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Letters

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Conservation Letter: Lead Poisoning of Raptors

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Lead poisoning of raptors is an ongoing and pervasive global conservation concern with potentially significant impacts for some species and populations. This Conservation Letter provides a scientific review of raptor lead poisoning globally and concludes by highlighting lessons learned and potential solutions. This letter is not intended as an exhaustive literature review. Rather, the intent of the Raptor Research Foundation (RRF) is to provide readers with enough evidence-based examples that they can appreciate the scope and prevalence of lead poisoning, understand the potential effects on raptor species and populations, and gain a basic understanding of the challenges associated with addressing lead poisoning of raptors across regions.

Lead is a nonessential metal that has a variety of uses in modern society including ammunition, fuel additives, and storage batteries. The same properties that make lead useful for anthropogenic applications worldwide—resistance to corrosion and low mobility—cause lead to remain in host environments for millennia (Jørgensen and Willems 1987, Davies et al. 1990). The mining, manufacturing, combustion, recycling, and disposal of lead and lead products has resulted in lead concentrations in the atmosphere, soil, and water that are several orders of magnitude higher than naturally occurring concentrations (Franson and Pain 2011). Emissions of lead into the air and water enable lead to be inhaled or ingested, the two most common pathways of exposure to terrestrial vertebrates (Franson and Pain 2011).

Exposure to lead, a highly poisonous neurotoxin, has been documented among raptor species worldwide (e.g., Haig et al. 2014, Krone 2018). The primary route of exposure is ingestion, typically through consumption of prey items containing lead fragments (Katzner et al. 2018, Krone 2018). Although lead does not generally appear to bioaccumulate through the food chain, secondary poisoning has been documented in raptors (e.g., Feierabend and Myers 1984). Lead poisoning can also be a secondary effect of shooting (persecution) when the shooting event itself is nonlethal, but lead remains lodged in the body (Berny et al. 2017). For more information on persecution, see the Conservation Letter: Raptor Persecution (Madden et al. 2019).

Effects of Lead Poisoning on Raptors. The lethal and sublethal effects of lead on raptors have been well documented (e.g., Watson et al. 2009, Krone 2018). Lead enters the bloodstream after being broken down by stomach acids following ingestion or is absorbed through the lungs after inhalation. After entering the bloodstream, lead is transported to soft tissues such as the kidney and liver and eventually to the skeletal system where lead replaces vital nutrients such as calcium in the bone matrix (Scheuhammer 1987, Gangoso et al. 2009). Blood lead concentrations can be reflective of both recent and past

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exposure events, as lead can be released from skeletal repositories back into the bloodstream; feathers, kidney, and liver reflect lead exposure over a moderate term, and bones reflect long-term or even life-time exposure (Franson and Pain 2011). Lead in the blood causes anemia even at low levels of exposure, and acute lead poisoning can result in kidney failure, liver lesions and swelling, enlarged gall bladder, brain lesions, and fibrin exudations under the pericardium (as reviewed in Krone 2018). What constitutes lethal concentrations of lead varies by species, with Turkey Vultures (*Cathartes aura*) and several hawk species being fairly tolerant of repeated lead exposure (Friend 1999, Carpenter et al. 2003) whereas California Condors (*Gymnogyps californianus*) and Andean Condors (*Vultur gryphus*) suffer high mortality rates from lead poisoning (Pattee et al. 2006, Finkelstein et al. 2010).

Sublethal lead exposure can result in lower fecundity (Pain et al. 2009) as well as indirect mortality. Elevated concentrations of lead can cause increased bone fragility, decreased vision via ocular lesions, and higher susceptibility to infections (as reviewed in Krone 2018), all of which can compromise the ability of a lead-poisoned individual to forage effectively or maneuver in flight (Burger 1995, Ecke et al. 2017). For example, research on Steller's Sea-Eagles (*Haliaeetus pelagicus*) and White-tailed Eagles (*Haliaeetus albicilla*) in Japan by Saito (2009) found that victims of vehicle collisions and electrocutions often had high concentrations of lead, and some individuals previously thought to have died of starvation had evidence of lead poisoning. Measuring the concentrations of lead in injured or dead raptors is not routinely performed for most species; thus, the proportion of indirect mortality caused by lead poisoning is likely underestimated (e.g., Wayland et al. 2003).

Sources of Lead Poisoning. There is a worldwide consensus that the most important source of lead poisoning in raptors comes from the ingestion of lead pellets and fragments from ammunition, with lead fishing tackle being of next greatest concern (Fisher et al. 2006). A review by Schulz et al. (2002) demonstrated that some areas in Missouri, USA, may have as much as one million lead shot pellets/ha. A recent review of lead poisoning in the northern Peruvian Amazon River basin by Cartró-Sabaté et al. (2019) found significant concentrations of lead in many non-raptor species, due primarily to subsistence hunting, which is permitted only for indigenous communities. Increasing awareness of this issue has led many countries to impose regulations regarding the use of lead ammunition and fishing tackle (e.g., USA, Argentina, see below); however, lead ammunition remains unregulated in many regions of the world (Avery and Watson 2009, Plaza et al. 2018).

The amount of lead entering the environment from fishing tackle varies by location. One study estimated that in Poland, 1000–1500 metric tons of lead sinkers were lost annually (Hansen et al. 2004). Areas with exceptionally high fishing pressure may pose an important threat to waterfowl (e.g., Scheuhammer and Norris 1996, Haig et al. 2014). Raptor species that feed on waterfowl (e.g., Bald Eagle [*Haliaeetus leucocephalus*], White-tailed Eagle) are therefore at risk due to secondary ingestion of lead fishing tackle (Rattner et al. 2008, Ishii et al. 2017). Improvements are still needed to quantify the amount of lead entering aquatic ecosystems (Rattner et al. 2008).

Other sources of lead exposure exist but are rarely documented in raptors. Researchers evaluating the effect on Osprey (*Pandion haliaetus*) of lead exposure from mining found no significant effects of lead from this source (Henny et al. 1991, Langner et al. 2012). However, if there is chronic exposure to low concentrations of lead, the effects could be subtle but significant. Unfortunately, investigating the effects of chronic exposure is challenging due in part to costly postmortem examinations. Microtrash is a known source of lead exposure for raptors, specifically scavengers like condors. However, the degree of lead poisoning risk from ingestion of microtrash and other debris is still unknown (Finkelstein et al. 2015). This research topic needs greater study, especially for raptor species that forage near urban areas and have greater exposure to e-waste. Regardless of the relative contribution of different sources of lead to poisoning in raptors, exposure sources likely act cumulatively, increasing the severity of exposure.

Implications to Global Raptor Populations. Worldwide, lead exposure has been documented in at least 42 predatory and scavenging bird species (Fisher et al. 2006, Pain et al. 2019). Feeding ecology is the primary predictor of lead exposure among raptor species, with exposure directly correlated to the extent a species scavenges (Slabe et al. 2020). New and Old World vultures and condors are susceptible year-round due to their ecological role as obligate scavengers. Conversely, facultative scavengers such as *Aquila* and *Haliaeetus* eagles are most susceptible during periods when they scavenge rather than periods when they focus on live prey (Slabe et al. 2020). Whereas some obligate scavengers appear to be the most susceptible to population-level impacts from lead, susceptibility varies among both obligate and facultative scavengers.

Vultures and condors are particularly susceptible to lead poisoning yet remain poorly studied worldwide with the exception of a few species (Plaza and Lambertucci 2019). The California Condor, a critically endangered species, is the highest profile avian scavenger affected by lead poisoning (Church et al. 2006). Lead exposure in the California Condor lowers reproductive rates and lead toxicosis is the primary cause of death in wild populations of adult individuals (Cade 2007, Finkelstein et al. 2012, Rideout et al. 2012). Andean Condors (near-threatened) are also known to be susceptible to lead poisoning (Pattee et al. 2006); however, studies on free-living individuals have been limited to a few studies conducted in southern Chile and Argentina. Here, introduction of exotic species for hunting purposes (Lambertucci et al. 2011) has led to an increase in the use of lead ammunition. At the same time, the increasing number of exotic animals has also shifted the Andean Condor's diet to almost exclusively introduced wild and domestic animals (Lambertucci et al. 2009). The change in diet together with the increase in hunting has led to an increase in ingestion of lead ammunition from carcasses, the main source of lead poisoning in Andean Condors (Lambertucci et al. 2011). Although it has been documented that the species is especially susceptible to lead poisoning (Pattee et al. 2006), the impacts on populations are poorly understood (Wiemeyer et al. 2016, Plaza et al. 2018).

A number of vulture species for which the IUCN conservation status is endangered or critically endangered are susceptible to lead poisoning. For example, lead poisoning is thought to be a major threat to Egyptian Vultures (*Neophron percnopterus*; endangered), which have elevated lead concentrations in multiple European countries (Gangoso et al. 2009, Plaza and Lambertucci 2019). In Africa, Cape Vultures (*Gyps coprotheres*; endangered), Lappet-faced Vultures (*Torgos tracheliotos*; endangered), and White-backed Vultures (*Gyps africanus*; critically endangered) have high lead concentrations in areas of trophy hunting, an important source of tourism income (Naidoo et al. 2012, Garbett et al. 2018, Plaza and Lambertucci 2019). In Asia, Long-billed Vultures (also known as Indian Vultures; *Gyps indicus*; critically endangered) and White-rumped Vultures (*Gyps bengalensis*; critically endangered) also have documented lead poisoning (Plaza and Lambertucci 2019). More studies are needed in Africa and Asia, areas experiencing rapid declines in vulture populations, to understand the overall impacts of lead poisoning to vulture species.

Multiple species of raptors that are facultative scavengers are also susceptible to lead poisoning, with global studies of lead exposure overwhelmingly focused on *Aquila* and *Haliaeetus* eagles. In Europe, researchers found that breeding success in Bonelli's Eagles (*Aquila fasciata*; endangered) was negatively affected by the ingestion of lead pellets present in small-game prey items (Gil-Sánchez et al. 2018). Lead exposure in Australian raptors is poorly studied; nonetheless, one study revealed that 27% of Wedge-tailed Eagles (*Aquila audax*; least concern) had elevated lead concentrations (Lohr et al. 2020). Golden Eagles (*Aquila chrysaetos*; least concern), a circumpolar apex predator, have documented lead exposure in the European Alps (Madry et al. 2015), the United Kingdom (Pain et al. 1995), and North America (Langner et al. 2015). Lead poisoning is estimated to cause between 2.1% and 4.8% of Golden Eagle mortality in the USA (Russell and Franson 2014, US Fish and Wildlife Service 2016) but may be underestimated as a result of reporting bias (e.g., Crandall et al. 2019).

Lead exposure in *Haliaeetus* eagles increases when carcasses and gut piles containing lead fragments from ammunition are used as a food source (Nadjafzadeh et al. 2013, Slabe et al. 2020). In Japan, the discovery of lead poisoning in Steller's Sea Eagle (vulnerable) and White-tailed Eagles resulted in ammunition restrictions for hunting (see below). Studies in Germany, Poland, and Japan revealed lead concentrations consistent with poisoning in the vital organs of White-tailed Eagles (Helander et al. 2009, Krone et al. 2009, Kitowski et al. 2017). Lead poisoning is the most significant source of anthropogenic mortality of this species in Finland (Isomursu et al. 2018). In the USA, lead poisoning accounted for 16.3% of 2980 Bald Eagle (least concern) deaths between 1975 and 2013 (Russell and Franson 2014).

Lead Remediation Efforts. Multiple legislative actions have been enacted worldwide to reduce the use of lead ammunition. In total, 33 countries have implemented some level of restriction on lead ammunition, with the majority of these restrictions enacted for the protection of waterfowl and wetlands (Stroud 2015). Australia has a number of hunting regulations, and along with New Zealand imposes restrictions on certain types or uses of lead shot (Avery and Watson 2009). Several African countries also have hunting regulations, with Mauritania setting the example in 1975 by prohibiting the use of lead ammunition for large game and sport hunting (Avery and Watson 2009). South Africa has a regulation prohibiting the use of lead shot for waterfowl hunting (Avery and Watson 2009). The European countries of Denmark, Sweden, and the Netherlands have passed some of the most stringent laws, resulting in countrywide bans on the use of lead ammunition (Mateo and Kanstrup 2019). France, Sweden, and Germany have banned the use of lead ammunition in wetlands and for waterfowl hunting. Countries in South America are increasingly concerned about the use of lead ammunition. For example, two provinces in Argentina have taken pioneering actions to prohibit the use of lead ammunition in wetland ecosystems. In addition, Argentina, Chile, Brazil, Uruguay, Paraguay, Bolivia, Ecuador, and Peru have signed the Convention on Migratory Species, committing to gradually eliminate the use of lead ammunition (Plaza et al. 2018). However, to date, many of these countries have not implemented restrictions. In the USA, California recently enacted a statewide ban on lead ammunition primarily as a result of continued population-level effects of lead on the California Condor. Three other laws have been enacted as a result of concern for a single raptor species: (1) a lead ammunition ban for waterfowl hunting in the USA was passed to protect Bald Eagles, (2) a ban in Germany on lead ammunition was passed due to concern for White-tailed Eagles (Thomas et al. 2019) and, (3) a lead ammunition ban in Hokkaido, Japan was enacted to protect *Haliaeetus* eagles (Saito 2009, but see voluntary program below).

Multiple lead remediation efforts in the USA have utilized on-the-ground communication and education efforts to encourage the voluntary use of non-lead ammunition. Voluntary programs are particularly important because on-the-ground actions can result in immediate behavior changes within the hunting community without the political and cultural divisiveness often associated with legislation. A successful non-lead ammunition outreach and distribution program in northwest Wyoming resulted in >50% voluntary participation in hunters employing non-lead ammunition for elk hunting (Bedrosian et al. 2012). An ongoing multi-year outreach and non-lead ammunition distribution program in the Arizona range of the California Condor by the Arizona Game and Fish Department and The Peregrine Fund has maintained an average annual rate of 87% hunter participation (Sieg et al. 2009; C. Parish, The Peregrine Fund, pers. comm.). A pilot effort by the Oregon Zoo's Non-lead Hunting Education Program, in coordination with The Nature Conservancy, Oregon Hunters Association, and Oregon Department of Fish and Wildlife, increased non-lead ammunition use to 77% of cow elk hunters on the Zumwalt Prairie Preserve over a 4 yr period and is now being adopted statewide (L. Brown, Oregon Zoo, pers. comm.). As of July 2020, the Arizona Game and Fish Department, the Utah Department of Natural Resources, the Oregon Department of Fish and Wildlife, and 25 hunting and conservation organizations, had signed a resolution to partner with the North American Non-lead Partnership (NANP, www.nonleadpartnership.org). Through this partnership, these state agencies and organizations promote the voluntary use of non-lead ammunition to licensed hunters as a form of conservation and stewardship action for scavenging wildlife (Spurling et al. 2018). The NANP promotes the use of non-lead ammunition through communication, education, and incentives, with a focus on both wildlife conservation and hunting heritage within the framework of the North American Model of Wildlife Conservation.

The ban of lead ammunition in Hokkaido, Japan, is one example where on-the-ground voluntary efforts effected a regulatory change. A civic group led by veterinarians was established in July 1998 (Saito 2009). They organized activities to prevent lead poisoning of *Haliaeetus* eagles including bringing in debilitated or dead eagles, patrolling hunting areas, disposing of deer carcasses and offal (as much as 1 ton/d), purchasing nontoxic ammunition for the local hunting association, and creating and publishing educational materials about lead poisoning in raptors. Two years later, regulations were passed to require use of nontoxic ammunition for deer hunting (including copper-jacketed lead bullets with low fragmentation rates), and were expanded in 2004 to cover all big-game hunting.

As a leading professional society for raptor researchers and raptor conservationists, the RRF is dedicated to the accumulation and dissemination of scientific information about raptors, and to resolving raptor conservation concerns (RRF 2020). Lead poisoning of raptors remains an ongoing conservation concern and presents a global threat to raptor populations, many of which have little to no direct regulatory protection. Based on the science summarized here, reducing the sources and scale of lead poisoning will allow long-term co-occurrence of raptor populations with human populations.

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