9-1-2023

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10.1016/j.envpol.2023.122004

Hampton, J. O., Lohr, M. T., Specht, A. J., Nzabanita, D., Hufschmid, J., Berger, L., . . . Pay, J. M. (2023). Lead exposure of mainland Australia's top avian predator. Environmental Pollution, 332, article 122004. https://doi.org/10.1016/j.envpol.2023.122004

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Environmental Pollution 332 (2023) 122004

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Lead exposure of mainland Australia's top avian predator☆,☆☆

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ARTICLE INFO

Keywords:
Ammunition
Australia
Avian
Biomonitoring
Environmental monitoring
Lead
Raptors
Scavengers

ABSTRACT

Lead (Pb) toxicity, through ingestion of lead ammunition in carcasses, is a threat to scavenging birds worldwide, but has received little attention in Australia. We analyzed lead exposure in the wedge-tailed eagle (*Aquila audax*), the largest raptor species found in mainland Australia and a facultative scavenger. Eagle carcasses were collected opportunistically throughout south-eastern mainland Australia between 1996 and 2022. Lead concentrations were measured in bone samples from 62 animals via portable X-ray fluorescence (XRF). Lead was detected (concentration >1 ppm) in 84% (n = 52) of the bone samples. The mean lead concentration of birds in which lead was detected was 9.10 ppm (±SE 1.66). Bone lead concentrations were elevated (10–20 ppm) in 12.9% of samples, and severe (>20 ppm) in 4.8% of samples. These proportions are moderately higher than equivalent data for the same species from the island of Tasmania, and are comparable to data from threatened eagle species from other continents. Lead exposure at these levels is likely to have negative impacts on wedge-tailed eagles at the level of the individual and perhaps at a population level. Our results suggest that studies of lead exposure in other Australian avian scavenger species are warranted.

1. Introduction

One critical way in which anthropogenic activities harm wild animals is through environmental pollution, recently recognized by the United Nations as the third global catastrophe (along with climate change and biodiversity loss) (United Nations, 2021). Lead (Pb) is a persistent and toxic element that historically had many environmental sources (e.g. paint, fuel), which have been progressively reduced through environmental regulation. Lead pollution is a typical One Health problem, which is defined as negatively impacting humans, as well as other animals, plants and ecosystems (Arnemo et al., 2022; Demayo et al., 1982).

Lead exposure at high levels can cause direct mortality in wild animals (Franson and Russell, 2014), but more commonly, it causes morbidity through nonlethal effects such as inhibited movement patterns (Ecke et al., 2017; Singh et al., 2021). Birds have been more widely affected by lead exposure than any other group of vertebrates (Franson and Pain, 2011). Pathways of exposure typically involve ingestion, and include ingestion of lead shot from waterfowl hunting (Lewis et al., 2021), fishing tackle (Pokras and Chafel, 1992), lead-based paint (Finkelstein et al., 2003), lead dust from mining operations (Gulson et al., 2009), and led fragments from bullets (Church et al., 2006). There has been awareness of lead originating from ammunition causing mortality and morbidity in waterbirds for over a century (Wetmore, 1919).

☆ This paper has been recommended for accept☆☆ ance by Christian Sonne.

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https://doi.org/10.1016/j.envpol.2023.122004
Received 15 March 2023; Received in revised form 24 May 2023; Accepted 8 June 2023

Research in recent decades has revealed that scavenging raptors that feed on shot animals are also severely affected in several global regions (Pain et al., 2019). Elevated levels of lead exposure derived from ammunition have been reported for individual birds from numerous scavenging species in Europe (Ecke et al., 2017), North America (Bakker et al., 2017), Africa (van den Heever et al., 2023), South America (Plaza et al., 2018) and Asia (Ishii et al., 2020). Negative consequences at the population-level have also been demonstrated for several of these species (Green et al., 2022; Slabe et al., 2022). Most famously, lead exposure, through the consumption of bullet fragments left in hunted carcasses, has contributed to the near-extinction of the iconic California condor (*Gymnogyps californianus*) (Bakker et al., 2017). However, until five years ago, little focus had been placed on this issue in Australia (Hampton et al., 2018).

There have been only three studies published on lead exposure in Australian avian scavengers, and all have focused on the wedge-tailed eagle (*Aquila audax*), Australia's largest raptor (Hampton et al., 2021; Lohr et al., 2020; Pay et al., 2021b). However, these studies have assessed highly localized geographical areas: eastern Victoria, Western Australia (south-west and central), and Tasmania, respectively, with a knowledge gap remaining around lead exposure of this species across landscape scales on mainland Australia. Of particular concern was the finding that more than half of birds sampled in eastern Victoria had elevated lead exposure (Hampton et al., 2021). In addition, recent studies have suggested that ammunition is currently causing harmful lead exposure in Australian species as diverse as the mammalian scavenger the Tasmanian devil (*Sarcophilus harrisii*) (Hivert et al., 2018) and the Pacific black duck (*Anas superciliosa*) (Nzabanita et al., 2023). With a couple of historical exceptions (see Gulson et al. (2009)), there are very few other potential lead sources (e.g. paint, fuel, mining) in most rural and remote areas of Australia that would be likely to explain lead exposure in these species.

One of the reasons that there is limited data on lead exposure in Australian wildlife is that attaining and analyzing suitable samples and interpreting the results in a meaningful way is challenging. When analyzing lead concentrations, different tissue types reflect varying timeframes of exposure. After lead is ingested and absorbed, it is primarily deposited in the bone, liver, and kidney, but also exhibits strong tropism towards the central nervous system (Franson and Pain, 2011). Bone stores lead throughout the life of the animal, and measuring lead concentrations in bone provides a means of estimating lifetime exposure to lead (Brown et al., 2022; Clark et al., 2021; Fisher et al., 2006). As such, bone lead concentrations can be used as a marker of chronic (repeated) exposure in animal populations (Ganz et al., 2018). Recent technological advances have made the measurement of concentrations of trace metals such as lead in biological tissues quicker, cheaper, and less destructive. For example, X-ray fluorescence (XRF) has allowed handheld, portable measurement of lead concentrations in hard tissues such as bone. XRF can produce real-time measurements while permitting sampling of archived specimens in a non-destructive manner. XRF has not been used widely for *in vivo* live animal sampling to date, although such applications do exist in human medicine (Chettle, 2005). Portable XRF has now been trialled for lead measurement in bone from several avian species (Nzabanita et al., 2023; Specht et al., 2019; Specht et al., 2018b), including the wedge-tailed eagle (Hampton et al., 2021).

In this study, we used portable XRF to measure bone lead concentrations and estimate lead exposure for wedge-tailed eagles across mainland south-eastern Australia. Our analysis had three parts: 1) extent of lead exposure, 2) extent of spatial clustering in bone lead concentrations between sites, and 3) influence of age groups. Our aim was to compile data comparable to those published for the same species in Tasmania (Pay et al., 2021b) to enable a comparison of mainland and island populations.

2. Materials and methods

2.1. Study species

Wedge-tailed eagles are found throughout mainland Australia, Tasmania and southern New Guinea (Olsen, 2005). They are the largest bird of prey throughout their range, weighing 3–5.5 kg (Debus, 2019), and with a wingspan of 1.9–2.3 m (Fig. 1a). They are generalist predators capable of shifting their diet in response to prey availability (Brun et al., 2022). Wedge-tailed eagles may act as an apex predator (Olsen, 2005), as well as a facultative scavenger, feeding on shot wildlife (Bragato et al., 2022; Brooker and Ridpath, 1980; Vandersteen et al., 2023) (Fig. 1b), and carcasses from other sources such as roadkill (Pay et al., 2022). As mainland Australia lacks any obligate (truly specialized) vertebrate scavenger (Brown et al., 2006) comparable to North America's California condor, wedge-tailed eagles have been identified as the scavenger species at highest risk of harmful exposure to lead of ammunition origin in Australia (Woodford et al., 2020).

2.2. Sample collection

We collected bone samples opportunistically from eagle carcasses. We used private and professional networks to identify individuals and institutions likely to be interested and capable of contributing samples to our study, as per recent studies examining anticoagulant rodenticides residues in Australian raptor species (Lohr and Davis, 2018). Our samples were derived from several sources: wind farms, museums, dead birds reported to government wildlife agencies, and veterinary hospitals (Table 1). To ensure that our results were directly comparable to those of Pay et al. (2021b), we restricted sampling to specimens collected since 1996. Sampling was geographically restricted to the Australian states and territories of Victoria, New South Wales and the Australian Capital Territory (Fig. 2).

Bone samples were accessed in two ways. Firstly, for non-collection specimens (i.e. those provided by wind farms, museums, government wildlife agencies, and veterinary hospitals), whole frozen birds (Fig. 1a) were generally provided. Most birds were so decayed that soft tissues indicative of shorter-term exposure (e.g. liver) (Pay et al., 2021b) could not be collected for analysis. Once carcasses were defrosted, samples were dissected from carcasses following the methods of Pay et al. (2021b). Carcasses were defrosted, we sectioned the diaphysis of the femur (≈3 cm length from the middle of the femur) at necropsy and immediately re-froze the bone specimen in a labelled plastic container until XRF analysis. Secondly, in the case of museum specimens (where dissection was not allowed by collection curators), we measured bones *in situ* (without dissection), as per Hampton et al. (2021), by taking XRF measurements of mid-femoral bones.

For non-collection specimens, eagles were classed as adults or pre-adults on the basis of plumage, as per Pay et al. (2021b). No attempts were made to sex birds with the exception of museum specimens that had sex recorded in specimen details. Cause of death information was not recorded, with the exception of specimens found by detector dogs under wind turbines on wind farms, where turbine strike was assumed to be the cause of death (Bennett, 2015, 2019).

2.3. Bone lead measurement

We used a portable XRF device, the Niton XL3t GOLDD+ (Thermo-Fisher Scientific, Omaha, USA), for bone lead measurements. This is the same device that has been used by all past published studies to utilize XRF for bone lead measurement in wild birds (Hampton et al., 2021; Nzabanita et al., 2023; Specht et al., 2019; Specht et al., 2018b). We used an optimized X-ray tube setting of 50 kV, 40 μA, and a filter combination of silver and iron, as per the afore-mentioned studies. Each sample was analyzed using a 180 s (3-min) read, as per convention (Zhang et al., 2021).

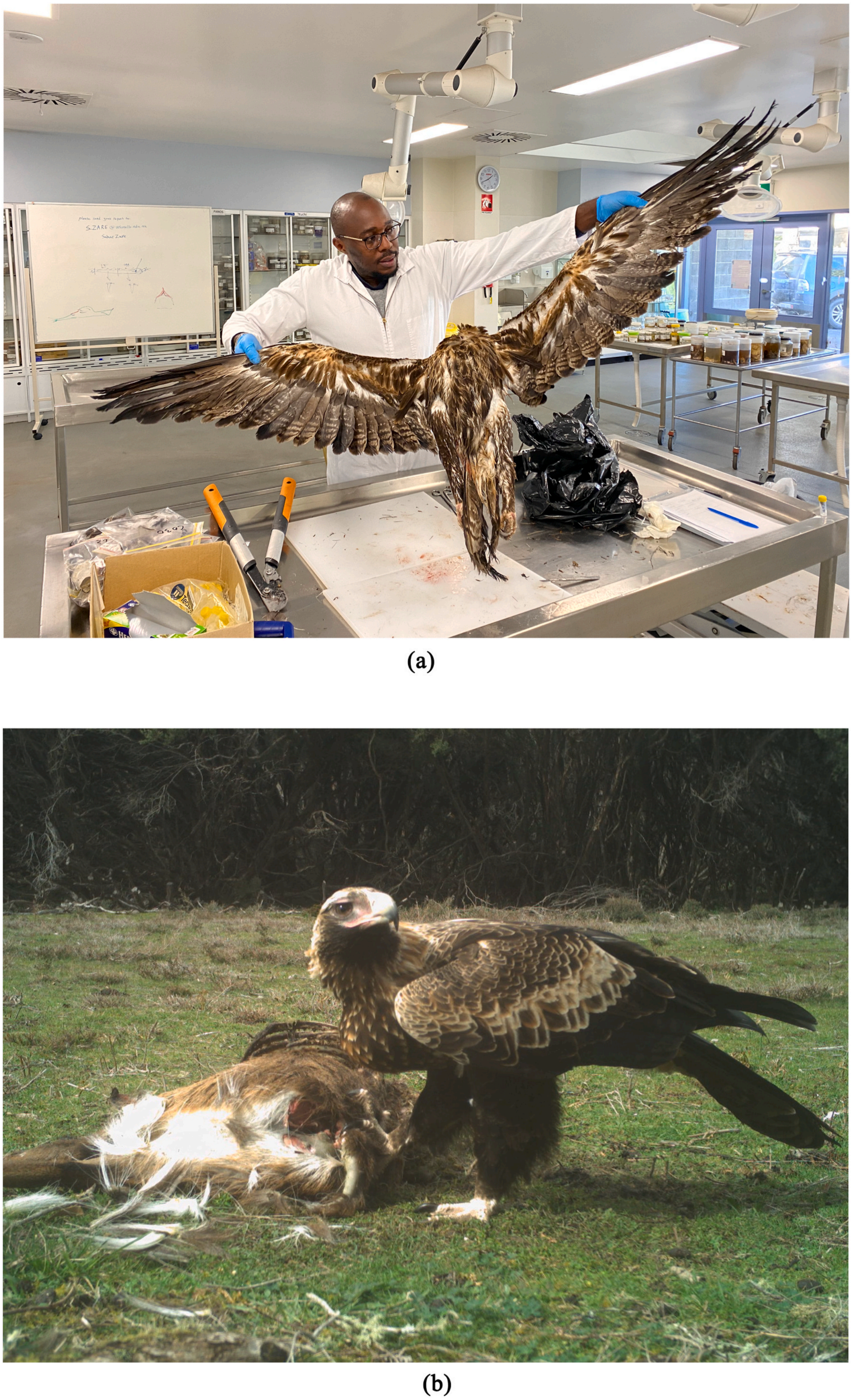

Fig. 1. Our study species, the mainland wedge-tailed eagle (Aquila audax), showing the size of the wingspan (a) and scavenging behavior: feeding on the carcass of a shot hog deer (*Axis porcinus*) (b).

Prior to measurement, all debris (dirt, blood, skin or feathers) was removed from each bone. Samples were not oven-dried. When all bones were available from a specimen (i.e. cadvaers or complete skeletons), the midline of the cortex of the femoral diaphysis was used as the site for XRF measurement, chosen to be representative of primarily cortical bone. Bones were placed flat on a clean surface and measured with the XRF device above them, in an attempt to get samples as close as possible to the XRF detector, while ensuring their orientation was parallel to the XRF aperture. The measurements were analyzed using the standard procedure described in previous studies (Hampton et al., 2021). Briefly, peak fitting was performed using MATLAB software (Mathworks) to identify the net counts of the lead peak and corresponding Compton

Table 1
Origins and demographic details of 62 wedge-tailed eagles (Aquila audax) collected from 1996 to 2022 from south-eastern mainland Australia.

	n	%
State		
Victoria	51	82
South Australia	9	15
New South Wales	2	3
Institution		
Wind farms	43	69
Museums	16	26
Private landholders	2	3
Veterinary clinics	1	2
Age		
Adult	20	32
Pre-adult	42	68

scattering peak associated with the silver X-ray tube anode. This was then used to normalize the geometry differences between samples of different sizes (Specht et al., 2018a).

The limit of detection (LOD) of the XRF for measuring lead concentration in bare bone was estimated at 1 ppm (Specht et al., 2019). The XRF generates a point estimate of exposure, which can be negative if the values are close to zero and the relative uncertainty is high. Uncertainty values from XRF readings were determined as per convention, using counting statistics in the fitted area for lead (Todd et al., 2002), using the equation described in Specht et al. (2019). These negative XRF values can be included in analyses to reduce bias in group statistical tests (Kim et al., 1995).

XRF values were then converted to ICP-MS equivalents to ensure consistency with previous work that has either used ICP-MS to measure bone lead concentrations (Pay et al., 2021b), or has used ICP-MS equivalents calculated from XRF values (Hampton et al., 2021). Differences between dry and wet weight concentrations are negligible when analyzing bone with XRF (Bellis et al., 2012). As such, we used the equation established in Hampton et al. (2021), whereby ICP-MS equivalent values were predicted using the equation:

$$ICPMS = \left(\beta_0 + \beta_1\left(\sqrt{XRF}\right)\right)^2$$

where $\beta_0 = 0.20$ and $\beta_1 = 0.80$.

2.4. Data analysis

The calculated ICP-MS bone lead concentrations were used in all analyses. We performed analyses in R, version 4.1.2 (R Core Team, 2016) using censored data techniques and the R packages 'NADA' (Lee, 2017) and 'CensReg' (Henningsen, 2022) to account for lead concentrations below the detection limit of the XRF. We censored data below the XRF detection limit and assigned these data a value of 1 ppm.

2.4.1. Extent of lead exposure

A Kaplan-Meier cumulative probability distribution (NADA function 'cenfit') was used to calculate censored summary statistics (mean, median and standard error) of bone lead concentrations detected in the sampled eagles. We also calculated standard (not censored) summary statistics for only the eagles in which lead was detected. These analogous summary statistics allowed comparisons among our study and prior work (e.g. Hampton et al., 2021).

We calculated the proportion of the sampled eagles that had bone lead concentrations within each of three published contamination thresholds (Franson and Pain, 2011). Bone lead concentrations <10 ppm were categorized as low exposure with limited health implications, concentrations 10–20 ppm were categorized as elevated exposure, and concentrations >20 ppm were categorized as severe exposure (Pay et al., 2021b). These threshold level or diagnostic categorizations have been reviewed in Franson and Pain (2011), and are consistent with past studies reporting bone lead concentrations in the wedge-tailed eagle (Hampton et al., 2021; Pay et al., 2021b).

2.4.2. Spatial clustering

Eagle carcasses were not collected in a spatially random manner, i.e. they were clustered around wind farms and human settlements.

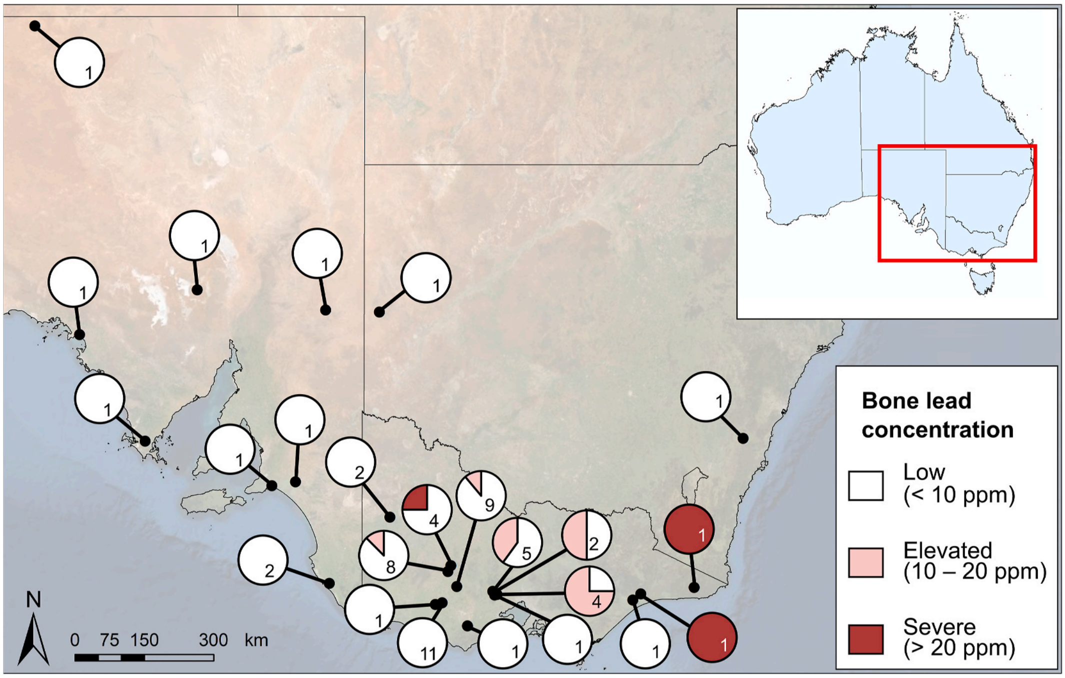

Fig. 2. Location of each of the sites (n = 24) where wedge-tailed eagle (*Aquila audax*) carcasses (n = 62) from birds that had died between 1996 and 2022 were collected. For each site, a pie chart shows the proportion of eagles with bone lead concentrations within each diagnostic category. The numbers refer to sample size per site.

Therefore, we tested for any spatial autocorrelation in the data to ensure each site could be considered independent. We used Moran's Index (function 'Moran.I' in R package 'Ape') (Paradis, 2022) to estimate the size of any spatial association in the bone lead concentrations between sites. A significant Moran's Index with a value close to |1| indicates spatial correlation in the data.

2.4.3. *Differences between age groups*

To test for age-specific differences in the bone lead concentrations we used a mixed-effect left-censored regression (panel-model; censReg function 'censReg') using the Berndt–Hall–Hall–Hausman algorithm (Berndt et al., 1974). The response variable in the regression was the log-transformed bone lead concentrations, with age class included as a fixed variable and site included as a random variable. We also calculated both censored and standard summary statistics separately for each age group. We used a significance level of $\alpha = 0.05$ in all analyses.

3. Results

We measured the bone lead concentrations in 62 eagle carcasses from 24 sites across three mainland Australia states: Victoria (n = 51), South Australia (n = 9), and New South Wales (n = 2) (Fig. 2). The exact date of carcass collection was recorded for 39 individuals. All birds were aged, with 42 birds identified as pre-adult and 20 as adult. Eight birds were sexed (one female and seven males). Cause of death was known for 44 eagles (43 wind turbine collisions, one vehicle collision) and unknown for 19 eagles (Table 1).

3.1. *Extent of lead exposure*

We recorded lead concentrations above the LOD (1 ppm) in 52 of the bone samples. The mean uncertainty for XRF measurements was 0.74 ppm (±SE 0.09). The mean lead concentration of birds in which lead was detected was 9.10 ppm (±SE 1.66) and the censored mean of the entire study sample was 7.70 ppm (±SE 1.45; Table 2). Bone lead concentrations were elevated (10–20 ppm) in 12.9% of the samples (one adult and seven pre-adults) and severe (>20 ppm) in 4.8% (one pre-adult and two adults; Fig. 3a and b; Fig. 4).

3.2. *Spatial clustering and differences between age groups*

All eagle carcasses with elevated (10–20 ppm) or severe (>20 ppm) lead concentrations were collected from sites in Victoria. However, there was no evidence of spatial organization in the wedge-tailed eagle bone lead concentrations (Moran's I: $I = -0.03$, $p = 0.61$, n = 62).

Both standard and censored summary statistics indicated a trend for higher bone lead concentrations in adult eagles compared to pre-adults (Table 2; Fig. 3; Fig. 4), however, bone lead concentrations were not significantly different between the two age groups (H_0: Adult concentration = Pre-adult concentration, $t = -1.920$, $df = 4$, $p = 0.055$; Table 3).

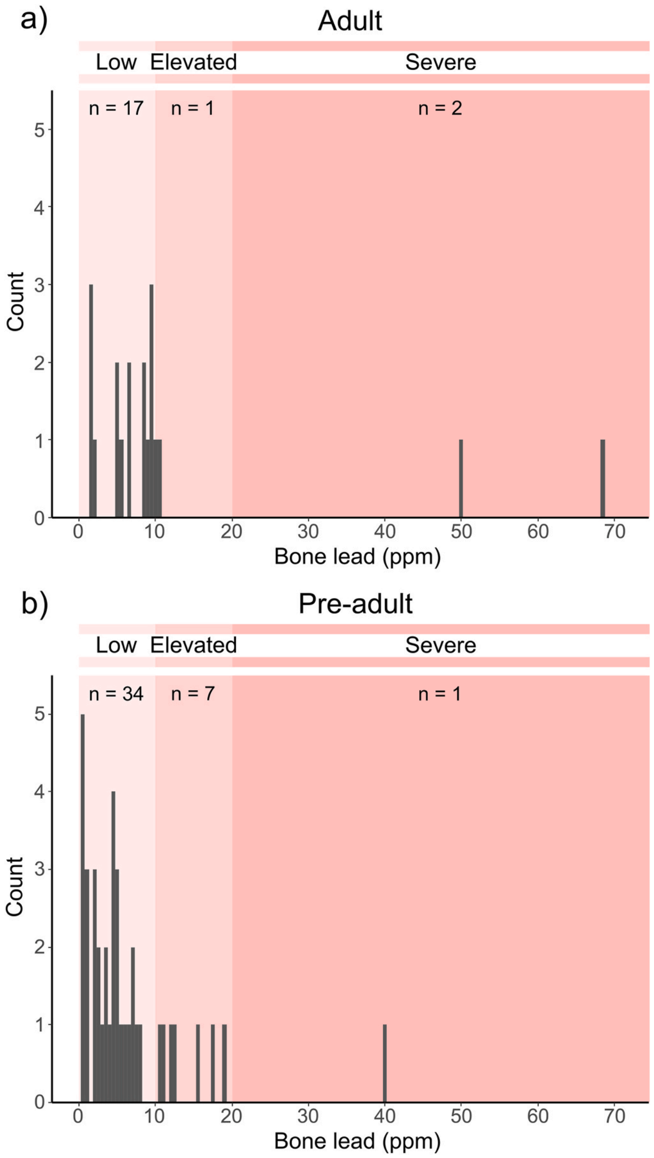

Fig. 3. Bone lead concentrations (ppm) for adult (a) and pre-adult (b) wedge-tailed eagles (*Aquila audax*) that died in south-east mainland Australia between 1996 and 2022. Each frequency histogram shows the number of samples within each 0.5 ppm bin. The number of eagles within each of the threshold values indicative of low (<10 ppm), elevated (10–20 ppm), and severe (>20 ppm) lead exposure is presented.

4. Discussion

This is the first study of lead exposure of the wedge-tailed eagle at a landscape level on mainland Australia. While a minority of birds (<20%) had elevated lead concentrations, there was strong evidence

Table 2
Summary statistics describing lead concentrations in the bone of 62 wedge-tailed eagle (*Aquila audax*) carcasses collected on south-eastern mainland Australia between 2020 and 2022. Non-censored and censored summary statistics are presented. Non-censored statistics were calculated using only the eagles with detected lead concentrations (n = 52). Censored summary statistics consider all individuals (n = 62), including eagles that had bone lead concentrations below the detection limit of the XRF.

	n	Min	Max	*Not censored*			*Censored*		
				Mean	Median	SE	Mean	Median	SE
Pre-adults	42	<LOD	39.84	7.43	5.21	1.29	6.06	4.26	1.10
Adults	20	<LOD	68.28	11.96	8.43	3.94	11.42	6.72	3.78
Total	62	<LOD	68.28	9.10	5.87	1.66	7.79	5.13	1.44

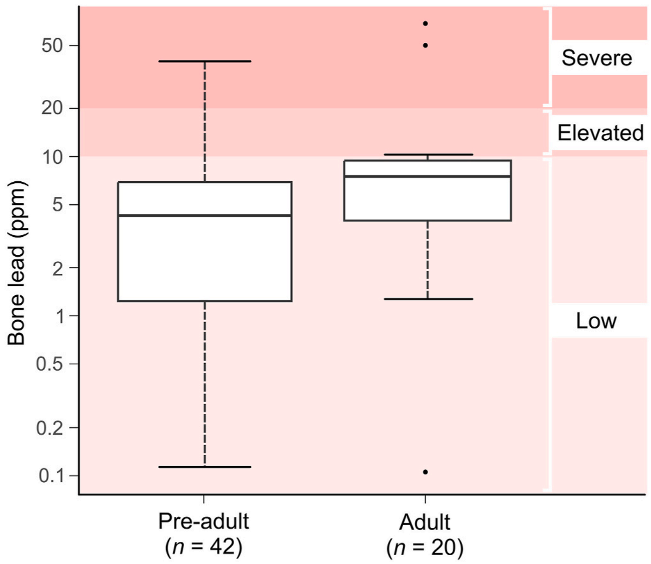

Fig. 4. Box plot of bone lead concentrations (ppm) for adult and pre-adult wedge-tailed eagles (*Aquila audax*) that died in south-east mainland Australia between 1996 and 2022. The threshold values indicative of low (<10 ppm), elevated (10–20 ppm), and severe (>20 ppm) lead exposure are presented. Box plot whiskers are extended to maximum values within 150% of the interquartile range; values beyond this are presented individually. The plot is presented on a log scale.

Table 3
Model coefficients for the mixed-effects censored regression assessing the response of bone lead concentrations to the age class of wedge-tailed eagles (Aquila audax) sampled from south-eastern mainland Australia from 1996 to 2022.

Parameter	Estimate	95% CI lower	95% CI upper	*t*	*P*
Intercept	1.875	0.384	2.366	7.479	<0.001
Age (Pre-adult)	−0.549	−1.110	0.0115	−1.920	0.055
logSigmaMu	−0.985	−2.440	0.470	−1.327	0.185
logSigmaNu	−0.043	−0.325	0.238	−0.305	0.760

that harmful exposure is currently occurring in this species on mainland Australia.

It is concerning that 13% of the birds we sampled had elevated (10–20 ppm) lead exposure, while 5% had severe (>20 ppm) lead exposure. In Tasmanian wedge-tailed eagle populations, these levels were found in just 3% and 1% of birds, respectively (n = 108) (Pay et al., 2021b). In south-western Australia, these levels were found in none of the wedge-tailed eagles sampled (n = 11) (Lohr et al., 2020). However, elevated levels of exposure were found in 47%, and severe levels in 13% of birds (n = 92), at one site in far-south-eastern mainland Australia (east Gippsland in the state of Victoria), a ‘hotspot’ for deer hunting and aerial shooting (Hampton et al., 2021).

Our observed trend towards higher lead concentrations in older birds when compared to pre-adults is consistent with findings from wedge-tailed eagles in Tasmania and suggests that eagles are repeatedly exposed throughout their lifetime. Older individuals of many species display higher bone lead concentrations (Ganz et al., 2018), including wedge-tailed eagles in Tasmania (Pay et al., 2021b). Bone lead concentrations reflect lifetime exposure due to the accumulation over time of lead in bone tissue (Fisher et al., 2006). Therefore, the higher levels we detected in adult birds suggests that eagles are repeatedly exposed throughout their lifetime.

Zooming out to a global perspective, the proportion of birds we observed with harmful bone lead concentrations (‘elevated’ or ‘severe’; >10 ppm), 18%, was lower than those levels reported for the raptor species known to be most heavily affected by lead exposure internationally. These species include golden eagles (*A. chrysaetos*), which have shown a prevalence of harmful lead concentrations of 71% (n = 17) (Jenni et al., 2015) and 65% (n = 46) (Ganz et al., 2018) in Europe, and 47% (n = 226) in North America (Slabe et al., 2022). Bald eagles (*Haliaeetus leucocephalus*) have shown a similar frequency (46%) of harmful exposure in North America (n = 222) (Slabe et al., 2022). The levels of elevated exposure observed in our data were more similar to those reported for scavenging raptors in southern Africa, namely 12% in white-backed vultures (*Gyps africanus*) (n = 18) (Van den Heever et al., 2019), and 9% in Cape vultures (*G. coprotheres*) (n = 75) (Van den Heever et al., 2019), or the United Kingdom, e.g. 10% in Eurasian buzzards (*Buteo*) (n = 220) (Taggart et al., 2020).

Given what is known about lead exposure in raptors globally (Pain et al., 2019), the eagles in our study almost certainly derived the lead present in their bones from ammunition. Risks of lead exposure for scavenging birds may be particularly heightened in the south-east corner of mainland Australia, owing to the relatively high human population density, and the scale and variety of shooting practices (Hampton et al., 2018). First, native marsupials are widely shot for commercial harvesting (Read and Wilson, 2004; Sharp et al., 2002) and culling (Newsome and Spencer, 2021; Vandersteen et al., 2023; Woodford et al., 2020). Second, several introduced large mammalian species are subjected to culling (including aerial shooting) or recreational hunting, covering deer (multiple spp.) (Gregory, 2017; Woodford et al., 2020), feral pigs (*Sus scrofa*) (Brown et al., 2006), and feral goats (*Capra aegagrus hircus*) (Brooker and Ridpath, 1980). Third, smaller introduced mammalian species such as European rabbits (*Oryctolagus cuniculus*), red foxes (*Vulpes*) and wild dogs (*Canis familiaris*) are also shot on farmland for agricultural protection (Peisley et al., 2017). Fourth, there is also the potential for ingestion of lead shotguns pellets or their fragments from game birds such as stubble quail (*Coturnix pectoralis*) that are wounded or not retrieved by recreational hunters during prescribed hunting seasons (Hampton et al., 2022). These risks may be further exacerbated by the fact that most culling, harvesting and hunting activities occur year-round rather than observing a regulated season, as is typical in other parts of the world. For example, deer hunting in Victoria is permitted during all months (Moloney and Flesch, 2022), and there is evidence from camera trap studies that wedge-tailed eagles commonly scavenge on these hunted deer carcasses (Woodford et al., 2020).

The lead exposure levels we detected may result in population-level effects. Recent continent-wide demographic modelling of the impact of lead exposure on two species of North American raptor suggests that it is suppressing population growth rates for bald eagles and golden eagles by ~4% and 1%, respectively (Slabe et al., 2022). Comparable demographic modelling has not been undertaken for wedge-tailed eagles. It would benefit the conservation of the species if age-specific analysis of survival rates and causes of death was undertaken, as has been recently performed for golden eagles in the USA (Millsap et al., 2022). Although we report lower levels of lead exposure in wedge-tailed eagles than those reported for the highest-risk North American raptor species, this issue warrants investigation. There are many anthropogenic causes of mortality and morbidity facing wedge-tailed eagles, including wind turbine strike (Hull and Muir, 2013), poisoning with anticoagulant rodenticides (Pay et al., 2021a), persecution by farmers (Du Guesclin et al., 1983), vehicle collisions (Pay et al., 2022), and electrocution by power lines (Bekessy et al., 2009). Even though lead poisoning might not be the most important threat facing the species, it is one of the easiest to address, through adoption of lead-free ammunition (Green et al., 2008).

Our findings underline the importance of efforts to address the ongoing contamination of Australian ecosystems with lead from ammunition. Harmful lead exposure levels in Australian birds are not likely to be confined to wedge-tailed eagles. Numerous raptor species are known to scavenge shot carcasses across mainland Australia, including little eagles (*Hieraaetus morphnoides*), black-breasted buzzards

(*Hamirostra melanosternon*), brown goshawks (*Accipiter fasciatus*), whistling kites (*Haliastur sphenurus*), and black kites (*Milvus migrans*) (Hampton et al., 2018). In addition, scavenging mammals, notably the Tasmanian devil, show occasional evidence of harmful lead exposure (Hivert et al., 2018; Hutchinson et al., 2023). This issue also extends to domestic animals (e.g. hunting dogs) frequently fed wildlife ('game') meat shot with lead-based ammunition (Hampton et al., 2023a), as well as human consumers of the same meat types (Hampton et al., 2023b).

In Europe and North America, use of lead-based ammunition is being increasingly restricted in recognition of the environmental and public health risks associated. Bans on lead-based ammunition are now in place, for example, in Denmark (Sonne et al., 2022) and the US state of California (Kelly et al., 2011). Further bans are being actively considered in many other countries (McBain Cohen, 2022; Sonne et al., 2019; Sonne et al., 2023). In addition, voluntary transitions to lead-free ammunition have been encouraged by many hunter education/outreach programs (Schulz et al., 2022). Reducing the use of lead-based ammunition can reduce lead exposure rates in wildlife, as demonstrated by several examples. Declines in blood lead levels were observed in California in scavenging bird species after bans on lead-based ammunition began in 2008 (Kelly et al., 2011). Declines in blood lead levels were also reported in American black ducks (*Anas rubripes*) $>$ 25 years after a local ban on lead shot for waterfowl hunting (Lewis et al., 2021). Finally, declines in bone lead levels were reported in an Australian duck species, the Pacific black duck, two decades after a local ban on lead shot for recreational duck hunting (Nzabanita et al., 2023).

Future efforts to understand this problem may want to focus on several key areas. Most importantly, it would be useful to increase the number of individuals evaluated. Although our sample size was larger than that in many comparable studies, e.g. Pain et al. (2005), it was still relatively small and inference of future studies would be stronger if more individuals could be considered. This could be achieved through improving processes around collecting, storing and recording eagle carcasses, which would vastly increase sample availability. The state of Tasmania have a more rigorous process for processing found carcasses of the threatened sub-species of the wedge-tailed eagle that occurs there (*A. a. fleayi*) (Pay et al., 2021b). Having similar centralized procedures in other Australian jurisdictions (states and territories) would permit more robust analyses of contaminant exposure in the mainland population.

Although challenging, it would be valuable to implement a random sampling protocol, whereas our sampling was heavily influenced by the location of windfarms. Sublethal lead exposure in eagles may increase the risk of mortality through processes such as wind turbine strike (Ecke et al., 2017), although this is contested (Viner and Kagan, 2021). Carcass sampling will always be opportunistic rather than random, whereas live capturing is less biased and trapping effort can be standardized across a study area (Descalzo et al., 2021). We propose that live-capture studies using blood level levels, e.g. van den Heever et al. (2023), would be particularly informative in this context. Clinical examination of live or recently deceased eagles would also provide information on the physiological effects of bone lead concentrations and allow for the assessment of health conditions that can increase lead uptake and confound the link between the amount of ingested lead and tissue lead concentrations. For example, in humans, certain comorbidities such as iron deficiency can lead to increased body burdens of lead by increasing the expression of the divalent metal transporter (DMT-1) gene (Kwong et al., 2004), and similar effects may occur in birds. Finally, future studies should analyze lead isotopes to attempt source attribution (Finkelstein et al., 2003; Finkelstein et al., 2014), noting that the long-term nature of lead deposition in bone would complicate such an undertaking.

The results of this study align with recent investigations in other parts of Australia (Hampton et al., 2021; Lohr et al., 2020; Pay et al., 2021b) to suggest that lead contamination is pervasive in scavenging birds in Australia. Mitigative efforts equivalent to those being applied in Europe and North America are warranted for consideration on mainland Australia to reduce lead exposure levels for raptor species.

5. Conclusions

Our results confirm that harmful lead is widespread in wedge-tailed eagles on mainland Australia. Lead poisoning is an underappreciated threat to populations of this iconic species. Future studies should evaluate lead exposure in the context of other sources of mortality for Australian eagles. Our preliminary data suggest that mitigation of lead exposure in Australia should be a high conservation priority, especially given the ease with which lead can be removed from the landscape, and in contrast to the difficulty associated with reducing impacts from other anthropogenic activities.

Credit author statement

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Funding

This research was funded by a grant from the NSW Wildlife Information Rescue and Education Service (WIRES), and the McKenzie Fellowship Program of the University of Melbourne. Dr. Aaron Specht was partially funded by a training grant from the National Institute of Occupational Safety and Health grant K01OH012528. Dr. James Pay was partially funded by ARC Linkage grant LP210200539.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

For access to samples, we acknowledge the following people: Tracy Lyten from Skylos Ecology; James Coburn from Windlab; Andrew Taylor from SMEC Australia; Leo Joseph and Chris Wilson from the National Wildlife Collection; Maya Penck from the South Australian Museum; Kevin Rowe, Karen Rowe, Kylea Clarke and Katie Date from Museums Victoria; Pam Whiteley from the University of Melbourne; Jenny McLelland from Zoos SA; and Charlie Carter from the Southern Highlands Veterinary Centre. For XRF hire, we thank Shellby Brookes, Denise Guldemond and Alex Toy from Portable Analytical Solutions. For fauna licences needed to collect and transport samples, we thank Sue Hadden and Roberta Campbell from the Victorian Department of Environment, Land and Water. For assistance with data analysis, we thank Andrew Bengsen from NSW DPI. For assistance with framing the discussion, we thank Todd Katzner from the US Geological Service, Debbie Pain from Cambridge University, and Jon Arnemo from the Inland University of

Norway. For assistance with study design and resourcing, we thank Cheryl Lohr from the Department of Biodiversity, Conservation and Attractions (Western Australia), Simon Cherriman from Murdoch University, Patrick Taggart from NSW DPI, and Simon Toop, Jason Flesch and Graeme Ford from the Victorian Game Management Authority.

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