al., 2007; Rodríguez-Seijo et al., 2017). While ingestion of a single contaminated

Table 5. Illustrative summary table highlighting species or species groups at risk via the different pathways combining likelihood of exposure and magnitude of exposure event (*indicates soil exposure within worm prey).

Order	Species or species group	Pathway 1 Direct ingestion from environment (shot/bullet/fishing weight)	2 Soil with elevated Pb from degraded shot/bullets/fishing weight	3 Vegetation with elevated Pb from degraded shot/bullets/fishing weight	4 Water with elevated Pb from degraded shot/bullets/fishing weight	5 Invertebrate prey with elevated Pb from degraded shot/bullets/fishing weight	6 Vertebrate prey with elevated Pb from degraded shot/bullets/fishing weight	7 Ingestion of live prey with embedded ammunition	8 Ingestion of discarded kill/gut piles with embedded ammunition	9 Ingestion of prey which has ammunition particulate in gastrointestinal (GI) tract	10 Retained ammunition from wound solubilized into tissue	11 Ingestion of fishing weight particulate in prey
Artiodactyla	*Deer*	2	2	3	1						2	
Artiodactyla	*Bison*	3	3	3	1							
Artiodactyla	*Ibex*		1	3	1						2	
Artiodactyla	*Wild boar*	3	2	3	1	2					3	
Carnivora	*Wolf*			1	1	2	3	4	4	2	2	
Carnivora	*Foxes*			1	1	2	3	4	4	2	2	
Carnivora	*Wild cats and lynx*				1		2	4	4	2		
Carnivora	*Wolverine*			1	1		2	4	4	2		
Carnivora	*Otter*				1					1		2
Carnivora	*Martens and other mustelids*			1	1	2	2	3	4	2		
Carnivora	*Bears*			1	1	2	2	4	4	2	2	
Chiroptera	*Bats*					2						
Lagomorpha	*Hares/rabbits*	1	1	3	1						3	
Rodentia	*Mice, voles and mole rats*	1		3	1	2						
Rodentia	*Squirrels/ground squirrels*	1	1	3	1						2	
Rodentia	*Beavers*			1	1						1	
Rodentia	*Lemmings*			3	1							
Rodentia	*Marmots*			3	1						2	
Soricomorpha	*Shrews*		2*		1	4						
Soricomorpha	*Moles*		2*		1	4						
Erinaceomorpha	*Hedgehogs*		2*	2	1	4						

invertebrate is unlikely to cause deleterious effects for a mammal, large volumes of prey with elevated Pb levels could lead to predator toxicosis. Shrews consume around 90% of their body weight in invertebrate prey daily (Pernetta, 1976) and were identified by Bennett et al. (2007) as having an elevated exposure risk from consumption of earthworms. Therefore, other predators of soil-dwelling annelids such as moles, badgers (*Meles meles*) and hedgehogs (Family: Erinaceidae) can be considered to have a greater risk of exposure, particularly when foraging in high deposition sites.

There is variation between aquatic and terrestrial system uptake of Pb by invertebrates. Those in terrestrial habitats have increased adverse effects from shooting range soils compared with aquatic organisms (Rodríguez-Seijo et al., 2017). However, species which intersect the two habitats have exhibited Pb levels correlated with that of the sediment. Ryan et al. (2019) examined caddisfly (*Leptocerus americanus*) Pb levels, finding that while approximately 90% of Pb was retained in larval cases during metamorphosis; the remaining 10% was distributed to adult body tissues. This highlights the role of macroinvertebrates in Pb transfer away from areas of high deposition and therefore increases the availability of degraded ammunition to a wider range of predatory species. Winged invertebrates are a preferential food source for bats (Chiroptera), of which 19 species have decreasing populations across Europe. It is known that Pb from ammunition/fishing weights can be detrimental to avian populations through dietary exposure (Pain et al., 2019; Wood et al., 2019) and while consumption of contaminated animal products is unlikely to cause acute clinical toxicosis in vertebrates, low level exposure can still affect cognitive function, particularly in young offspring (Sharpe and Livesey, 2006). Therefore, there is potential for mammal population health to be affected.

4.5. Pathway 7 - Ingestion of live prey with embedded ammunition

Studies of both bird and mammal quarry species indicate that relatively high proportions of living animals have survived being shot and carry retained ammunition (e.g. 10–44%), most typically Pb shot (Pain et al., 2015; Stankevičiūtė et al., 2013). For mammalian predators and scavengers of these species, there is a relatively high risk of exposure, and to a high dose, due to not just the high prevalence of contaminated prey but also their greater likelihood of their predation due to their injured state.

4.6. Pathway 8 - Gut piles with embedded ammunition

Some 62% of European mammals were assessed to take live vertebrate/invertebrate prey, with 23 predatory or scavenging species known to feed on viscera discarded by humans. The relative ease with which scavenger presence at gut piles can be explored has led to a series of studies (Legagneux et al., 2014; Gomo et al., 2017; Carrasco-Garcia et al., 2018; Fuchs et al., 2021).

Where large game hunting occurs, scavengers can be expected to be exposed to ammunition, and importantly the dose can be expected to be high at some feeding events. Alteration in eagle migrations coincide with game meat harvesting and have resulted in eagle mortality risk increasing by 3.4 times due to Pb ammunition ingestion in gut piles (Singh et al., 2021) and this pattern is likely mirrored in mammalian predators such as wolves (*Canis lupus*), foxes (*Vulpes sp.*) and bears (*Ursus arctos*). Bears often dominate gut pile resources (Rogers et al., 2012; Legagneux et al., 2014) and have been identified as highly exposed to environmental Pb (Boesen et al., 2019). The relationship between mammalian exposure and scavenging is yet to be fully explored despite a direct link between toxicosis and scavenging behaviour in raptors and corvids (Mee and Snyder, 2007; Legagneux et al., 2014; Golden et al., 2016; Pain et al., 2019). As omnivores, bears have multiple opportunities to ingest Pb, including vertical toxin transfer from females to cubs as Pb is endogenously released from bone during lactation, exposing dependent offspring to concentrations well above neurotoxicity thresholds for humans (Fuchs et al., 2021). The literature on gut pile usage provides evidence of the range of scavengers making use of this valuable resource; understanding the feeding ecology, diet, and behaviour of wild mammals provides opportunities for further research on prediction of risk of exposure to Pb ammunition.

4.7. Pathway 10 - Retained ammunition from wound solubilized into tissue

This route of Pb exposure in birds is being recognised as being of greater importance than previously thought (Berny et al., 2017) and is worthy of further investigation in mammals given the high proportion of quarry species that can carry embedded ammunition (Stankevičiūtė et al., 2013).

5. Conclusion

While the initial review of current literature surrounding wild mammal Pb ingestion may have been subject to contextual bias, the risk assessment presented here simply indicates the likely interaction of European mammals with ammunition and fishing weight debris. The detrimental effects of Pb exposure through either single ingestion events or low, frequent doses are well documented in waterfowl and raptors (Pain et al., 2019; Monclus et al., 2020) and, given knowledge of mammalian toxicological responses to Pb, it must be concluded that wild mammals will also be impacted by the continued use of leaded ammunition and fishing weights.

The assessment indicates that there are multiple and diverse Source-Pathway-Receptors linkages for European mammal exposures to Pb and evidence from the literature of exposure, from Europe and elsewhere, exists for some herbivores, carnivores, omnivores and insectivores. Based on current literature and extrapolation of similar feeding ecologies, it can be predicted that the majority of European mammals have the potential for high likelihood of exposure to Pb from ammunition and fishing weight sources when foraging in high deposition areas. Whether mammal population level threats can be attributed to these sources is unclear and will require further investigation.

The potential for exposure in areas of low deposition is more difficult to judge for most taxa particularly as deposition of Pb is heterogenous. The pathways by which a mammal can become exposed still exist but the frequency at which they may consume contaminated forage or prey is greatly reduced. It is also important to recognise, however, the mechanisms by which Pb is 'transferred' from areas of high deposition into wider food chains e.g. via water, flying invertebrates and herbivores. This is of concern both for mammals and birds, but also other taxa such as fish, amphibians and reptiles (Stansley and Roscoe, 1996; Mariussen et al., 2017).

Predatory and scavenging species risk periodic high levels of exposures to Pb from embedded ammunition in prey or carrion in particular gut piles. Delayed offspring development, reduced fecundity and neurological disorders have been attributed to Pb exposure in a range of mammals including humans (Bellinger et al., 2013; WHO, 2019; Blakley, 2021) and both fatal and more likely non-fatal chronic and acute exposures may be expected to occur in wild European mammalian species, including those in poor conservation status. These qualitative results should be further investigated to quantitatively define the contribution to mammal Pb exposure for each pathway and the associated harm from this heavy metal.

Risk management options include the siting of high deposition areas, such as permanent and semi-permanent shooting ranges, away from natural settings. The risk management option without residual risks is the use of non-lead ammunition and fishing weights. This will require a change in behaviour of shooters, hunters and fishers which will require regulation as has been required to tackle the other anthropogenic sources of lead (ECHA, 2021).

The authors wish to thank the following for their expert contributions to this study: Dr. Kevin Wood, (Principal Research Officer, WWT), Prof. Jon Arnemo (Department of Forestry and Wildlife Management, Inland Norway University of Applied Sciences), Dr. Marie-Pierre Ryser (Head of Wildlife Division, Centre for Fish and Wildlife Health, University of Bern), Helle Hydeskov (School of Animal Rural & Environmental Sciences, NTU) and Lydia Galbraith (CSA Environmental). We are also grateful to Rachael Leeman for the individual illustrations used to construct the flow diagram in figure 1.

Declarations

Author contribution statement

Louise Chiverton: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ruth Cromie: Conceived and designed the experiments; Analyzed and interpreted the data.

Richard Kock: Contributed reagents, materials, analysis tools or data.

Funding statement

This work was supported by the Royal Veterinary College (RVC) [URN SR2021-0136].

Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

Agency for Toxic Substances and Disease Registry (ATSDR), 2020. Toxicological Profile for Lead. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Angelova, V.R., Ivanova, R.V., Todorov, J.M., Ivanov, K.I., 2010. Lead, cadmium, zinc, and copper bioavailability in the soil-plant-animal system in a polluted area. Sci. World J. 10, 273–285.

Armstrong, H.M., 1996. The grazing behaviour of large herbivores in the uplands. Scottish Nat. Herit. Info. Advis. Note 47.

Arrondo, E., Navarro, J., Perez-García, J.M., Mateo, R., Camarero, P.R., Martin-Doimeadios, R.C.R., Jiménez-Moreno, M., Cortés-Avizanda, A., Navas, I., García-Fernández, A.J., Sánchez-Zapata, J.A., 2020. Dust and bullets: stable isotopes and GPS tracking disentangle lead sources for a large avian scavenger. Environ. Poll. 266, 115022.

Bar-On, Y.M., Phillips, R., Milo, R., 2018. The biomass distribution on Earth. Proc. Natl. Acad. Sci. USA 115 (25), 6506–6511.

Bellinger, D.C., Burger, J., Cade, T.J., Cory-Slechta, D.A., Finkelstein, M., Hu, H., Kosnett, M., Landrigan, P.J., Lanphear, B., Pokras, M.A., Redig, P.T., Rideout, B.A., Silbergeld, E., Wright, R., Smith, D.R., 2013. Health risks from lead-based ammunition in the environment. Environ. Health Perspect. 121, a178–a179.

Bennett, J.R., Kaufman, C.A., Koch, I., Sova, J., Reimer, K.J., 2007. Ecological risk assessment of lead contamination at rifle and pistol ranges using techniques to account for site characteristics. Sci. Total Environ. 374 (1), 91–101.

Berny, P.J., Mas, E., Vey, D., 2017. Embedded lead shots in birds of prey: the hidden threat. Eur. J. Wildl. Res. 63, 101.

Blakley, B.R., 2021. Lead poisoning in animals. MSD Manual; Veterinary Manual (online) Available at: https://www.msdvetmanual.com/toxicology/lead-poisoning/lead-poisoning-in-animals?query=lead. (Accessed 26 June 2021).

Boesen, A.H., Thiel, A., Fuchs, B., Evans, A.L., Bertelsen, M.F., Rodushkin, I., Arnemo, J.M., 2019. Assessment of the LeadCare® plus for use on scandinavian Brown bears (Ursus arctos). Front. Vet. Sci. 6, 285.
Burco, J., Myers, A.M., Schuler, K., Gillin, C., 2012. Acute lead toxicosis via ingestion of spent ammunition in a free-ranging cougar (Puma concolor). J. Wildl. Dis. 48 (1), 216–219.
Carrasco-Garcia, R., Barroso, P., Perez-Olivares, J., Montoro, V., Vicente, J., 2018. Consumption of big game remains by scavengers: a potential risk as regards disease transmission in central Spain. Front. Vet. Sci. 5, 4.
Chrastný, V., Komárek, M., Hájek, T., 2010. Lead contamination of an agricultural soil in the vicinity of a shooting range. Environ. Monit. Assess. 162 (1-4), 37–46.
Comino, E., Menegatti, S., Fiorucci, A., Schwitzguebel, J.P., 2011. Accumulation and translocation capacity of As, Co, Cr and Pb by forage plants. Agrochimica 55 (2), 105–115.
Dinake, P., Mokgosi, S.M., Kelebemang, R., Kereeditse, T.T., Motswetla, O., 2021. Pollution risk from Pb towards vegetation growing in and around shooting ranges–a review. Environ. Poll. Bioavailab. 33 (1), 88–103.
ECHA – European Chemicals Agency, 2021. Annex XV restriction report – lead in outdoor shooting and fishing. ECHA. EUROPA. EU. Available at: https://echa.europa.eu/documents/10162/da9bf395-e6c3-b48e-396f-afc8dcef0b21.
European Commission, 2021. Commission Regulation (EU) 2021/57 Amending Annex XVII to Regulation (EC) No 1907/2006 Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as Regards lead in Gunshot in or Around Wetlands (Text with EEA Relevance). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R0057.
European Environment Agency, 2018. *European data*. [online] European red lists of species. Available at: https://www.eea.europa.eu/data-and-maps/data/european-red-lists-7. (Accessed 10 May 2021).
European Union (EU), 2021. Countries | European Union. [online] European Union. Available at: https://europa.eu/european-union/about-eu/countries_en. (Accessed 13 May 2021).
Fahr, M., Laplaze, L., Bendaou, N., Hocher, V., El Mzibri, M., Bogusz, D., Smouni, A., 2013. Effect of lead on root growth. Front. Plant Sci. 4, 175.
Frape, D.L., Pringle, J.D., 1984. Toxic manifestations in a dairy herd consuming haylage contaminated by lead. Vet. Rec. 114, 615–616.
Fuchs, B., Thiel, A., Zedrosser, A., Brown, L., Hydeskov, H.B., Rodushkin, I., Evans, A.L., Boesen, A.H., Græsli, A.R., Kindberg, J., Arnemo, J.M., 2021. High Concentrations of lead (Pb) in Blood and Milk of Free-Ranging Brown Bears (Ursus arctos) in Scandinavia. Environ. Poll., 117595
Ganz, K., Jenni, L., Madry, M.M., Kraemer, T., Jenny, H., Jenny, D., 2018. Acute and chronic lead exposure in four avian scavenger species in Switzerland. Arch. Environ. Contam. Toxicol. 75 (4), 566–575.
Gieger, S., Furmaga, E., 2020. Chemical Poisonings. Technical Disease Card. OIE Science Department and USGS National Wildlife Health Center. Available at: https://www.oie.int/en/disease/chemical-poisoning/.
Golden, N.H., Warner, S.E., Coffey, M.J., 2016. A review and assessment of spent lead ammunition and its exposure and effects to scavenging birds in the United States. Rev. Environ. Contam. Toxicol. 237, 123–191.
Gomo, G., Mattisson, J., Hagen, B.R., Moa, P.F., Willebrand, T., 2017. Scavenging on a pulsed resource: quality matters for corvids but density for mammals. BMC Ecol. 17 (1), 1–9.
Grade, T., Campbell, P., Cooley, T., Kneeland, M., Leslie, E., MacDonald, B., Melotti, J., Okoniewski, J., Parmley, E.J., Perry, C., Vogel, H., 2019. Lead poisoning from ingestion of fishing gear: a review. Ambio 48 (9), 1023–1038.
Green, R.E., Pain, D.J., 2019. Risks to human health from ammunition-derived lead in Europe. Ambio 48 (9), 954–968.
Hivert, L.G., Clarke, J.R., Peck, S.J., Lawrence, C., Brown, W.E., Huxtable, S.J., Schaap, D., Pemberton, D., Grueber, C.E., 2018. High blood lead concentrations in captive Tasmanian devils (Sarcophilus harrisii): a threat to the conservation of the species? Aust. Vet. J. 96 (11), 442–449.
Jacks, G., Byström, M., Johansson, L., 2001. Lead emissions from lost fishing sinkers. Boreal Environ. Res. 6 (3), 231–236.
Jumba, I.O., Kisia, S.M., Kock, R., 2007. Animal health problems attributed to environmental contamination in Lake Nakuru National Park, Kenya: a case study on heavy metal poisoning in the waterbuck Kobus ellipsiprymnus defassa (Ruppel 1835). Arch. Environ. Contam. Toxicol. 52 (2), 270–281.
Kajander, S., Parri, A., 2014. Management of the environmental impact of shooting ranges. In: Best Available Techniques, 4. The Finnish Environment.
Kelly, J., Carstensen, M., Hildebrand, E.C., Long, L., 2021. Assessing lead exposure in free-ranging gray wolves (Canis lupus) in Minnesota, USA. J. Wildl. Dis.
Kollander, B., Widemo, F., Ågren, E., Larsen, E.H., Loeschner, K., 2017. Detection of lead nanoparticles in game meat by single particle ICP-MS following use of lead-containing bullets. Anal. Bioanal. Chem. 409 (7), 1877–1885.
Lacher Jr., T.E., Davidson, A.D., Fleming, T.H., Gómez-Ruiz, E.P., McCracken, G.F., Owen-Smith, N., Peres, C.A., Vander Wall, S.B., 2019. The functional roles of mammals in ecosystems. J. Mammal. 100 (3), 942–964.
Lazarus, M., Orct, T., Sergiel, A., Vranković, L., Marijić, V.F., Rašić, D., Reljić, S., Aladrović, J., Zwijacz-Kozica, T., Zięba, F., Jurasović, J., 2020. Metal (loid) exposure assessment and biomarker responses in captive and free-ranging European brown bear (Ursus arctos). Environ. Res. 183, 109166.
Legagneux, P., Suffice, P., Messier, J.-S., Lelievre, F., Tremblay, J.A., et al., 2014. High risk of lead contamination for scavengers in an area with high moose hunting success. PLoS One 9 (11), e111546.
Lemarchand, C., Rosoux, R., Berny, P., 2011. Ecotoxicology of the Eurasian otter (Lutra lutra) along Loire River (France) and predictable trends due to global change. In: Proceedings of XIth International Otter Colloquium, pp. 5–14.
Lewis, L.A., Poppenga, R.J., Davidson, W.R., Fischer, J.R., Morgan, K.A., 2001. Lead toxicosis and trace element levels in wild birds and mammals at a firearms training facility. Arch. Environ. Contam. Toxicol. 41 (2), 208–214.
Ma, W.C., 1989. Effect of soil pollution with metallic lead pellets on lead bioaccumulation and organ/body weight alterations in small mammals. Arch. Environ. Contam. Toxicol. 18 (4), 617–622.
Mariussen, E., Heier, L.S., Teien, H.C., Pettersen, M.N., Holth, T.F., Salbu, B., Rosseland, B.O., 2017. Accumulation of lead (Pb) in brown trout (Salmo trutta) from a lake downstream a former shooting range. Ecotoxicol. Environ. Saf. 135, 327–336.
Mason, C.F., Macdonald, S.M., 1993. Impact of organochlorine pesticide residues and PCBs on otters (Lutra lutra) in eastern England. Sci. Total Environ. 138 (1-3), 147–160.
Mateo, R., 2009. Lead poisoning in wild birds in Europe and the regulations adopted by different countries. In: Ingestion of lead from Spent Ammunition: Implications for Wildlife and Humans, pp. 71–98.
Mateo, R., Baos, A.R., Vidal, D., Camarero, P.R., Martinez-Haro, M., Taggart, M.A., 2011. Bioaccessibility of Pb from ammunition in game meat is affected by cooking treatment. PLoS One 6 (1), e15892.
Mee, A., Snyder, N.F., 2007. California Condors in the 21 St Century—Conservation Problems and Solutions. In: California condors in the 21st century, pp. 243–279.
Migliorini, M., Pigino, G., Bianchi, N., Bernini, F., Leonzio, C., 2004. The effects of heavy metal contamination on the soil arthropod community of a shooting range. Environ. Poll. 129 (2), 331–340.
Monclús, L., Shore, R.F., Krone, O., 2020 Dec 15. Lead contamination in raptors in Europe: a systematic review and meta-analysis. Sci. Total Environ. 748, 141437. Epub 2020 Aug 8. PMID: 32818895. https://pubmed.ncbi.nlm.nih.gov/32818895/.
Morley, E.L., Jones, G., Radford, A.N., 2014. The importance of invertebrates when considering the impacts of anthropogenic noise. Proc. Biol. Sci. 281 (1776), 20132683.
National Geographic Society, 2012. Europe: Physical Geography [online] National Geographic Society. Available at: https://www.nationalgeographic.org/encyclopedia/europe-physical-geography/. (Accessed 13 May 2021).
North, M.A., Lane, E.P., Marnewick, K., Caldwell, P., Carlisle, G., Hoffman, L.C., 2015. Suspected lead poisoning in two captive cheetahs (Acinonyx jubatus jubatus) in South Africa, in 2008 and 2013: case report. J. S. Afr. Vet. Assoc. 86 (1), 1–5.
Pain, D.J., Cromie, R., Green, R.E., 2015. Poisoning of birds and other wildlife from ammunition-derived lead in the UK. In: Delahay, R.J., Spray, C.J. (Eds.), Proceedings of the Oxford Lead Symposium. Lead Ammunition: Understanding and Minimising the Risks to Human and Environmental Health. Edward Grey Institute, The University of Oxford, pp. 58–84. Available at: http://oxfordleadsymposium. info. (Accessed October 2015). Accessed.
Pain, D.J., Mateo, R., Green, R.E., 2019. Effects of lead from ammunition on birds and other wildlife: a review and update. Ambio 48 (9), 935–953.
Payne, J., Livesey, C., 2010. Lead poisoning in cattle and sheep. Practice 32 (2), 64–69.
Payne, J.H., Holmes, J.P., Hogg, R.A., van der Burgt, G.M., Jewell, N.J., Welchman, D.D.B., 2013. Lead intoxication incidents associated with shot from clay pigeon shooting. Vet. Rec. 173 (22).
Peralta-Videa, J.R., Lopez, M.L., Narayan, M., Saupe, G., Gardea-Torresdey, J., 2009. The biochemistry of environmental heavy metal uptake by plants: implications for the food chain. Int. J. Biochem. Cell Biol. 41 (8-9), 1665–1677.
Pernetta, J.C., 1976. Diets of the shrews *Sorex araneus L.* and *Sorex minutus L.* in Wytham grassland. J. Anim. Ecol. 899–912.
Rice, McLoughlin, Blanchflower, et al., 1987. Chronic lead poisoning in steers eating silage contaminated with lead shot. Bull. Environ. Contam. Toxicol. 39, 622–629.
Rodríguez-Seijo, A., Cachada, A., Gavina, A., Duarte, A.C., Vega, F.A., Andrade, M.L., Pereira, R., 2017. Lead and PAHs contamination of an old shooting range: a case study with a holistic approach. Sci. Total Environ. 575, 367–377.
Rogers, T.A., Bedrosian, B., Graham, J., Foresman, K.R., 2012. Lead exposure in large carnivores in the greater Yellowstone ecosystem. J. Wildl. Manag. 76 (3), 575–582.
Ryan, S.C., Belby, C.S., King-Heiden, T.C., Haro, R.J., Ogorek, J., Gerrish, G.A., 2019. The role of macroinvertebrates in the distribution of lead (Pb) within an urban marsh ecosystem. Hydrobiologia 827 (1), 337–352.
Sehube, N., Kelebemang, R., Totolo, O., Laetsang, M., Kamwi, O., Dinake, P., 2017. Lead pollution of shooting range soils. S. Afr. J. Chem. 70, 21–28.
Sharpe, R.T., Livesey, C.T., 2006. Lead poisoning in cattle and its implications for food safety. Vet. Rec. 159 (3), 71–74.
Singh, N.J., Ecke, F., Katzner, T., Bagchi, S., Sandström, P., Hörnfeldt, B., 2021. Consequences of migratory coupling of predators and prey when mediated by human actions. Divers. Distrib. 27, 1848–1860.
Sneddon, J., Clemente, R., Riby, P., Lepp, N.W., 2009. Source-pathway-receptor investigation of the fate of trace elements derived from shotgun pellets discharged in terrestrial ecosystems managed for game shooting. Environ. Pollut. 157 (10), 2663–2669.
Stankevičiūtė, J., Pėtelis, K., Baranauskaitė, J., Narauskaitė, G., 2013. Influence of lead Shot Pellets In-Jury on Meat Yield of European Hare (Lepus Europaeus Pallas), 2013. Rural Develop., p. 249
Stansley, W., Roscoe, D.E., 1996. The uptake and effects of lead in small mammal and frogs at a trap and skeet range. Arch. Environ. Contam. Toxicol. 30, 220–226.
Stroud, D.A., 2015. Regulation of some sources of lead poisoning: a brief review. In: Delahay, R.J., Spray, C.J. (Eds.), Proceedings of the Oxford Lead Symposium. Lead Ammunition: Understanding and Minimising the Risks to Human and Environmental

Health, 8–26. Edward Grey Institute, The University of Oxford. In: http://www.oxfordleadsymposium.info/wp-content/uploads/OLS_proceedings/papers/OLS_proceedings_stroud.pdf.

Vallverdú-Coll, N., López-Antia, A., Martinez-Haro, M., Ortiz-Santaliestra, M.E., Mateo, R., 2015. Altered immune response in mallard ducklings exposed to lead through maternal transfer in the wild. Environ. Poll. 205, 350–356.

WHO - World Health Organization, 2019. Lead poisoning and health [online] Who.int. Available at: https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health>. (Accessed 21 June 2021).

Wierzbicka, M., Antosiewicz, D., 1993. How lead can easily enter the food chain—a study of plant roots. Sci. Total Environ. 134, 423–429.

Wood, K.A., Brown, M.J., Cromie, R.L., Hilton, G.M., Mackenzie, C., Newth, J.L., Pain, D.J., Perrins, C.M., Rees, E.C., 2019. Regulation of lead fishing weights results in mute swan population recovery. Biol. Conserv. 230, 67–74.

Zabka, T.S., Haulena, M., Puschner, B., Gulland, F.M., Conrad, P.A., Lowenstine, L.J., 2006. Acute lead toxicosis in a harbor seal (*Phoca vitulina richardsi*) consequent to ingestion of a lead fishing sinker. J. Wildl. Dis. 42 (3), 651–657.