Title: Lead exposure in brown bears is linked to environmental levels and the distribution of moose kills

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Brown, Ludovick; Fuchs, Boris; Arnemo, Jon Martin; Kindberg, Jonas; Rodushkin, Ilia; Zedrosser, Andreas; Pelletier, Fanie.
Lead exposure in brown bears is linked to environmental levels and the distribution of moose kills. Science of the Total Environment 2023 ;Volum 873. s
10.1016/j.scitotenv.2023.162099.

Abstract

Lead (Pb) is heterogeneously distributed in the environment and multiple sources like Pb ammunition and fossil fuel combustion can increase the risk of exposure in wildlife. Brown bears (*Ursus arctos*) in Sweden have higher blood Pb levels compared to bears from other populations, but the sources and routes of exposure are unknown. The objective of this study was to quantify the contribution of two potential sources of Pb exposure in female brown bears (n = 34 individuals; n = 61 samples). We used multiple linear regressions to determine the contribution of both environmental Pb levels estimated from plant roots and moose (*Alces alces*) kills to blood Pb concentrations in female brown bears. We found positive relationships between blood Pb concentrations in bears and both the distribution of moose kills by hunters and environmental Pb levels around capture locations. Our results suggest that the consumption of slaughter remains discarded by moose hunters is a likely significant pathway of Pb exposure and this exposure is additive to environmental Pb exposure in female brown bears in Sweden. We suggest that spatially explicit models, incorporating habitat selection analyses of harvest data, may prove useful in predicting Pb exposure in scavengers.

Keywords: *Ursus arctos*, Pb, scavenger, slaughter remain, resource selection function

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1. Introduction

Lead (Pb) is a naturally occurring trace element that is heterogeneously distributed in the environment and its geochemical cycle has been affected by human activities (Arnemo et al., 2022; Komárek et al., 2008). Atmospheric Pb emissions declined in most countries following the ban on leaded gasoline during the late-20th century (Danielsson and Karlsson, 2015; Nriagu, 1990; Strömberg et al., 2008), but unleaded gasoline and smelter emissions may still influence environmental Pb levels (Chételat et al., 2022; Chrastný et al., 2018; Widory et al., 2018). Pb also has a long residence time in soils and certain areas with high historic Pb depositions still contain high levels (Berglund et al., 2009). Thus, organisms inhabiting areas with high Pb levels are at greater risk of Pb exposure either by direct soil ingestion or by foraging on soil organisms or plants (Berglund et al., 2009; Scheifler et al., 2006). For instance, passerines sampled in urban environments, where the soils were contaminated by vehicle emissions, have higher blood Pb concentrations when compared to birds sampled in rural environments (Chatelain et al., 2021; McClelland et al., 2019; Roux and Marra, 2007).

Several types of human activities, such as hunting with Pb-based ammunition, can increase the level of Pb found in the environment. Bullets used in hunting rifles are designed to expand upon penetration and shed metal fragments in tissues (Green et al., 2022; Hunt et al., 2006; Kollander et al., 2017; Leontowich et al., 2022; Menozzi et al., 2019; Stokke et al., 2017). Carcasses and gut piles discarded during the hunting season have high numbers of embedded bullet fragments and animals that scavenge on this food resource can be exposed to high Pb levels (Fisher et al., 2006; Helander et al., 2021; Legagneux et al., 2014); and the resulting risk is not uniform in space because it is intrinsically linked to the distribution of hunters on the landscape.

Spatially explicit models can be used to predict the risk of Pb exposure from multiple sources in wildlife (Mateo-Tomás et al., 2016). These models are known for being sensitive to scale (Johnson et al., 2021); yet we are currently lacking information on the fine-scale variations in risk of Pb exposure from bullet fragments embedded in discarded slaughter remains. Many studies have investigated the relationship between hunting and Pb exposure in scavengers without considering the spatial variation (Craighead and Bedrosian, 2008; Ecke et al., 2017; Legagneux et al., 2014), or only consider this aspect at coarser spatial scales (Kelly and Johnson, 2011; Singh et al., 2021), which may limit the identification of exposure sources, especially when the variations in environmental Pb levels are recorded at scales larger than the area used by model organisms (Johnson et al., 2021). In this study, we first modelled the fine-scale distribution of moose (*Alces alces*) harvest in Sweden by analysing moose harvest locations with habitat selection analysis, which originally has been developed to analyse data from GPS-collared animals (Northrup et al. 2022). Second, we determine whether variations in blood Pb levels in brown bears (*Ursus arctos*) were related to the distribution of harvested moose. Most studies that have investigated Pb exposure from bullet fragments embedded in slaughter remains in scavengers were on birds, but mammalian scavengers are also likely at risk of increased Pb exposure when feeding on slaughter remains (Brown et al., 2022; Chiverton et al., 2022; Kelly et al., 2021).

As model organism, we used the brown bear, an opportunistic omnivore that occupies large home ranges (Dahle and Swenson, 2003; Graham and Stenhouse, 2014; Schwartz et al., 2003) and feeds across trophic levels. In Sweden, brown bears feed mostly on berries, invertebrates, such as ants, as well as vertebrates, including moose calves and ungulate carcasses when available (Bojarska and Selva, 2012; Schwartz et al., 2003; Stenset et al., 2016). Due to

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their habitat use and foraging behaviours, brown bears could be exposed to multiple potential sources of Pb, including fossil fuel combustion and ammunition. Brown bears in Sweden are exposed to Pb from unconfirmed sources (Fuchs et al., 2021). The mean (SD) blood Pb level of 96.6 (35.6) µg/L reported by Fuchs et al. (2021) is higher than the means of 55 (40) µg/L and 58.0 (34.7) µg/L reported in North American and other European brown bears, respectively (Lazarus et al., 2018; Rogers et al., 2012). However, none of these studies have identified sources of Pb exposure in brown bears. Due to the high toxicity of Pb for vertebrates at low concentrations (Pain et al., 2019), it is important to identify the sources and understand the route of exposure in vertebrate scavengers to implement efficient management actions aiming at reducing Pb exposure in wildlife.

The aim of this study is to build a spatially explicit model to quantify the contribution of two potential sources of Pb to the blood Pb concentrations measured in Scandinavian brown bears: Pb from plant roots (hereafter refer to environmental Pb level) and Pb from ammunition used by moose hunters. We hypothesised that the environmental Pb levels, and the distribution of moose kills influence blood Pb concentrations in brown bears. We predicted that blood Pb concentrations in Scandinavian brown bears would be positively related to both environmental Pb levels, and the probability of moose kill.

2. Material and methods

2.1 Study area

The study area was in Dalarna and Gävleborg counties, south-central Sweden (~61°N, 15°E). The landscape mainly consists of a highly managed boreal forest with stands of different age

Brown, Ludovick; Fuchs, Boris; Arnemo, Jon Martin; Kindberg, Jonas; Rodushkin, Ilia; Zedrosser, Andreas; Pelletier, Fanie.
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classes and interspersed by lakes and bogs (Martin et al., 2010). The canopy is mainly composed of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and birch (*Betula* spp.), whereas the underlayer mainly consists of berry shrubs (*Vaccinium* spp.), heather (*Calluna vulgaris*) and grasses with mosses and lichens covering the ground (Elfström et al., 2008; Ordiz et al., 2013; Swenson et al., 1999). The area is also characterized by a dense network of forest roads (0.7 km/km^2) and low human density (4-7 inhabitants/km^2) (Martin et al., 2010; Ordiz et al., 2013).

Moose hunting in Sweden during the study period was allowed from the first Monday of September to the end of January and, on average, 84,000 moose are harvested annually during this period. Most moose (~75%) are harvested between September and the end of October (Wikenros et al., 2013). Brown bears in Sweden typically enter their den towards the end of October (Evans et al., 2016; Friebe et al., 2014, 2001) and thus have access to the slaughter remains discarded by hunters. Those slaughter remains likely contain Pb fragments because most hunters in Scandinavia use Pb ammunition (Stokke et al., 2017).

2.2 Environmental Pb concentrations and hunting variable

We obtained a biogeochemistry (Biogeokemi) database from the Geological Survey of Sweden (© Sveriges Geologiska Undersökning) that contains the concentrations of trace elements, including Pb, of plant roots (*Carex* spp*., Fontinalis antipyretica* or *Filipendula ulmaria)* collected in or near small streams in Sweden between 1982 and 1996. The methods used for sampling and conducting chemical analyses are described in Lax and Selinus (2005). The trace element concentrations in plant roots reflect the concentrations in the water as well as those of the surrounding soil and bedrock and thus represent reliable estimates of the amount of trace elements circulating in the environment (Lax and Selinus, 2005). Our study area in south-central

Brown, Ludovick; Fuchs, Boris; Arnemo, Jon Martin; Kindberg, Jonas; Rodushkin, Ilia; Zedrosser, Andreas; Pelletier, Fanie.
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Sweden was represented by a total of 2,264 samples of plant roots in this database. We used these samples to predict environmental Pb concentrations on a dry weight basis across our study area by using ordinary kriging. We fitted a Matern variogram with Stein's parameterization (nugget = 0.224, psill = 0.366, kappa = 0.3, range = 0 – 23,594 m) with the *fit.variogram* function [*gstat* package (Gräler et al., 2016)] to predict Pb concentrations across our study area with a resolution of 500 m. The interpolated surface was generated with the *krige* function [*gstat* package, (Gräler et al., 2016)]. We log-transformed Pb concentrations and added a constant (C = 2.5) to all observations to obtain normally distributed data (W = 0.99, p = 0.06). We then back-transformed the predicted values to the original scale to obtain a map with predicted Pb concentrations across our study area. We used five-fold cross validation [*krige.cv* function; *gstat* package, (Gräler et al., 2016)] to assess the predictive power of the variogram.

The distribution of moose kills in south-central Sweden was estimated following the approach in Brown et al. (in review) by applying resource selection functions (RSF) to moose harvest locations during 2017-2019. Briefly, the RSF was estimated by using a logistic regression that contrasted the landscape characteristics at used (i.e., moose harvest locations provided by hunters) and available (i.e., random) locations (Fieberg et al., 2021; Manly et al., 2002). Hunters typically use areas that are located closer too roads and that have good lateral visibility (e.g., clearcuts), but avoid rugged terrain with poor visibility. The RSF included landcover types (i.e., forest composition, clearcut and bogs), distance to closest road and other variables such as elevation, and terrain ruggedness index, which may impede the movement of hunters across the landscape. The values produced by an RSF are proportional to the probability of selection (Johnson et al., 2006; Manly et al., 2002) or, in this specific example, they are proportional to the probability of hunters killing a moose at any location within our study area.

The relative probability of moose kill was estimated for each year based on moose harvest locations from the previous fall_{t-1}. The RSF model is described and validated in Brown et al. (in review).

2.3 Capture, sample collection and chemical analyses

We carried out a total of 61 captures of adult female brown bears (n = 34 individuals), during 2017-2020. The captures were carried out as part of the Scandinavian Brown Bear Research Project, which mainly focuses on the demography of female brown bears. A total of 34 samples were collected from lactating females, whereas 27 samples were collected from females that were not lactating. Some individuals (n = 16) were captured and sampled more than once. Bears were darted from a helicopter with a remote drug delivery system (Dan-Inject, Børkop, Denmark) during the spring (April to June). See Arnemo and Evans (2017) for more details on the capture protocol. The capture location was recorded with a hand-held GPS. At each capture, 4 or 6 mL of blood were collected from the jugular vein with evacuated K3EDTA tubes (n = 26) (Vacuette, Greiner Bio-One International GmbH, Kremsmünster, Austria) or evacuated heparin trace element tubes (n = 35) (Vacuette), respectively. The samples were first stored in a cooler in the field and then frozen at -20˚C until they were processed in the lab. The Pb concentrations was measured by inductively coupled plasma sector field mass spectrometry (ICP-SFMS, ELEMENT XR, Thermo-Scientific, Bremen, Germany). The blood samples collected during 2017-2019 (n = 42) were part of a previous study (Fuchs et al., 2021), which mainly aimed at determining whether blood Pb concentrations were correlated to life history traits. The Pb concentrations in digestion blanks were low (< 2µg/L) compared with sample results and the difference between measured and expected Pb concentration in the certified reference material

(Seronorm Trace Elements Whole Blood Levels 1 and 2 from SERO AS, Norway) was < 6% (Fuchs et al. 2021). See Fuchs et al. (2021) for further details about sample collections and Rodushkin et al. (2000) for further details about chemical analyses.

2.4 Statistical analyses

We calculated the mean environmental Pb concentrations, and the mean relative probability of moose kill (fall $_{t-1}$) within circular buffers with a radius of 2, 4 and 6 km around the capture locations. We used multiple linear regressions [*lm* function; *stats* package (R Core Team, 2021)] to determine if the environmental Pb concentrations and the probability of moose kill around the capture locations influenced blood Pb concentrations in brown bears. We started by building a set of six candidate models (Table 1). This set contained a null model, a model in which Pb concentrations only changed according to sampling year, and another model in which blood Pb concentration in female brown bears was affected by their lactation status (Table 1). Other models within that set contained either the relative probability of moose kill, or the environmental Pb concentrations. The last model contained a combination of all the variables (Table 1). All the models (except the null model) included the year of sample collection as a variable to control for potential differences between years. We did not include the age of bears because it was previously shown that this variable was not related to blood Pb concentrations in Scandinavian brown bears (Fuchs et al., 2021).

Although our dataset contained 16 females sampled more than one year, we could not use mixed effect models with a random intercept with bear ID due to insufficient replication (bears were sampled 1.79 times on average over the study period). Model selection was conducted by

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Akaike's Information Criterion corrected for small sample size (AICc) by using the *aicmodavg* package (Mazerolle, 2020) in R. We considered models with a ΔAICc < 2 to be equivalent. We first conducted the model selection for each scale (2, 4 and 6 km) separately and then carried out a second AICc with the top-ranked model of each scale to determine the best performing model. We used diagnostic plots to ensure that model assumptions were fulfilled. We log-transformed the response variable (i.e., blood Pb concentrations) to achieve normality of residuals. The environmental Pb concentration was not correlated to the probability of moose kill within buffers at the three scales (2 km, rho = 0.03, $p = 0.79$; 4 km, rho = -0.04, $p = 0.76$; 6 km, rho = -0.02, $p = 0.87$). All statistical analyses were conducted in R version 4.1.0 (R Core Team, 2021).

3. Results

Female brown bears had a mean (SD) blood concentration of 91 (36) µg/L. Lactating females (n = 34) had a mean blood Pb concentration of 104 (36) µg/L (range: 56-221 µg/L), whereas this value was 73 (36) µg/L (range: 25-155 µg/L) in non-lactating females (n = 27). Our kriging model predicted environmental Pb concentrations ranging from 4.6 to 95 mg/kg (dry weigth) on the measured scale (i.e., back-transformed; exp(x)-2.5) and showed large spatial variations with the highest Pb concentrations being in the west of the study area (Fig. 1a). The cross-validation procedure revealed that observed and predicted values of environmental Pb concentrations were positively correlated (rho = 0.60, $p < 0.001$), indicating that the model indeed predicted environmental Pb concentrations. Residuals were uncorrelated to predicted values (rho = 0.02, $p = 0.45$). The mean of residuals was < 0.01, which also indicates that the prediction errors were small relative to predicted values.

Brown, Ludovick; Fuchs, Boris; Arnemo, Jon Martin; Kindberg, Jonas; Rodushkin, Ilia; Zedrosser, Andreas; Pelletier, Fanie.
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The model that performed best at explaining blood Pb concentrations in bears was the Full model (Akaike weight = 0.86) that included effects of the lactation status, the sampling year, the environmental Pb concentration and the relative probability the moose kill (fall $_{t-1}$) extracted within 2 km buffers around the capture locations (Table 2). The second-best performing model was the Environmental Pb models (Akaike weight = 0.14), which had a ΔAICc of 3.69 with the best model (Table 2). The other models received considerably less support as their ΔAICc were > 19 with the top-ranked model (Table 2). The results were similar across scales (Table A1), but the 2 km-scale performed best (Table A2). Thus, we only discuss the results with variables extracted at 2 km and present the other results as supporting information (Table A3).

The following effect sizes and confidence intervals (95% CI) are expressed in percent of change, and they were calculated by back-transforming the coefficients (multiplied by the standard deviation for continuous variables), subtracting 1 and multiplying the results by 100. Our models indicated that blood Pb concentration in female brown bears was positively related to the environmental Pb concentration around the capture location (Figure 2; Table 3). For every unit-increase of 16.02 mg/kg in environmental Pb concentrations (1 unit of standard deviation), the blood Pb concentrations in female brown bears increased by 18.5 % (Lower: 10.5%, Upper: 27.1%). Similarly, our model predicted higher blood Pb concentrations in brown bears captured in areas where hunters were more likely to kill moose during the previous fall (Figure 2; Table 3). Blood Pb concentrations in brown bears increased by 9.1% (Lower: 1.5%, Upper: 17.2%) for every increase of 0.17 (1 unit of standard deviation) in the relative probability of moose kill. Lactating females also had blood Pb concentrations that were 37.7% higher (Lower: 17.8%, Upper: 61.0%) when compared to non-lactating females.

Brown, Ludovick; Fuchs, Boris; Arnemo, Jon Martin; Kindberg, Jonas; Rodushkin, Ilia; Zedrosser, Andreas; Pelletier, Fanie.
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4. Discussion

Our results support the hypothesis that the environmental Pb levels and moose kills jointly influenced blood Pb concentrations in Scandinavian brown bears. Our model explained 56% of the variation in blood Pb concentrations in female brown bears, while the environmental Pb concentrations and probability of moose kill explained 20% and 9% of the variations in blood Pb concentrations, respectively. We found strong support for our prediction that higher environmental Pb levels and availability of moose kill by hunters are related to higher blood Pb concentrations in brown bears.

Our results indicate that blood Pb concentrations in brown bears reflect the concentration of Pb that circulates in the environment within their home range. Bears could be exposed to Pb by accidental ingestion of soil when, for example, digging their den or foraging on ants and plants (Gall et al., 2015). Berries are the main food source of bears during hyperphagia in Sweden (Stenset et al., 2016), which may explain why environmental Pb concentrations were a greater contributor to blood Pb levels in bears. We also acknowledge that the environmental Pb concentrations estimated from plant roots may not be entirely representative of Pb concentrations in food items consumed by bears. Different parts of plants may incorporate Pb from different sources. Roots mainly incorporate Pb from the surrounding soil, whereas leaves and stems also incorporate Pb from atmospheric sources (Klaminder et al., 2005); berries may also be coated with dust from atmospheric depositions (Stachiw et al., 2019). Additionally, the rationale behind the use of the plant root data was not to establish a direct link with the bears' diet, but rather to estimate and compare the amount of Pb that circulates in the different regions of our study areas.

Our conservative approach with buffers of various radii centred on capture locations was sufficiently accurate to correlate blood Pb levels with the concentrations of Pb circulating in the

Brown, Ludovick; Fuchs, Boris; Arnemo, Jon Martin; Kindberg, Jonas; Rodushkin, Ilia; Zedrosser, Andreas; Pelletier, Fanie.
Lead exposure in brown bears is linked to environmental levels and the distribution of moose kills. Science of the Total Environment 2023 ;Volum 873. s
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environment around those sites. Models predicting the tissue concentration of contaminants in animals can be refined further by incorporating movement or space use parameters (Sorais et al., 2021, 2020). Adding data from GPS transmitters could have improved the performance of our model. Spatially explicit models also need to account for the physiological state of an individual (i.e., reproductive status) and failure to do so may introduce bias in the models, as evidenced by the blood Pb concentrations that were 38% higher on average in lactating females when compared to non-lactating females. During lactation, there is remobilization of calcium (and Pb) from bones into the bloodstream and lactating females are exposed to an additional endogenous source of Pb (Fuchs et al., 2021).

Our results also indicate that high probabilities of moose kills are linked to higher blood Pb levels in brown bears. Some concerns have been raised previously regarding the risk of Pb exposure from bullet fragments in mammalian scavengers (Kelly et al., 2021; Legagneux et al., 2014; Rogers et al., 2012), but so far this source of Pb exposure had mostly been reported in avian scavengers (Pain et al., 2019). Pb ammunition is an important source of Pb exposure in avian scavengers and can have consequences at both the individual and population levels (Helander et al., 2021; Pain et al., 2019; Slabe et al., 2022). For instance, Pb from ammunition has been linked to increased risk of mortality (Singh et al., 2021) and altered flight behaviour (Ecke et al., 2017) in avian scavengers, and has prevented the recovery of the California condor (*Gymnogyps californianus*) (Finkelstein et al., 2012).

The blood Pb levels reported in Scandinavian brown bears are in general below the 180 µg/L hazardous concentration for 5% of mammals reported by Buekers et al. (2009). However, values below toxicity thresholds should not be labelled as “safe” because sublethal and subclinical effects of Pb can still be harmful. For instance, subclinical effects on movement behaviour have been reported in golden eagles at blood Pb levels (25 µg/L) well below toxicity thresholds for birds (Ecke et al., 2017), and it has been reported that eagles with blood Pb levels above 25 µg/L were more likely to die compared to individuals below this threshold (Singh et al., 2021). Although the conclusions of these studies cannot be directly translated to brown bears, they suggest that subclinical effects of increased Pb exposure can occur at levels well below commonly reported guidelines and that some bears may be subjected to those consequences. However, we did not investigate this topic and were not able to confirm whether there were deleterious effects in bears. If subclinical or sublethal effects of Pb occur in brown bears, the consumption of slaughter remains discarded by hunters could be considered an evolutionary trap (Schlaepfer et al., 2002), because there is no reason for an opportunistic omnivore to not consume easily accessible, energy-rich and easily digestible foods when encountered (DeVault et al., 2003; Pritchard and Robbins, 1990). However, this ‘easy meal’ acquired at low costs may be deleterious in the long term, because it may contain high concentrations of Pb (Gremse et al., 2014; Hunt et al., 2006; Menozzi et al., 2019; Stokke et al., 2017).

A previous study on Scandinavian brown bear showed that they generally did not modify their behaviour in order to gain access to slaughter remains during the fall and concluded that the scavenging behavior of bears in Sweden is mostly opportunistic (Brown et al. In review). Despite this seemingly low exposure rate, we found a positive relationship between blood Pb levels, and the probability of moose kill around the capture locations. Studies conducted on bears from other populations in North America have shown that bears actively use areas where they are likely to find slaughter remains (Lafferty et al., 2016; Legagneux et al., 2014; Ruth et al., 2003), suggesting that bears from other populations may be at greater risk of Pb exposure than Scandinavian brown bears, especially in areas where the peak of the hunting season is earlier during their active period. The risk of increased Pb exposure should thus be evaluated in bears and other mammalian scavengers from other populations with an appropriate design.

The risk of Pb exposure in relation with the timing of the hunting season has been extensively studied in avian scavengers (Ecke et al., 2017; Fisher et al., 2006; Legagneux et al., 2014; Pain, 2009), while other studies have also looked at the risk of Pb exposure across a gradient of harvest density (Kelly and Johnson, 2011; Singh et al., 2021). The distribution of kill sites or harvest density is typically calculated at the scale of management areas by counting the number of animals that were harvested with a firearm within a specific area (Helander et al., 2021; Kelly and Johnson, 2011); however, this approach is based on the assumption that the distribution of hunter kills is uniform within the area. This assumption is inaccurate in most cases. Hunter kills are neither randomly nor uniformly distributed across the landscape, but are rather concentrated around specific features that provide accessibility, concealment, and/or visibility, depending on the hunting style (Gaynor et al., 2022; Norum et al., 2015). Ignoring the fine-scale distribution of kill sites might not matter for avian scavengers because they can efficiently travel between patches with high harvest densities and easily access slaughter remains (DeVault et al., 2003). However, mammals do not travel as efficiently as most avian scavengers and those movement constraints restrict their ability to access slaughter remains (DeVault et al., 2003), which underlines the importance of reliable estimates of the fine-scale distribution of hunter kill sites. Using an RSF-based approach on ungulate kill sites provided by hunters may be useful for predicting the fine-scale distribution of hunter kills and, by extension the increased risk of Pb exposure, within an area.

The advantage of using an RSF-based approach to predict the fine-scale distribution of harvest locations is that it only requires a subsample of the total harvest. It essentially allows to circumvent the problem of obtaining all the harvest locations within an area. A potential disadvantage is that, depending on the number of included variables, it may still require hundreds of harvest locations, and by extension, it also requires the cooperation of many hunters, which may choose to not disclose or collect information on harvest locations for research purposes. Wildlife management agencies can however obtain this information relatively easily from voluntary hunters, or by making it mandatory to disclose the harvest locations when harvested animals are registered. RSF are relatively easy to fit with widely available statistical softwares, but their results may be difficult to interpret properly. Fortunately, multiples tools are now available to facilitate the implementation of RSF and the interpretation as well as the validation of their results (Fieberg et al., 2021; Muff et al., 2020; Northrup et al., 2022; Roberts et al., 2017).

Potential limitations of our study include the relatively small sample size, the absence of males from the analyses, and the timing of blood sampling. A sample size of 34 females may be small for many species, but considering that, in 2008, the entire population of bears in Sweden was estimated at ~3,300 individuals (Kindberg et al., 2011), our sample size can be considered acceptable. Due to the absence of samples from adult males, we also could not investigate exposure in this demographic group. Larger males commonly monopolize foraging locations (Ben-David et al., 2004; Zedrosser et al., 2013) and could deter females from using slaughter remains; however, it is unlikely a problem in our study because avoidance of males by females with dependent offspring is more common during the mating season (June-July) compared to the fall when slaughter remains are available (Steyaert et al., 2013). Another potential limitation of our study is that it may be difficult to relate Pb concentrations from blood samples collected during spring to moose hunting activities that occurred during the previous fall. Other studies

Brown, Ludovick; Fuchs, Boris; Arnemo, Jon Martin; Kindberg, Jonas; Rodushkin, Ilia; Zedrosser, Andreas; Pelletier, Fanie.
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have shown that the blood Pb concentrations in scavengers decrease during the winter and spring (Craighead and Bedrosian, 2008; Slabe et al., 2022) and our model may have underestimated the contribution of ammunition as a Pb source due to the timing of blood sampling. Nevertheless, our conclusions are similar to those reported by Arrondo et al. (2020) who also found that soil was an important source of Pb exposure in vultures from Spain. Additionally, it is also possible that bears scavenge on thawed slaughter remains after den emergence and are thus exposed to Pb during the spring, as suggested by Fuchs et al. (2021); however, no information is available on the frequency of this behaviour.

An alternative explanation based on Pb kinetics is likely a better explanation for the relationship between spring blood Pb levels and the distribution of moose kills during the previous fall. We do not know if and how hibernation affects Pb kinetics, but blood half-life of elimination may be extended because bears do not urinate nor defecate during this period (Nelson et al., 1983), thereby suggesting no or minimal excretion from the body during the winter. However, we can reasonably expect a blood half-life of elimination of four to five weeks in active bears (Arnemo et al., 2022). Due to this rapid turnover rate, blood Pb concentrations typically reflect short time exposure, but this parameter also depends on the equilibrium between the different compartments of the body in which Pb is stored (Rabinowitz, 1991). For instance, Pb stored in bones, which reflects long time exposure, may be remobilized into the bloodstream during periods of nutritional stress, gestation and lactation (Arnemo et al., 2022). Bears do not eat nor drink during hibernation and Pb may be mobilized from bones in all individuals; this phenomenon was especially obvious in lactating females (Fuchs et al., 2021). Therefore, blood Pb concentrations in bears during the spring are likely the results of a mixture of recent intakes and long-term exposure from blood-organ-bone equilibrium (i.e., mobilisation of Pb from bones).

5. Conclusion

We found a link between the distribution of moose kills by hunters and the blood Pb concentrations in bears; however, the environmental Pb level was a greater contributor to bears' blood Pb concentrations. Pb from ammunition is mainly available for a few weeks during the hunting season and potentially the spring through the consumption of soft tissues with embedded metal fragments, although slaughter remains also include hides and bone dumps that may last longer. Despite that relatively short period during which Pb exposure from ammunition likely occurs in bears, it still represents a potential risk for bears and possibly other mammalian scavengers. We also propose that an RSF-based approach with harvest locations provided by hunters should be relatively easy to implement in other systems, thereby improving our capacity to better understand the risk of increased Pb exposure from bullet fragments in scavengers. This study suggests that regulations on both Pb ammunition and other anthropogenic Pb emissions are needed to reduce Pb exposure in bears.

Brown, Ludovick; Fuchs, Boris; Arnemo, Jon Martin; Kindberg, Jonas; Rodushkin, Ilia; Zedrosser, Andreas; Pelletier, Fanie.
Lead exposure in brown bears is linked to environmental levels and the distribution of moose kills. Science of the Total Environment 2023 ;Volum 873. s
10.1016/j.scitotenv.2023.162099.

Acknowledgement

We thank the field crew who took part in the capture and sampling of the bears, especially David Ahlqvist and Andrea Friebe.

Conflict of interest

The authors declare no conflict of interest.

Funding

The Norwegian Environment Agency, the Swedish Environmental Protection Agency and the Research Council of Norway are the primary funders of the Scandinavian Brown Bear Research Project. Blood sampling and element analyses were funded by the Inland Norway University of Applied Sciences and the Norwegian Environment Agency [grant number 19047048 to JMA]. FP was supported by NSERC Discovery grant [grant number 2018-05405] and E.W.R. Steacie Memorial Fellowship [grant number 549146-2020].

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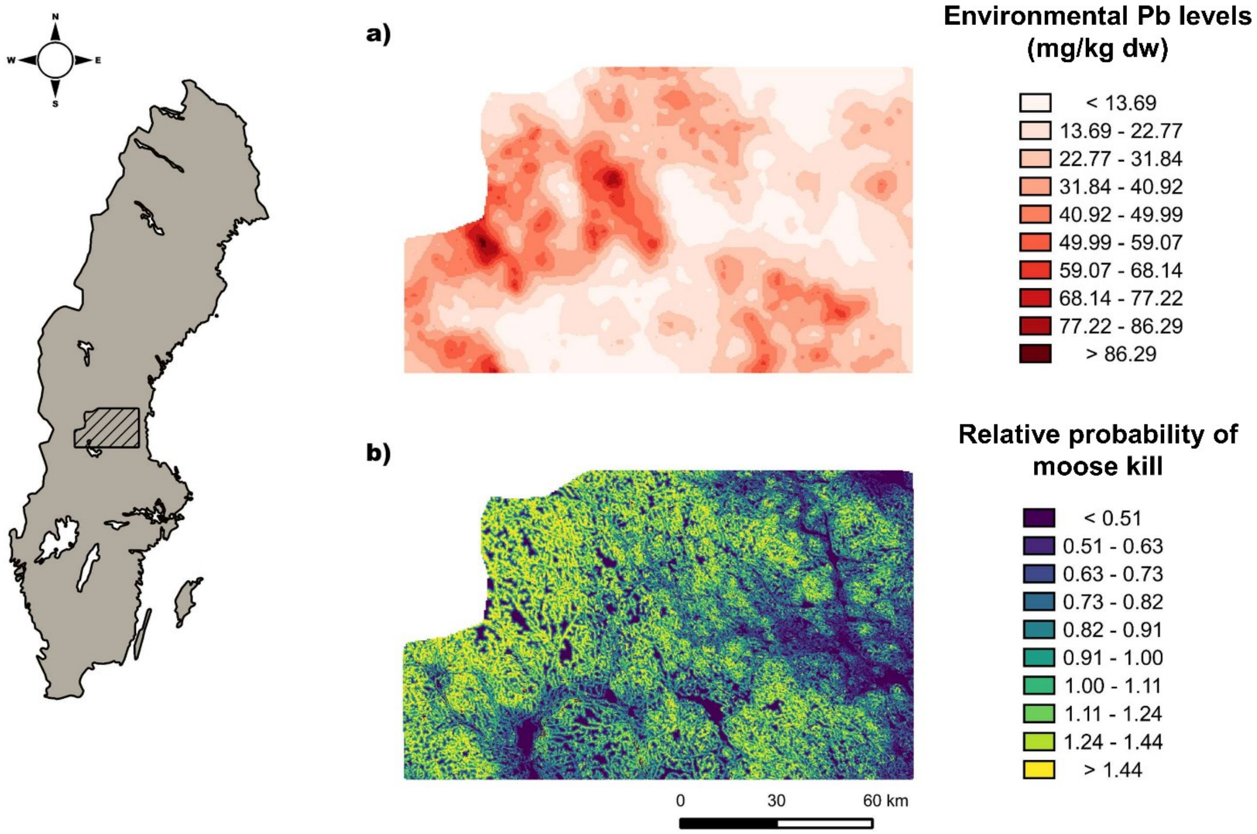

Figure 1. a) Predicted environmental lead (Pb) concentration (mg/kg dry weight) at a 500m resolution in the study area in south-central Sweden. The interpolated surface was generated by using ordinary kriging on Pb concentrations measured in plant roots. The data were extracted from the biogeochemistry database of the Geological Survey of Sweden (© Sveriges Geologiska Undersökning). b) Predicted probability of moose kill at a 100m resolution in the study area. The relative probabilities were calculated from a resource selection function based on moose harvest locations that were provided by hunters [modified from Brown et al. (in review)]. See Brown et al. (in review) for more details about the resource selection function.

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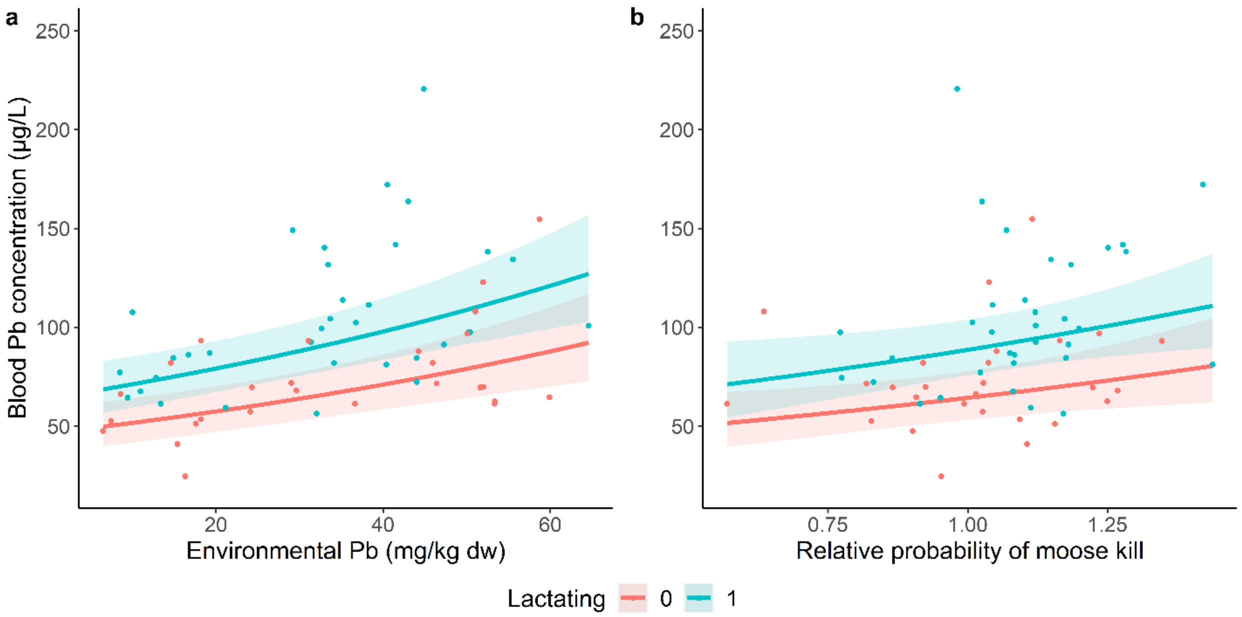

Figure 2. Predicted blood Pb concentrations (µg/L) in female brown bears (*n* = 34 individuals; *n* = 61 samples) in relation to a) environmental Pb concentrations (mg/kg dry weight) and b) the relative probability of moose kill during the previous hunting season (*t* - 1) around the capture locations (2 km buffer) in south-central Sweden during 2017-2020. Lines show predictions and shaded polygons represent 95% confidence intervals of the models, whereas the points represent raw data. Blue points/lines indicate that the female was lactating (lactating = 1), whereas red points/lines indicates that they were not (lactating = 0).

Table 1. The structure and biological hypotheses of candidate linear models used to predict the main source of lead (Pb) exposure in female brown bears (*n* = 34 individuals; *n* = 61 samples) from south-central Sweden, during 2017-2020.

	Model structure	Biological hypotheses
Null	log(Pb) ~ 1	Pb is constant
Year	log(Pb) ~ Year	Pb is influenced by year only
Lactation	log(Pb) ~ Lactation	Pb is influenced by lactation only
RSF hunt	log(Pb) ~ Probability of moose kill + Lactation + Year	Pb is influenced by probability of moose kill, lactation and year
Environmental Pb	log(Pb) ~ Environmental Pb + Lactation + Year	Pb is influenced by Environmental Pb, lactation and year
Full	log(Pb) ~ Environmental Pb + Probability of moose kill + Lactation + Year	Pb is influenced by Environmental Pb, probability of moose kill, lactation and year

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Table 2. Model selection by Akaike information criterion corrected for small sample size (AICc). The model set was used to identify potential sources of Pb exposure in female brown bears (*n* = 34 individuals; *n* = 61 samples) with variables extracted within 2 km buffers centred around capture locations in south-central Sweden, during 2017-2020.

	K	AICc	ΔAICc	*w*	LL
Full	8	24.47	0	0.86	-2.85
Environmental Pb	7	28.16	3.69	0.14	-6.02
RSF hunt	7	44.04	19.57	0	-13.96
Lactating	6	45.89	21.42	0	-16.17
Year	5	57.32	32.85	0	-23.12
Null	2	59.36	34.89	0	-27.58

Notes: K = the number of parameters, ΔAICc = the AICc difference with the top-ranked model, *w* = Akaike weight within the set and LL = log-likelihood of the model.

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Table 3. Parameters of the top-ranked model used to predict blood Pb concentrations [log(Pb µg/L)] in female brown bears (*n* = 34 individuals; *n* = 61 samples) from south-central Sweden, during 2017-2020.

Variables	Estimate	S.E.	95% CI	
			Lower	Upper
Intercept	3.262	0.247	2.768	3.757
Environmental Pb	0.011	0.002	0.006	0.015
Hunter RSF	0.511	0.210	0.090	0.932
Lactating	0.320	0.078	0.164	0.477
Year 2018	0.035	0.106	-0.177	0.248
Year 2019	0.287	0.101	0.085	0.490
Year 2020	0.050	0.102	-0.154	0.256

Multiple $R^2 = 0.56$, Adjusted $R^2 = 0.51$

Notes: S.E. = standard error, Hunter RSF = Relative probability of moose kill. Variables were extracted within 2 km buffers centred on capture locations.

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