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Short Communication

The seasonal threat of lead exposure in bald eagles

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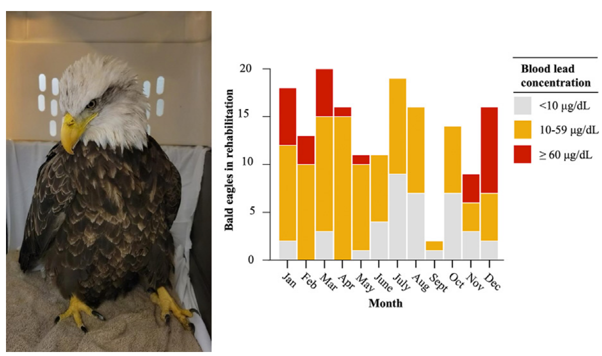
HIGHLIGHTS

- Lead from spent hunting ammunition impairs and kills many bald eagles.
- We tested for lead in free-flying bald eagles and those in rehabilitation.
- ~ 90 % of bald eagles had blood lead concentrations ≥ 10 μg/dL post-hunting season.
- Bald eagles in rehab had a higher incidence of clinical lead exposure (≥ 60 μg/dL).
- Rehabilitators can serve a vital role in lead surveillance and lead-free education.

GRAPHICAL ABSTRACT



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ABSTRACT

Bald eagles often scavenge hunting remains embedded with lead bullet fragments, which debilitate and kill many eagles. Measuring blood lead concentrations (BLC) in free-flying bald eagles and those received by rehabilitators allows researchers to both actively and opportunistically monitor exposure. From 2012 to 2022, we captured 62 free-flying bald eagles and measured their BLC following the big-game hunting season in Montana, USA, which occurs from late October through late November. Between 2011 and 2022, we also measured the BLC of 165 bald eagles received by Montana's four raptor rehabilitation centers. Most of the free-flying bald eagles (89 %) had BLC above background (≥10 μg/dL), and BLC of juveniles tended to be lower as winter progressed ($\rho = -0.482$, $P = 0.017$). Bald eagles received by rehabilitators had an almost identical prevalence of BLC above background (90 %) over that same timeframe ($n = 48$). However, those eagles in rehabilitation were more likely to have BLC exceeding the clinical threshold (≥ 60 μg/dL), which we observed only from November through May. Between June and October, 45 % of bald eagles in rehabilitation had sub-clinical BLC (10–59 μg/dL), suggesting that many eagles may live with BLC chronically above background concentrations. Hunters may help lower BLC in bald eagles by switching to lead-free bullets. Those mitigation efforts could be evaluated through a continued monitoring of BLC in both free-flying bald eagles and those received by rehabilitators.

1. Introduction

Big-game hunting creates a major pathway for avian scavengers to consume lead (Haig et al., 2014). Lead bullets fragment upon impact,

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embedding metal particles in animal tissue (Hunt et al., 2006; Leontowich et al., 2022). If the contaminated tissue remains in the field, either through offal piles, carcasses, or unretrieved game, scavengers can ingest lead (Haig et al., 2014). Bald eagles (*Haliaeetus leucocephalus*) are facultative scavengers that readily eat carrion, especially in the winter (Buehler, 2020). In western Montana, USA, bald eagles scavenged at 23 % (n = 31) of the sites where hunters set remote cameras to watch animal remains (McTee and Stone, 2022). After an eagle ingests metallic lead, stomach acids mobilize lead into the bloodstream before it is stored in soft tissues and bones. The half-life of lead in raptor blood is assumed to be roughly 14 days (Fry et al., 2009), therefore blood lead concentrations (BLC) best reflect recent exposure (Franson and Pain, 2011). Additionally, older eagles tend to have more lead in their soft tissues and bones than younger birds (Slabe et al., 2022). That reservoir of lead may later reenter the bloodstream and prevent a bird's BLC from falling below pre-exposure concentrations (Rabinowitz et al., 1976). It is critical to measure BLC in eagles to establish a baseline for later comparison as mitigation strategies develop.

Lead exposure in bald eagles becomes widespread during and after hunting seasons. In a study that spanned the U.S., Slabe et al. (2022) reported that 46 % of bald eagles had BLC >40 μg/dL, with the highest prevalence of poisoning occurring in the fall and winter. Similarly, rehabilitation centers frequently receive bald eagles in the winter that are rendered flightless and debilitated from lead poisoning (Stauber et al., 2010; Yaw et al., 2017). By then, many bald eagles could have repeatedly consumed lead bullet particles. Capturing bald eagles that are actively scavenging carrion allows for the testing of BLC in free-flying individuals during the winter, while testing birds in rehabilitation creates an opportunity to test bald eagles all year. Blending both methods may build a more comprehensive understanding of lead exposure within a region, as seen with birds of prey in Spain (Descalzo et al., 2021).

Although the bald eagle population in the Lower 48 States of the U.S. has rebounded to an estimated 300,000+ individuals (United States Fish and Wildlife Service, 2020), two studies have reported that lead-associated mortalities reduce the population's growth rate (Hanley et al., 2022; Slabe et al., 2022). For surviving eagles, sub-lethal lead exposure damages their nervous system (Pattee et al., 1981), possibly impairing their ability to fly and forage. In golden eagles (*Aquila chrysaetos*), birds have exhibited reduced flight height and movement with BLC as low as 2.5 μg/dL (Ecke et al., 2017), ¼ the concentration sometimes used as a background threshold for eagles in the Northern Rockies, USA (10 μg/dL; Bedrosian et al., 2012; Domenech et al., 2021).

Lead exposure in iconic wildlife also generates considerable public attention and motivates mitigation efforts. For instance, the state of California, USA, and Denmark have banned lead bullets for hunting (Kelly et al., 2011; Sonne et al., 2022). Meanwhile organizations have petitioned the U.S. government to restrict the use of lead bullets nationwide (Center for Biological Diversity et al., 2012). The U.S. Department of the Interior also ordered the expanded use of nontoxic ammunition and fishing tackle on lands and waters managed by the U.S. Fish and Wildlife Service (USFWS; United States Department of the Interior [USDOI], 2017a), an order which was revoked months later (United States Department of the Interior [USDOI], 2017b). More recently, the USFWS has proposed to limit the use of lead ammunition and fishing tackle on some national wildlife refuges (United States Fish and Wildlife Service, 2021). Meanwhile, biologists have developed outreach programs that encourage hunters to voluntarily shoot lead-free ammunition (e.g. North American Non-Lead Partnership, Sporting Lead-Free, and Hunters for Eagle Conservation).

Many studies that report BLC data for bald eagles admitted to rehabilitation or health centers are run by veterinarians or biologists (Stauber et al., 2010; Cruz-Martinez et al., 2012; Franson and Russell, 2014). Yet, measuring BLC in sick and injured eagles may not accurately reflect the BLC in free-flying bald eagles. Additionally, many raptor rehabilitation centers are operated as non-profits by staff who may not have the time to publish their data. These federally permitted centers offer tremendous potential to scale-up data collection, most notably by helping identify hot-spots of lead exposure (Yaw et al., 2017). As opposed to catching free-flying bald eagles, receiving bald eagles at rehabilitation centers requires less up-front effort in obtaining samples, so data can be taken opportunistically. Furthermore, staff at rehabilitation centers often conduct outreach, meaning they are in a prime position to inform the public about lead exposure.

Our overarching objective was to evaluate the severity and seasonal trends of BLC in bald eagles living in Montana, USA, a state that supports over 200,000 hunters annually (United States Fish and Wildlife Service, 2021). Within that objective, we evaluated the viability of combining data from free-flying bald eagles and those received by rehabilitators to better monitor lead exposure in the species. To do this, we captured free-flying bald eagles over 10 winters (2012 – 2022) in the Bitterroot Valley of western Montana. We then measured their BLC and tested whether it declined over the capture season (6 December to 7 March) or depended on year of sampling or age class. Second, we tested the BLC of bald eagles received by Montana's four raptor rehabilitation centers between 2011 and 2022. We categorized each eagle's BLC based on exposure severity (e.g., Neumann, 2009; Bedrosian et al., 2012, and Domenech et al., 2021). We then evaluated whether that severity varied seasonally. For free-flying bald eagles, we hypothesized that BLC would remain high over the winter for adults because they had likely been repeatedly exposed to lead compared to juveniles. For birds admitted to rehabilitation centers, we predicted a spike in the number of bald eagles with at least clinical BLC in the winter that then subsided into the spring and summer. Finally, we expected a higher percentage of those birds would have at least clinical exposure (≥60 μg/dL) compared to our free-flying sample.

2. Material and methods

2.1. Study area

We captured free-flying bald eagles on private lands in the Bitterroot Valley of western Montana, USA, between 2012 and 2022 (Fig. 1). The valley spans approximately 7500 km^2, with elevations ranging from roughly 1000 m to 3000 m (McTee and Stone, 2022). Lower elevations are mainly comprised of grasslands, agricultural fields, and residential development. Higher elevations are dominated by mixed conifer forest and bare rock. Extensive hard-rock mining has polluted certain streams and soils in western Montana (Moore and Luoma, 1990). However, mine waste likely does not account for an appreciable source of lead exposure in bald eagles—at least from the ingestion of fish—because osprey (*Pandion haliatus*) in these contaminated areas often have BLC <2 μg/dL (Langner et al., 2012).

Big-game hunters in the Bitterroot Valley primarily target mule deer (*Odocoileus hemionus*), white-tailed deer (*O. virginianus*), and elk (*Cervus canadensis*). The general rifle hunting season begins in late October and ends in late November. Supplementary rifle seasons—principally for elk—sometimes occur on private land in late August and following the general

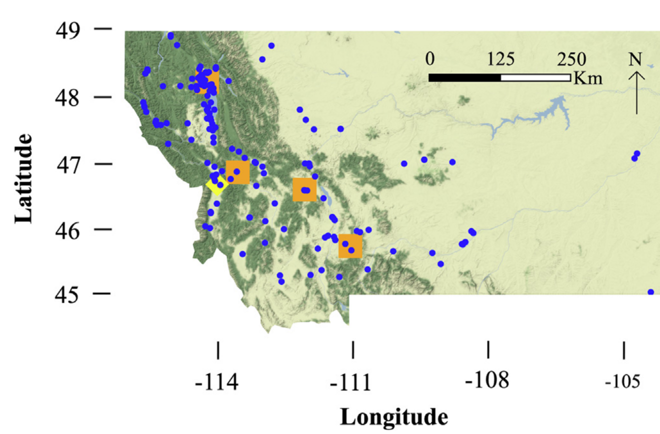

Fig. 1. The approximate locations of bald eagles admitted to rehabilitation (blue circles; 2011–2022), rehabilitation centers (orange squares), and where we captured free-flying bald eagles (yellow diamond; 2012–2022) in Montana, USA.

rifle hunting season, ending mid-February. Between 2012 and 2021 in the Bitterroot Valley, hunters harvested an estimated 816 elk and 2034 deer annually with rifles (Montana Fish, Wildlife, and Parks, unpublished data). Depending on the year, an estimated 67–169 elk were harvested by rifle in August and up to 168 were harvested following the general rifle hunting season. Carrion from deer and elk hunting is often left in the field as offal, bones, blood-shot meat, and wounded but unretrieved animals.

Rehabilitation centers received bald eagles from across Montana, particularly from the western half of the state, where the denser human population likely increases the potential of someone finding a sick or injured bald eagle (Fig. 1). The state encompasses various land cover types, including, forests, grasslands, and mountains. Elevations range from approximately 550 m to 3900 m. Between 2011 and 2020, hunters harvested an estimated 22,165 elk and 87,373 deer annually with rifles statewide (Montana Fish, Wildlife and Parks, unpublished data).

2.2. Capture and blood sampling

From 2012 to 2022, we captured free-flying bald eagles between 6 December and 7 March by luring them with road-killed ungulates and catching them with mini-net launchers (Trapping Innovations, Jackson Hole, WY, USA). We caught an average of six bald eagles annually (min = 2; max = 15; Supplementary material). We grouped eagles into the following age classes: juvenile (< 1 year old), immature (2–4 years old), and adult (≥ 5 years old) based on plumage and the colors of irises, beaks, and ceres (McCollough, 1989). The capturing and sampling of free-flying bald eagles followed the criteria set forth by the United States Geological Survey Bird Banding Permit 23353.

Our blood sampling and lead analysis followed Domenech et al. (2021). Briefly, we sampled blood (2–4 mL) with a Monoject 3 mL syringe and 23-gauge × 3/4″ (0.635 mm × 1.9 mm) needle (Cardinal Health, Dublin, Ohio, USA). We stored blood in glass collection tubes containing anticoagulant tripotassium ethylenediaminetetraacetic acid (K_3 EDTA). We first measured BLC on-site using anodic stripping voltammetry (ASV; LeadCare® 2; Magellan Diagnostics, Chelmsford, MA, USA), which was calibrated with two manufacturer-supplied standards at least once for every 10 samples measured. We refrigerated samples (~4 °C) until later analysis.

To obtain more accurate BLC, the Environmental Biogeochemistry Lab at the University of Montana, USA, analyzed a subset of samples (n = 9) for lead with an inductively coupled plasma mass spectrometer (ICP-MS) described in Langner et al., 2012. Briefly, samples were digested with concentrated HNO_3 and H_2O_2 at increased temperature before analysis by ICP-MS, with a detection limit of 0.5 μg/dL. Measured lead concentrations for standard references were within the ranges given by the manufacturer (Bio-Rad Lypochek Whole Blood Metals Controls; levels 1, 2, 3; n = 3). When that instrument became unavailable for subsequent analyses, we sent additional samples (n = 51) to the Louisiana Animal Disease Diagnostic Laboratory (Baton Rouge, Louisiana, USA). Samples were diluted with a 0.1 % Triton X-100 solution, acidified with 35 % HNO_3, digested at 85 °C, and cooled to ambient temperatures. Technicians then analyzed for lead using an atomic absorption spectrometer (AAS; PerkinElmer AAnalyst 800, Waltham, MA, USA), with a detection limit of 0.075 μg/dL. The lab used Seronorm Trace Elements Whole Blood L-2 and L-3 as standard references (Sero AS, Billingstad, Norway). Lead measurements by ICP-MS and AAS both produce accurate and precise measurements (Herring et al., 2018). The BLC for one bald eagle measured 2270 μg/dL. To verify the result, we submitted a second sample for analysis and the BLC equaled 2100 μg/dL. We averaged the two results. We observed no obvious desiccation in the sample, which would have enriched the lead concentration.

Because we had blood samples that were tested for lead by both ASV and spectrometry (n = 54), we paired those measurements and developed a linear relationship to estimate BLC based on ASV only (Fig. 2), similar to Herring et al. (2018). We had insufficient blood from two free-flying bald eagles to measure BLC by spectrometry, but we did have values measured by ASV, so we estimated their BLC using Fig. 2.

We also recorded the BLC in bald eagles admitted year-round to the four raptor rehabilitation centers in Montana. The facilities and years of sampling are as follows: Wild Skies Raptor Center in Potomac (2011 − 2022), Montana Wild Wings Recovery Center in Kalispell (2016–2021), Montana WILD in Helena (2017–2020), and Montana Raptor Conservation Center in Bozeman (2019–2021). The rehabilitation of bald eagles was in accordance with the following U.S. Fish and Wildlife Service rehabilitation permit numbers: MB54054B-0, MB810769, MB720845, and MB148387. Birds had suffered from collision, fractured bones, poisonings, electrical shock, emaciation, and gunshots wounds, among other ailments. Some birds expressed poor health while the underlying cause remained unclear and many injuries went unrecorded, so the types of injuries did not enter our analysis. We did not age every bald eagle admitted for rehabilitation, so that factor was left out of our analysis. We measured BLC with the ASV instrument within 24 h of admission. If bald eagles appeared severely dehydrated or had very low blood pressure, measurements were sometimes delayed by 24–48 h. We then estimated the actual BLC of each sample using our relationship between ASV and spectrometry (Fig. 2).

Researchers have proposed various exposure categories for BLC in raptors (Franson and Pain, 2011; Langner et al., 2015; Ecke et al., 2017), but we set our categories to be consistent with other eagle studies in the Northern Rockies, USA (Bedrosian et al., 2012; Domenech et al., 2021). The categories were: background (<10 μg/dL), sub-clinical (10–59 μg/dL), clinical (60–100 μg/dL), and acute (>100 μg/dL; Neumann, 2009; Bedrosian et al., 2012; Domenech et al., 2021). Sub-clinical concentrations (10–59 μg/dL) reflect exposure where physiological effects may not be readily apparent, although less obvious symptoms, such as altered flight behavior and reduced delta-aminolevulinic acid dehydratase activity, can occur at BLC <5 μg/dL (Martínez-López et al., 2004; Franson and Pain, 2011; Ecke et al., 2017). Clinical concentrations (60–100 μg/dL) are associated with many possible physiological effects, including, anemia, green diarrhea, and anorexia (Franson and Pain, 2011). Acute or severe lead exposure (>100 μg/dL) can be directly life threatening (Franson and Pain, 2011). Because the ASV cannot measure BLC over 65 μg/dL, we were unable to differentiate between clinical and acute concentrations for birds in rehabilitation.

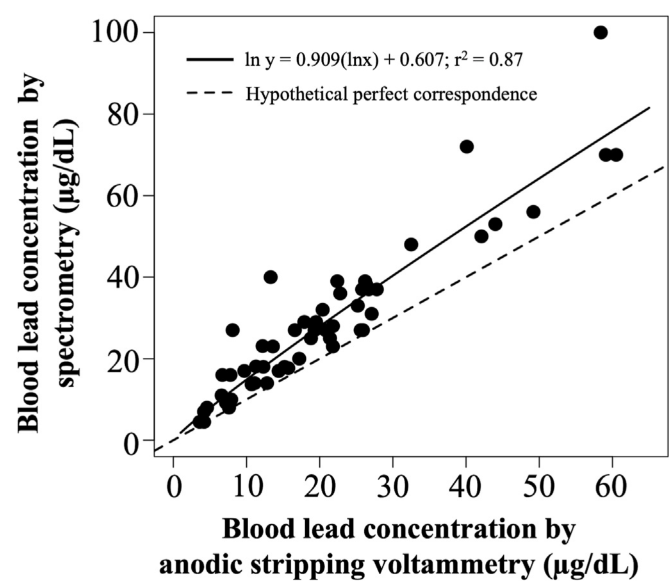

Fig. 2. Relationship between blood lead concentrations in bald eagles measured by anodic stripping voltammetry (ASV; LeadCare® 2) and spectrometry (inductively coupled plasma mass spectrometry [ICP-MS; n = 8] and atomic absorption spectroscopy [AAS; n = 46]). The dashed line represents a hypothetical perfect relationship between ASV and spectrometry measurements. Points above the dotted line show lead concentrations greater than what was reported by ASV. We sampled blood from free-flying bald eagles captured from 6 December through 7 March from 2012 to 2022 in the Bitterroot Valley, Montana, USA.

2.3. Statistical analysis

To compare BLC among free-flying bald eagles depending on year of sampling and age class, we first checked the distributions for normality using a Shapiro test. All data were right skewed, so we log-transformed the data, which did not yield normal distributions. Consequently, we performed a Kruskal-Wallis test for year of sampling. Blood lead concentrations did not differ among years ($H = 8.620$, $P = 0.569$), so we pooled all years for subsequent analyses. To determine whether BLC differed among age classes, we used a generalized linear mixed model with a gamma distribution that had BLC as the response to age class and time during the capture season, with the measurement instrument (ICP-MS and AAS) being a random effect. We then used the emmeans package (Lenth, 2020) to compare treatments with a Tukey post-hoc analysis. To further explore the influence of time during the capture season on BLC, we then used Spearman's correlations for each age class. We created graphics and analyzed data in Program R (version 4.2.1; R Core Team 2022) using the RStudio platform (version 2022.07.1; RStudio Team 2022). We produced Fig. 1 using the ggmap package (Kahle and Wickham, 2019). The locations of four bald eagles were not recorded, so they were not included in Fig. 1.

Table 2
Results from the generalized linear mixed model with a gamma distribution that used blood lead concentrations (BLC) in golden eagles as a response to age class and day of capture as predictors (AIC = 628). The instruments used to analyze BLC were included as a random effect (Inductively Coupled Plasma Mass Spectrometer [ICP-MS] vs. Atomic Absorption Spectrometer [AAS]). Free-flying bald eagles were captured from 6 December and 7 March between 2012 and 2022 in the Bitterroot Valley of western Montana, USA.

Fixed effects				
	Estimate	SE	*t*	P
Intercept	5.031	0.474	10.611	<0.001
Juvenile bald eagle	−1.480	0.296	−5.003	<0.001
Immature bald eagle	−0.684	0.377	−1.816	0.0694
Day of capture	−0.015	0.006	−2.386	0.0170

Random effects		
	Variance	SD
Instrument	0.711	0.844
Residual	4.083	2.021

3. Results

3.1. Free-flying bald eagles

We caught 24 juvenile, 12 immature, and 26 adult free-flying bald eagles (Table 1). Across 10 winters, 89 % of the 62 bald eagles had BLC exceeding background concentrations (>10 μg/dL). The median concentration equaled 27 μg/dL, with an interquartile range of 21 μg/dL. Most birds (76 %; n = 47) suffered from sub-clinical concentrations of lead (10–59 μg/dL), although we observed clinical signs (60–100 μg/dL) in five birds (8 %) and acute exposure (>100 μg/dL) in three (5 %).

Blood lead concentrations were lower in juveniles than in adults ($z = 5.00$, $P < 0.001$; Table 2) but not immatures ($z = -2.07$, $P = 0.095$). Juvenile bald eagles exhibited other differences than older birds. First, BLC decreased over the capture season (6 December to 7 March; years 2012 to 2022) for juveniles, while we observed no trend with immatures and adults (Fig. 3). Second, only 4 % (n = 1) of juveniles had BLC ≥ 60 μg/dL, compared to 25 % (n = 3) for immatures and 15 % (n = 4) for adults (Table 1).

3.2. Bald eagles received by rehabilitators

Bald eagles were admitted for rehabilitation year-round between 2011 and 2022 (n = 165; Fig. 1), but they showed clinical BLC only from November through May (Fig. 4). Of the 28 birds with clinical exposure, 54 % were received in December and January, immediately following Montana's general rifle season. When we restricted the dataset to match the timeframe we caught free-flying bald eagles (6 December to 7 March; years 2012 to 2022; n = 48), 90 % of the birds admitted to rehabilitation had BLC above background concentrations. Over that period of time, 54 % of the bald eagles had sub-clinical BLC while 35 % had BLC exceeding the threshold for clinical exposure. Although no birds had clinical BLC from June to October (n = 62), 45 % of them had sub-clinical concentrations.

Table 1
The percentage and number (n) of free-flying bald eagles for each age class that had blood lead concentrations in four exposure categories. From 2012 to 2022, we caught bald eagles between 6 December to 7 March in the Bitterroot Valley, Montana, USA.

	Background	Sub-clinical exposure	Clinical exposure	Acute exposure
	<10 μg/dL	10–59 μg/dL	60–100 μg/dL	>100 μg/dL
Juvenile	13 (3)	83 (20)	4 (1)	0
Immature	8 (1)	67(8)	17(2)	8 (1)
Adult	11 (3)	73 (19)	8 (2)	8 (2)
Total	11 (7)	76 (47)	8 (5)	5 (3)

We based categories for blood lead concentrations on Neumann (2009), Bedrosian et al. (2012), and Domenech et al. (2021).

4. Discussion

Bald eagles readily scavenge hunting remains, putting them at risk of lead exposure. Most of the free-flying bald eagles (89 %) we sampled in the winter had BLC above background concentrations (Table 1). For birds admitted to rehabilitation centers, we documented bald eagles with clinical BLC or higher only between November and May (Fig. 4), months that include and follow the October and November general rifle hunting season. Those birds had a higher prevalence of at least clinical lead exposure than free-flying bald eagles captured over the same timeframe (35 % vs. 13 %; Table 1; Fig. 4). From June through October—over six months from the end of the general hunting season—45 % of bald eagles received by rehabilitators had sub-clinical BLC. This suggests that BLC were still elevated from past exposures or bald eagles had likely ingested lead from bullet fragments, shot, or fishing tackle (Scheuhammer and Norris, 1996).

We found an almost identical prevalence of BLC exceeding the background threshold between free-flying bald eagles and those received by rehabilitators between 6 December to 7 March (89 % vs. 90 %, respectively). However, free-flying birds had a lower prevalence of BLC exceeding the clinical threshold than birds in rehabilitation (13 % vs. 35 %). These results suggest bald eagles with BLC exceeding 60 μg/dL are more likely to be admitted to rehabilitation or less likely to be captured on carrion. Indeed, lead exposure may elevate a bald eagle's chances of being injured, such as by collision, as seen with mute swans (*Cygnus olor*; Kelly and Kelly, 2005). However, one retrospective analysis of bald and golden eagles found no clear link between cause of death and BLC (Franson and Russell, 2014).

Nearly every bald eagle we tested was captured in the Pacific Flyway (100 % of free-flying; 90 % in rehabilitation). In a study spanning the United States, Slabe et al. (2022) found that 46 % of the bald eagles they tested in the winter had BLC >40 μg/dL, although only three of those samples came from the Pacific Flyway. When we restricted our dataset to match the dates defined as winter in Slabe et al. (2022) 18 % of the free-flying bald eagles and 37 % of the birds in rehabilitation had BLC >40 μg/dL. Franson and Russell (2014) used necroscopy data to conclude that bald eagles in the Pacific Flyway stood lower odds of dying from lead poisoning than bald eagles in the Mississippi or Central Flyways. It is unclear whether these disparities are caused by differences in scavenging rates, differences in the availability of carrion, or other factors.

Monclús et al. (2020) conducted a systematic review and meta-analysis on various European raptors, but no previous studies reported a mean BLC higher than what we found for free-flying bald eagles (69 μg/dL [95 % CI: −1, 139]). However, when an outlying value (2185 μg/dL) was omitted,

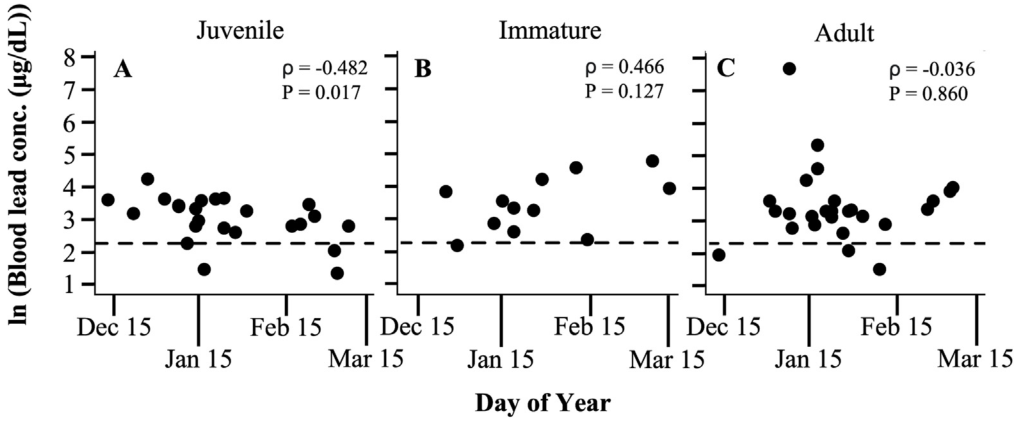

Fig. 3. Blood lead concentrations (BLC) of A) juvenile (n = 24), B) immature (n = 12), and C) adult free-flying bald eagles (n = 26). The dashed line represents the threshold for BLC above background concentrations (10 μg/dL). The ρ and P-values resulted from a Spearman's correlation. We captured bald eagles from 6 December to 7 March in the Bitterroot Valley, Montana, USA, between 2012 and 2022.

the mean BLC for bald eagles decreased to 34 μg/dL (95 % CI: 26, 43). This value falls within the range reported for other species, such as marsh harriers (*Circus aeruginosus*), griffon vultures (*Gyps fulvus*), and some of the species that had the highest reported BLC (Monclús et al., 2020).

Nearly half (45 %) of the bald eagles admitted for rehabilitation from June–October had sub-clinical BLC (Fig. 4). In Montana, hunters can pursue black bears (*Ursus americanus*) and turkeys (*Meleagris gallopavo*) in the spring, possibly creating scavenging opportunities for eagles. The shooting of small mammals also exposes scavengers to lead, but a game camera-based study in Montana did not record bald eagles consuming shot ground squirrels (*Urocitellus* spp.) or black-tailed prairie dogs (*Cynomys ludovicianus*; McTee et al., 2019). Bald eagles could also be preying on fish that ingested lead sinkers or lures (Scheuhammer and Norris, 1996). Conversely, the lead in many of these eagles may have originated from prior exposure events, where the birds' BLC were still decreasing as lead was being stored in bodily tissues or previously stored lead had reentered their bloodstreams.

Raptor rehabilitators often use ASV (i.e., the LeadCare® 2 instrument) to measure BLC in eagles. The instrument produces rapid and inexpensive results, but it often underreports actual BLC and cannot measure BLC > 65 μg/dL (Fig. 2; Herring et al., 2018). This upper limit prevents rehabilitators from knowing the actual concentrations, unless they dilute and rerun the sample or submit blood for analysis by spectrometry. It also limits the capacity for statistical analysis that compares BLC measurements by ASV and spectrometry. Still, if rehabilitators across North America use ASV to measure BLC in bald eagles, regardless of injury, the data could uncover hotspots of lead exposure and help researchers determine whether mitigation efforts reduce BLC in bald eagles. In Montana, rehabilitators have made testing a default step during the intake process for bald and golden eagles. The impetus for testing resulted in part due to our collaborative research and outreach (McTee, 2022), but also because the prevalence of lead exposure is now understood to be widespread. Test results also influence treatment strategies that maximize an eagle's chance of recovery and release back into the wild (Fallon et al., 2017). Submitting BLC data to online repositories, such as Wildlife Rehabilitation MD (wrmd.org, Accessed 29 November 2022) or Wild-One (wildlifecenter.org, Accessed 29 November 2022), could streamline long-term data collection. Raptor rehabilitators could also pair lead concentrations with metabolic data and signs of injury to evaluate how bald eagles respond to treatment depending on their condition. Another step would be for rehabilitators to collaborate with researchers and attach GPS transmitters to bald eagles and track their survival, movements, and behavior post-treatment.

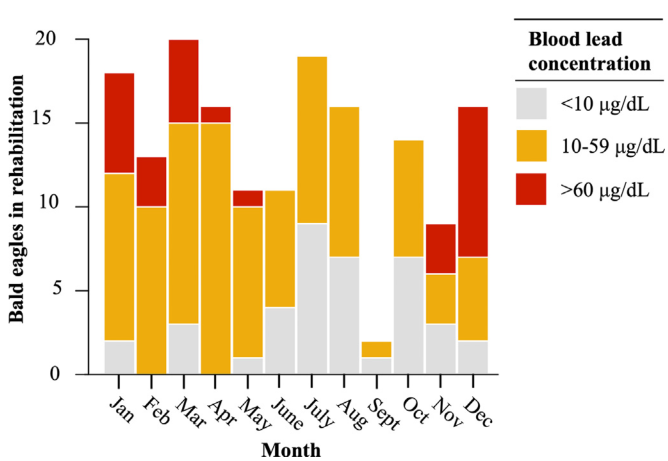

Fig. 4. Lead exposure in bald eagles (n = 165) tested by rehabilitators in Montana, USA, from 2011 to 2022. Colors represent different exposure categories.

Blood lead concentrations trended downward as the winter progressed for juveniles (Fig. 3A). We observed a similar trend with juvenile golden eagles caught in the study area (Domenech et al., 2021), and other studies have reported BLC in bald eagles decreasing as winter transitions to spring and summer (Harmata, 2011; Slabe et al., 2022). Several factors may have contributed to BLC remaining high across the capture season in our study for immature and adult bald eagles. First, older birds tend to have more lead stored in their tissues, likely from multiple exposure events (Slabe et al., 2022). Second, older birds possess more foraging experience and may locate carrion easier than juveniles. Older birds may also assert dominance over younger birds at feeding sites, although we deem this unlikely because bald eagles often feed communally and in mixed age classes (McTee and Stone, 2022).

Montana's general rifle hunting season coincides with migratory bald eagles arriving in the state to overwinter alongside resident birds (Fink et al., 2022), meaning the region is likely a source of lead exposure for a substantial number of eagles. The general rifle hunting season closes in late November, but supplemental hunts sometimes continue until mid-February, lengthening the timeframe that bald eagles may consume bullet fragments from big-game hunting. In early January of 2022, for example, we observed >100 bald eagles congregating in a field in the Bitterroot Valley, where hunters had left multiple piles of elk carrion.

We captured one free-flying bald eagle with a BLC that measured 2185 μg/dL, over 200× the background threshold. Assuming our measurements accurately reflected the BLC in this bird, the concentration was roughly 20× higher than concentrations known to kill bald eagles. Rehabilitation centers have documented similarly high BLC in bald eagles (Manning et al., 2019), but those birds were in poor condition and required treatment. Astonishingly, the bird we caught exhibited no apparent physical symptoms of lead poisoning, such as wing droop or clenched talons.

5. Conclusions

Lead exposure in bald eagles is pervasive throughout Montana, USA, particularly after the general rifle hunting season in October and November. Testing BLC in free-flying bald eagles may offer a less biased sample of the population than sampling birds in rehabilitation, yet rehabilitators can opportunistically test eagles across broad spatial scales. Those data can reveal temporal trends in BLC and identify regional hotspots of exposure. Raptor rehabilitators could potentially leverage their data with outreach efforts that accelerate the adoption of lead-free bullets—many of which have excellent weight retention, are much less toxic (Franson et al., 2012), and kill as effectively as lead bullets (Gremse et al., 2014; Stokke et al., 2017; Stokke et al., 2019). Outreach programs that encourage hunters to shoot lead-free bullets can reduce the amount of lead available to bald eagles (Bedrosian et al., 2012) and should also be considered by agencies, hunting groups, and conservation advocates. Rehabilitators and biologists can evaluate the efficacy of these outreach efforts with continued monitoring BLC in bald eagles.

CRediT authorship contribution statement

Michael McTee: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Becky Kean:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Ali Pons:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Philip Ramsey:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Adam Shreading:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Katharine Stone:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Brooke Tanner:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Beth Watne:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Robert Domenech:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data can be found in the supplementary material.

Declaration of competing interest

Michael McTee is the author of Wilted Wings: A Hunter's Fight for Eagles. All remaining 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.

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Appendix A. Supplementary data

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