The Journal of Wildlife Management 9999:1–8; 2011; DOI: 10.1002/jwmg.277

Research Article

Lead Exposure in Large Carnivores in the Greater Yellowstone Ecosystem

THOMAS A. ROGERS,[1] *Division of Biological Sciences, The University of Montana, 32 Campus Drive, Missoula, MT 59812, USA*
BRYAN BEDROSIAN, *Avian Program, Craighead Beringia South, 6955 East Third Street, Kelly, WY 83011, USA*
JON GRAHAM, *Department of Mathematical Sciences, The University of Montana, 32 Campus Drive, Missoula, MT 59812, USA*
KERRY R. FORESMAN, *Division of Biological Sciences, The University of Montana, 32 Campus Drive, Missoula, MT 59812, USA*

ABSTRACT Ingestion of lead rifle bullet fragments found in discarded hunter-harvested ungulate gut piles negatively affects avian wildlife. Some large carnivores, such as grizzly bears, are also known to target these gut piles as a food source and are therefore potentially at risk of lead exposure. We investigated whether large carnivores in the greater Yellowstone ecosystem were exposed to lead, and if so, if ammunition ingested from gut piles was an apparent source of exposure. Grizzly bears (*Ursus arctos*, $n = 82$) exhibited higher blood lead levels (median = 4.4 μg/dL, range 1.1–18.6 μg/dL) than black bears (*Ursus americanus*, $n = 35$, median = 1.6, range 0.5–6.9 μg/dL), but blood lead levels did not increase during the autumn hunting season when potentially lead-tainted gut piles are available. Wolves (*Canis lupus*, $n = 21$) and cougars (*Puma concolor*, $n = 8$) showed lead concentrations near or below the minimum level of detection in both blood and tissue samples. Unlike findings in previous studies on avian scavengers, we did not find lead ammunition fragments to be a widespread source of lead exposure in large carnivores. Grizzly bears do, however, exhibit blood lead levels that are higher than what is considered safe in humans, but the source of this exposure remains unknown. © 2011 The Wildlife Society.

KEY WORDS ammunition, black bear, carnivore, cougars, grizzly bear, lead, scat, wolf, Yellowstone.

Ingestion of lead artifacts from anthropogenic sources has been widely documented in birds (Fisher et al. 2006) but rarely investigated for mammals (Beyer et al. 2007). Ingestion of lead shot and lead fishing tackle is known to cause lead toxicity in waterfowl, upland game birds, and raptors (Franson et al. 2003, Fisher et al. 2006). Similarly, scavenging birds such as California condors (*Gymnogyps californianus)* and ravens (*Corvus corax*) ingest fragments of lead rifle bullets when scavenging from large ungulate offal piles (gut piles) and unrecovered big game carcasses discarded by hunters (Cade 2007, Craighead and Bedrosian 2008). Lead core and solid lead bullets are widely used among hunters for large game mammal hunting and fragment substantially upon impact, spreading far beyond the site of entry (Hunt et al. 2006). Radiographs confirm that many of these fragments, which range in size from dust-sized fragments to several millimeters in diameter, remain in the gut pile left behind after the hunt (Hunt et al. 2006, Craighead and Bedrosian 2008). Additionally, up to 21% of shot big game animals are killed but not recovered by hunters (Smith and Anderson 1998). Each of these carcasses contain an average of 160 visible particles of lead throughout their body cavity (Hunt et al. 2006) and provide numerous scavenging opportunities. Hunters annually discard approximately 500 tons of meat biomass into the greater Yellowstone ecosystem (Servheen et al. 1986).

Like avian scavengers, mammalian scavengers may also consume gut piles and unretrieved game (Wilmers et al. 2003). During the autumn hunting season, grizzly bears (*Ursus arctos*) leave Yellowstone National Park and seek out areas with high hunting pressure, likely searching for hunter provided food supplements (Ruth et al. 2003). Grizzly bears are also more likely to be in areas with high human hunting pressure during years with lower abundance of alternative food sources such as whitebark pine seeds *(Pinus albicaulis*; Haroldson et al. 2004). Conversely, cougars (*Puma concolor*) avoid human hunting pressure following elk herds into Yellowstone National Park, and wolves (*Canis lupus*) do not change their movement patterns (Ruth et al. 2003). Wolves occasionally scavenge, but to a much lesser extent than bears (Wilmers et al. 2003) and cougars have been found to scavenge roughly 2–3% of feeding occurences (Anderson and Lindzey 2003, Knopff et al. 2010). Black bears (*Ursus americanus*) scavenge (Carson et al. 2000), but in the presence of dense grizzly bear populations, black bears may avoid highly desirable food resources to avoid conflicts with grizzly bears, particularly during years when those food resources are more limited (Belant et al. 2006). Coyotes (*Canis latrans*) are well-known scavengers at hunter discarded offal and big-game carcasses (Wilmers et al. 2003). Therefore, grizzly bears are more frequent scavengers than

Received: 29 June 2010; Accepted: 6 July 2011

[1]*E-mail: thomasalanrogers@gmail.com*

black bears, wolves scavenge infrequently, and cougars rarely scavenge (Ruth et al. 2003, Wilmers et al. 2003, Belant et al. 2006). Gut piles provided by hunters may supplement these species' diets to widely varying degrees (Ruth et al. 2003).

Ingestion of lead rifle bullet fragments from consuming gut piles results in elevated blood lead levels, clinical toxicosis, and death among many species of birds (Fisher et al. 2006, Cade 2007, Craighead and Bedrosian 2008). Although mammals may also consume gut piles, no research has yet documented whether they exhibit signs of lead exposure. We tested to see if large carnivores were being exposed to lead from the environment, and if so, if lead ammunition was a contributing source of exposure.

If carnivores were being exposed to lead from lead ammunition from hunter-harvested ungulate gut piles, we predicted that blood and liver tissue lead levels would be highest among bears, moderate to low among wolves, and lowest among cougars, based on known differences in levels of scavenging among these species (Ruth et al. 2003). Further, if bears were being exposed to lead from gut piles, we expected black bears to have lower blood lead levels than grizzly bears because of conspecific avoidance. We also predicted that blood lead levels should be higher and spikes in blood lead level should be more frequent during the fall elk hunting season than during other times of the year. In addition, lead fragments should be present in scat piles after a carnivore has consumed ammunition and it has passed through the gastrointestinal tract partially undigested.

STUDY AREA

We analyzed blood, tissue, and scat samples collected from large carnivores in the greater Yellowstone ecosystem in Wyoming, Idaho, and Montana for the presence of lead. The greater Yellowstone ecosystem included 2 national parks (Yellowstone National Park and Grand Teton National Park), the National Elk Refuge, and the 5 surrounding National Forests (Bridger-Teton, Custer, Gallatin, Shoshone, and Targhee). This area provided an ideal setting because the greater Yellowstone ecosystem hosted a complete large carnivore guild including grizzly bears, black bears, wolves, cougars, and coyotes (Ruth et al. 2003) and was home to one of the largest big-game hunts in North America that resulted in abundant annual harvests (Wilmers et al. 2003, Haroldson et al. 2004). In addition, there were roughly concurrent hunting seasons for moose, bison, and deer. Rifle hunting season for elk started on or around 20 September in Wyoming, where most of the blood and scat samples were collected. Rifle-hunting season for elk started in mid-October in both Montana and Idaho. Elk hunting seasons ended after most bears had gone into winter dormancy. These hunts provided an environment rich in food supplements in the form of hunter-wounded animals, skeletal frames with meat removed, and gut piles (Haroldson et al. 2004, Craighead and Bedrosian 2008). Yellowstone National Park was closed to hunting, Grand Teton National Park was open to elk hunting in parts of the eastern half of the park, and the surrounding national forests and private lands were open to multiple species game hunting with varying degrees of restrictions.

METHODS

Blood lead level is a standard indicator for acute exposure. The turnover rate of lead in the circulatory system ranges from 12 to 25 days in avifauna (Craighead and Bedrosian 2008) and 28 to 36 days in humans (Griffin et al. 1975, Rabinowitz et al. 1976). We collected blood samples from free-roaming wild wolves, cougars, black bears, and grizzly bears from collaborating biologists from the Interagency Grizzly Bear Study Team, Grand Teton National Park, the United States Fish and Wildlife Service Interagency Wolf Recovery Team, Craighead Beringia South, and Wyoming Game and Fish. Blood samples were taken from animals that were captured for research and management purposes independent of this study. Animals were handled according to Animal Care and Use protocols defined by those individual agencies and approved by the Institutional Animal Care and Use Committee at The University of Montana (permit no. TU08-08KFDBS-120508). Blood samples were collected intravenously at the time of capture and were stored refrigerated or frozen in 0.2% ethylenediaminetetraacetic acid blood tubes. We considered individuals captured multiple times over the course of the study as independent samples if they were captured more than 3 months apart because any lead present in the blood at the time of initial capture would no longer be in the bloodstream by the time of recapture (Rabinowitz et al. 1976, Miranda et al. 2006, Craighead and Bedrosian 2008).

We analyzed blood samples using the ESA Leadcare® System (LCS; ESA Biosciences, Inc, Chelmsford, MA; Craighead and Bedrosian 2008), which gives results in units of μg/dL. The LCS measures blood lead levels by anodic stripping voltammetry and the accuracy of the LCS has been confirmed for human blood samples (Shannon and Rifai 1997) and for avian samples (B. Bedrosian, Craighead Beringia South, unpublished data) using both graphite furnace atomic absorption spectrometry and inductively coupled mass spectrometry. In some avian species, LCS may give results that are slightly lower than other methods of lead analysis such as inductively coupled plasma mass spectrometry (ICPMS) but is still useful to compare the level of exposure of individuals (Bedrosian et al. 2009). We calibrated the LCS using bovine blood controls provided by ESA before each set of tests. In addition, we re-ran a subset of grizzly bear samples 1 year after initial tests ($n = 8$), several weeks after the initial test ($n = 6$), and immediately after the initial test ($n = 1$). Ninety-three percent of these samples were within the range of variation expected for control samples. The lower limit of LCS, below which an individual reading is no longer considered accurate, is 1.4 μg/dL. All results below this number may therefore be considered simply "below 1.4 μg/dL." For this analysis, the value given by the machine was used, because this value may be more accurate than reporting a result of either 1.4 or 0.0 μg/dL.

We collected liver tissue samples from individuals euthanized for management purposes independent of this study. Samples were analyzed using ICPMS at the Michigan State University Diagnostic Center for Population and Animal Health. Although blood samples give a measure of exposure to lead within the past several weeks, lead levels in liver samples indicate level of exposure to lead within the past 2–6 months (Rabinowitz et al. 1976, Sharma et al. 1982, Todorovic et al. 2008). The lower limit for detection of lead in tissue samples using ICPMS is 5.0 μg/dL and all readings below this are presented as "<5.0 μg/dL."

We collected scat samples by walking trails in and around areas open to fall elk hunting in Grand Teton National Park and Bridger-Teton National Forest. Each pile of scat was counted as 1 sample. If 2 piles were within a few meters of each other, we designated them as separate samples if they differed in apparent age or contents. We also analyzed scat collected from within the traps of bears captured for research or management to potentially match high or low lead levels in blood samples with the presence or absence of lead particles in scat samples for an individual.

We recorded the date and Global Positioning System location for each sample collected. We collected scat samples during the months of June, July, and August for a summer subset, and during the month of October for an autumn subset. We identified samples to genus using visual field identification marks (Halfpenny 2001). Scat samples that we identified as canid and were ≥30 mm in diameter were considered wolf samples; samples <30 mm were considered unknown *Canis* sp. samples (Weaver and Hoffman 1979). We were unable to assign a species to samples identified as bear scat because there is not a defined method for distinguishing these samples with certainty in the absence of analyzing DNA (Kendall et al. 1992).

We autoclaved each scat sample and dried them in a drying oven. We then ground samples with a coffee grinder and placed them in a Petri dish on a labeled cardboard grid. Petri dishes were radiographed at a local veterinarian's office and the radiographs were digitized. Small lead particles such as those coming from lead rifle bullet fragments or lead shot are visible by radiograph and are discernable from bone or other fragments (Hunt et al. 2006, Pauli and Buskirk 2007, Hunt et al. 2009). We experimentally placed discharged shotgun pellets and lead filling shaved from shotgun pellets in 2 Petri dishes with ground carnivore scat as controls. Both lead pellets and fragments from the controls were easily visible on the radiographs and served as a benchmark with which we were able to compare visible, bright white patches on the radiographs of samples. If we saw any spots on the radiographs, we dissected the sample to remove the particle for elemental analysis at the University of Montana Electron Microscopy Facility to confirm the presence of lead. Methods for electron microscopy were performed following the instructions from the Quartz Imaging Corporation (Vancouver, BC, Canada).

We used a Shapiro-Wilk test to determine the data for blood samples were right skewed for both black bears ($W = 0.84$, $P < 0.01$), and grizzly bears ($W = 0.81$, $P < 0.01$). We performed a log transformation, which normalized the distribution for both black bears ($W = 0.98$, $P = 0.73$) and grizzly bears ($W = 0.98$, $P = 0.18$). We then used the log-transformed data to perform parametric tests. Because blood samples collected outside either Grand Teton National Park or Yellowstone National Park tended to have more days between collection and analysis for grizzly bears (Pearson correlation 0.46, $P < 0.01$) and black bears (Pearson correlation 0.38, $P = 0.03$), we included this as a random variable in the analysis of variance (ANOVA) to control for this effect when comparing blood lead level among these 3 treatments and among years. Pair-wise comparisons were made using a Bonferroni post hoc test. We performed a 1-way ANOVA to compare blood lead level among the 4 test species. We did not perform statistical tests on liver tissue samples because there was not complete enough sample to make meaningful comparisons.

We found a general trend of increasing blood lead levels in grizzly bears sampled later in the year regardless of whether they were sampled before or during the hunting season ($R^2 = 0.026$, $P = 0.04$), so we tested these data using a segmented regression model to determine if the slope changed from before hunting season to during hunting season. The steady annual increase suggests a constant source of ingested lead for the population. To determine if lead from gut piles was a significant additional source of lead exposure, we used a segmented regression, which determined the slope of the relationship between lead level and time (magnitude of ingestion) before the hunting season started and after the hunting season started. By comparing the 2 regression slopes before and after the hunting season started, we were able to investigate if a greater amount of lead was being ingested at a faster rate as a result of an additional source of lead (gut piles). This would be evidenced by an increase in the slope during the hunting season. We also performed separate segmented regressions in both the populations inside and outside Yellowstone National Park to test for a difference in hunting and non-hunting season blood lead level rates in each population independently.

Because we had an adequate sample size of grizzly bear blood samples, we examined the following variables for potential influence on the blood lead levels: age, gender, capture location (latitude and longitude), if the bear was a problem bear or not, and if the bear was captured for management or research purposes. We also included a binary variable of capture location inside or outside Yellowstone National Park since there is no hunting or lead fishing tackle allowed in the park. We defined problem bears as individuals relocated or euthanized because they showed aggressive behavior towards people or property. We tested capture location to determine if there were any noticeable areas with high lead contamination (i.e., around currently active lead mines). We investigated the variables using a simple linear regression model and Bonferroni corrections. We used Mallow's C_p to identify the best models among a group of competing linear models in all linear regressions performed.

RESULTS

We tested blood samples from 4 carnivore species: grizzly bears ($n = 82$), black bears ($n = 35$), wolves ($n = 12$), and cougars ($n = 6$). In addition, we tested liver tissue samples from wolves ($n = 9$) and cougars ($n = 2$). Blood lead levels in grizzly bears were significantly higher than all other species tested ($P < 0.01$, Table 1). Black bears had lower blood lead levels than grizzly bears ($P < 0.01$) and higher blood lead levels than wolves ($P < 0.01$). Cougars did not have different blood lead level from black bears and wolves, although this may have been because of the small sample size of cougar blood tested.

We analyzed blood samples from 82 grizzly bears captured during 2007 ($n = 15$), 2008 ($n = 38$), and 2009 ($n = 29$). There was no difference in blood lead levels in grizzly bears across the 3 years of the study, so data from the 3 years were pooled ($F = 0.207$, $P = 0.81$). The highest blood lead level tested in grizzly bears was from a bear captured before the start of the hunting season, as were 7 out of the 11 bears with blood lead levels above 10 μg/dL (Fig. 1). We did not observe high outliers characteristic of acute lead poisoning during the hunting season. To control for a trend of increased blood lead levels later in the year, we used a segmented regression model to compare geometric mean blood lead levels before and after the 20 September start of hunting season. In this segmented regression model, there was no difference in the slopes of blood lead levels over time in grizzly bears captured before ($n = 59$) and after the start of hunting season ($n = 23$; $\beta < 0.001$, $P = 0.95$). When the populations inside and outside Yellowstone National Park were analyzed separately, there was still no difference between these blood lead level slopes before and after the 20 September start of hunting season ($\beta < 0.01$, $P = 0.34$ inside Yellowstone National Park, $\beta > -0.01$, $P = 0.73$ outside Yellowstone National Park).

The regression model identified no explanatory variables for grizzly bear blood lead levels. However, we found moderate evidence that bears captured inside Yellowstone National Park had lower lead levels than bears captured outside the Park as confirmed by the simple linear regression model ($F = 6.65$, $P = 0.012$). To further investigate this potential difference, we tested for a relationship between blood lead levels and the Euclidean distance from the bear's capture location to the nearest edge of Yellowstone National Park, hypothesizing that if Yellowstone was providing some level of protection against lead exposure then bears captured closer to the surrounding national forests would exhibit higher lead levels. Using simple linear regression, we found that the blood lead level was inversely related to the distance to the edge of the Park ($R^2_{adj} = 0.24$, $P = 0.002$). There were no geographic clusters of higher or lower blood lead levels and many of the higher values were found in bears on the far Southern portion of the ecosystem away from lead mines (Fig. 2).

Table 1. The mean, median, range, and standard deviation of blood lead levels from samples of grizzly bears, black bears, wolves, and cougars collected from 2007–2009 in the greater Yellowstone ecosystem. All measurements are in units of μg/dL. The abbreviation b.d.l. (below detectable limit) indicates that the measurement was below the lower detectable limit for the ESA Leadcare® system and can therefore not be accurately reported. The lowest value for all species was below the detectable limits.

Species	Mean	Median	SD	Highest value
Grizzly bear	5.5	4.4	4.0	18.6
Black bear	1.9	1.6	1.2	6.9
Wolf	b.d.l.	b.d.l.	0.5	1.4
Cougar	b.d.l.	b.d.l.	0.5	1.4

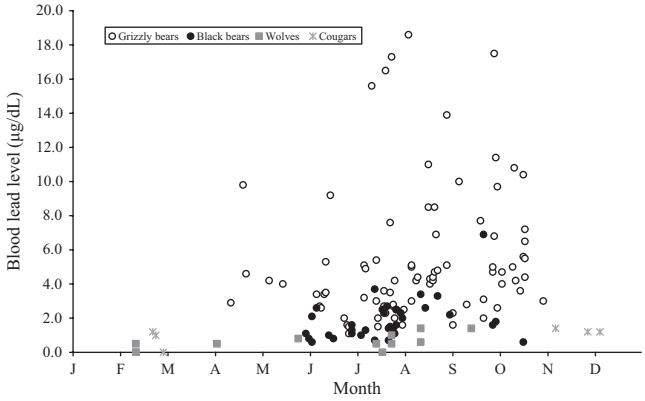

Figure 1. Blood lead level of grizzly bears ($n = 82$), black bears ($n = 35$), wolves ($n = 12$), and cougars ($n = 6$) captured from 2007–2009 in the greater Yellowstone ecosystem.

We tested blood lead levels in black bears (Fig. 1) captured in 2007 ($n = 15$), 2008 ($n = 14$), and 2009 ($n = 6$). There were no significant differences among the 3 years sampled in a 1-way ANOVA ($F = 1.117$, $P = 0.21$), so the data were pooled. We noted no difference in blood lead levels of black bears captured before ($n = 31$) or during ($n = 4$) the hunting season ($F = 0.957$, $P = 0.39$), although the sample size during the hunting season may not have been large enough for meaningful statistical comparison. We found no significant difference in blood lead levels of male ($n = 12$) and female ($n = 23$) black bears ($F = 0.437$, $P = 0.67$). There was no increase in blood lead levels with increased age ($F = 0.538$, $P = 0.47$). Blood lead levels in black bears captured in Yellowstone National Park, Grand Teton National Park, and outside the parks were similar ($P = 0.69$).

Wolves ($n = 12$) all had blood lead levels near or below detectable limits (b.d.l.; Table 1). No blood samples were collected from wolves during the fall elk hunting season. In addition, all wolf liver samples ($n = 9$) were below the detection limit for lead in tissues using ICPMS (<5 μg/dL), and similarly were not collected during or immediately following fall hunting season.

Cougars ($n = 6$) all had blood lead levels near or b.d.l. (Table 1). Two blood samples were collected from cougars during or immediately following elk hunting season. Both cougar liver samples, taken from 2 cougars collected during hunting season, were below the limits of detection for lead in tissue samples using ICPMS.

We collected scat of grizzly bears, black bears, wolves, and coyotes during the summer ($n = 209$) and fall ($n = 214$) of

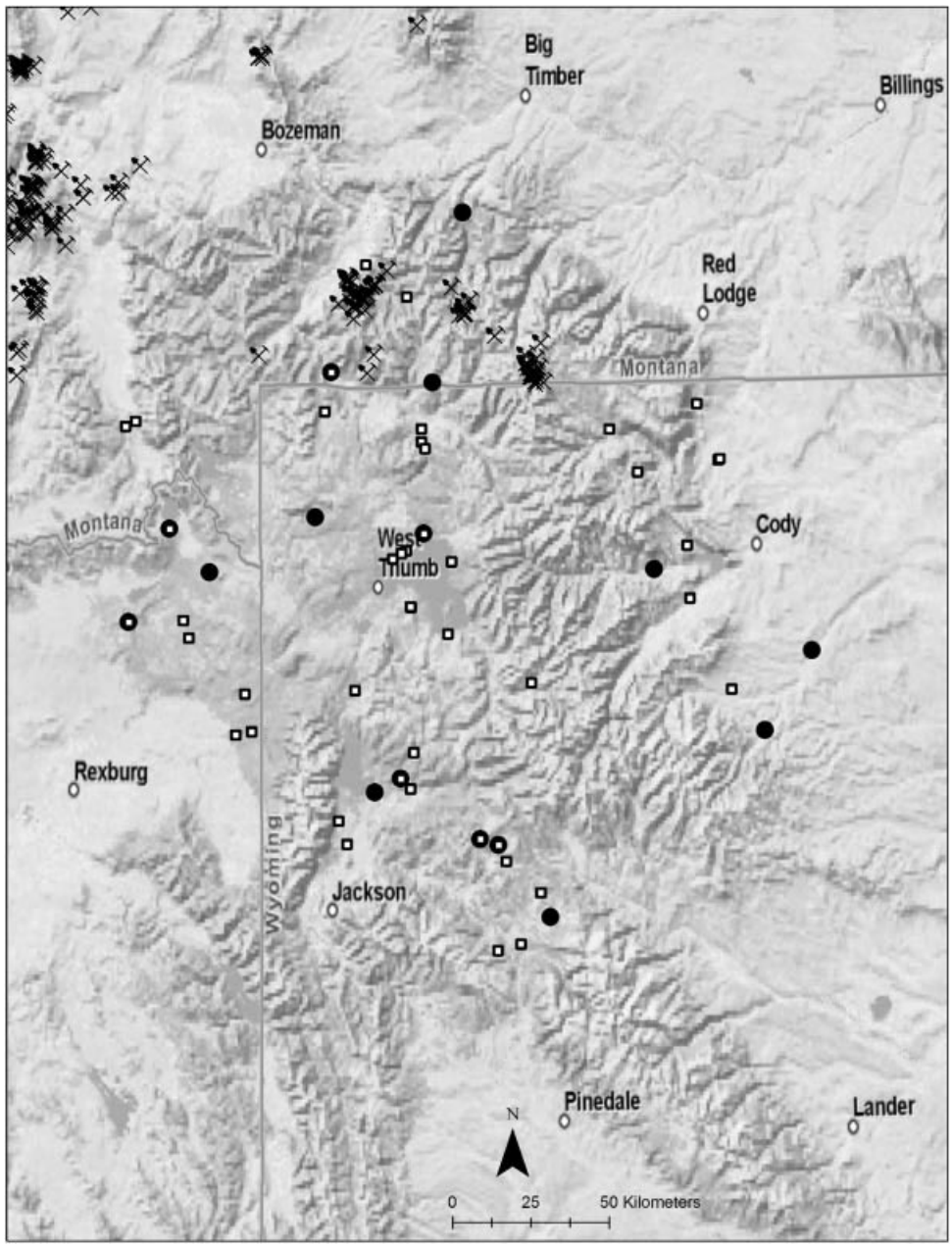

Figure 2. Distribution of grizzly bear captures from individuals tested for blood lead from 2007–2009 in the greater Yellowstone ecosystem. Individuals marked with a black circle had blood lead levels ≥8 μg/dL; those marked with a white square were below this level. Locations in which multiple bears with blood lead levels both above and below 8 μg/dL are marked with overlapping black circle and white square symbols. The shovel and pick symbols indicate locations of current and historical lead mines throughout the greater Yellowstone ecosystem (United States Geological Survey 2010).

2009. Of the summer subset collected in the field, 12 were identified as bear scat, 19 as wolf scat, and 149 were below 30 mm in diameter and were identified as unknown canid scat samples, although it is likely that many of these were coyote scat. Of the fall subset collected in the field, we identified 8 as bear scat, 33 as wolf scat, and 168 as unknown canid scat samples. We also tested 13 non-hunting season coyote scat samples collected by a collaborating group at the University of Wyoming in 2006. Of scat samples collected from bear traps, 14 scat samples were from grizzly bears captured during the summer, 1 scat sample was from a black bear captured during the summer, and 4 scat samples were from grizzly bears captured during the fall hunting season.

When we analyzed digital radiographs of the ground scat samples, fragments and shavings of lead ammunition in the control samples were clearly visible. None of the particles in test samples that resembled the clarity and brightness of particles in control samples contained any lead signature upon electron microscopic analysis; we did not detect lead ammunition fragments in the scat of these carnivores.

DISCUSSION

We found that lead levels were highest for grizzly bears, intermediate for black bears, and lowest for cougars and wolves. Lead levels were also higher in grizzly bears and black bears in individuals captured outside Yellowstone

National Park. However, we did not see the spike in lead levels in some individuals during the fall hunting season characteristic of a population affected by lead ammunition ingestion (Craighead and Bedrosian 2008), nor did we see a significant increase in blood lead levels in any species during the fall hunting season. We saw no differences in lead levels for problem grizzly bears and non-problem grizzly bears and found no difference in lead levels among the 3 years sampled despite differences in availability of food sources during these years (Haroldson and Podruzny 2010). In the absence of these trends, we are unable to confirm the hypothesis that grizzly bears or black bears are ingesting lead from ammunition sources. We are unable to determine if wolves or cougars are ingesting lead ammunition because of the scarcity of samples taken from these species during the fall hunting season. However, it is clear that baseline blood lead levels in wolves and cougars are lower than in grizzly bears in this study area.

Although we did not find lead ammunition fragments in the scat of these target species, the sample size may have needed to be several orders of magnitude larger in order to expect to find samples that contain fragments. Given the large number of times over a season an individual may defecate and the relatively few times that an individual may come across a lead ammunition-tainted meal, it may be rare to find the few scat piles that contain fragments. Although our findings provide some evidence that exposure to lead ammunition fragments may not be extremely widespread, as with any presence-absence study, the lack of detection does not equal the absence of a trend.

Our results showed that there was a small but significant general increasing trend for lead ingestion in grizzly bears throughout the year. These data may indicate a steady and continual source of lead exposure rather than a point source. Although we did not take blood samples during winter dormancy, lead exposure may be annually cyclical, increasing during the active time of year and decreasing during dormancy. Our analysis of lead levels before and after the start of big game hunting seasons after controlling for this continual source of lead also indicates a lack of effect of hunting season on grizzly bear blood lead levels, contrary to our predictions.

The effect of the lead levels we measured in grizzly bears remains unknown. In the absence of data describing physiological or behavioral effects of exposure to lead in grizzly bears, it is difficult to assign a specific toxic or background level of exposure for this species. However, the median blood lead level in grizzly bears was more than twice as high as levels suggested by Menke et al. (2006) to be safe in humans (2 μg/dL) and some grizzly bears had blood lead levels that were more than 9 times this benchmark. Lead levels in grizzly bears are also many times higher than the level found in preindustrial humans of 0.016 μg/dL (Flegal and Smith 1992), but they are lower than recommended safe levels of exposure established by the Center for Disease Control (10 μg/dL for children). Although it is not currently known what levels of exposure may have detrimental physiological or behavioral effects in grizzly bears, it may be worth further investigation to determine possible point sources of lead exposure for grizzly bears.

Several factors could potentially be contributing to lead exposure in bears. Leaded gasoline, once a major contributor to environmental lead, is no longer a source of exposure in humans or wildlife (Nriagu 1990). Although it does remain in relatively higher concentrations alongside roadways (Nriagu 1990), it is likely not a major source of exposure for bears. Lead remains relatively inert when deposited in soil and water, and plants do not readily take up lead deposited in soils and water within the normal range of acidity (Tsuji and Karagatzides 1998, Holdner et al. 2004). Therefore, contaminated soil must be ingested directly for lead to have an effect, rather than ingested through plants or water sources (Beyer et al. 1997, Tsuji and Karagatzides 1998).

Soil and sediment contaminated with mine tailings have previously contributed to lead exposure in species that directly or indirectly consume soil (Beyer et al. 1997, Beyer et al. 2007). In cattle, lead deposition from mine tailings has caused seasonal increases in blood lead levels, similar to what we measured in grizzly bears (Sharpe and Livesey 2006). The greater Yellowstone ecosystem contains many current or historical lead mines, particularly in the northeastern and northwestern corners of Yellowstone National Park (Fig. 2). Unlike wolves, coyotes, and cougars, which are almost exclusively carnivorous, black bears and grizzly bears are omnivorous, with the majority of their diet consisting of plant matter in the greater Yellowstone ecosystem (Robbins et al. 2004). There are several types of food consumed by grizzly bears that may cause them to ingest some soil indirectly when foraging. Yellowstone grizzly bears are known to feed on earthworms (Mattson et al. 2002*a*), roots (Mattson 1997), mushrooms, and truffles (Mattson et al. 2002*b*). They may also dig up pocket gopher dens and eat both the gopher and its food cache (Mattson 2004). If mine tailings do in fact contribute at least partially to levels of lead exposure seen in bears, this could explain some of the differences in lead exposure between omnivorous bears and the more strictly carnivorous wolves and cougars. Unlike bears, wolves and cougars do not forage for roots and truffles and would therefore not have the potential to be exposed through indirect consumption of soil. However, this would not explain differences observed in blood lead levels between grizzly bears and black bears and the lack of geographic trends (Fig. 2) in exposure levels suggest mine tailings may not be the exclusive source of lead.

Limits exist to what can be determined about the home range of an individual grizzly bear based on where it was captured because home range sizes for grizzly bears in the greater Yellowstone ecosystem average 884 km^2 for females and 3,757 km^2 for males (Blanchard and Knight 1991). Capture location may, however, give a reasonable idea of the general area the bear was located for several days prior to capture because grizzly bears move as little as 1–2 km per day (Blanchard and Knight 1991). Capture location may therefore be a useful index of areas with higher potential for lead exposure throughout the ecosystem. Lead levels in grizzly bears and black bears are lower inside Yellowstone National

Park, where there are no mines, than outside the park where current and historical lead mines exist. One other possible explanation for this difference may be due to lead fishing tackle. In 1996, Yellowstone National Park banned the use of leaded fishing tackle, which has been the cause of lead based mortality in a variety of waterfowl species and secondarily in raptors (Franson et al. 2003). Bears may be opportunistically feeding on fish with embedded leaded fishing tackle or secondarily on waterfowl that have ingested spent lead shot or tackle. This may occur less frequently within Yellowstone National Park because of the ban.

Although the data we collected do not point to lead ammunition as a point source of lead, they do not strictly exclude this possibility. Wildlife may be exposed to lead from ammunition at times of the year other than hunting season. Non-game animals such as ground squirrels, prairie dogs, and coyotes that are shot with lead ammunition and left in the field during times of the year outside of hunting season have been proposed as a potential source of lead exposure in scavenging hawks and eagles (Pauli and Buskirk 2007). If bears are ingesting lead from these sources of ammunition, they may not show the large spikes in blood lead levels because they are proportionally much larger than the size of an ammunition fragment than birds are (a 200-kg mammal rather than a 1-kg bird).

Grizzly bears and black bears may exhibit intrinsically different rates of lead absorption and deposition in the blood than birds and other mammals previously tested. Although lead exposure for black bears and grizzly bears may be similar to other species tested in this study, they may be exhibiting different levels of blood lead because of physiological differences in their response to lead exposure, as has been the case for different bird species feeding on the same lead sources (B. Bedrosian, unpublished data). For example, grizzly bears have higher concentrations of persistent organic pollutants in their fat following winter dormancy compared with before winter dormancy (Christensen et al. 2007). Although lead is not concentrated in fat (Medvedev 1999), winter dormancy may change other physiological aspects of lead absorption and distribution in the body of bears in other ways. Bears overcome bone loss during disuse in winter dormancy by maintaining bone formation and resorption during this time (McGee-Lawrence et al. 2009), which would likely mobilize lead stored in bones back into the bloodstream (Gwiazda et al. 2005). Although rates of bone turnover during the time period of activity for a bear would be similar to the other mammals we have examined, perhaps this process for mitigating bone loss contributes in some way to higher mobilization of lead stores in the bones of bears than in cougars and wolves, which do not go into winter dormancy.

MANAGEMENT IMPLICATIONS

It is difficult to establish a specific toxic level of exposure to lead in grizzly bears. Blood lead levels are higher than levels considered safe for humans (2 μg/dL; Canfield et al. 2003, Menke et al. 2006), but they are lower than recommendations set forth by the Center for Disease Control for children. Although these recommendations for unhealthy levels of exposure in humans may or may not reflect unhealthy levels of exposure in grizzly bears, it would be in the interest of grizzly bear conservation to mitigate lead exposure because even low level lead exposure negatively affects reproductive rates and intelligence in other species tested. Grizzly bears reproduce slowly and rely heavily on their intelligence as opportunistic omnivores. Therefore, recovery efforts may be aided by mitigating potential sources of lead exposure in grizzly bears.

ACKNOWLEDGMENTS

We thank our collaborators in this research, M. Boyce, M. Bruscino, S. Cain, S. Dewey, M. Haroldson, M. Jimenez, H. Quigley, S. Schmitz, C. Schwartz, S. Wolff, and their respective field crews. We thank D. Craighead, S. Craighead, O. Crino, R. Domenech, V. Ezenwa, M. Krebs, H. Langer, J. Levine, J. Moore, D. Newton, M. Parrish, D. Pletscher, and J. Rogers for their assistance in this research and in developing this manuscript. Scat samples were analyzed in the office of Dr. M. Pruyn, DVM in Missoula, MT and Dr. E. Patterson DVM in Jackson, WY. We thank the field crew, J. Alberts, J. Boersma, S. Hilty, and A. Potticary. Funding for this research was provided by The Montana Chapter of the Wildlife Society, the Charles Redd Center for Western Studies, and the University of Montana, with donations-in-kind made by Craighead Beringia South.

LITERATURE CITED

Anderson, C. R., Jr., and F. G. Lindzey. 2003. Estimating cougar predation rates from GPS location clusters. Journal of Wildlife Management 67:307–316.

Bedrosian, B., C. N. Parish, and D. Craighead. 2009. Differences between blood lead level detection techniques: analysis within and among three techniques and four avian species. Extended abstract *in* R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, editors. Ingestion of lead from spent ammunition: implications for wildlife and humans. The Peregrine Fund, Boise, Idaho, USA.

Belant, J. L., K. Kielland, E. H. Follmann, and L. G. Adams. 2006. Interspecific resource partitioning in sympatric Ursids. Ecological Applications 16:2333–2343.

Beyer, W. N., L. J. Blus, C. J. Henny, and D. Audet. 1997. The role of sediment ingestion in exposing wood ducks to lead. Ecotoxicology 6:181–186.

Beyer, W. N., G. Gaston, R. Brazzle, A. F. O'Connell, Jr., and D. J. Audet. 2007. Deer exposed to exceptionally high concentrations of lead near the Continental Mine in Idaho, USA. Environmental Toxicology and Chemistry 26:1040–1046.

Blanchard, B. M., and R. R. Knight. 1991. Movements of Yellowstone grizzly bears. Biological Conservation 58:41–68.

Cade, T. J. 2007. Exposure of California condors to lead from spent ammunition. Journal of Wildlife Management 71:2125–2133.

Canfield, R. L., C. R. Henderson, Jr., D. A. Cory-Slechta, C. Cox, T. A. Jusko, and B. P. Lanphear. 2003. Intellectual impairment in children with blood lead concentrations below 10 ug per deciliter. New England Journal of Medicine 348:1517–1526.

Carson, E. A., V. H. Stefan, and J. F. Powell. 2000. Skeletal manifestations of bear scavenging. Journal of Forensic Sciences 45:515–526.

Christensen, J. R., M. MacDuffee, M. B. Yunker, and P. S. Ross. 2007. Hibernation-associated changes in persistent organic pollutant (POP) levels and patterns in British Columbia grizzly bears (*Ursus arctos horribilis*). Environmental Science & Technology 41:1834–1840.

Craighead, D., and B. Bedrosian. 2008. Blood lead levels of common ravens with access to big-game offal. Journal of Wildlife Management 72:240–245.

Fisher, I. J., D. J. Pain, and V. G. Thomas. 2006. A review of lead poisoning from ammunition sources in terrestrial birds. Biological Conservation 131:421–432.

Flegal, A. R., and D. R. Smith. 1992. Lead levels in preindustrial humans. New England Journal of Medicine 326:1293–1294.

Franson, J. C., S. P. Hansen, T. E. Creekmore, C. J. Brand, D. C. Evers, A. E. Duerr, and S. DeStefano. 2003. Lead fishing weights and other fishing tackle in selected waterbirds. Waterbirds 26:345–352.

Griffin, T. B., F. Coulston, H. Willis, and J. C. Russell. 1975. Clinical studies on men continuously exposed to airborne particulate lead. Environmental Quality and Safety 2:221–240.

Gwiazda, R., C. Campbell, and D. Smith. 2005. A noninvasive isotopic approach to estimate the bone lead contribution to blood in children: implications for assessing the efficacy of lead abatement. Environmental Health Perspectives 113:104–110.

Halfpenny, J. C. 2001. Scat and Tracks of the Northern Rocky Mountains. Morris Book Publishing, Guilford, Connecticut, USA.

Haroldson, M. A., and S. Podruzny. 2010. Whitebark pine cone production: 2009 project summary. U. S. G. S., Northern Rocky Mountain Science Center, Interagency Grizzly Bear, Study Team, Bozeman, Montana, USA.

Haroldson, M. A., C. C. Schwartz, S. Cherry, and D. S. Moody. 2004. Possible effects of elk harvest on fall distribution of grizzly bears in the greater Yellowstone ecosystem. Journal of Wildlife Management 68:129–137.

Holdner, J., B. Wainman, R. Jaysinghe, E. Van Spronsen, J. D. Karagatzides, E. Nieboer, and L. J. Tsuji. 2004. Soil and plant lead of upland habitat used extensively for recreational shooting and game bird hunting in southern Ontario, Canada. Bulletin of Environmental Contamination and Toxicology 73:568–574.

Hunt, W. G., W. Burnham, C. N. Parish, K. K. Burnham, B. Mutch, and J. L. Oaks. 2006. Bullet fragments in deer remains: implications for lead exposure in avian scavengers. Wildlife Society Bulletin 34:167–170.

Hunt, W. G., R. T. Watson, J. L. Oaks, C. N. Parish, K. K. Burnham, R. L. Tucker, J. R. Belthoff, and G. Hart. 2009. Lead bullet fragments in venison from rifle-killed deer: potential for human dietary exposure. PLoS One 4:Article No.: e5330.

Kendall, K. C., L. H. Metzgar, D. A. Patterson, and B. M. Steele. 1992. Power of sign surveys to monitor population trends. Ecological Applications 2:422–430.

Knopff, K. H., A. A. Knopff, and M. S. Boyce. 2010. Scavenging makes cougars susceptible to snaring at wolf bait stations. Journal of Wildlife Management 74:644–653.

Mattson, D. J. 1997. Selection of microsites by grizzly bears to excavate biscuitroots. Journal of Mammalogy 78:228–238.

Mattson, D. J. 2004. Exploitation of pocket gophers and their food caches by grizzly bears. Journal of Mammalogy 85:731–742.

Mattson, D. J., M. G. French, and S. P. French. 2002*a*. Consumption of earthworms by Yellowstone grizzly bears. Ursus 13:105–110.

Mattson, D. J., S. R. Podruzny, and M. A. Haroldson. 2002*b*. Consumption of fungal sporocarps by Yellowstone grizzly bears. Ursus 13:95–103.

McGee-Lawrence, M. E., S. J. Wojda, L. N. Barlow, T. D. Drummer, A. B. Castillo, O. Kennedy, K. W. Condon, J. Auger, H. L. Black, O. L. Nelson, C. T. Robbins, and S. W. Donahue. 2009. Grizzly bears (*Ursus arctos horribilis*) and black bears (*Ursus americanus*) prevent trabecular bone loss during disuse (hibernation). Bone 45:1186–1191.

Medvedev, N. 1999. Levels of heavy metals in Karelian wildlife, 1989–91. Environmental Monitoring and Assessment 56:177–193.

Menke, A., P. Muntner, V. Batuman, E. K. Silbergeld, and E. Guallar. 2006. Blood lead below 0.48 μmol/L (10 μg/dL) and mortality among US adults. Circulation 114:1388–1394.

Miranda, M., M. Lopez-Alonso, P. Garcia-Partida, J. Velasco, and J. L. Benedito. 2006. Long-term follow-up of blood lead levels and haematological and biochemical parameters in heifers that survived an accidental lead poisoning episode. Journal of Veterinary Medicine Series A 53:305–310.

Nriagu, J. O. 1990. The rise and fall of leaded gasoline. Science of the Total Environment 92:13–28.

Pauli, J. N., and S. W. Buskirk. 2007. Recreational shooting of prairie dogs: a portal for lead entering wildlife food chains. Journal of Wildlife Management 71:103–108.

Rabinowitz, M. B., G. W. Wetherill, and J. D. Kopple. 1976. Kinetic analysis of lead metabolism in healthy humans. Journal of Clinical Investigation 58:260–270.

Robbins, C. T., C. C. Schwartz, and L. A. Felicetti. 2004. Nutritional ecology of ursids: a review of newer methods and management implications. Ursus 15:161–171.

Ruth, T. K., D. W. Smith, M. A. Haroldson, P. C. Buotte, C. C. Schwartz, H. B. Quigley, S. Cherry, K. M. Murphy, D. Tyers, and K. Frey. 2003. Large-carnivore response to recreational big-game hunting along the Yellowstone National Park and Absaroka-Beartooth Wilderness boundary. Wildlife Society Bulletin 31:1150–1161.

Servheen, C., R. Knight, D. Mattson, S. Mealy, D. Strickland, J. Varley, and J. Weaver. 1986. Report to the Interagency Grizzly Bear Committee on the availability of foods for grizzly bears in the Yellowstone ecosystem. U.S. Fish and Wildlife Service, Missoula, Montana, USA.

Shannon, M., and N. Rifai. 1997. The accuracy of a portable instrument for analysis of blood lead in children. Ambulatory Child Health 3:249–254.

Sharma, R. P., J. C. Street, J. L. Shupe, and D. R. Bourcier. 1982. Accumulation and depletion of cadmium and lead in tissues and milk of lactating cows fed small amounts of these metals. Journal of Dairy Science 65:972–979.

Sharpe, R. T., and C. T. Livesey. 2006. Lead poisoning in cattle and its implications for food safety. Veterinary Record 159:71–74.

Smith, B. L., and S. H. Anderson. 1998. Juvenile survival and population regulation of the Jackson elk herd. Journal of Wildlife Management 62:1036–1045.

Todorovic, T., D. Vujanovic, I. Dozic, and A. Petkovic-Curcin. 2008. Calcium and magnesium content in hard tissues of rats under condition of subchronic lead intoxication. Magnesium Research 21:43–50.

Tsuji, L. J. S., and J. D. Karagatzides. 1998. Spent lead shot in the western James bay region of northern Ontario, Canada: soil and plant chemistry of a heavily hunted wetland. Wetlands 18:266–271.

United States Geological Survey. 2010. Current and historical lead mines in Idaho, Montana, and Wyoming. Mineral Resources Data System. Compiled by D.E. Guberman, Washington, D.C., USA.

Weaver, J. L., and Stephan W. Hoffman. 1979. Comparison of coyote and wolf scat diameters. Journal of Wildlife Management 43:786–788.

Wilmers, C. C., D. R. Stahler, R. L. Crabtree, D. W. Smith, and W. M. Getz. 2003. Resource dispersion and consumer dominance: scavenging at wolf- and hunter-killed carcasses in Greater Yellowstone, USA. Ecology Letters 6:996–1003.

Associate Editor: Matt Gompper.