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Lead poisoning of raptors: state of the science and cross-discipline mitigation options for a global problem

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ABSTRACT

Lead poisoning is an important global conservation problem for many species of wildlife, especially raptors. Despite the increasing number of individual studies and regional reviews of lead poisoning of raptors, it has been over a decade since this information has been compiled into a comprehensive global review. Here, we summarize the state of knowledge of lead poisoning of raptors, we review developments in manufacturing of non-lead ammunition, the use of which can reduce the most pervasive source of lead these birds encounter, and we compile data on voluntary and regulatory mitigation options and their associated sociological context. We support our literature review with case studies of mitigation actions, largely provided by the conservation practitioners who study or manage these efforts. Our review illustrates the growing awareness and understanding of lead exposure of raptors, and it shows that the science underpinning this understanding has expanded considerably in recent years. We also show that the political and social appetite for managing lead ammunition appears to vary substantially across administrative regions, countries, and continents. Improved understanding of the drivers of this variation could support more effective mitigation of lead exposure of wildlife. This review also shows that mitigation strategies are likely to be most effective when they are outcome driven, consider behavioural theory, local cultures, and environmental conditions,

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effectively monitor participation, compliance, and levels of raptor exposure, and support both environmental and human health.

Key words: behavioural theory, birds of prey, laws and regulations, lead ammunition, non-lead ammunition, One Health.

CONTENTS

I. INTRODUCTION

Lead, one of the most abundant heavy metals in the Earth's crust, is also a common environmental toxicant made available primarily by human activity (Walker *et al.*, 2012; Liang & Mao, 2015). Lead has been recognized for millennia as a toxicant (Hernberg, 2000), and sources of lead pollution include batteries, vehicle exhaust, paint, water piping, mining, smelting, industrial emissions, fishing tackle, and firearm ammunition (ATSDR, 2020). However, especially in developed countries, effective campaigns that included regulation have substantially reduced lead pollution from many sources, although there is continued widespread use of lead acid batteries, ammunition, and fishing tackle.

Lead negatively impacts the functioning of most or all organ systems within vertebrates, including humans (Fallon *et al.*, 2017; ATSDR, 2020). Because of the many historical uses of lead and the impacts of chronic exposure on cognitive function of children, lead poisoning remains a high-profile and preventable human health concern. However, lead poisoning also is a global health concern for wildlife, with documented individual and population-level consequences for many species (Pain, Mateo & Green, 2019).

Birds of prey (raptors) are important as top predators (Sergio *et al.*, 2014), ecological indicators (Rodríguez-Estrella, Donázar & Hiraldo, 1998; Natsukawa *et al.*, 2021), cultural icons (Tingay & Katzner, 2010; Schuetz & Johnston, 2019; Wilcox, Boissinot & Idaghdour, 2019), and because their conservation delivers benefits to a suite of other non-raptor species (Sergio, Newton & Marchesi, 2005; Sergio *et al.*, 2006). Because of their ecological role and physiology, raptors can be excellent sentinels of environmental contamination, being frequently exposed to, highly affected by, and indicative of ecosystem effects, of a very wide suite of anthropogenic environmental pollutants (Richards *et al.*, 2017; Baudrot *et al.*, 2018; DeSorbo *et al.*, 2018; Movalli *et al.*, 2018; Wiens *et al.*, 2019; González-Rubio *et al.*, 2021; Hofstadter *et al.*, 2021). This is especially the case for lead exposure (Haig *et al.*, 2014; Golden, Warner & Coffey, 2016; Pain *et al.*, 2019), and today, lead poisoning is the most widespread form of heavy metal poisoning of birds of prey (Franson, 1996; Mautino, 1997; Fisher, Pain & Thomas, 2006).

Lead exposure is a global and preventable problem for birds of prey, and high rates of lead exposure have been detected on the six continents where raptors are found (Golden *et al.*, 2016; Garbett *et al.*, 2018; Plaza *et al.*, 2018; Pain *et al.*, 2019; Pay *et al.*, 2021). The majority of reported exposure is from residues or fragments of rifle bullets, shotgun pellets ('shot'), or shotgun slugs (Haig *et al.*, 2014; Golden *et al.*, 2016). Less commonly, exposure occurs from fishing tackle (Haig *et al.*, 2014; Golden *et al.*, 2016), and lead paint (Finkelstein *et al.*, 2012). The individual-level effects of lead exposure on raptors are well documented, but an increasing number of recent studies have demonstrated population-level effects of lead poisoning (Finkelstein *et al.*, 2012; Grade *et al.*, 2018; Green, Pain & Krone, 2022*a*; Hanley *et al.*, 2022; Millsap *et al.*, 2022; Slabe *et al.*, 2022).

Garvin, Slabe & Cuadros Díaz (2020) presented a succinct overview of the issue of lead poisoning of raptors, and others have summarized aspects of this issue for certain regions of the world (Golden *et al.*, 2016; Pain *et al.*, 2019). However, global data and literature on lead poisoning of, and mitigation for, raptors have not been comprehensively collated since Watson *et al.* (2009). This information gap is especially relevant in light of a number of important factors. First, in recent years there has been an increase in the number of studies documenting lead exposure and its effects on avian and raptor physiology and populations [see table 2 in Pain *et al.* (2019), although this summary is already 5 years old]. Second, as is documented in the recent literature, evidence for and scientific understanding of this problem is substantially more global than it was in the recent past (as an example, only one of >50 articles in Watson *et al.* (2009) evaluates lead issues outside of Europe or North America). Finally, the growth of the science has led to development of a range of novel technologies, conservation policies, and mitigation actions based on behavioural theory, but few of these have been summarized previously. Compiling all information on these themes into a comprehensive review thus provides a starting point for next steps and further growth and advances to address this problem.

II. OBJECTIVES AND METHODS

To update information on lead poisoning of raptors, a virtual two-day meeting was held in October 2021. This meeting included presentations from, and debate among, specialists in a variety of disciplines related to lead poisoning of raptors. Participants came from across the Americas, Eurasia, and Australasia. This virtual meeting provided the foundation for this review and participants were offered the opportunity to contribute as co-authors.

Herein, we use the information from that meeting, supplemented by a literature review, to summarize the state of science and mitigation for lead exposure of raptors. We begin with a summary, focusing on prior syntheses and reviews, of physiological effects of lead exposure to raptors, identifying and treating lead exposure of raptors, routes of lead exposure, the global nature of the problem, and population-level effects. We close that section with a discussion of data gaps in the science. Subsequently, we review developments in manufacturing of non-lead ammunition and knowledge gaps associated with that ammunition. We then review options for mitigation for use of lead ammunition and fishing tackle, as it pertains to raptors, we discuss the sociology of mitigation for lead exposure, and we cover lead exposure as a One Health issue. We close this section by reviewing actions taken to mitigate lead exposure of raptors, separately considering regulatory and voluntary approaches taken across the globe. Finally, we end our review with next steps, for science and mitigation, to address this problem.

The content we present is drawn both from the scientific literature and from personal narratives. We used a hybrid approach to evaluating existing literature on raptors and lead exposure.

First, each section of this manuscript was written by a co-author who was an expert in a subject area pertinent to the topic covered in that section. We also asked a subset of expert co-authors or colleagues from each geographic region to review legislation from their continent, to help us identify existing local legislation and regulations on the use of lead ammunition. Using expert contributions is important for several reasons: first because much information on local issues is unpublished, and second because search engines tend to focus on English-language literature and would thus fail to capture the global nature of this problem.

Second, to ensure that the subject area experts had covered pertinent literature since Watson *et al.* (2009), we performed a *Google Scholar* search covering the time period 2008–2022 for the words 'lead' and 'raptor' (see online Supporting Information, Appendix S1). We evaluated the first 100 records returned in this search. We reviewed those records to ensure that relevant themes were included in our review and, when appropriate, we added references and relevant content that our experts had missed. Because this search uncovered no new themes and contributed few new papers, we did not extend our search beyond the first 100 records.

Third, because of documented issues with relevance sorting, repeatability, and personalization associated with *Google Scholar*, best practices suggest use of multiple search engines for reviews (Anderson, 2013; Giustini & Boulos, 2013; Haddaway *et al.*, 2020). Likewise, 'raptor' and 'lead' are generic terms used in many fields and there is value to searching with more specific terminology. To avoid these problems, we also performed systematic searches in *Web of Science* and *PubMed*, focusing on papers published from 2008 through 2024 (searches were conducted on 26 January 2024). In this second search, we used highly specific search terms to focus on reports that we might have missed with our first search, especially those focused on empirical results and population-level impacts. Our searches used the words 'lead' and 'heavy metal' in combination with terms describing common names, family names, and genera for all raptors. To ensure that this effort was comprehensive, we designed the search so that all species studied would have repeated opportunities to be detected in search results. At the same time, to ensure efficiency, we did not include specific names for each species. Additional details on how the search was conducted, and the search terms used are provided in Appendix S1.

The *Web of Science* search returned 1760 articles, of which 232 were relevant to the theme of this paper and unique (there were many duplicates). The *PubMed* search returned 1107 articles, of which 191 were relevant and unique. Once again, we reviewed the records returned in this literature search to ensure that relevant themes were included in this review and, when appropriate, we added references and relevant content that our experts had missed.

III. STATUS OF THE SCIENCE

(1) Past information syntheses

Historically, little information existed on lead poisoning of raptors, other than data from a few studies of wild species from the USA poisoned by shotgun pellets or bullet fragments, and from experimental poisoning of captive birds fed lead or lead-tainted game (Pain *et al.*, 2019). Research effort increased through the 1990s and early 2000s (Fisher *et al.*, 2006), as summarized in proceedings from the conference on 'Ingestion of lead from spent ammunition: implications for wildlife and humans' (Watson *et al.*, 2009). Those proceedings highlighted a number of fundamental issues (Newton, 2009). Key among these are the detrimental effects of lead on humans and wildlife, the likely linkages between use of lead ammunition for hunting and negative outcomes for human health, the positive effects for raptors from constraints on use of lead shotgun pellets for hunting of waterfowl, the important role of fragmentation of lead rifle bullets in creating exposure risk for scavenging wildlife, and the potentially broad swath of species affected by lead poisoning. Several next steps were also identified in those proceedings, all linked to knowledge gaps on the effects of ammunition-based lead on wildlife and humans, and on the best ways to mitigate the effects of lead exposure on wildlife (i.e. legislative *versus* voluntary approaches).

Since Watson *et al.* (2009), there have been several reviews of the effects of lead from ammunition on wildlife and human health and associated mitigation strategies. Those of Delahay & Spray (2015) and those edited by Kanstrup, Thomas & Fox (2019*b*) have a European focus, while Haig *et al.* (2014) has a global focus. Pain *et al.* (2019) focused on all birds, but included a summary of studies on predatory and scavenging birds from five continents. We know of only one review (Golden *et al.*, 2016) focused exclusively on raptors, and that was geographically limited to the USA. Garvin *et al.* (2020) presented a succinct global overview of lead poisoning in raptors, but this was not intended to be an exhaustive literature review.

Together, these summaries clearly show advances in the state of knowledge that begin to address the 'next steps' identified by Newton (2009). These advances fall primarily into three different areas: physiological effects of lead exposure for raptors, routes of exposure of raptors to lead and species affected, and mitigation of the problem. The current state of knowledge of these issues is covered in following subsections, as are other topics of importance that are mentioned but treated less thoroughly in prior reviews (ammunition types and technologies, demographic effects of lead exposure, and global awareness of the problem).

(2) Raptor taxa affected

Lead exposure occurs in nearly all raptor taxa (Golden *et al.*, 2016; Kanstrup *et al.*, 2019*a*; Pain *et al.*, 2019). In part this is because many raptor taxa scavenge (Fig. 1). It seems intuitive that true obligate scavengers – the 'Old World Vultures' of the family Accipitridae, and the 'New World Vultures' of the family Cathartidae – are widely reported to be affected by lead poisoning. Likewise, raptors that scavenge opportunistically or seasonally (Slabe *et al.*, 2022) including many genera of eagles, caracaras, hawks (buzzards), and kites are also widely known to be lead exposed. However, reports of lead exposure include many other taxa that scavenge more than has been recognized previously (Fig. 1). These include harriers (*Circus* spp.), falcons (*Falco* spp.), owls (Strigiformes), and Accipitrinae hawks (*Accipiter* spp.) and relatives (Pain *et al.*, 2019). Beyond scavenging, exposure of these species may occur through a series of other routes covered below (see Section III.5).

(3) Effects of lead exposure on raptors

Lead is a toxic heavy metal that is not known to be a biological requirement for any species and that can potentially affect all systems within the body (Locke, 1996; Redig & Cruz-Martinez, 2009; Pain, 1996). Lead absorption and the subsequent response of the animal are related to many factors including species, age, sex, nutritional status, and environmental stressors (Friend, Franson & Ciganovich, 1999; Carpenter *et al.*, 2003; Pattee & Pain, 2003; Fisher *et al.*, 2006; Pattee *et al.*, 2006; Finkelstein *et al.*, 2010).

Once lead has been inhaled or ingested (either directly from the environment or indirectly through consuming lead in the flesh of other animals), a proportion is absorbed into the blood and transported to soft tissues such as the kidney or liver (Bassi *et al.*, 2021). Eventually that lead is stored in the bones, where it replaces calcium, an essential nutrient for development (Scheuhammer, 1987; Gangoso *et al.*, 2009). Consequently, bones provide a record of lead exposure over the lifetime of the bird and lead concentrations in bones of older birds often are higher than those in younger birds (Slabe *et al.*, 2022), bone lead concentrations are often higher than those in other tissues (Behmke, Mazik & Katzner, 2017), and large proportions of populations can show evidence of chronic poisoning (Behmke *et al.*, 2015; Slabe *et al.*, 2022).

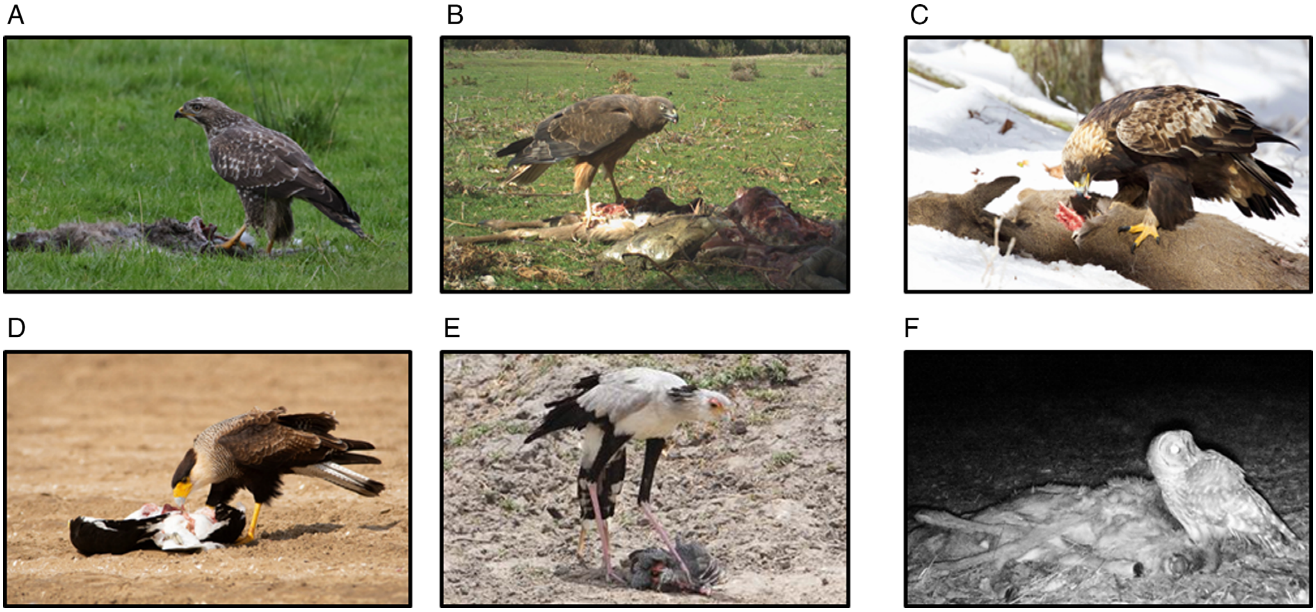

Fig. 1. Examples showing the geographic breadth and taxonomic diversity of raptors that may be exposed to lead while scavenging. Photographs show scavengers including (A) common buzzard (*Buteo buteo*) from the UK, Europe (D. Pain); (B) swamp harrier (*Circus approximans*) in Victoria, Australia (J. Hampton, University of Melbourne); (C) golden eagle (*Aquila chrysaetos*) in Pennsylvania, USA, North America (R. Flament); (D) southern caracara (*Caracara plancus plancus*) in Buenos Aires, Argentina, South America (M. Encabo, Fundación Cabure-í); (E) secretarybird (*Sagittarius serpentarius*) from Waza National Park, Cameroon, Africa (R. Buij, The Peregrine Fund); and (F) barred owl (*Strix varia*) in Pennsylvania, USA, North America (Eastern Golden Eagle Working Group).

Lead concentrations are typically intermediate in soft tissue and feathers and lowest in blood, although acute exposure events can cause high concentrations in soft tissue and blood (Franson & Pain, 2011).

Even at comparatively low concentrations, lead in the blood can cause anaemia (Franson *et al*., 1983; Pain & Rattner, 1988; Krone, 2018). Lead exposure can negatively affect fertility and fecundity of birds in a number of ways including effects on sperm quality, fertilization rate, egg quality and production, hatchability, and nestling mortality (Elder 1954, Grandjean, 1976, Golden *et al*., 2016, Vallverdú-Coll *et al*., 2016; Gil-Sánchez *et al*., 2018; Bakker *et al*., 2023) and may cause birds to be more susceptible to other sources of mortality [e.g. collision, starvation (Eisler, 1988; De Francisco, Ruiz Troya & Agüera, 2003; Franson & Pain, 2011)]. Although only a few of these studies are focused on raptors, results from non-raptor birds should also be informative. One study found no relationship between the lead levels in pellets regurgitated by Eurasian eagle owls (*Bubo bubo*) and their reproductive output (Shin, Oh & Kim, 2018).

Higher levels of lead exposure can result in kidney failure, liver lesions and swelling, enlarged gall bladder, brain lesions, fibrin exudations under the pericardium, increased fragility of bone, ocular lesions and decreased visual performance, and higher susceptibility to infection and impairment of the immune system (Redig *et al*., 1991; Grasman & Scanlon, 1995; Krone, 2018). There is also good evidence of physiological harm caused by lead exposure, as indicated by changes in blood chemistry and indicators of oxidative stress (Martínez-López *et al*., 2004; Stout *et al*., 2010; Espín *et al*., 2016, Kanwal *et al*., 2020).

Once physiology is impacted, lead exposure can affect functional attributes of the animal (Burger, 1995). Existing evidence suggests that lead exposure may alter behaviour and sibling recognition by herring gulls (*Larus argentatus*; Burger & Gochfeld, 1994), affect movement behaviour of golden eagles (*Aquila chrysaetos*; Ecke *et al*., 2017), reduce breeding success of Bonelli's eagles (*Aquila fasciata*; Gil-Sánchez *et al*., 2018), Eurasian blackbirds (*Turdus merula*; Fritsch, Jankowiak & Wysocki, 2019) and northern mockingbirds (*Mimus polyglottos*; Hitt *et al*., 2023), increase collision risk of mute swans (*Cygnus olor*; Kelly & Kelly, 2005), alter immune response of mallard (*Anas platyrhynchos*) ducklings (Vallverdú-Coll *et al*., 2015) and black-headed gulls (*Chroicocephalus ridibundus*; Ushine *et al*., 2022, 2023), and affect health (e.g. changes in mass; Helander *et al*., 2021) and physiology [e.g. changes to delta aminolevulinic-acid dehydratase (δ-ALAD) (Gómez-Ramírez *et al*., 2011; Herring *et al*., 2020; Descalzo *et al*., 2021)] of raptors. One study found no relationship between lead exposure of golden eagles and fatalities at wind turbines (Viner & Kagan, 2021). Although the extent to which sub-lethal lead poisoning can reduce individual survival has not been quantified in field studies, it is clear that deaths due to lead exposure have population-level consequences for some species (Pain, Fisher & Thomas, 2009; see also more recent work in Section III.7).

(4) Identifying and treating lead exposure of raptors

Radiographs (X-rays) can assist in identifying metal fragments in raptors or other animals (Fig. 2), and even their regurgitated pellets (Mateo *et al.*, 2001). Lead cannot be differentiated from other metals using this technique (but see Leontowich, Panahifar & Ostrowski, 2022), although lead tends to fragment more than other harder metals (Stokke, Brainerd & Arnemo, 2017) and recovered fragments can be analytically tested to identify their composition (Shin *et al.*, 2018). More definitive diagnosis of lead exposure typically relies on chemical analysis of blood or other body tissues. In recent years, there has been an increase in availability of point-of-care systems that use anodic stripping voltammetry to test for lead exposure in blood. Although useful for diagnosis of wildlife in clinical settings (e.g. Domenech *et al.*, 2021), these devices were designed for use with human blood (Ishii *et al.*, 2017). As such, concerns have been raised about the utility of uncorrected data from these devices for scientific inference on birds (Herring *et al.*, 2018) and other species (Boesen *et al.*, 2019), and the gold standard for testing remains either graphite-furnace atomic absorption spectrometry (GFAAS) or inductively coupled mass spectrometry (ICP-MS; Herring *et al.*, 2018). ICP-MS has also been used for analysis of other tissue types, including liver, bone, and feathers (Slabe *et al.*, 2022). X-ray fluorescence (XRF) technology is increasingly being utilized to quantify lead and other metals in bones of both live (Specht *et al.*, 2018) and *post-mortem* specimens (Specht *et al.*, 2018; Hampton *et al.*, 2021*c*).

As lead testing has become faster, easier, and more cost-effective, guidelines for treatment criteria for wild raptors have been published and reviewed (Samour & Naldo, 2002; Redig & Arent, 2008; Fallon *et al.*, 2017; Williams *et al.*, 2017). Although it is not our goal to review treatment options, we mention here the basic approaches covered in the papers cited above, and we encourage interested readers to explore those publications, as well as others, for additional details. When radiographs indicate presence of probable lead fragments in the gastrointestinal tract, removal of those pieces *via* lavage, endoscopy, or surgery improves health outcomes. Subsequently, chelation therapy can be administered, often with Succimer® (dimercaptosuccinic acid), $CaNa_2$ ethylene diamine tetraacetic acid (CaEDTA) or other medications. These chelation agents are associated with potential harm, although risks from treatment usually are deemed lower than those from the lead exposure. Finally, in conjunction with chelation, supportive care can be administered, *via* fluids, anti-seizure medicines, and treatment of other conditions. For raptors with mild to moderate lead toxicosis, removal of lead fragments and chelation can take several weeks and may result in a healthy animal that can be released back to the wild. However, chelation cannot reverse the damage from lead exposure to the brain, heart, kidneys, or other organs. In rehabilitation settings, severe lead poisoning often leads to death or euthanasia of affected animals.

(5) Routes of lead exposure

Lead exposure of raptors is most commonly associated with scavenging (Pain *et al.*, 2019; Golden *et al.*, 2016). However, when not scavenging, raptors also can be lead exposed from

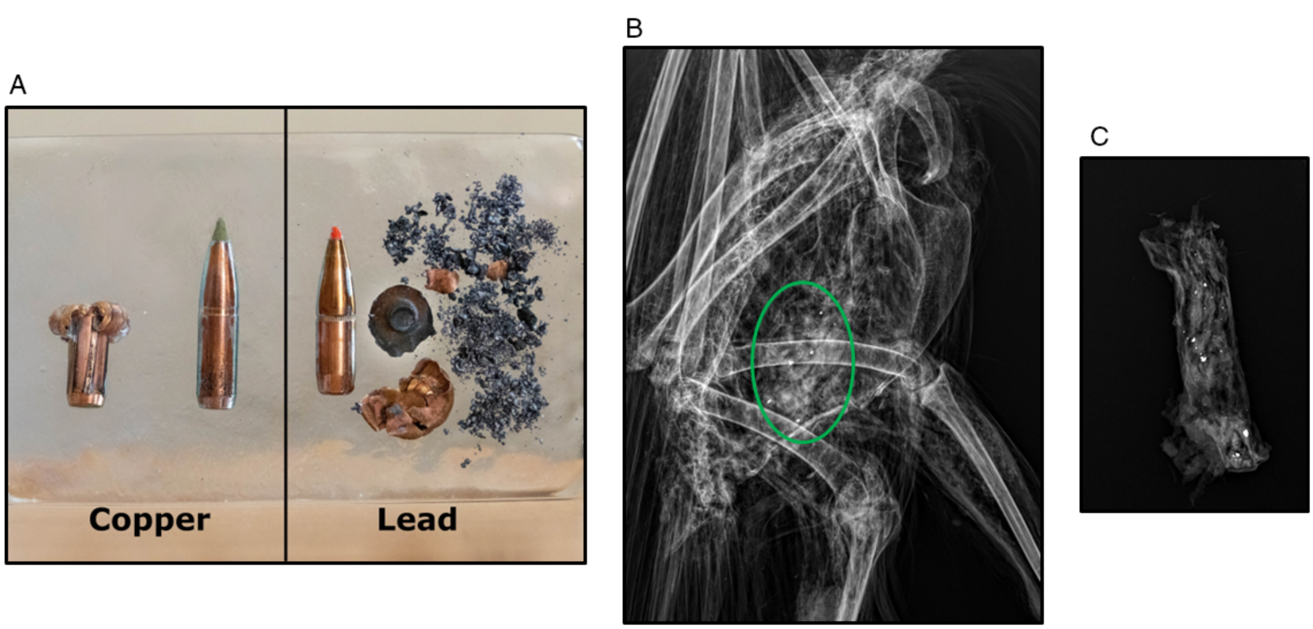

Fig. 2. Lead ammunition *in vitro* and *in vivo*. (A) Comparison of copper and lead rifle bullets prior to firing, when fully intact (centre) and after being fired and impacting a target (left and right sides). The fragmenting of lead into hundreds or thousands of pieces creates risk for raptors that scavenge upon shot animals or discarded viscera. Such fragments are shown in (B) the abdomen (green circle) and (C) excised intestine of an adult golden eagle (*Aquila chrysaetos*) tagged in Quebec, Canada and recovered dead in rural West Virginia, USA. Image credits: M. McTee (A) and E. Thomason (B, C).

embedded pellets or fragments resulting from non-fatal shooting (Berny, Mas & Vey, 2017), through predation on wounded or lead-poisoned wildlife (Kanstrup *et al.*, 2019*a*) and invertebrates (Slabe *et al.*, 2019*b*), consumption of lead paint (Finkelstein *et al.*, 2012), and from ingestion of fishing tackle (Grade *et al.*, 2019) (Fig. 3).

There is ample evidence that scavenging offal or carcasses resulting from shooting of big game is a common route by which raptors are exposed to lead (Figs 1–3). Although historical regulations have focused especially on shotgun pellets, concern has grown recently about fragments from bullets and slugs, with one study suggesting that nearly 60% of lead-poisoned bald eagles (*Haliaeetus leucocephalus*) were exposed *via* fragmented ammunition (SOAR, 2022). Lead often is deposited when a bullet impacts an animal (Stokke *et al.*, 2017). If this occurs, gut piles (offal) from hunted animals can contain a high number of lead fragments (Craighead & Bedrosian, 2008; Hunt *et al.*, 2009; Warner *et al.*, 2014), and tissue from those animals can be contaminated with lead (Lindboe *et al.*, 2012). Golden eagles captured while feeding on ungulate carcasses had statistically higher blood lead concentrations than those captured with live lures, suggesting increased risk of lead exposure for birds targeting carrion as a food source (Langner *et al.*, 2015). Furthermore, the presence of elevated blood lead concentrations in raptors is more likely during the autumn and winter months in regions where big game hunting produces a pulse of gut piles and killed but unrecovered animals on the landscape (Cruz-Martinez, Redig & Deen, 2012; Nadjafzadeh, Hofer & Krone, 2013; Slabe *et al.*, 2020, 2022; Helander *et al.*, 2021). Lead exposure of raptors increases over hunting seasons as the number of harvested big game animals increases (Legagneux *et al.*, 2014). Likewise, isotopic ratios in blood with elevated lead concentrations match those of the recycled metallic lead used in ammunition (Legagneux *et al.*, 2014; Madry *et al.*, 2015; Pay *et al.*, 2021). Some studies have shown that programs to increase use of non-lead ammunition to harvest big game can be correlated with lower blood lead concentrations of scavenging raptors (Green *et al.*, 2008; Kelly *et al.*, 2011; Bedrosian, Craighead & Crandall, 2012), although other work has shown no effect (VCF, 2021). Finally, a potentially important source of lead in carcasses of big game are injured animals euthanized in the field *via* shooting, and animals killed for management purposes, i.e. culling (B. Bedrosian, unpublished observations, Hampton *et al.*, 2022*c*).

Shooting of small mammals also is common, particularly in the western USA. Most species shot in this manner are exempt from 'wonton waste' laws and so are typically left where they lie and thus are available to scavengers. Typically, such shooting is conducted using highly frangible rimfire or small-calibre centrefire cartridges (Herring, Eagles-Smith & Wagner, 2016; Pauli & Buskirk, 2007), although shotgun hunting also occurs. Because of this, shooting of small mammals for pest control and recreation can provide food for scavenging raptors and a pathway for lead exposure (McTee, Hiller & Ramsey, 2019; Herring *et al.*, 2020). Large numbers of prairie dogs (*Cynomys* spp.), >60 per shooter/day in Colorado, USA (Seglund *et al.*, 2004) and >1.5 million/year in South Dakota, USA (Huxoll, 2012), are shot for recreation, making lead-containing carcasses substantial in quantity. This pathway

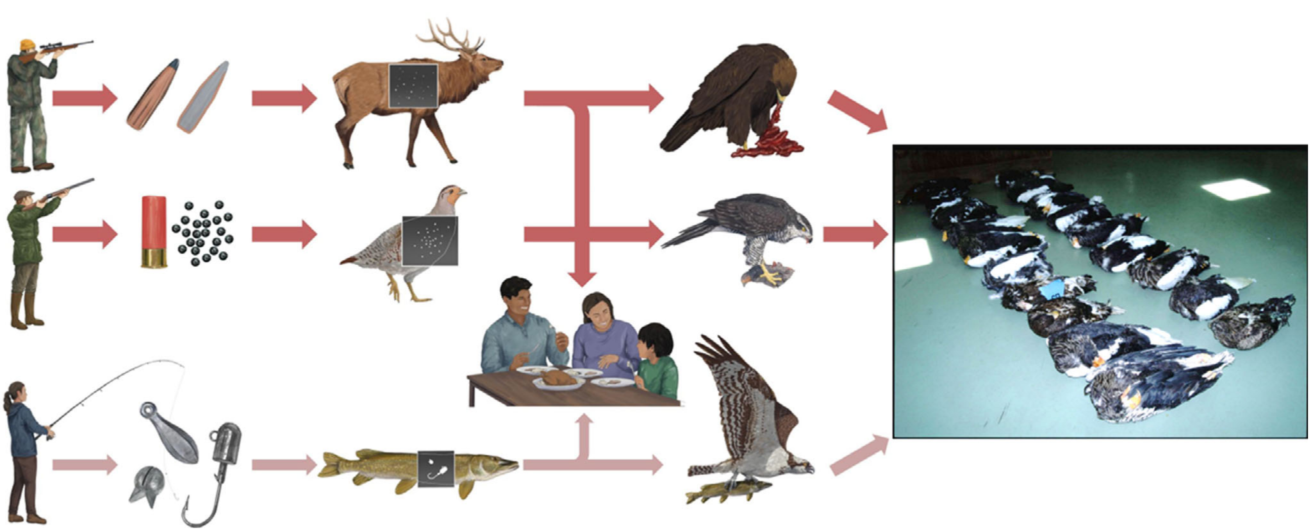

Fig. 3. Examples of pathways by which raptors may be exposed to lead, through use of lead projectiles (bullets, slugs, sabots), lead pellets (shotgun or pistol), and, less frequently (as designated by the paler arrows), lead fishing tackle (sinkers, weights, lures, etc.). Other pathways also exist – e.g. game birds may ingest shotgun pellets as grit, and waterbirds may ingest lead fishing tackle, and subsequently either can be eaten by raptors. However, once a raptor ingests lead, it commonly is injured or killed by the toxicant. Lead poisoning is a One Health issue that can also affect many components of the environment, including humans. The photograph on the right shows 18 lead-poisoned Steller's sea eagles (*Haliaeetus pelagicus*) (photograph credit: K. Saito). Graphic by A. Connington.

differs from that of shooting of big game because of the sheer volume of animals killed, the proportion of each small carcass that is contaminated with lead residue, the availability to raptors of numerous carcasses and wounded animals, and the feasibility with which small carcasses can be carried to nests and fed to nestlings (Herring *et al.*, 2016; McTee *et al.*, 2017, 2019). One recent study demonstrated that in the western USA, hunter-killed ground squirrels (Sciuridae) are an important source of both food and lead for nesting golden eagles (Herring *et al.*, 2021).

Shooting of birds and small mammals with lead shotgun pellets (hereafter 'shot') or small-calibre lead-based bullets is a globally common practice (Pain *et al.*, 1993; Pain, Bavoux & Burneleau, 1997; Pain *et al.*, 2009, 2010, 2022; Pain, Cromie & Green, 2014; Herring *et al.*, 2016; McTee *et al.*, 2017, 2019; Taggart *et al.*, 2020). Whether this activity is for recreational, commercial, or management purposes, it can be an important vector of exposure for wildlife, *via* either lead embedded in wounded animals or deposition of lead on the landscape. The use of lead shot to hunt waterfowl has been prohibited in the USA since 1991 (USFWS, 2022*c*), in the EU from February 2023 (European Union, 2021), and in a few other countries (Mateo & Kanstrup, 2019). However, lead shot it is still commonly used over wetlands in other regions and it is widely used in all but a few countries for shooting gamebirds and small mammals in terrestrial habitats. It is estimated that use of shot spreads massive amounts of lead across the landscape [13,000–15,000 metric tons/year in EU terrestrial habitats (ECHA, 2021); 6–9 million kg of lead/year in US dove-hunting areas (Kendall *et al.*, 1996; Pierce *et al.*, 2015)] and densities of lead pellets per hectare can reach the hundreds of thousands (Kendall *et al.*, 1996). As with bullets, lead shot deposited in the flesh of animals is frequently accompanied by numerous small lead fragments (Pain *et al.*, 2010; Green *et al.*, 2022*b*), the greater surface area to volume ratio of which is likely to facilitate lead absorption in an avian digestive tract. In the UK, liver lead concentrations of common buzzards (*Buteo buteo*) collected over 11 years showed a consistent tendency to increase coincident with the timing of the UK gamebird hunting season, and isotopic signatures of lead matched those in shotgun ammunition (Taggart *et al.*, 2020).

Outdoor shooting ranges (e.g. skeet, trap, pistol, and rifle ranges) present another documented source of possible lead exposure in the environment and to wildlife (e.g. Ma, 1989; Stansley & Roscoe, 1996; Lewis *et al.*, 2001; Sorvari, Antikainen & Pyy, 2006). Animals ingesting deposited shot or feeding on wildlife contaminated *via* elevated soil or plant lead concentrations could be eaten by raptors. Surface-feeding birds such as mourning doves (*Zenaida macroura*; Schulz *et al.*, 2007) and American woodcock (*Scolopax minor*; French *et al.*, 2017) may ingest available pellets, succumb to lead poisoning (Schulz *et al.*, 2006), and be eaten by raptors or scavengers. In the same way, soils in heavily managed dove hunting fields may be lead contaminated (Castrale, 1989; Best, Garrison & Schmitt, 1992; Buck, 1998; Schulz *et al.*, 2002) and earthworms and other taxa used for food by raptors can potentially transmit that lead to raptors (Slabe *et al.*, 2019*b*). That said, there is limited recent information on the significance to raptors of potential exposure *via* outdoor shooting areas.

Raptors may be exposed to lead *via* prey contaminated through point-source exposure unrelated to ammunition. For example, a high proportion of red grouse (*Lagopus lagopus scoticus*) from one site in England were found to have elevated bone lead concentrations with isotopic ratios consistent with a combined exposure to ingested lead shot and lead from galena mining in the region (Thomas, Scheuhammer & Bond, 2009). Similarly, waterbirds and passerines have been exposed to lead from mining and smelting activities in northern Idaho, USA (Blus *et al.*, 1995). These UK and USA species are all potential prey items for several raptor species, but, again, the significance of this exposure route is not well understood.

Although the main source of documented lead ingestion by raptors comes from pellets and fragments from spent ammunition (Bellinger *et al.*, 2013; Haig *et al.*, 2014), incidental ingestion of lead fishing gear also poisons wildlife (Grade *et al.*, 2019; Wood *et al.*, 2019). The volume of lead fishing tackle lost in and along waterways is immense. One study from Poland estimated that 1000–1500 metric tons of lead sinkers were lost annually (Hansen *et al.*, 2011), another from Minnesota, USA, suggested that across five study lakes anglers lost 1 metric ton per year of lead-based items (Radomski *et al.*, 2006). In other areas, densities of sinkers in heavily fished water bodies can reach as high as 16/m^2 (Haig *et al.*, 2014). As a consequence, areas with high fishing pressure are thought to pose an important threat to waterfowl (e.g. Scheuhammer & Norris, 1996; Haig *et al.*, 2014) and fish (Rattner *et al.*, 2008; Ishii *et al.*, 2017; Slabe *et al.*, 2019*a*), and lead poisoning from ingested fishing tackle is well documented for some piscivorous avian species (Grade *et al.*, 2019; MacDonald, 2018). Although lead fishing tackle is pervasive in aquatic ecosystems, research on its effects only rarely is focused on fish-eating raptors, but the possibility of exposure cannot be discounted (Ishii *et al.*, 2020).

The primary documented health risks for raptors from exposure to environmental lead are from ingestion. Inhalation is unlikely as a route of exposure to lead for raptors (Katzner *et al.*, 2018). That said, other avenues may also be relevant. In particular, lead can be absorbed from lead particles or fragments embedded in soft tissues after an animal survives being shot (Finkelstein *et al.*, 2014; Berny *et al.*, 2017; Pain *et al.*, 2019). Likewise, there are routes of lead exposure documented for other species that may occasionally be relevant to raptors. For example, during incubation, common eiders (*Somateria mollissima*) fast and the resulting physiological stress causes mobilization of lead stored in liver and bones during prior exposure events, resulting in increasing blood lead concentrations over the course of the incubation period (Lam *et al.*, 2020). Likewise, maternal transfer has been shown to occur for some species (Vallverdú-Coll *et al.*, 2015) and seems plausible for raptors. The frequency and extent to which these routes of exposure are demographically relevant is not known.

(6) The global nature of the problem

In the years since the first broad-based summary of the effects of lead poisoning on raptors (Watson *et al.*, 2009), it has become clear that lead exposure of raptors is not confined to North America and Europe. In fact, there is growing evidence that lead exposure occurs on every continent and major island where raptors occur. Here, we briefly review some of that global evidence, focusing on South America, Asia, Africa, and Australia. Because of the quantity of literature on lead exposure in North America and Europe (Plaza & Lambertucci, 2019), literature from those two continents makes up most of the citations in other sections of this review and so we do not cover those continents in this section. That said, the paucity of information on this problem on other continents is notable.

In South America, the frequency of research on this topic is increasing, resulting in verification of lead-exposure events for both predatory raptors and vultures (Saggese *et al.*, 2009; Plaza *et al.*, 2018). Lead exposure of vultures has been studied both with non-invasive (Lambertucci *et al.*, 2011; Plaza *et al.*, 2018) and invasively collected samples (Wiemeyer *et al.*, 2017). These studies expressed concerns for Andean condor (*Vultur gryphus*) conservation due to acute and chronic lead exposure in Argentina and regionally. In some parts of South America, lead exposure of avian scavengers may be from sources such as mining (López-Berenguer *et al.*, 2021).

In Asia, a study from Japan tested blood, liver and kidney samples from Steller's sea eagles (*Haliaeetus pelagicus*) and white-tailed eagles (*H. albicilla*) as well as 14 other species of raptor (Ishii *et al.*, 2017). These data indicated lead poisoning of 42% of Steller's sea eagles and 24% of white-tailed eagles. Isotopic analyses from a subset of these birds were consistent with exposure to ammunition used in hunting. Since 1996, lead poisoning has been identified as the cause of death for 151 Steller's, 66 white-tailed, and 37 mountain hawk eagles (*Nisaetus nipalensis*) (Saito, 2000, 2009; K. Saito, unpublished observations). In South Korea, 16 of 20 cinereous vultures (*Aegypius monachus*) found dead had elevated lead concentrations in their livers; for one of these, concentrations were high enough to be consistent with death from lead poisoning (Nam & Lee, 2009). Other raptors in South Korea and Pakistan are also sometimes lead exposed (Kim, Lee & Koo, 2008, Mustafa *et al.*, 2015; Kim & Oh, 2016) and can show physiological harm from that exposure (Kanwal *et al.*, 2020).

In Africa, poisoning is cited as the single most important cause of vulture fatalities (Ogada *et al.*, 2016). Types of poisoning noted are primarily those targeted at mammalian scavengers but include secondary lead exposure. We are aware of few studies of, or mitigation programs for, the problem of lead poisoning in Africa. That said, recent research in South Africa found that 66% of white-backed vultures (*Gyps africanus*; $N = 110$) and 80% of Cape vultures (*Gyps coprotheres*; $N = 15$) had blood lead concentrations exceeding the standard biologically relevant threshold for exposure of 10 μg/dl (van den Heever *et al.*, 2019). Bone samples from the same species revealed that 12% of white-backed vultures ($N = 18$) and 9% of cape vultures ($N = 75$) suffered from some level of clinically relevant lead poisoning upon their death. In Botswana, bone lead concentrations (11.79 ± 8.34 μg/g) indicated chronic exposure of bearded vultures (*Gypaetus barbatus*; Krüger & Amar, 2018). In the same country, more than 30% of blood samples from white-backed vultures ($N = 566$) exceeded the 10 μg/dl threshold, with higher values noted during the recreational hunting season (Garbett *et al.*, 2018). There is additional isotopic evidence from South Africa that the lead in these birds is from ammunition (van den Heever *et al.*, 2023).

In Australia, shooting for animal control, commercial harvest, and recreational hunting is widespread, and a range of native scavenging species are susceptible to lead exposure. Lead was detected in 100% of femur and liver tissues from 109 Tasmanian wedge-tailed eagle (*Aquila audax fleayi*) carcasses opportunistically collected between 1996 and 2018 (Pay *et al.*, 2021). Concentrations were elevated in 10% of 106 livers (>6 mg/kg dry wt) and 4% of 108 femurs (>10 mg/kg dry wt). Of the liver samples with elevated lead, 73% had lead 207/206 isotope ratios within the published range of lead-based bullets available in Tasmania (Pay *et al.*, 2021). In the same study, lead was also detected in 96% of blood samples from 24 live nestlings, with 8% at elevated concentrations (>10 μg/dl). Analysis of bone samples from wedge-tailed eagles (*A. audax audax*) on mainland Australia indicated that 27% of 11 individuals from the south-west of the continent (Lohr *et al.*, 2020), and 65% of 92 birds from the south-east of the continent (Hampton *et al.*, 2021*c*) had elevated bone lead concentrations [>6.75 mg/kg in Lohr *et al.* (2020); >10 mg/kg in Hampton *et al.* (2021*c*)]. In the first of these, from southwest Australia, isotope ratios again suggested ammunition as a likely source of the lead found in bone samples. In New Zealand, approximately half of 25 Australasian harriers (*Circus approximans*) brought to a veterinary clinic had elevated blood lead concentrations (>10 μg/dl; mean of c. 80 μg/dl; Youl, 2009). This species frequently scavenges on introduced brush-tailed possums (*Trichosurus vulpecula*) which are commonly killed with lead shot or bullets. One of nine birds that underwent radiographic examination had a metal fragment in its ventriculus (Youl, 2009).

(7) Population-level impacts

There is a limited but growing body of research showing population-level consequences of lead poisoning for birds of prey. Historically, within the USA, large numbers of birds have been necropsied and rates of lead poisoning evaluated (Franson & Russell, 2014; Russell & Franson, 2014), but demographic consequences of this lead exposure have not been quantified. Until recently, the only evidence of demographic consequences to raptors from lead poisoning came from the closely monitored population of California condors (*Gymnogyps californianus*), in a study that showed that lead poisoning was the primary factor preventing recovery of this species (Finkelstein *et al.*, 2012).

Three studies published in 2022 focused on populations of eagles in the USA. Hanley *et al.* (2022) used necropsy data on frequency of lead exposure as input to model negative demographic effects from lead exposure for bald eagles in the northeastern USA. Millsap *et al.* (2022) used mortality data from Global Positioning System (GPS)-tagged golden eagles in the western USA to model the demographic relevance of many causes of death, including lead poisoning, for that species. Finally, Slabe *et al.* (2022) evaluated a large sample of living and dead bald and golden eagles from across North America to understand rates of lead poisoning. Those data then were used as input to models to understand continent-wide consequences of lead exposure to population growth rates for both species.

Outside the USA, a recent European study used liver lead concentrations from several thousand raptors found dead or dying in the wild and population models to estimate demographic effects of lead poisoning for 10 species (Green *et al.*, 2022*a*), and another study developed a framework to assess population-level impacts for raptors and other species (Meyer *et al.*, 2022). In Europe, the adult populations of golden eagles and white-tailed eagles are estimated to be 13% and 14% lower, respectively, than they would be in the absence of lead poisoning (Green *et al.*, 2022*a*).

Together, these demographic studies illustrate that populations of multiple raptor species, including golden eagles, bald eagles and white-tailed eagles, are being suppressed, sometimes substantially, by lead poisoning. An implication of this growing body of work is that populations of other species on these and other continents may also be affected by this anthropogenic stressor.

(8) Data gaps in the science

As is the case in any scientific endeavour, data gaps exist in understanding the full extent of the impacts of lead exposure of raptors. As noted above, there is considerable evidence of lead-induced mortalities for individual raptors that appears additive and thus is expected to reduce population size. However, the majority of data collected have been from North America and Europe, and studies from other continents are lacking. Likewise, to date, empirical evidence for population-level impacts is sparse and limited to a few species in North America and Europe. Thus, an important area for biological research is in understanding the taxonomic and geographic breadth of demographic impacts to raptors from lead poisoning.

Another key data gap lies in our understanding of sublethal effects of lead on raptors. Extensive data cover the cognitive, behavioural, and sublethal consequences for humans and laboratory animals of even low levels of lead exposure (ATSDR, 2020; Ramírez Ortega *et al.*, 2021). There also is ample evidence that other toxicants, for example mercury, can have sublethal effects on reproductive output, immune function, and behaviour of non-raptor bird species in laboratory settings (Whitney & Cristol, 2017). However, there are fewer, but increasing, quantities of data on lead poisoning of wild birds, especially raptors (see Section III.3). Few of these studies are experimental, however, and they paint an incomplete picture of sublethal effects in raptors and other birds from lead exposure. Thus, it seems reasonable to expect that further research will continue to inform our understanding of the sublethal effects of lead on raptors.

A third data gap lies in the interpretation of tissue lead concentration measurements in the context of health outcomes, particularly at lower levels of exposure. As is the case for many contaminants, 'threshold' tissue concentrations have been suggested to help interpret the severity of lead toxicity in birds (Franson, 1996). These thresholds are based upon the relationships between physiological effects and clinical signs of poisoning associated with blood lead concentrations in live birds, and pathological observations and liver or kidney lead concentrations in dead birds (Franson & Pain, 2011). Despite their frequent use in clinical settings (e.g. Fallon *et al.*, 2017; Herring *et al.*, 2018), threshold tissue concentrations are not definitive and are used as a guide or part of the toolkit used to diagnose and predict health effects. For individual birds the toxic effects of lead depend upon numerous factors other than tissue concentrations. For example, the chronicity of exposure is important, and it is unclear if similar health outcomes may be associated with different tissue lead concentrations resulting from long-term and low-level exposure *versus* short-term yet high-level exposure. Similarly, many other factors, particularly relating to species, diet, age, sex, and physiological status of individual birds, may also influence tissue lead concentrations and health outcomes resulting from exposure (Franson & Pain, 2011).

Existing thresholds for tissue lead concentrations have been based upon experimental research supplemented with information from field studies (e.g. Hoffman *et al.*, 1981, 1985*a*,*b*; Franson *et al.*, 1983; Custer, Franson & Pattee, 1984; Beyer *et al.*, 1988; Stendell, Beyer & Stehn, 1989; Redig *et al.*, 1991; Pattee *et al.*, 2006; Torimoto *et al.*, 2021). As more information has become available over time, these thresholds have been revised (Pain, 1996; e.g. Franson & Pain, 2011). That said, these thresholds have not been reviewed recently and there is considerable new knowledge that they do not incorporate. This new knowledge is especially relevant to the second data gap above: the sublethal effects at low levels of exposure. Although current thresholds used to suggest clinical or severe clinical poisoning still appear valid, physiological and behavioural effects have been observed at far lower tissue lead concentrations. This is partly because technical advances have facilitated both accurate and precise measurement of very low tissue lead concentrations and increased understanding of various aspects of behaviour and health. For example, using modern tracking technology, Ecke *et al.* (2017) found that blood lead concentrations as low as 2.5 μg/dl appeared negatively to affect flight altitude and movement rate of wild golden eagles; this contrasts with the previously suggested threshold for subclinical poisoning at 20 μg/dl (Franson & Pain, 2011).

Also, Helander *et al.* (2021) estimated that in the absence of any influence of ingested lead from ammunition, liver lead concentrations from 'background' environmental exposure was ≤0.6 μg/g dry wt, substantially below a previously suggested minimum threshold of 2.0 μg/g dry wt for subclinical effects in raptors (Franson & Pain, 2011). These data, combined with those on sub-lethal effects described above, suggest that even very low levels of residual exposure may be associated with measurable effects on health and behaviour, and thus that thresholds for use in clinical and diagnostic settings may need to be revised.

A fourth data gap lies in the limited number of ways to measure lead exposure *in vivo*. Expanding the suite of tools for *in vivo* measurements of lead concentrations of raptors would strengthen the ability to detect exposure, particularly chronic exposure, of birds, and make substantial contribution to diagnosis of lead poisoning. A newly emerging technique to measure lead concentration in bone tissue of live birds is X-ray fluorescence. Early work with this tool suggests that these measurements correlate well with ICP-MS measurements of archived bone samples for California condors (Specht *et al.*, 2018) and wedge-tailed eagles (Hampton *et al.*, 2021*c*).

A fifth data gap pertains to the adverse impacts on individual birds from sub-lethal lead exposure, i.e. animal welfare impacts. Modern approaches increasingly apply holistic assessments that include consideration of indirect effects of anthropogenic activities (Fraser & MacRae, 2011). However, while the welfare impacts on predators and scavengers have been recognized from other sources of environmental toxicants, such as use of anticoagulant rodenticides (Fisher *et al.*, 2019), to date there has been little consideration of welfare impacts suffered by raptors due to lead exposure (Hampton *et al.*, 2022*c*).

Finally, and perhaps most importantly, there are substantial gaps in understanding how best to communicate the effects of lead on raptors and of how to bring about change in human behaviour to reduce lead exposure of wildlife. There is a small amount of social science research on this issue (Schulz *et al.*, 2019), and there has been an analysis of the factors associated with the successful transition to a total lead shot ban in Denmark (Kanstrup, 2019). In general, though, although the scientific community generally accepts the significance of lead exposure to individuals and populations, this message is not broadly accepted by all relevant stakeholder groups. Likewise, the challenges associated with communication of this message vary dramatically across countries and regions, where different cultures have different relationships with guns, gun ownership, and hunting (i.e. EU vs. USA). This issue is discussed in more detail in Section IV.

IV. STATUS OF NON-LEAD AMMUNITION

(1) Frontiers in non-lead ammunition

Numerous options for non-lead ammunition exist for shooting wildlife or targets with shotguns (ECHA, 2021; USFWS, 2022*c*). Development of alternative materials for shot began in the second half of the 20th century (Longcore *et al.*, 1974; Friend, Franson & Anderson, 2009), and common materials approved as non-toxic include steel, bismuth, and tungsten. Steel shot is less dense than lead, and in certain circumstances larger shot sizes are recommended to match terminal performance. Bismuth offers shot of similar density to lead and can be used in barrels that do not meet pressure standards for steel shot (Thomas, 2015). Tungsten alloy shot can match or exceed the density of lead and provide terminal performance that matches or exceeds the performance of lead (Cromie *et al.*, 2015; Thomas, 2015). Maximum velocity and pressure guidelines for modern shotgun ammunition, including steel and other shot types, are established by the Sporting Arms and Ammunition Manufacturers, Inc. (SAAMI) and Permanent International Commission for the Proof of Small Arms (CIP). Gun and cartridge manufacturers test to agreed standards, although these standards and requirements differ between Europe (often, but not always, regulatory; varies among countries) and the USA (voluntary), the latter of which allows for higher and faster loads (SAAMI, 2019; BASC, 2022).

The technology associated with production of non-lead ammunition, especially bullets and slugs, continues to advance. Many of the major ammunition manufacturers in the USA and Europe now produce copper or copper alloy projectiles, including centrefire and rimfire bullets, shotgun slugs, and muzzleloader bullets. Several companies specialize exclusively on non-lead projectiles, often designing bullets for improved external and terminal ballistics, even at long range. Consequently, factory-loaded non-lead ammunition has increased in availability for a broad range of cartridges (Thomas, 2013; Thomas, Gremse & Kanstrup, 2016, Kanstrup & Thomas, 2019). During periods of normal manufacturing and retail availability, factory-loaded non-lead rifle ammunition is consistently similar in price to premium lead-based hunting ammunition. A notable exception to this trend is in the development and availability of non-lead 0.22 long rifle (0.22 LR) ammunition, one of the world's most commonly purchased cartridges. As of 2021, only a few non-lead options for the 0.22 long rifle have been released, but their availability and product testing have been limited, with mixed performance evaluations (Hampton, DeNicola & Forsyth, 2020; McTee & Ramsey, 2022).

Non-lead shotgun slugs and muzzle-loading rifle options also have increased in availability, albeit to a lesser degree than centrefire rifle ammunition. Despite the increase in options, the variety of calibres and types of weapons in which they can be used are limited in comparison to the diversity of options available for centrefire rifles (L. Brown, unpublished data). Within the USA, non-lead sabot shotgun slugs are available in several gauges for use with rifled barrels, but we know of only two manufacturers making non-lead shotgun slugs for use with smooth bore barrels. Non-lead sabot muzzleloader projectiles also are available but tend to be restricted to inline 0.50 calibre muzzleloaders. There are few non-lead options available for muzzle-loading firearms with slow rifling twist rates designed for patched round-ball ammunition (Epps, 2014). Consequently, there are limited options for non-lead ammunition for use with more traditional flintlock or percussion cap muzzleloaders, or full-bore projectile weapons.

Modern non-lead rifle bullets provide performance that has been demonstrated to be appropriate *via* ballistic testing and that has been validated under normal conditions in the field, including hunting for big game (Kanstrup, Balsby & Thomas, 2016; Stokke, Arnemo & Brainerd, 2019) and culling and euthanasia (Hampton *et al.*, 2021*b*). Some non-lead bullets and bullet manufacturers have received industry awards (Shooting Illustrated, 2016, 2020). Smaller calibre modern rimfire non-lead bullets have been shown to have effective terminal performance in some circumstances (McTee *et al.*, 2017).

Animal welfare concerns are important to development of non-lead ammunition (Hampton *et al.*, 2021*a*). Adoption of non-toxic shotgun shot and adjustment to its performance is associated with a reduction of wounding loss for waterfowl (Ellis & Miller, 2022), and use of steel or lead shot had no impact on harvest rates for mourning doves (Pierce *et al.*, 2015). Several studies have demonstrated suitable animal welfare outcomes (often measured by animal flight distances, a measure of a bullet's lethality) for non-lead bullets or no differences in outcomes between lead and non-lead bullets for a variety of big game species in Scandinavia (Stokke *et al.*, 2019), Germany (Martin *et al.*, 2017), the USA (McCann, Whitworth & Newman, 2016), Denmark (Kanstrup *et al.*, 2016), and Australia (Hampton *et al.*, 2020). Another study found an interaction between ammunition and rifle, with the precision of the non-lead 0.22 long rifle ammunition equal to or better than that of three types of lead-based ammunition for four of the five rifles used, but less than that for the fifth (McTee & Ramsey, 2022). Research on terminal performance of the same 0.22 long rifle bullet in European rabbit (*Oryctolagus cuniculus*) management showed higher incidences of adverse animal welfare outcomes (Hampton *et al.*, 2020). These studies suggested that to minimize animal welfare concerns, shooters would want to test the precision of any ammunition used with their specific firearms and establish distances at which they can confidently place their bullet (McTee & Ramsey, 2022).

(2) Knowledge gaps associated with non-lead ammunition

Most research on the terminal performance of expanding bullets focuses on fragmentation rates of lead-based (Stewart & Veverka, 2011; Cruz-Martinez *et al.*, 2012; Sanchez, Epps & Taylor, 2016; Broadway *et al.*, 2020) and non-lead ammunition (Trinogga *et al.*, 2013; Stokke *et al.*, 2017; McTee *et al.*, 2023*b*). There is a limited but growing body of work (see Section IV.1) on the lethality of available non-lead bullets in a variety of settings. However, the information available does not cover all species shot with firearms, all shooting practices, or shooting of game animals at long distances. For some specialized but numerically important shooting practices [e.g. harvesting and culling of kangaroos (*Macropus* spp. and *Osphranter* spp.) in Australia], there have been no published trials of non-lead ammunition (Hampton *et al.*, 2022*c*). In addition, recent developments in non-lead bullet technology, including sub-sonic ammunition and frangible and fragmenting bullet designs, have not been reviewed thoroughly (Caudell, Courtney & Turnage, 2013; Hampton *et al.*, 2021*b*; McTee *et al.*, 2023*b*). Despite the number of recent studies on these issues, adoption of non-lead ammunition by stakeholders is limited by concerns linked to availability, perceptions about cost differences, and limitations to the evidence about terminal performance (Cromie, Newth & Strong, 2019; Hampton *et al.*, 2021*b*).

Another important knowledge gap associated with non-lead ammunition lies in the potential toxicity of alternative metals. Fourteen shot types, including those containing steel, bismuth, and tungsten have, to date, passed through the system for 'Approval of nontoxic shot types and shot coatings' (50 CFR § 20.134) and have been legally designated as non-toxic in the United States (USFWS, 2022*a*). The requirement to use these shot types applies to the taking of waterfowl, American coots (*Fulica americana*), and any other species that make up aggregate bag limits for these migratory game birds (50 CFR § 20.21). However, beyond the USA and Canada, no similar safety testing and approval system is in place for non-lead shot (Thomas, 2019). It has therefore been suggested that only those shot types that have met the environmental safety standards to enable them to pass the US approval system be permitted for use in the EU (Thomas, Kanstrup & Pain, 2021). This is because potentially toxic shot types that have not passed through or have failed the US approval system, such as those made predominantly of zinc (Levengood *et al.*, 2000; Thomas *et al.*, 2021), can be marketed elsewhere.

Within the USA, non-lead shot for hunting of upland (terrestrial) birds or other non-waterfowl species is generally not required to go through the non-toxic approval and designation process (Thomas, 2019). Likewise, materials used for single projectiles in rifle, shotgun, or muzzleloader hunting are often different than those used for shot and, within the USA, have not gone through a legal designation process.

The lack of knowledge about non-lead ammunition types is important because putatively 'non-toxic' substances can negatively affect animals under specific conditions or exposure levels. For example, non-lead shot can be made from tungsten, and non-lead rifled bullets typically are made from copper, a metal that is an essential micronutrient for most animal species. Tungsten may be a carcinogen (Kalinich, 2005). Likewise, there is evidence that both lead and non-lead bullets can introduce copper and zinc into edible parts of hunter-killed game, although this exposure does not appear to create danger for humans (Schlichting *et al.*, 2017). It has been suggested that large, sharp, and hard fragments of copper from non-lead bullets could potentially cause mechanical damage to gastrointestinal tracts of scavengers that ingest them (Hampton *et al.*, 2021*b*).

Likewise, although copper is typically not retained in large quantities in the digestive system of terrestrial wildlife (Bryan & Langston, 1992), high levels of exposure may be hazardous (Eisler, 1988; Gaetke & Chow, 2003). That said, dosing studies of raptors with copper projectiles suggested no negative physiological response for American kestrels (*Falco sparverius*; Franson *et al*., 2012) or turkey vultures (*Cathartes aura*; Risebrough *et al*., 2001). Similarly, simulated digestion of common non-lead bullet materials demonstrated release of copper or zinc at levels below daily intake limits, although similar experiments with aluminium or nickel indicated potential for increased risk of exposure for wildlife (Paulsen *et al*., 2015). A case study of a California condor with an intact copper bullet in the digestive tract for over 20 days did not exhibit elevation of copper levels, consistent with published studies, although small lead fragments present with the copper bullet did contribute to lead toxicity (Finkelstein *et al*., 2023). Nevertheless, elevated copper concentrations have been identified in at least three California condors, with no direct evidence of a source (J. Zuba, personal communication; C. Parish, unpublished data). If it was discovered that a novel type of non-lead ammunition caused wildlife toxicosis, that would have substantial policy and biology relevance, thus highlighting the importance of adequate testing of non-lead alternatives.

A final data gap associated with non-lead ammunition involves the economics of ammunition production. Adoption of non-lead ammunition will be more likely if products meet economic benchmarks for manufacturers, with value for the manufacturer associated with increased production, and therefore, increased availability for the consumer. In recent years the availability of non-lead ammunition has been a limiting factor for some US hunters seeking this ammunition, particularly during the height of the COVID-19 pandemic (∼2020–2022; V. Slabe & M. McTee, unpublished data). Study of the economics of ammunition production, and efforts to ensure continuous availability and comparable pricing of non-lead ammunition, would provide information critical to addressing lead exposure of raptors.

V. STATUS OF MITIGATION

(1) Background

Among the most consequential steps taken since prior summaries of lead exposure of raptors has been advancement of mitigation programs to avoid, reduce, or replace wildlife deaths from lead poisoning. In countries where there are effective bans on use of lead in wetlands, most lead use is in terrestrial environments. Raptors are therefore among the wildlife taxa most commonly affected by lead exposure, and consequently they are the focus of many mitigation programs. In locations across the globe without bans on use of lead in wetlands, lead shot may continue to be a substantial contributor of exposure to waterfowl and other birds.

Mitigation for lead exposure of birds of prey has been achieved primarily either through advances in veterinary medicine or through programs to reduce use of lead ammunition in hunting. Medical treatment for lead exposure is possible but addresses only the small proportion of affected birds that are rehabilitated by humans. Furthermore, there are few scientific studies, and a poor understanding, of outcomes when treated birds are returned to the wild. Thus, medical care can be seen as treating a symptom (lead poisoning) rather than a cause (availability of lead on the landscape) of a problem. By contrast, numerous programs to reduce use of lead ammunition in hunting (see examples below) target the exposure pathway. Successful programs often are couched in the argument that reduction in lead has positive outcomes for wildlife. Despite that, the cultural significance of guns, the extent of trust in government, and the social and political interest to address the issue vary dramatically by jurisdiction. Thus, the effectiveness of different approaches to reducing lead exposure is highly region-specific (again, see examples below).

(2) The sociology of mitigation for lead exposure of raptors

Mitigating for lead exposure of raptors involves effective communication of scientific results to hunters, anglers, wildlife managers, and other relevant stakeholders. There have been a number of consensus statements on human, wildlife, and environmental health risks from the use of lead-based products and proposals for a transition to non-lead ammunition (Bernhoft *et al*., 2014; Andersen *et al*., 2018, 2020; Cromie *et al*., 2019; Kanstrup & Thomas, 2020; Pain, Swift & Green, 2020; Treu, Drost & Stock, 2020). Despite this, communicating published science to members of the general public presents challenges that have been described as 'socio-political' (Arnemo *et al*., 2016), and few studies evaluate tools and approaches to making this communication effective. Reviews of regulatory and voluntary efforts do not always evaluate barriers to change, instead focusing on end results (rates of non-lead ammunition use, proportion of wildlife exhibiting lead exposure, etc.). Although critical measurements of success, those indices do not always identify and address human psychology, economics, or other components that influence the effectiveness of mitigation interventions (Baruch-Mordo *et al*., 2011).

One factor relevant to understanding this problem in the USA is that a major proportion of the funds for conservation management, including for potential management of lead poisoning of wildlife, depends on sales of guns and ammunition (Casellas Connors & Rea, 2022). Specifically, much funding for wildlife conservation comes to US states principally from either sale of hunting licenses or from excise taxes on equipment used for outdoor activities including shooting, hunting, and fishing. Furthermore, some reports suggest that the lead industry has sometimes questioned scientific studies and used other tactics to deflect criticism and downplay hazards of lead (Gottesfeld, 2022). The contradictions brought about by sources of funding, scientific consensus statements, and industry tactics, are thought to polarize this issue and constrain progress on developing solutions (Totoni *et al.*, 2022). Although funding for wildlife conservation flows differently in the EU, managers there face similar challenges linked to this issue.

In this complex social environment, there are gaps in understanding of (*i*) information and misinformation on the issue, and (*ii*) how educator training, targeted messaging, and broadened outreach efforts can be effective in solving this conservation problem. The U.S. Fish and Wildlife Service (USFWS) established an outreach program during 2016–2018 to encourage deer hunters to use non-lead ammunition while hunting on selected National Wildlife Refuges (NWRs) in the Upper Midwest, USA. A set of behavioural psychology studies using both qualitative and quantitative methodologies was implemented to assess the outreach program, the factors influencing program implementation, and staff support for the program (Schulz *et al.*, 2019, 2021*a*,*b*, 2022). Based on this study, the authors suggested that outreach programs (*i*) be communicated by trained individuals and targeted to specific audiences, and (*ii*) consider the importance of human health issues and relevance of non-hunters as stakeholders. This research illustrated how social science theory can provide a useful framework for implementing and evaluating a program to promote use of non-lead ammunition.

Information alone does not always result in behavioural change, and a stumbling block for existing outreach programs is that they sometimes fail to incorporate *a priori* a theoretical framework for program development or implementation (Schulz *et al.*, 2019). Indeed, behavioural theory and understanding how and why new ideas spread can be highly relevant to influencing outcomes from such programs (Rogers, 2003; Fishbein & Cappella, 2006). Principles for effective communication have been established in the literature from other fields [e.g. climate change (see tab. 1 in Schweizer *et al.*, 2009); cessation of smoking (Fishbein & Capella, 2006); 'nudges' (Kosters & Van der Heijden, 2015)], and there are established theories for behaviour change within the natural resources field. A recent approach with potential application to mitigation for non-lead ammunition, the Outdoor Recreation Adoption Model (ORAM), is designed around recruitment, retention, and reactivation efforts for outdoor sports (Byrne & Dunfee, 2018). Understanding these models can assist managers of mitigation programs to understand how stakeholders might adopt new activities or behaviours, and to design programs to bring about behaviour change. Key components of a successful approach can involve collaboration with social scientists as well as careful identification of stakeholder populations, understanding the values and traditions of stakeholders, selection of desired changes in behaviour, understanding factors influencing behaviours, development of interventions focused on those behaviours, and outcome monitoring (Steg & Vlek, 2009; Ross-Winslow & Teel, 2011). Schulz *et al.* (2019) outline a conceptual framework for application of this approach to the problem of mitigating lead exposure of wildlife (including raptors).

(3) Lead exposure as a One Health issue

The 2008 conference 'Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans' (Watson *et al.*, 2009) was the first to bring together experts in lead poisoning of raptors and of humans. This meeting stimulated broader research on the interdisciplinary nature of this issue, all of which has led to mitigation action, particularly in Europe.

Today, lead poisoning from ammunition is widely recognized as a One Health issue (Bellinger *et al.*, 2013; Bernhoft *et al.*, 2014; Andersen *et al.*, 2018, 2020; Arnemo *et al.*, 2022), a valuable perspective in linking the health of people to that of animals and the environment (CDC, 2022). It is established that use of lead ammunition presents risks to terrestrial and aquatic birds (Pain *et al.*, 2019), domestic animals (Fernández *et al.*, 2021; Pain *et al.*, 2023) livestock (Payne *et al.*, 2013; Pain *et al.*, 2022), humans (Tsuji *et al.*, 2008; Iqbal *et al.*, 2009; Laidlaw *et al.*, 2017; Buenz & Parry, 2018; Green & Pain, 2019; Thomas *et al.*, 2022) and wild mammals (Kelly *et al.*, 2021). Mitigative actions taken to protect any of these taxa may also reduce risks to raptors. Communication of the One Health risks from lead ammunition has helped stimulate and inform integrated risk reduction actions across the EU and in other European countries (see citations below in this section). Anecdotal evidence gathered by us suggests that initiating discussions based on human health issues has been less effective within the USA. Instead, taking an ecosystem-based approach is seen as more effective in the USA, since few users of ammunition will argue that reducing lead in the food chain is detrimental to ecosystem health (C. Parish, unpublished data).

Meat from shot wildlife ('game') is widely sold in Europe, southern Africa, Australia, and New Zealand. However, such sale is not permitted in the USA, although many US states do have game meat donation programs. Research shows that mean lead concentrations in meat from commercially available small and large game substantially exceed legal EU maximum levels for marketed meats from farmed animals (Pain *et al.*, 2022; ECHA, 2021). Another study shows similar results for game birds shot with lead ammunition (Green *et al.*, 2024). Such lead is bioavailable (Hunt *et al.*, 2009; Green & Pain, 2012) and several studies show a positive correlation between the use of lead for harvesting game meat and human blood lead concentrations (Bjerregaard *et al.*, 2004; Johansen *et al.*, 2006; Berky *et al.*, 2022). European food safety agencies consider children, pregnant women, and frequent consumers of wild-shot game to be most at risk, and these groups are advised to substantially reduce or avoid eating such meat (Knutsen *et al.*, 2014). While careful butchering of large game animals to remove visible lead fragments can reduce exposure, this can result in considerable food wastage, and it does not remove microscopic fragments which can be numerous (Leontowich *et al.*, 2022). Likewise, when small game animals are killed with lead shot, lead fragments are dispersed throughout the carcass and cannot feasibly be removed by butchering (Grund *et al.*, 2010; Pain *et al.*, 2010; Green *et al.*, 2022*b*). The U.S. Food and Drug Administration (FDA) does not set a legal limit for lead in meat (Totoni *et al.*, 2022) and beyond the UK and EU, other international health agencies have generally not yet acknowledged this issue (Thomas *et al.*, 2022).

The One Health perspective is important also to mitigation, as it is a contributing consideration for recent proposals for regulation of lead ammunition under UK and EU-wide chemical safety regulations (DEFRA & Pow, 2021; ECHA, 2021). Likewise, this perspective has led to several multilateral environmental agreements or organizations calling for the replacement of lead with non-toxic ammunition. These include the Convention on Migratory Species (UNEP-CMS, 2014) and the International Union for the Conservation of Nature (IUCN, 2016), and a recent United Nations Environment Assembly Resolution (UNEP, 2017). Evaluating the effectiveness of these actions is an important next step.

(4) Actions to mitigate lead exposure of raptors

Every permanently inhabited continent has some type of regulatory, voluntary, or dual program to mitigate wildlife exposure from use of lead ammunition. Regulatory bans on use of lead ammunition sometimes also limit its sale or possession. A broad range of programs regulate use of shot for hunting waterfowl or over wetlands, with fewer focused on the use of shot in terrestrial habitats or of rifle bullets in general. Voluntary programs generally include education and training, sometimes accompanied by incentive programs offering discounted or free ammunition. Such programs aimed at rifle ammunition appear to be growing in frequency, especially in the USA. Dual programs often involve an initial voluntary stage aimed at facilitating a subsequent regulatory transition from lead to non-lead ammunition. To illustrate actions to mitigate lead exposure of raptors, and to begin to evaluate their context-specific effectiveness, we present here brief summaries from across the globe, organized by type (regulatory or voluntary) and then continent. These brief summaries are supported by longer descriptive examples in Appendix S2. Many of these are particularly informative because they were written by the co-authors who studied or developed and implemented the programs they document.

(*a*) *Regulatory approaches*

Regulatory programs focused on lead have been reviewed for parts of the world (e.g. Mateo & Kanstrup, 2019) but there is no comprehensive source for regulations dealing with this issue. In 2009, at least 29 countries had some type of regulation on use of lead ammunition (Avery & Watson, 2009; this number includes countries that ban hunting altogether). Here, we considered 201 countries, of which we reviewed or received information on regulations in 87, and we found evidence of regulation of lead ammunition and fishing tackle in 46 (unlike earlier work, this count does not include countries that ban hunting altogether; Table 1).

We found evidence of regulatory programs governing use of lead ammunition on every continent and most geographic regions where people hunt (Table 1, Table S1). For the 56 countries identified in Africa, we found limited information on regulations focused on lead ammunition. It appears that lead ammunition of all types is banned in Mauritania and in South Africa lead is banned for some types of hunting (Avery & Watson, 2009). Seven other countries have some level of ban, typically on shotgun shot, and lead is also banned in some areas designated as 'Vulture Safe Zones' in South Africa (BirdLife South Africa, 2018). We found no information on use of lead in fishing tackle or on regulations dealing with lead in fishing. We also found no information on regulations for any countries in the Caribbean region or Oceania (excluding Australia and New Zealand, see Table S1 for countries in these regions).

For Asia, we found slightly more information, with Japan having some of the most comprehensive regulations (Table 1, Table S1). Japan has some lake-specific regulations on the use of shot for waterfowl hunting, and the use of any type of lead ammunition (rifle or shotgun) has been banned for hunting big game on the island of Hokkaido (Ishii *et al.*, 2020; K. Saito unpublished data). In 2014, specific regulations were promulgated prohibiting possession (not just use) of lead ammunition during deer season in Hokkaido (K. Saito unpublished data). Use of lead ammunition in the rest of the country will be regulated starting in 2025, with a goal to eliminate lead poisoning in birds completely by 2030 (Shimbun, 2021). Avery & Watson (2009) also report a ban on lead shot for waterfowl hunting in Malaysia. There are no regulations on the use of lead ammunition in central Asia. Western Asia (including the Caucasus and the Middle East) has two countries with regulations (Israel and Cyprus) and we confirmed an absence of regulations in the Caucasus and Türkiye. Lead fishing tackle is banned in the Republic of Korea. There are substantial data gaps in our knowledge of regulations in all other parts of Asia.

In Australia, lead shot is banned for waterfowl hunting in some states and territories (Hampton *et al.*, 2018), but not in others (NSW-DPI, 2021). However, lead-based ammunition is still allowed for other recreational activities including hunting of terrestrial game birds (Hampton *et al.*, 2022*b*) and mammals such as Bennett's (red-necked) wallabies (*Notamacropus rufogriseus*) in Tasmania. There are no regulations in Australia covering lead in rifle bullets (Hampton *et al.*, 2022*c*), and >1 million macropods are shot annually with lead-based ammunition (Hampton *et al.*, 2022*c*). At wetlands in New Zealand, lead shot is not allowed for use with most guns, but it is still allowed for smaller shotguns (0.410 bore) and in terrestrial settings. Lead fishing tackle is restricted in some contexts in New Zealand. Finally,

Table 1. Confirmed presence of regulations on use of lead ammunition (shotgun shot, rifle bullets, shotgun slugs, etc.) or fishing tackle, by global region (in grey-shaded cells) and subregion. Regions and subregions are from the United Nations Statistics Division (2020), with countries and source details provided in Table S1. Values are the number of countries in each region or subregion, the number of countries confirmed with (Yes Regs) and without (No Regs) regulations on use of lead ammunition or fishing tackle, and the breakdown of those regulations by type (i.e. whether they pertain to shotgun shot, rifle bullets, or fishing tackle). The presence of regulations does not imply a total ban, and when lead is regulated, those regulations typically apply only to certain settings (e.g. ban on use of shotgun lead shot in a specific park or region, or over wetlands but not terrestrial habitats). For most countries other than the 87 noted here, we were unable to obtain information on presence or absence of regulations on use of lead ammunition or fishing tackle.

Region	Subregion	# Countries	Yes Regs	No Regs	Shotgun	Rifle	Fishing
Africa		*56*	*9*	*1*	*9*	*1*	*0*
	Middle Africa	9	1	0	1	0	0
	Northern Africa	6	1	0	1	0	0
	Southern Africa	5	1	0	1	0	0
	Sub-Saharan/Eastern Africa	20	1	0	1	0	0
	Western Africa	16	5	1	5	1	0
Asia		*49*	*5*	*10*	*4*	*1*	*1*
	Central Asia	5	0	5	0	0	0
	Eastern Asia	6	2	1	1	1	1
	South Asia	9	0	0	0	0	0
	South-Eastern Asia	11	1	0	1	0	0
	Western Asia	18	2	4	2	0	0
Caribbean		*16*	*0*	*0*	*0*	*0*	*0*
Europe		*45*	*22*	*22*	*22*	*3*	*1*
	Eastern Europe	22	7	15	7	0	0
	Western Europe	23	15	7	15	3	1
Latin America		*21*	*6*	*8*	*6*	*5*	*1*
	Central America	8	0	8	0	0	0
	South America	13	6	0	6	5	1
North America		*2*	*2*	*0*	*2*	*1*	*2*
Oceania		*10*	*0*	*0*	*0*	*0*	*0*
South Pacific		*2*	*2*	*0*	*2*	*0*	*1*
Total	**Total**	**201**	**46**	**41**	**45**	**11**	6

New Zealand currently has no restrictions on use of lead-based bullets or shot for other hunting, culling and commercial harvesting activities.

In Europe prior to 2023, lead shot use was banned for shooting waterfowl or over wetlands in at least 22 countries (Mateo & Kanstrup, 2019; note that the UN list we use puts Cyprus in Asia). Regulations were recently passed and implemented (in February 2023) banning the use and carrying of lead shot in and around wetlands in all 27 EU countries under EU chemicals regulation (European Union, 2021) as well as those in the European Economic Area (EEA), a total of 30 countries. The use of lead bullets has been banned in some regions, sites, or National Parks in Germany, Italy, and Spain (Mateo & Kanstrup, 2019), and country-wide in Denmark (implemented in April 2024). This will make Denmark the first country to ban all lead ammunition for hunting (and even possession and trade), having already banned lead shot in 1996 (Sonne *et al.*, 2022). A broad restriction on the placing on the market and use of lead in outdoor shooting and fishing has been proposed by the European Chemicals Agency (ECHA) under EU Chemicals Regulation (ECHA, 2021), with a final decision likely in 2024. There appear to be no regulations on lead ammunition or fishing tackle in European countries outside the EEA.

In North America, the use of lead for waterfowl hunting was banned in both the USA and Canada, in 1991 and 1996, respectively, and some US states have additional regulations concerning the use of lead shot (Avery & Watson, 2009). The California State Legislature passed the Ridley-Tree Condor Preservation Act (2007) requiring the use of non-lead ammunition for the take of big game and coyotes. The law was amended in 2013 with Assembly bill 711, to require the use of non-lead ammunition after a phase-in period for the take of all wildlife in the state of California. The USFWS recently announced a proposal to ban some types of lead rifle bullets for big game hunting on some lands associated with National Wildlife Refuges (USFWS, 2021). Some public and some private lands also require use of non-lead ammunition (M. McTee, unpublished observations; AMB West, 2023; FOX 9 KMSP, 2023). Finally, some areas, particularly in New England, limit use of lead fishing tackle (e.g. New Hampshire Fish and Game Department, 2023).

In South America, Central America, and the Caribbean, there appear to be some regulations on use of lead shot, but fewer for bullets or fishing tackle. We found data on partial bans for use of lead shot in Argentina, Bolivia, Chile, Columbia, Ecuador, and Peru (Table S1). Several regulations are also proposed for some parks and provinces in Argentina, to ban use of lead shot for waterfowl hunting (Plaza *et al.*, 2018; NPA Argentina, 2019). We found good evidence that no regulations exist for lead ammunition in central America, and few data suggesting regulations for other countries in South America or the Caribbean.

Understanding compliance and effectiveness of regulations is a critical component of effective management for lead poisoning of raptors. Despite this, globally, research and data reporting the effectiveness of and compliance with regulation are limited. In Japan, although use of any type of ammunition for hunting large animals was banned in Hokkaido in 2004, large numbers of lead-caused fatalities of raptors are still occurring (Ishii *et al.*, 2020). Some data are available from Europe, where regulation of lead shot spans >40 years (Mateo & Kanstrup, 2019). Where monitored in countries with regulatory bans on the shooting of waterfowl or over wetlands (i.e. partial bans), compliance has generally been poor. For example, despite a 1999 ban on use of lead for waterfowl hunting in England, about 70% of ducks obtained for compliance studies conducted between 2001 and 2010 had been illegally shot with lead, and in the 2018–2019 season this had risen to 87% (Cromie *et al.*, 2015; Cromie, Strong & Newth, 2022). Low compliance with partial bans has been reported elsewhere in Europe (e.g. Widemo, 2021). However, in the Ebro delta of Spain, compliance appeared to improve with increased vigilance and enforcement by park rangers; these actions likely benefitted from a threat from local authorities to ban hunting in the protected areas if non-compliance persisted (Mateo *et al.*, 2014). Likewise, compliance appears high in Denmark, where a total ban on use, possession, and trade of lead shot was implemented in 1996, following an 11-year transition period. This ban has resulted in a markedly lower prevalence of lead shot in hunted mallards and common pheasants (*Phasianus colchicus*; Kanstrup, 2012; Kanstrup & Balsby, 2019) and of lead concentrations in game meat (Pain *et al.*, 2022). Similarly, liver samples from 136 raptors collected in Denmark between 2013 and 2016 had lead concentrations below thresholds for negative health effects and were generally lower than in birds from elsewhere in Europe (Kanstrup *et al.*, 2019*a*). Together, these limited data suggest that across Europe effective regulation has been associated with repeated education campaigns, support for mitigation efforts by impacted communities, a phase-in process, complete rather than partial bans, development and wide availability of high-quality non-lead ammunition, and strict law enforcement and compliance monitoring (Kanstrup, 2019; Mateo & Kanstrup, 2019; Pain *et al.*, 2022).

In the USA and Canada, compliance with regulations banning the use of lead shot for hunting waterfowl appears to have been high. In particular, compliance has been measured by a marked reduction in waterfowl poisoning (e.g. Anderson, Havera & Zercher, 2000; Samuel & Bowers, 2000; Stevenson, Scheuhammer & Chan, 2005). Compliance has not been evaluated for more recent regulations in California. A ban on the use of lead ammunition for hunting large game and non-game species (but not for hunting terrestrial game birds and small game mammals, the latter of which are commonly scavenged) in the California condor range in 2008 was correlated with a decrease in blood lead exposure of turkey vultures and golden eagles (Kelly *et al.*, 2011). This study was, however, conducted at a site that may not be representative and the authors did not infer causality. Furthermore, modern rates of lead poisoning of condors have continued at a similar rate as prior to the ban (USFWS, 2022*b*).

Several international treaties and agencies contain resolutions that set a framework for regulations to replace lead with non-toxic ammunition. These include the Convention on Migratory Species (UNEP-CMS, 2014), the African-Eurasian Agreement on the Conservation of Migratory Waterbirds (AEWA), and the International Union for the Conservation of Nature (IUCN, 2016). Additionally, the United Nations Environment Assembly has a Resolution that aims to raise awareness of this issue (UNEP, 2017). Resolutions to replace lead shot with non-toxic alternatives, particularly under AEWA, have driven much of the legislation governing use of lead shot in wetlands in European countries. However, despite the long-standing presence of these resolutions associated with international commitments, there appears to be little recognition of this issue by international health agencies (Thomas *et al.*, 2022).

(*b*) *Voluntary approaches*

Voluntary programs to reduce the use of lead ammunition and fishing tackle are widespread globally. However, these programs have not yet been summarized or reviewed. We briefly describe several of these programs below, with additional detail on provided in Appendix S2.

In Africa, the Namibian government is engaged in efforts to make non-lead ammunition cheaper and more widely available (Thomson, 2021). Non-lead ammunition is used for some culling programs for introduced species in both Australia (Hampton *et al.*, 2021*b*) and New Zealand (Williams, 2021) and some hunting organizations are proactively discussing transitioning away from the use of lead ammunition (ADA, 2020). In Europe, voluntary initiatives by hunters to use non-lead bullets are being developed in France in Cévennes National Park, the Alps in Haute Savoie, and in the Pyrenees (Mateo & Kanstrup, 2019). In South America, the National Parks Administration of Argentina promoted a voluntary plan to phase out lead ammunition for hunting within its jurisdiction (NPA Argentina, 2019).

Voluntary initiatives have been attempted in the UK, in conjunction with activities intended to raise awareness and provide advice on the issue and with training workshops on the use of non-lead shot (Green *et al.*, 2022*c*). In 2019, the major UK supermarket chain that sells wild game announced that it would voluntarily transition to selling only game killed with non-lead ammunition (Barkham, 2019). Other retailers and many landowners, game dealers, and suppliers have implemented, or announced intentions to implement, similar transitions (The Lead Ammunition Group, 2015). In 2020, nine of the major shooting and rural organizations issued a joint statement of intent to voluntarily switch to non-lead shot for hunting within five years (BASC, 2020). Their stated goal was to protect wildlife, the environment and to ensure a market for the healthiest game products. Despite these stated intents, during the first two years after these commitments, 99.5% of 395 common pheasant purchased from retail outlets still contained lead shot (Green *et al.*, 2022*c*); this proportion fell to 94% after 3 years (Green *et al.*, 2023). This independently measured outcome contrasted with surveys of attitudes and intentions of groups of hunters, which indicated that a large proportion had already implemented, or intended to implement, the transition to non-lead shot (Green *et al.*, 2022*c*).

Voluntary programs focused primarily on rifle bullets are abundant in the USA and in some cases participation rates have been well studied. A few also include a focus on lead in shot and fishing tackle. These programs use a combination of education and outreach, raffles and prizes, and free non-lead ammunition to increase participation. Educational efforts tend to focus on the environmental, rather than human-health, consequences of use of lead ammunition for hunting, typically promoting consequences to condors, eagles, and other scavengers. They also highlight performance aspects of non-lead bullets.

The longest-running voluntary program in the USA was developed by Arizona Game and Fish Department and The Peregrine Fund in 2005 (Seng, 2005; Sieg, Sullivan & Parish, 2009; C. Parish, unpublished observations). This effort was developed on a foundation of surveys of ranchers and hunters, has maintained an ~87% participation rate for over a decade, and subsequently has been copied in neighboring Utah, a state that also supports condor populations. In California, there are at least two ongoing programs, one initiated by the Institute for Wildlife Studies (IWS), the other by Ventana Wildlife Society (VWS; L. Brown, unpublished observations). IWS (https://huntingwithnonlead.org/) coordinates information sharing with hunter education programs and provides opportunities for stakeholders to test non-lead ammunition. VWS focuses on actions within the range of the free-flying condor population segment their organization supports, and, in addition to education and outreach, has provided >11,000 boxes of bullets or ammunition at no cost to hunters (https://www.ventanaws.org/ammunition.html).

The Oregon Zoo manages the Non-lead Hunting Education Program (NHEP), an in-state non-lead hunting education program started in 2015, which uses educational programming, testing of ammunition, outreach on traditional and social media, and a prize-based incentive program (https://www.oregonzoo.org/conserve/non-lead-hunting-education-program; L. Brown, unpublished data). The NHEP worked with partners to develop an incentive program at The Nature Conservancy's Zumwalt Prairie Preserve which reached 77% hunter participation after three years, upon which the incentive programs were expanded state-wide. Following outreach, 89% of participants state-wide were willing to use non-lead ammunition for a portion of their hunting activities (L. Brown, unpublished data).

The progress achieved in the programs mentioned above motivated the establishment of the North American Non-lead Partnership (NANP; https://nonleadpartnership.org/; C. Parish, unpublished observations). The NANP philosophy and approach focuses on non-political conservation messaging and behaviour change strategies to overcome barriers to eliminating the threat of lead poisoning. Strategies promoted to reduce lead poisoning involve increasing the use of non-lead ammunition or removing lead-contaminated remains from the field. Since 2018 the partnership has grown to include nearly 50 organizations across North America, including four state wildlife agencies, hunting groups, landowners, and two of the four regional wildlife management agency associations.

There are two privately run voluntary non-lead programs with programs in several US states. Sporting Lead-Free (https://sportingleadfree.org/) is a non-political Wyoming-based initiative that uses education and outreach, including shooting demonstrations, non-lead fishing tackle giveaways, and free screening of meat for donation programs (B. Bedrosian, unpublished observations). The initiative also provides information on non-lead ammunition options and works with local retailers to stock and identify suitable options. Hunters for Eagle Conservation (HFEC; https://huntersforeagleconservation.org/) is a research-based program designed to evaluate environmental impacts of reduction in use of lead ammunition (V. Slabe & R. Crandall, unpublished observations). HFEC has programs in Wyoming, Montana, and New York that provide free or discounted non-lead ammunition to hunters, with distribution done in a manner allowing harvest and ammunition-use data to be used to empirically model reduction in eagle deaths.

There are several non-lead outreach efforts in the Mid-West, including the Get the Lead Out program (https://www.pca.state.mn.us/air-water-land-climate/getting-lead-out-of-fishing-tackle) by the Minnesota Pollution Control Agency. This effort provides free tackle to anglers across the state. Lead-Free Wildlife Minnesota (https://www.leadfreewildlifemn.com/) is a voluntary program in Minnesota focusing on education and outreach of hunters in Minnesota and led by the Minnesota Chapter of The Wildlife Society.

VI. MOVING FORWARD

Our review illustrates how the science underpinning understanding of lead poisoning of raptors has expanded over the last 15 years. Now known are the pathways by which birds are exposed to lead, mechanisms to diagnose and treat exposure, physiological indicators of harm to individuals, demographic consequences of lead poisoning for some species, and the global nature of the problem. Furthermore, approaches are being developed and tested to mitigate both the availability of lead from ammunition and the consequences of exposure.

Despite this depth of knowledge, data gaps exist. From a biological perspective, additional knowledge would broaden understanding of demographic and sublethal effects of lead, linkages between tissue lead concentrations, physiological harm, suffering, and health outcomes, *in vivo* measurement of lead exposure, and potential consequences of non-lead ammunition types that have not yet undergone toxicity testing. Nonetheless, and importantly, filling these biological knowledge gaps is not necessary to address the problem of lead exposure of raptors.

By contrast, gaps on the social science side are likely more immediately relevant to solving this issue. In particular, there would be great value to scientific study of attitudinal perspectives and the region-specific utility of voluntary, regulatory, or combined approaches to reduce the use of lead ammunition. The suite of regulatory, voluntary, and educational programs detailed above has been designed to mitigate this problem. Formal study of these, the effectiveness of their application of behaviour theory, and perhaps meta-analyses comparing their effectiveness and success rates, could help devise programs to increase acceptance rates.

Most prior reviews of lead exposure have focused largely on a single continent or region (e.g. Haig *et al*., 2014; Golden *et al*., 2016; Mateo & Kanstrup, 2019; Pain *et al*., 2019). By contrast, our review highlights the global nature of this problem and the great variation in mitigation efforts. We illustrate that despite a global consensus on the biological science underpinning the problem, the political and social appetite for regulations focused on ammunition and contaminants varies substantially across administrative regions, countries, and continents. Similarly, the ways in which hunting is managed vary considerably across continents, along with the levels of local monitoring and enforcement of prevailing hunting laws (Thomas *et al*., 2021). Variation in these social and legal structures undoubtably will influence which measures are most likely to result in successful outcomes in different locations, at different times, under different political administrations, and in the context of international and intergovernmental drivers of change.

Perhaps the best illustration of this region-specific variability is the relative effectiveness of regulatory and voluntary approaches to date in the USA and in Europe. There is evidence that the impact of voluntary schemes in Europe is limited and that, alone, they are rarely effective at achieving significant behavioural change (Lords STC, 2011; McCarthy & Morling, 2015). Furthermore, across Europe neither voluntary measures nor partial regulations, i.e. banning lead shot only for waterfowl hunting or over wetlands, appear to have been particularly effective. In fact, only in Denmark, where a total ban on sale, use and possession of lead shot was proceeded by a long phase-in period, is there published evidence of high compliance with regulation (Kanstrup & Balsby, 2019), a measurable reduction in lead present in commercially available game meat (Pain *et al*., 2022) and lower risks to wild raptors (Kanstrup, 2019).

The EU situation contrasts with the USA where hunt management practices are different (Thomas *et al*., 2021) and where federal regulation banning lead shot use reduced waterfowl deaths from lead poisoning. Despite opposition (Thomas, 1997), perhaps aided by nearly a century of knowledge of the issue (Calvert, 1876; Grinnell, 1894), the successful US ban on use of lead shot for waterfowl hunting was supported by extensive messaging effort from agencies and conservation groups (e.g. Ducks Unlimited; Schroeder *et al*., 2012). Beyond the important role of stakeholder participation, two other important factors in this effort may have been that (*i*) migratory waterfowl are managed under international treaties and thus are regulated at the federal, not state, level, and (*ii*) the hunter's quarry was directly affected by lead.

Next steps in the process to address this problem in the EU and the USA further reflect the variation in cultures, approaches, economics, and regulatory systems between the two regions (Ellis & Miller, 2022). Under its overarching chemicals regulation (EU REACH), the EU has recently implemented a ban on use and possession of lead shotgun ammunition in and around wetlands (European Union, 2021) and is undertaking a restriction process for a ban on use of lead in all outdoor shooting and fishing activities (ECHA, 2021). Despite some differences between the US and Europe in terms of gun culture, political climate, and the emphasis on tradition, a general resistance from hunting-associated organizations, and sometimes industry, to restrictions on lead ammunition use has historically been a common feature. In Europe though, discussions appear to have moved on from whether the evidence justifies restriction to defining appropriate timetables for transition (e.g. Ellis & Miller, 2022; NSSF, 2022). By contrast, perhaps because of the large amount of effort put into voluntary programs, incorporation of behaviour science, and the implicit commitment to the 'North American Model of Wildlife Conservation' (Lawrence, 2022), appeals for use of non-lead rifle ammunition based on protection of wildlife resonate strongly with the US hunting community. These sometimes even draw support from those same organizations that oppose bans (NSSF, 2022).

The recent science reviewed herein illustrates that considerable work is still needed to achieve success in addressing the ongoing problem of lead poisoning of raptors. Regardless of location, the success of mitigation measures ultimately depends not upon levels of compliance but rather on whether the intended outcomes have been achieved. For raptors, useful outcomes would focus on reductions in rates of sublethal and lethal poisoning to levels where affected populations can be stable or increasing. While there has been considerable progress in development of a range of mitigation actions, solving the problem of the demographic consequences of lead exposure of raptors and other wildlife is a cross-disciplinary problem that requires continued advances in biological and social sciences. Furthermore, it is not clear the degree to which approaches used in Europe, North America, and Japan will be successful in other areas. What is clear though is that success largely depends on cross-disciplinary solutions that are situation, region, and sometimes species specific, and that include effective monitoring of both compliance and changes in levels of raptor poisoning. Thus, policies and mitigation strategies can be most effective when crafted in a manner that considers local cultures and conditions, while simultaneously protecting environmental and human health.

VII. CONCLUSIONS

(1) Lead poisoning is an important threat to humans and to many types of wildlife, especially birds of prey. A huge diversity of taxa of raptors are poisoned when they scavenge carcasses of wildlife shot with lead ammunition, but less is known about population-level impacts from exposure of individuals. Although a global problem, most information on lead poisoning of wildlife comes from Europe and North America. There are several knowledge gaps linked to the biology of lead poisoning, but filling these gaps is not necessary to address the well-established problem of lead exposure of raptors.
(2) There is an increasing number of types of non-lead ammunition, although availability of those options is sometimes limited. There are knowledge gaps associated with both performance, economics, and unexpected effects associated with these new ammunition types.
(3) Lead poisoning is a One Health issue that links the health of people to that of animals and the environment. Concomitantly, efforts to reduce lead exposure of raptors have been most effective when they are cross-disciplinary and incorporate behavioural theory into program design.
(4) Mitigation of lead poisoning of wildlife occurs through both regulatory and voluntary approaches. Regulatory approaches occur on every continent, although they are most widespread in Europe; compliance with regulations is not always well understood. Voluntary approaches involving education and sometimes free non-lead ammunition have occurred on several continents, although they are most widespread in North America.
(5) Our review suggests cross-disciplinary and region-specific paths forward to mitigate lead poisoning of wildlife and protect environmental and human health.

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X. SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Additional details on the literature search supporting this review.

Appendix S2. Case studies of actions to mitigate or evaluate lead poisoning of raptors.

Table S1. Confirmed presence of lead regulations by country and region of the world.

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