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*REVIEW*

# The persistent problem of lead poisoning in birds from ammunition and fishing tackle

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## ABSTRACT

Lead (Pb) is a metabolic poison that can negatively influence biological processes, leading to illness and mortality across a large spectrum of North American avifauna (>120 species) and other organisms. Pb poisoning can result from numerous sources, including ingestion of bullet fragments and shot pellets left in animal carcasses, spent ammunition left in the field, lost fishing tackle, Pb-based paints, large-scale mining, and Pb smelting activities. Although Pb shot has been banned for waterfowl hunting in the United States (since 1991) and Canada (since 1999), Pb exposure remains a problem for many avian species. Despite a large body of scientific literature on exposure to Pb and its toxicological effects on birds, controversy still exists regarding its impacts at a population level. We explore these issues and highlight areas in need of investigation: (1) variation in sensitivity to Pb exposure among bird species; (2) spatial extent and sources of Pb contamination in habitats in relation to bird exposure in those same locations; and (3) interactions between avian Pb exposure and other landscape-level stressors that synergistically affect bird demography. We explore multiple paths taken to reduce Pb exposure in birds that (1) recognize common ground among a range of affected interests; (2) have been applied at local to national scales; and (3) engage governmental agencies, interest groups, and professional societies to communicate the impacts of Pb ammunition and fishing tackle, and to describe approaches for reducing their availability to birds. As they have in previous times, users of fish and wildlife will play a key role in resolving the Pb poisoning issue.

*Keywords:* birds, copper bullets, endangered species, fishing jigs, fishing sinkers, fishing tackle, lead, lead ammunition, lead poisoning

**Problema persistente de envenenamiento por plomo en aves debido a municiones y aparejos de pesca**

## RESUMEN

El plomo (Pb) es un veneno metabólico que puede influenciar negativamente los procesos biológicos produciendo enfermedades y la muerte de un gran espectro de aves de América del Norte (>120 especies) y de otros organismos. El envenenamiento por Pb puede provenir de múltiples fuentes, incluyendo la ingestión de fragmentos de balas y perdigones que quedan en los cadáveres de los animales, municiones usadas y dejadas en el campo, aparejos de pesca abandonados, pinturas a base de Pb, minería a gran escala y actividades de fundición de Pb. Los disparos que contienen Pb han sido prohibidos para la caza de aves acuáticas en Estados Unidos (desde 1991) y Canadá (desde 1999). Sin embrago, la exposición no intencional de muchas aves al Pb continua. A pesar de que existe una enorme cantidad de literatura científica sobre la exposición y los efectos toxicológicos del Pb en las aves, existe aún controversia sobre los impactos a nivel poblacional. Evaluamos estos aspectos y subrayamos las áreas que necesitan investigación: (1) variación en la sensibilidad a la exposición al Pb entre las especies de aves; (2) extensión espacial y fuentes de contaminación de Pb en los hábitats en relación con la exposición de las aves en esas mismas localidades; e (3) interacciones entre la exposición de las aves al Pb y otras fuentes de estrés a escala de paisaje que afectan de modo sinérgico la demografía de las aves. Exploramos múltiples iniciativas que apuntan a la reducción de la exposición de las aves al Pb que: (1) reconocen aspectos comunes en un rango de intereses afectados; (2) han sido aplicadas a la escala local y nacional; e (3) involucran agencias de gobierno, grupos de interés y sociedades de profesionales para comunicar los impactos de las municiones de Pb y de los aparejos de pesca y para describir los enfoques para reducir su disponibilidad para las aves. Como ha ocurrido en otras ocasiones, los usuarios consuntivos de los peces y de la vida silvestre jugarán un rol muy importante para resolver el tema del envenenamiento por Pb.

*Palabras clave:* aparejo de pesca, aves, balas de cobre, envenenamiento por plomo, especies en peligro, munición de plomo, plantillas de pesca, plomadas de pesca, plomo

## INTRODUCTION

Lead (Pb) has long been recognized as an ecological and human health hazard because exposure to this cumulative metabolic poison has negative consequences for all organisms studied (DeMichele 1984, Scheuhammer and Norris 1995, Hernberg 2000, Goddard et al. 2008, Watson et al. 2009, Centers for Disease Control 2013, Chen 2013). Although Pb occurs naturally as a trace element of geological materials (Figure 1), human activities have greatly increased the distribution and abundance of Pb in the environment because it is used widely in the production of batteries, pigments and dyes, caulks, and metal alloys, as well as in aviation fuel for small piston-engine aircraft (Rattner et al. 2008, Carr et al. 2011). The physical properties of Pb (e.g., high density, low melting point, malleability, corrosion resistance), as well as its low cost compared with alternative metals, have made it the primary metal used in the manufacturing of ammunition and fishing sinkers (Goddard et al. 2008, Thomas 2013).

Although wildlife exposure to Pb has been linked to a variety of anthropogenic sources, such as mining (Blus et al. 1999, Henny 2003) and legacy Pb-based paint (Finkelstein et al. 2003), a great deal of attention is currently focused on Pb ammunition and fishing tackle because of their widespread recreational and subsistence use in wildlife habitats (Rattner et al. 2008, Goddard et al. 2008). Pb ammunition can also be a threat to human health, as evidenced by OSHA regulations protecting workers at shooting ranges (e.g., https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=NEWS_RELEASES&p_id=22524). These concerns are particularly applicable to birds because their mobility and diverse foraging strategies contribute to potential exposure and subsequent toxicological impairment in a broad array of species.

Birds are sensitive to Pb exposure, leading to apparent sublethal or lethal toxic responses, and exposure has been documented in >120 species (reviewed by Scheuhammer and Norris 1995, Fisher et al. 2006, Goddard et al. 2008, Pain et al. 2009, Tranel and Kimmel 2009; Figure 2). However, the extent of the problem is difficult to quantify because the rapid onset of toxicity results in low detectability in species that are not intensively monitored and tested. Thus, the magnitude of the issue and the breadth of its conservation and health implications remain controversial (Bellinger et al. 2013).

This review was initiated to summarize scientific information pertaining to the conservation threat of Pb ammunition and fishing tackle in birds. Our goal is to point out the broad spectrum of options that are available to decision-makers seeking to reduce Pb poisoning in birds. These approaches are not mutually exclusive, and it is likely that the combination of several would most effectively reduce or eliminate Pb exposure in birds from ammunition and fishing tackle. For example, in order to

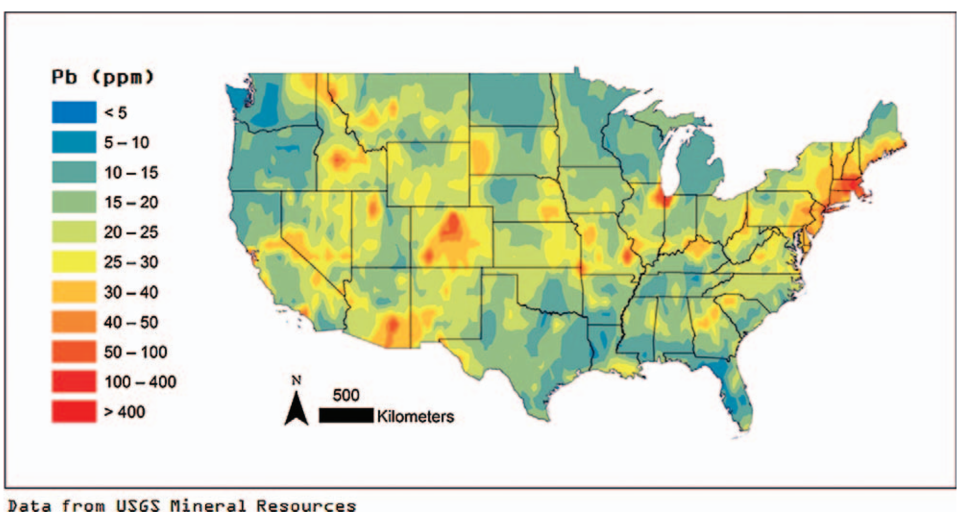


**FIGURE 1.** Spatial distribution of soil Pb concentrations (ppm dry weight) across the continental United States. These background levels range from 50 to 400 ppm; soil concentrations that exceed ~100 ppm are considered elevated. Pb levels in soil near mines, smelters, and similar sites can range upward of 12,000 ppm. Data were obtained from the USGS National Geochemical Survey database (http://mrdata.usgs.gov/geochem/). Spatial interpolation of Pb concentrations was conducted in ArcMap 10.0, based on data density of one sample per 289 km$^2$.

properly address particular situations, decision-makers may need to know factors such as (1) population effects across the continuum of potentially affected species; (2) identification of species directly and indirectly affected; (3) the degree to which other sources of Pb in the environment may be contributing to poisoning; and (4) the potential impact on human health.

We begin by evaluating the physiological effects of Pb in birds and critically examining the evidence of avian injury and mortality from spent ammunition and fishing tackle. We then review regulatory and voluntary approaches to reduce avian exposure to Pb and outline future directions that could minimize the magnitude of Pb impacts on avian populations. Although we acknowledge that this is a global issue and cite examples from around the world (Mateo 2009, Newth et al. 2012, United Nations Environment Programme 2013), our review is primarily focused on North American birds.

## Pb in the Environment and Its Significance for Avian Conservation

**The anthropogenic Pb cycle.** Pb is widely distributed across the atmosphere, lithosphere, hydrosphere, and biosphere (Figure 1). Beginning in Roman times, ~95% of Pb in the environment resulted from human activities, including mining, smelting, coal combustion, battery processing, waste incineration, and fuel additives (Alfonso et al. 2001, Goddard et al. 2008). Modeled loss estimates from primary Pb emission vectors suggest that ~48% of all Pb newly brought into use is ultimately lost to the environment (Mao et al. 2009). The second-largest loss, accounting for 21% (670,000 metric tons Pb $yr^{-1}$) of the annual environmental Pb deficit, is Pb dissipated following use (Mao et al. 2009). In the United States alone, >69,000 metric tons of Pb were used in the production of ammunition in 1 yr (U.S. Geological Survey 2013). Among the initial 15 countries of the European Union, ~34,600 metric tons of Pb shot and ~4,000 metric tons of Pb bullets and pellets are used per year (European Commission 2004). Annual estimates of Pb fishing weights sold amount to 3,977 metric tons in the United States, up to 559 metric tons in Canada, and 2,000–6,000 metric tons in Europe (Scheuhammer et al. 2003, European Commission 2004, United Nations Environment Programme 2011). Radomski et al. (2006) estimated 16 tons of Pb tackle in 5 surveyed lakes over a 20-yr period, or an average ~320 pounds Pb $lake^{-1}$ $yr^{-1}$.

Although these estimates provide context for the raw distribution of Pb into ammunition and fishing tackle, it is important to note that they are clearly unrepresentative of the amount of Pb that is distributed and available for avian exposure (Figure 1). To appropriately estimate potential exposure coefficients, data are needed that quantify (1) the proportion of purchased ammunition and fishing tackle that is actually used; (2) the proportion of use that occurs in outdoor environments where birds can be exposed; (3) the proportion of ammunition and fishing tackle used in outdoor environments that is left in such a form or location that avian exposure is possible (i.e. bullet fragments left in carcasses); and (4) the probability that a bird will be exposed to any available Pb-based ammunition or fishing tackle (Figure 3). Although ample evidence shows considerable avian Pb exposure from ammunition and fishing tackle, we need to address these data gaps to generate ecosystem- or regional-scale estimates of potential avian Pb exposure. A distinct understanding of primary exposure pathways is important for managing scenarios where avian risk to Pb exposure is high.

**FIGURE 2.** Black-billed Magpies (*Pica hudsonia*) feed on mule deer (*Odocoileus hemionus columbianus*) shot near Penticton, British Columbia, Canada. Photo courtesy of Laure Wilson Neish.

**Pathways of avian exposure.** Among toxicologically significant sources (e.g., Pb-based paint, mining, smelters, and combustion residue of leaded gasoline; Blus et al. 1999, Church et al. 2006, Beyer et al. 2013), spent ammunition and lost fishing tackle are the primary exposure pathways for birds in terrestrial and aquatic systems (Kendall et al. 1996, Liu et al. 2008, Rattner et al.

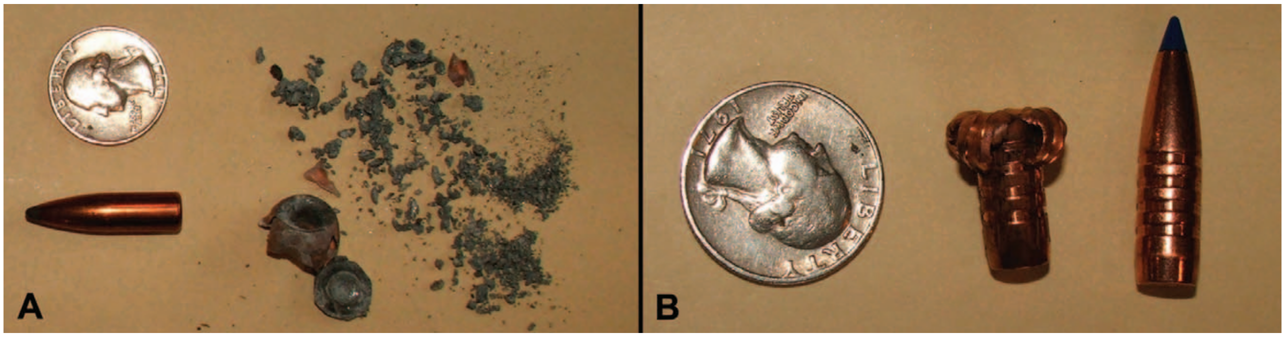


**FIGURE 3.** The remains of Pb and copper bullets fired into a water barrel from a .30-06 rifle. (**A**) Unfired Pb core bullet (with a copper alloy jacket) next to remains from a fired bullet of similar type. Tiny bullet fragments provide a great deal of surface area allowing for increased absorption of Pb once ingested by scavengers. (**B**) Unfired copper bullet next to the remains from a fired bullet of similar type. Photos courtesy of Clinton Epps (C. Epps and D. Sanchez personal communication).

2008), and these are pathways that can be controlled and managed.

The highest human-caused Pb concentrations associated with ammunition are found in and near shooting ranges (United Nations Environment Programme 2013), where patches of Pb shot may attain concentrations of 5–17 kg Pb $m^{-2}$ (Rattner et al. 2008). However, it is important to note that these values are localized extremes, and there is considerable variability in the soil Pb content in shooting ranges (Bennett et al. 2007). Nevertheless, many grit-seeking birds pick up Pb fragments at or near shooting ranges.

Conversely, traditional hunting areas may be more representative of the potential Pb exposure risk to wild birds. Although Pb densities are substantially lower than in target ranges (Ferrandis et al. 2008), the deposition of Pb pellets from historical waterfowl and contemporary Mourning Dove (*Zenaida macroura*) hunting provide some of the strongest examples of the amount of Pb that can be associated with hunting activities within a confined area (Box 1). During the period of Pb use for hunting migratory waterfowl, Bellrose (1959) estimated densities as high as 125,970 pellets $ha^{-1}$; more recently, Pain (1991) reported pellet densities of nearly 2 million pellets $ha^{-1}$. In managed upland dove-hunting fields where Pb shot is legal, shot densities range from tens of thousands to hundreds of thousands of pellets per hectare (Box 1 and Figure 4). However, there are differences in how long Pb pellets deposited on the landscape are available to birds, particularly between wetland and upland habitats. Flint and Schamber (2010) estimated that Pb pellets in the sediment of wetlands would be available to most species of waterfowl for $\geq$25 yr. If so, the risk of exposure to Pb pellets from past hunting for most waterfowl species in North America should be nearly eliminated, given that it has been 14 and 22 yr since Pb shot has been banned in Canada and the United States, respectively. However, legacy Pb exposure in some waterfowl species, such as swans, is still a concern because of the greater depths at which they forage within sediments (Smith et al. 2009). Furthermore, drying of seasonal wetlands can expose pellets that upland species (e.g., doves and pheasants) ingest.

More difficult to estimate is bullet fragment density from big-game hunting, in which Pb is associated with offal (i.e. gut piles) and carcasses. Although the densities of Pb fragments are necessarily lower than those associated with shot, they are also more localized and associated with an attractant (animal carcasses or offal) that could substantially increase the probability of avian exposure.

The density of Pb fishing tackle in aquatic environments is highly variable yet can have significant impacts on aquatic species such as loons and swans. Duerr (1999) estimated 0.01 and 0.47 sinkers $m^{-2}$ in areas of low and high fishing pressure in the United States, respectively. In the United Kingdom, estimates have ranged between 0.84 and 16.3 sinkers $m^{-2}$ along the Thames River (Sears 1988) and between 24 and 190 sinkers $m^{-2}$ in shoreline areas in Wales (Cryer et al. 1987). It is important to note that these large estimates of lost-tackle densities are from locations with exceptionally high fishing pressure and may not be representative of tackle densities in other locations. To understand subsequent risk, it is crucial to understand relative waterbird use of the high-risk zone. For example, Radomski et al. (2006) utilized creel surveys of walleye fishermen to evaluate rates of tackle loss across 5 Minnesota lakes and estimated that Pb tackle densities in 1 of these lakes was $<$0.002 sinkers $m^{-2}$. Across the 5 lakes, whose combined area was 267,933 ha, cumulative total estimated Pb-tackle losses were found to be $>$100,000 pieces, or $\sim$1 metric ton $year^{-1}$ of the study (Radomski et al. 2006). It is unclear what waterbird exposure rates might be at these Minnesota lakes; however, Pokras et al. (2009) found that 118 of 522 (23%) Common Loon (*Gavia immer*) carcasses from 6 New England states contained ingested Pb objects, primarily sinkers and jigs, as

**BOX 1. Mourning Dove Hunting and Pb Pellet Dispersion**

Declines in resident upland game-bird populations of Northern Bobwhite (*Colinus virginianus*; Brennan 1991) and Ring-necked Pheasant (*Phasianus colchicus*; Riley and Schulz 2001, Frey et al. 2003) have prompted many state and provincial resource management agencies to increase Mourning Dove shooting opportunities on public lands, especially near urban population centers, by creating attractive feeding spots (Schulz et al. 2003; Figure 4). However, Pb pellet deposition accumulates on fields managed for dove hunting. For example, on 5 public hunting areas managed for dove hunting in Missouri during 2005–2011, the average amount of traditional Pb ammunition deposited per year ranged between 2.5 and 8.9 kg $ha^{-1}$ among areas, and the estimated average number of no. 8 Pb pellets, which measure 2.26 mm in diameter, ranged between 35,624 and 128,632 ha $yr^{-1}$ among areas (Schulz et al. 2012). During 1998–1999, Pb shot deposition related to dove hunting in southern Nevada ranged from 8,970 to 22,559 pellets $ha^{-1}$ in fields managed primarily for dove hunting (Gerstenberger and Divine 2006). Posthunt pellet densities from 15 managed dove fields in Indiana during 1987 ranged from 2,152 to 83,928 pellets $ha^{-1}$ (Castrale 1989). Sampling of the upper soil layer in southeastern New Mexico during 1987 showed prehunt estimates of 167,593 pellets $ha^{-1}$ and posthunt estimates of 231,731 pellets $ha^{-1}$ (Best et al. 1992). Posthunt pellet densities in Tennessee were estimated at 107,821 pellets $ha^{-1}$ (Lewis and Legler 1968).

Within a national context, ~960,000 dove hunters routinely harvest 16.6 million doves annually (Seamans et al. 2012), taking approximately 4 or 5 shots $dove^{-1}$ (Schulz et al. 2012) and potentially depositing 1,900–2,400 metric tons of Pb shot on publicly owned wildlife habitat across the country. Thus, reducing the deposition of Pb shot resulting from Mourning Dove hunting on public areas has the potential to substantially reduce Pb exposure in terrestrial wildlife, especially for a suite of ground-feeding passerines (Fisher et al. 2006) and game birds (Hunter and Rosen 1965, Keel et al. 2002, Schulz et al. 2002, Potts 2005, Larsen et al. 2007, S. D. Holladay et al. 2012).

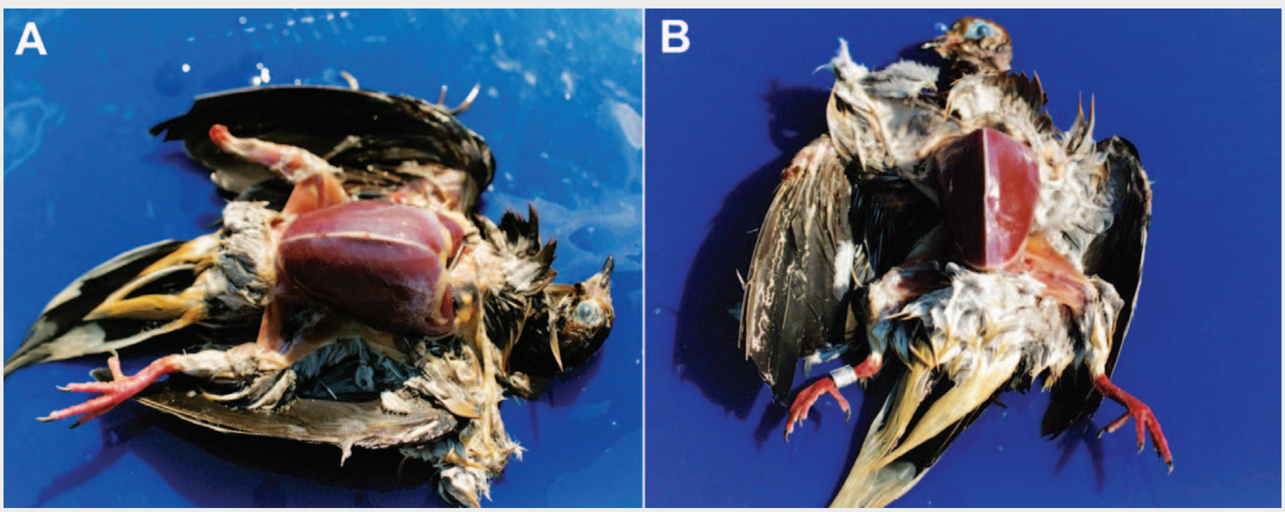


**FIGURE 4.** (**A**) Healthy pectoralis in a Mourning Dove. (**B**) Eroded breast muscle due to loss of appetite and reduced physical activity following ingestion of Pb pellets (shot size no. 7.5). Muscle erosion occurred in <22 days in captive birds (Schulz et al. 2006). Photo courtesy of John Schulz.

well as ammunition. This suggests that although overall densities may be low across entire lakes, Pb tackle may be concentrating in habitat sectors that increase exposure risk, assuming that densities of tackle in New England and Minnesota lakes are comparable.

**Direct exposure.** Direct exposure occurs when birds mistake Pb objects for seeds or grit and purposefully ingest them, often in areas of heavy hunting and fishing pressure or at established shooting ranges (Boxes 1 and 2). In terrestrial areas, this pathway to Pb poisoning is most relevant to seed-eating birds that obtain grit for muscular grinding of seeds in the gizzard (Fisher et al. 2006, Rattner et al. 2008). Some waterbirds also consume Pb objects for use in the gizzard and become poisoned through the same route (Smith et al. 2009) or in combination with Pb that they consume when diving (Pokras et al. 2009).

**Indirect exposure.** Indirect exposure to Pb occurs when predators and scavengers incidentally ingest Pb when consuming the flesh of an animal that has been shot with Pb ammunition or that ingested Pb sinkers or a soil-dwelling organism containing high Pb levels (Boxes 1, 2, and 3; Figure 4). Scavenging raptors such as eagles, vultures, and condors are typically influenced by this route of Pb poisoning (Box 2; Figures 5 and 6). They make extensive use of offal from harvested animals and from carcasses of animals that are killed for recreation (e.g., prairie dogs [*Cynomys* spp.]) or for animal control purposes or that are shot by hunters but cannot be retrieved (Fisher et al. 2006, Kelly et al. 2011, Bedrosian et al. 2012, Harmata and Restani 2013). Importantly, Pb bullets expand or "mushroom" and then fragment, dissipating the bullet's energy. As a result, an average of 235 (range: 15–621) and 170 (range: 85–521) Pb fragments remain in the eviscerated carcass and viscera, respectively (Hunt et al. 2007, 2009; Knott et al. 2010; Figures 5 and 6). This fragmentation increases the likelihood that multiple individuals can be exposed to Pb from a single carcass or gut pile. In addition, the small size and increased surface area of the fragments that stem from spent ammunition also increase the uptake of Pb into the bloodstream (Hunt et al. 2009). Although these exposure sources may be highly localized, the magnitude of their negative effects is increased when they are used as food resources by widely dispersing, highly social scavengers (e.g., vultures and condors). Finally, indirect exposure can also occur in ground-feeding species that rely heavily on earthworms as prey (Scheuhammer et al. 1999, 2003), such as the American Robin (*Turdus migratorius*; Beyer et al. 2004, 2013) and American Woodcock (*Scolopax minor*; Scheuhammer et al. 1999, 2003).

**Lead impact on avian physiology.** Pb ingested from Pb pellets or bullet fragments is absorbed into the circulatory system, aided by the grinding action in the gizzard; thus, diet can affect Pb uptake rates (Marn et al. 1988, Locke and Thomas 1996, Vyas et al. 2001). Once Pb is absorbed into the body, its toxicological effects are diverse. However, as is true with nearly all contaminants, interspecific variation in tolerance to Pb is considerable, which makes it difficult to assess risk solely on the basis of blood Pb levels. For example, the California Condor (*Gymnogyps californianus*) experiences significant mortality as a result of Pb ingestion (Finkelstein et al. 2012). Conversely, Carpenter et al. (2003) found that Turkey Vultures (*Cathartes aura*) repeatedly dosed with large numbers of Pb shot and constant redosing survived much longer than other species of avian scavengers, such as Bald Eagles (*Haliaeetus leucocephalus*), that received similar doses of Pb (Hoffman et al. 1981). These studies suggest that complex physiological processes regulate exposure and toxicity risk to Pb and vary even between close relatives. Thus, factors beyond the gross number of Pb pellets or bullet fragments ingested are important in understanding how environmental exposure is linked to toxicological responses.

At the organismal level, Pb poisoning can modify the structure and function of kidney, bone, the central nervous system, and the hematopoietic system, leading to adverse biochemical, histopathological, neurological, and reproductive effects (Boggess 1977, Nriagu 1978, DeMichele 1984, Eisler 1988, Rattner et al. 2008, Franson and Pain 2011). These effects can be observed at a very young age, as shown by studies of nestling Western Bluebirds (*Sialia mexicana*) and Japanese Quail (*Coturnix japonica*; Fair and Myers 2002, Fair and Ricklefs 2002). The range of physiological effects is mirrored by the range of potential responses to exposure. Acute poisoning may occur rapidly, without characteristic signs such as emaciation or lack of coordination (Locke and Thomas 1996). Chronic exposure results in lethargy and anorexia, breast-muscle atrophy, loss of strength and coordination, drooping wings, and changes in vocalization (see Figure 6).

**Modes of action.** Neurological impacts of Pb on animals are highly contingent on the chemical form of Pb, dose, and exposure duration, as well as the age, sex, and health of the bird (Müller et al. 2008). In the avian body, Pb mimics calcium and substitutes for it in many fundamental cellular processes, including nervous-system function (Simons 1993, Flora et al. 2006). For example, Pb can activate protein kinase C, which plays a critical role in the vertebrate nervous system by controlling the function of other proteins (Hwang et al. 2002). Pb poisoning also leads to anemia by reducing heme synthesis and decreasing the life span of erythrocytes (Eisler 1988, Goyer 1996). Pb affects the nervous system by changing calcium homeostasis and inhibiting cholinergic nerve cells, thus interfering with signal transmission across nerve synapses and leading to behavioral changes (Sanders et al. 2009). The cerebellum is the primary target for Pb toxicity in the brain and is the major determinant for behavioral changes (Alfano and Petit 1981). Experimental studies with environmentally relevant Pb doses in wild nestling Herring Gulls (*Larus argentatus*) demonstrated that Pb impairment can result in decreased health, less vigorous food-acquisition behaviors, poor coordination, and decreased survival (Burger and Gochfeld 1994).

Pb also impairs the enzymes δ-aminolevulinic acid dehydratase (δ-ALAD) and ferrochelatase, ultimately interfering with heme synthesis, and resulting in anemia if exposure is high enough (Hoffman et al. 1985). Northern Bobwhites (*Colinus virginianus*) dosed with a single no. 9 Pb shot (i.e. 2 mm in diameter) exhibited only 8% of normal ALAD activity 8 wk after dosing (S. D. Holladay et al. 2012). The same dose regime resulted in blood Pb levels >80 times higher than background in captive Rock Pigeons (*Columba livia*; J. P. Holladay et al. 2012). In wild birds, δ-ALAD and intermediary metabolites such as

**BOX 2. Demographic Effects of Pb Ingestion on California Condors and Other Avian Scavengers**

California Condors were nearly driven to extinction in the 1980s, and the cause of their decline was unknown at that time (Snyder and Snyder 2000, Walters et al. 2010, D'Elia and Haig 2013). Substantial evidence now points to ingestion of Pb ammunition in carcasses as the primary factor preventing California Condors from achieving self-sustaining populations (Church et al. 2006, Walters et al. 2010, Finkelstein et al. 2012). A related study of Pb isotopes in Andean Condor (*Vultur gryphus*) feathers in northwest Patagonia suggests that they are also being exposed to Pb from ammunition (Lambertucci et al. 2011). Other avian scavengers that share one or more of the following traits and occur in regions where Pb is available in gut piles or dead animals may also be at elevated risk of adverse effects.

**Obligate scavenger**. Obligate scavengers represent an extreme specialization in the animal kingdom, being completely reliant on other agents to kill their food. These species are limited to the condors and vultures (Ruxton and Houston 2004). Their inability to procure live prey places them at greater risk of exposure to Pb shot from animals left in the field or offal from harvested animals.

**Large size**. Large avian scavengers search out food in large quantities to meet their energy requirements (Ruxton and Houston 2004). This preference for larger food items may increase their exposure to Pb in areas frequented by big-game hunters. Their large size also means that they consume a relatively large quantity of meat at each carcass, increasing their risk of exposure to any contaminants that may be disproportionately distributed throughout the carcass.

**Life-history pattern of low reproduction and high annual survival**. Low reproductive output of 1 or 2 offspring every 1 or 2 yr, an extended subadult period of several years prior to recruitment into the breeding population, and a long life span of several decades or more define a life-history pattern that can be sensitive to small changes in adult survival rates (Mertz 1971, Meretsky et al. 2000). Long-lived species are also at greater risk of multiple exposures and, thus, at greater risk of sublethal effects (Hunt 2012).

**Social foraging**. Species that tend to roost and feed communally as an adaptation for finding resources that are large and ephemeral are at greater risk than species whose individuals roost and forage alone (Dermody et al. 2011). Social behavior such as communal roosting and sharing of food resources may increase the risk that a single contaminated carcass can poison a large number of individuals in the same feeding.

**Physiological factors**. A number of intrinsic factors influence species' susceptibility to Pb poisoning, including retention of Pb after ingestion versus regurgitation (Stendell 1980), nutritional status and diet, and chemical environment in the lumen (Pattee et al. 2006). Species that fail to regurgitate ingested Pb fragments are likely to suffer greater exposure.

Multiple lines of evidence point to Pb ammunition as the primary source of Pb poisoning in avian scavengers. These include the spatiotemporal relationship of Pb exposures to hunting areas and season, Pb isotope ratios in feathers and blood (Scheuhammer and Templeton 1998, Church et al. 2006, Lambertucci et al. 2011), elevated copper concentrations in the kidneys of Pb-exposed eagles as an indicator of

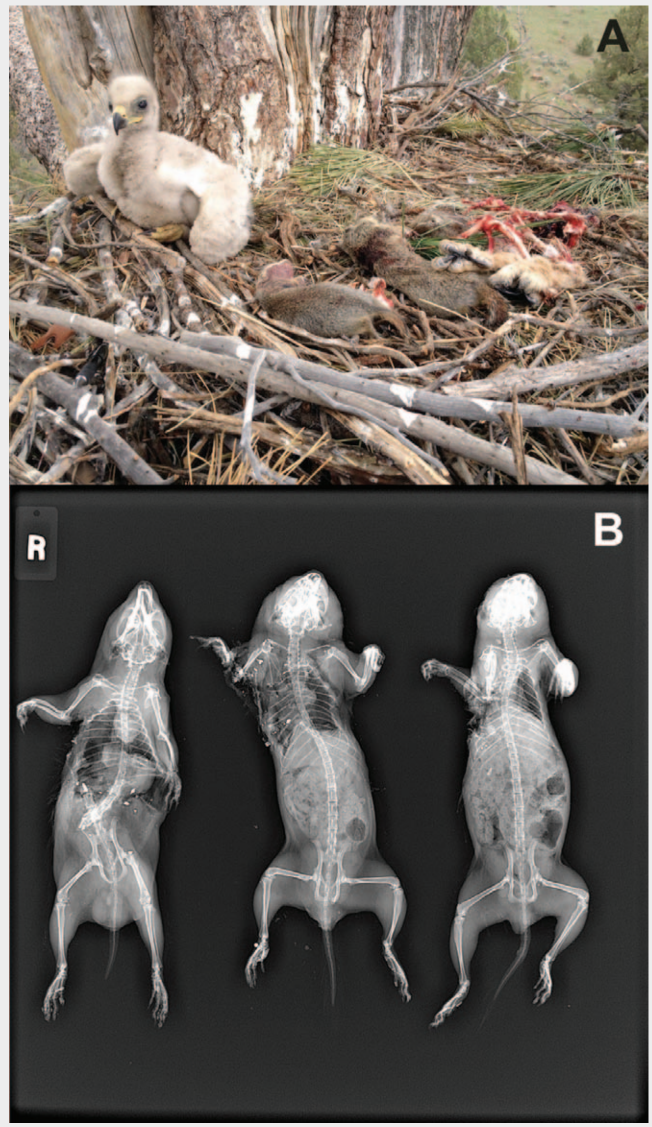


**FIGURE 5.** (**A**) Golden Eagle (*Aquila chrysaetos*) chick with a Belding's ground squirrel (*Spermophilis beldingini*) food source (Upper Malheur River, Harney County, May 2013). Photo courtesy of Eric Forsman. (**B**) Radiograph of Pb fragments in Belding's ground squirrels found dead in a field. Photo courtesy of Jeff Cooney.

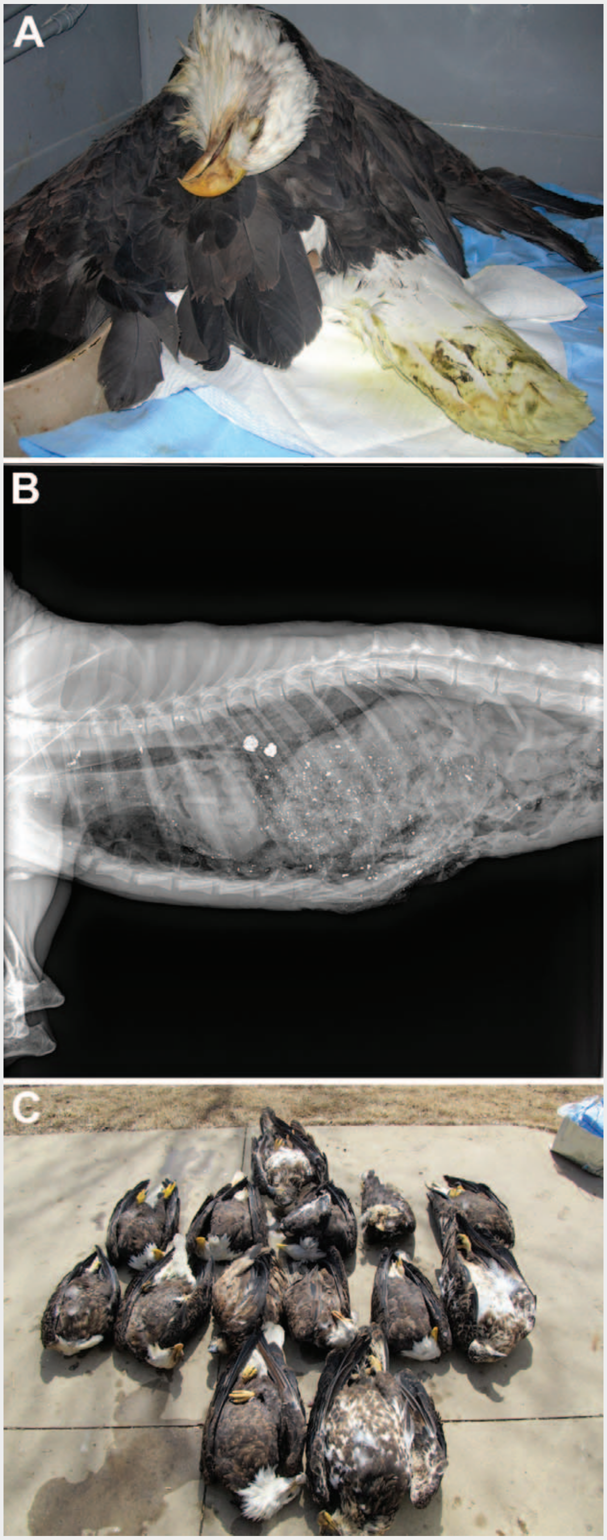


FIGURE 6. Pb poisoning in Bald Eagles following consumption of carcasses containing Pb bullet fragments. (**A**) Adult showing muscle degeneration, unable to stand, open-mouth breathing, weakness, and wing droop. (**B**) X-rays indicating location of Pb bullet fragments in coyote. (**C**) Pb-poisoned Bald Eagles collected in one Iowa location over 1 yr by Project SOAR. Photo courtesy of Project SOAR.

the presence of copper-jacketed Pb bullets (Cruz-Martinez et al. 2012), radiographs of Pb-exposed scavenger gastrointestinal tracts (e.g., Helander et al. 2009; Figure 6) and food items (Knopper et al. 2006, Hunt et al. 2009; Figure 5), and toxicological studies combined with direct field observations and necropsies (e.g., Finkelstein et al. 2012). Taken together, and without a reasonable alternative hypothesis, these studies collectively provide a compelling indication that ammunition is the predominant source of Pb poisoning in scavenging birds.

The association in time and space between elevated Pb levels or Pb exposure rates in avian scavengers and big-game hunting has been observed in multiple species across diverse regions of the world: Bald and Golden eagles in the upper midwestern United States (Kramer and Redig 1997, Strom et al. 2009, Cruz-Martinez et al. 2012); Bald Eagles and Common Ravens (*Corvus corax*) in the Rocky Mountains (Craighead and Bedrosian 2008, Bedrosian et al. 2012); Golden Eagles, Turkey Vultures, and California Condors in southern California (Hall et al. 2007, Kelly and Johnson 2011, Kelly et al. 2011); California Condors in Arizona and Utah (Hunt et al. 2007); and Steller's Sea Eagles (*Haliaeetus pelagicus*) and White-tailed Sea Eagles (*H. albicilla*) in Hokkaido, Japan (Saito 2009). These findings are consistent with the hypothesis that scavengers are consuming Pb in carcasses from hunting.

Not all studies have found a significant relationship between Pb concentrations or Pb exposure rates and big-game hunting seasons (Martina et al. 2008, Stauber et al. 2010) and, even where significant correlations exist, many studies have found that Pb exposures are not strictly limited to big-game hunting seasons. Furthermore, Pb pellets and .22 bullets not associated with big-game hunting have been recovered in the digestive tracts of California Condors (Rideout et al. 2012), Bald and Golden eagles (Cruz-Martinez et al. 2012), and sea eagles (Helander et al. 2009), and in the pellets of Egyptian Vultures (*Neophron percnopterus*; Donázar et al. 2002).

The fact that ammunition can be delivered via multiple sources to avian scavengers means that in many areas, effective treatment of this threat will require more than simply eliminating Pb ammunition use by big-game hunters. However, these hunters remain the key to survival for most scavengers in the world (Mateo-Tomás and Olea 2010). They are now the top predator in modern ecosystems, and the remnants of hunting are a more important wildlife food source now than at any other time in history.

protoporphyrin in blood are used as biomarkers of exposure (Locke and Thomas 1996). Time for δ-ALAD recovery to normal levels is dose dependent, organ specific, and usually directly correlated with blood Pb levels.

**Population-level effects of Pb.** The potential effects of Pb poisoning on individual birds are clearly established. Far less clear are the population-level consequences of current rates of Pb exposure in many species. The best examples are from waterfowl, in which losses to Pb poisoning were estimated to be 2–3% overall, with an estimated 4% annual loss in Mallards (*Anas platyrhynchos*; Sanderson and Bellrose 1986). Similarly, Grand et al. (1998) estimated that survival rates of female Spectacled Eiders (*Somateria fischeri*) exposed to Pb shot from ingestion were 34% lower than those of unexposed females (77%) and suggested that Pb exposure may have been preventing local population recovery. California Condor populations appear to be at substantial risk from Pb exposure (e.g., Cade 2007, Walters et al. 2010, Finkelstein et al. 2012). Pb sinkers appear to be a regulatory factor for Common Loons in New Hampshire, where 49% of known mortalities are attributed to Pb poisoning from fishing tackle (Vogel 2013).

**Significance of Pb exposure to avian conservation.** Given proof that elevated Pb exposure can greatly influence the health of individual birds and can result in mortality, the environmental distribution of Pb from ammunition and fishing tackle could be an important factor influencing the conservation of avian communities. Here, we discuss (1) the apparent contradiction in results of some studies regarding avian exposure and levels of impairment caused by different contaminant concentrations; (2) unease with the implicit assumption of many published studies that Pb is the ultimate source of mortality for birds found dead with elevated Pb concentrations; and (3) lack of clarity over the relative threat of Pb to birds in comparison to other major impacts such as invasive species, habitat loss, human disturbance, domestic cats, and collisions with vehicles, power transmission lines, and buildings.

We have already presented several examples of increases in avian Pb exposure in association with ammunition and tackle. Similarly, we have outlined many instances of toxicity associated with environmental and lab-derived exposure to Pb. However, the results of other studies add a layer of ambiguity to this topic that is important to acknowledge. For example, even at relatively similar Pb exposure levels, studies have shown clear effects on blood chemistry (Kerr et al. 2010, Carpenter et al. 2003, Hoffman et al. 1981, Pattee et al. 2006), egg production (Edens and Garlich 1983), behavior (Burger and Gochfeld 1994, 2004), and survival (Schulz et al. 2006, Grand et al. 1998, Pattee et al. 2006, Rideout et al. 2012), whereas others demonstrated limited responses to many of the same endpoints (McBride et al. 2004, Schulz et al. 2007, Ferrandis et al. 2008). Although differences in methodology likely played some role, a more plausible explanation is intrinsic interindividual and interspecific variability in sensitivity to Pb. This source of variation complicates overall estimates of Pb risk to avian communities and represents a key data gap in Pb ecotoxicology.

Acute toxicity leading to mortality can often be determined from physical or behavioral cues, especially if tissues are analyzed for Pb content postmortem. But it is uncommon to encounter Pb-intoxicated birds for which this information can be obtained, which complicates attempts to estimate actual mortality due to Pb. As a result, numerous studies have reported Pb levels in tissues from dead birds, making the implicit assumption that mortality was a result of Pb exposure in those birds with elevated concentrations (Helander et al. 2009, Hernández and Margalida 2009, Kenntner et al. 2001, Wayland and Bollinger 1999). In some cases, mortality is likely due to Pb poisoning, but as we noted above, the tremendous range in sensitivities among individuals and species can make the use of tissue thresholds to infer cause of death problematic. Thus, the proportion of birds found dead with elevated Pb concentrations is often a poor and biased (under or over) estimator of mortality rates.

The cumulative body of scientific evidence unequivocally suggests that Pb exposure from ammunition and fishing tackle is directly responsible for numerous bird deaths each year and is clearly a serious threat to the population trajectory of the endangered California Condor (Franson et al. 2003, Walters et al. 2010, Finkelstein et al. 2012; Box 2). However, for many bird species, the impact of Pb exposure is much less clear given the assortment of other anthropogenic hazards and conservation threats they face. For example, >1 billion birds year$^{-1}$ are estimated to be killed by domestic cats in the United States (Loss et al. 2013), and millions of bird mortalities each year result from collisions with power lines, fixed objects, and vehicles (Loss et al. 2014). In addition, habitat loss and intensified land use can have an immeasurable impact on the conservation status of many bird species at global scales. However, addressing the Pb issue is tractable because it entails a relatively simple solution: replacing Pb-based ammunition and fishing tackle with non-Pb alternatives.

Proponents of this solution contend that alternatives to Pb are readily available and of comparable cost and that the costs are expected to decrease with increases in demand that accompany improved efficiencies in ballistics (Thomas 2013). Conversely, supporters of continued Pb use in ammunition and fishing tackle argue that the increased costs of non-Pb alternatives require robust and clear scientific evidence of impacts before any changes are made. However, these competing ideas are not mutually exclusive. Progress could be made in reasonably short order to reduce avian Pb exposure and increase scientific knowledge of Pb's impacts through an integrated plan of voluntary Pb replacement programs coupled with large-scale research efforts to evaluate the effects of Pb management on avian Pb exposure.

## Priority Research Directions

Results from countless studies have concluded that Pb continues to be introduced into the environment through Pb ammunition and fishing tackle, and that these forms of Pb are being ingested by a wide diversity of avian taxa, causing illness and mortality. There are additional areas of investigation that might identify key areas to target Pb reduction and could inform priorities for broader Pb-reduction programs in the future. Thus, we identify four future research questions to improve our understanding of the threat posed by Pb poisoning: (1) What factors are responsible for interspecific variation in sensitivity to Pb exposure? (2) What is the spatial extent of Pb contamination in habitats, and how is this linked to bird exposure in those same locations? (3) How does the interaction of Pb exposure and landscape-level or environmental stressors affect birds at the population level? And (4) what is the influence of Pb on key demographic parameters (e.g., survival) in relation to other causes of morbidity and mortality?

**Variation in Pb sensitivity.** Numerous studies have evaluated toxicological responses of birds to Pb exposure (Franson and Pain 2011), but a consistent, ecologically meaningful, and standardized approach does not currently exist. This makes it challenging to prioritize how best to manage for Pb risk and makes comparative assessments across multiple taxa difficult. Thus, an important step in reducing Pb exposure in birds is the development of a standardized vulnerability assessment that considers life-history traits, exposure likelihoods, and sensitivity to the toxic effects of Pb. Of note, the concept of differential sensitivity among avian species that allows for thresholds that vary among taxa is well established for a range of contaminants (e.g., organochlorine pesticides, polychlorinated biphenyls, mercury, and selenium; Eisler 1986, Heinz et al. 2009, Blus 2011, Ohlendorf and Heinz 2011, and many others). For example, Buekers et al. (2009) summarized results of 13 repeated-dosage studies of Pb for 12 avian species. Including a range of endpoints in their analysis, they found a 50-fold range in estimates of no-observed–effect concentrations. Thus, similar Pb exposure levels will likely elicit a wide range of effects across a gradient of species. Unfortunately, few studies encompass the range of primary exposure mechanisms with similar exposure periods under standardized conditions. These estimates are important for providing context to Pb exposure across the landscape and should incorporate ecologically relevant endpoints (e.g., growth, survival, behavior, and reproduction).

**BOX 3. Recreational Shooting of Ground Squirrels**

One component of the environmental distribution of Pb-based ammunition that is poorly understood but that may be an important source of Pb exposure for avian scavenger species is the recreational shooting of ground squirrels such as Belding's ground squirrel, California ground squirrel (*S. beecheyi*), and Richardson's ground squirrel (*S. richardsonii*) (Knopper et al. 2006, Pauli and Buskirk 2007). Ground-squirrel shooting is generally unregulated, individual squirrels are commonly not retrieved, and recreational shooters almost exclusively use expandable Pb bullets that result in hundreds of Pb fragments in ground-squirrel carcasses (Pauli and Buskirk 2007). Further, it is not uncommon for individual recreational shooters to shoot $>$170 squirrels in a single day (Pauli and Buskirk 2007). Across large portions of avian habitats, the total number of available Pb-laced squirrel carcasses is difficult to estimate, and they are likely very patchily distributed, given land-ownership patterns and squirrel densities. However, Reeve and Vosburgh (2005) reported that $>$1.1 million ground squirrels were shot over a 1-yr period (2000) in South Dakota. Moreover, Pauli and Buskirk (2007) demonstrated that in ground squirrels shot with expandable Pb-based bullets, $\sim$70% of the fragments remaining in the carcass were small ($<$25 mg). Smaller fragments are more easily ingested than large ones, and smaller fragments present relatively greater surface area, increasing the rate of Pb absorption into the bloodstream of the scavenger. Further, Pauli and Buskirk (2007) found that 47% of all prairie dogs shot with expandable Pb-based bullets had sufficient quantities of Pb in a single carcass to result in mortality of nestling raptors. There are $\geq$13 species of birds that regularly scavenge dead ground squirrels, including Bald Eagles, Ferruginous Hawks (*Buteo regalis*), Golden Eagles, and Swainson's Hawks (*Buteo swainsoni*; Schmutz et al. 1989, Harmata and Restani 1995, Hoogland 2003). Given the degree to which Pb-laced ground-squirrel carcasses may be available to avian scavengers, particularly raptor scavengers whose populations are decreasing, such as Swainson's Hawk, there is an immediate need for information to better understand the spatial and temporal risks associated with contamination by Pb bullet fragments.

**Pb contamination and distribution.** The spatial distribution and availability of Pb in the environment are complicated by the need to account for multiple Pb source types (Figure 1). Studies that focus on ammunition sources

**BOX 4. Position Statements on Avian Pb Poisoning from Professional Societies and Environmental Groups in the USA and Canada**

**American Association of Avian Veterinarians**
http://www.aav.org/?page=leadbasedammo
**American Bird Conservancy**
http://www.abcbirds.org/abcprograms/policy/toxins/lead.html
**Association of Fish and Wildlife Agencies**
http://www.fishwildlife.org/files/AFWA-lead-Resolution_9-10.pdf
**Chocolay Raptor Center**
https://www.facebook.com/ChoclayRaptorCenter
**Defenders of Wildlife**
http://www.defenders.org/press-release/wildlife-groups-and-sportsmen-petition-feds-end-lead-ammunition-public-lands
**Fund for Animals**
http://www.fundforanimals.org/
**Health Risks from Lead-Based Ammunition in the Environment—A Consensus Statement of Scientists**
http://escholarship.org/uc/item/6dq3h64x
**Humane Society of the United States**
http://www.humanesociety.org/
**International Wildlife Rehabilitation Council**
http://theiwrc.org/
**Izaak Walton League**
http://www.iwla.org/index.php?ht1/4d/ContentDetails/i/17544
**National Wildlife Rehabilitators Association**
http://www.nwrawildlife.org/
**National Wolfwatcher Coalition**
http://wolfwatcher.org/
**Natural Resources Defense Council**
http://www.nrdc.org/
**North American Falconers Association**
http://www.flyrodreel.com/blogs/tedwilliams/2012/may/hunting-ammunition-fishing
**Northwood Alliance**
http://www.northwoodalliance.org/
**Peregrine Fund**
http://www.peregrinefund.org/lead
**Raptor Research Foundation**
http://raptorresearchfoundation.org/wp-content/uploads/2010/12/2011_lead_poisoning.pdf
**South Florida Wildlife Center**
http://www.humanesociety.org/animal_community/shelters/wildlife_care_center/
**Trumpeter Swan Society**
http://www.trumpeterswansociety.org/docs/Trumpetings_July_2008.pdf
**Upper Peninsula Environmental Coalition**
http://www.upenvironment.org/
**Western Association of Fish and Wildlife Agencies**
http://wdfw.wa.gov/conservation/loons/final_wafwa_resolution_re_lead_and_wildlife_-approved_7-21-10.pdf
**Wildlife Conservation Society**
http://www.wcs.org/
**Wildlife Society**
http://joomla.wildlife.org/documents/positionstatements/lead_final_2009.pdf

for birds commonly fail to account for other potential environmental Pb exposures. However, we can get a coarse estimate of Pb deposited in the environment by counting the number of harvested animals in a particular location, assuming that all were killed by Pb bullets and that offal remains were left in the field. For example, annual harvests of >200,000 white-tailed deer (*Odocoileus virginianus*) in Minnesota, an estimated 2 million prairie dogs in 3 U.S. states, and 3.1 million roe deer (*Capreolus capreolus*) in Germany, France, Austria, Poland, and the Czech Republic have been reported (cf. Thomas 2013). Recent isotopic studies, in conjunction with field studies, are now helping to disentangle exposure histories and have demonstrated that differentiating among multiple sources of Pb is possible (Church et al 2006, Finkelstein et al. 2010, Lambertucci et al. 2011). Other studies have confirmed Pb bullet fragments or fishing gear as the source of mortality through x-rays and necropsies (e.g., Pokras and Chafel 1992, Franson et al. 2003, Cruz-Martinez et al. 2012).

Pb contamination associated with hunting and recreational shooting is not homogeneous across the landscape, and the combination of seasonal hunting activity and annual variation in harvest rates among locations adds a temporal component to Pb risk across the landscape. Thus, exposure risk is likely maximized when spatial and temporal patterns of Pb availability converge in important habitats and life stages, such as in foraging ranges associated with nest sites (Walters et al. 2010) or in migration corridors for raptors (McBride et al. 2004). As a result, if managers are to identify key areas for targeting Pb reduction, there is a clear need for more robust, temporally dynamic, and higher-resolution estimates of Pb availability on the landscape that are separately associated with various sources of Pb.

**Pb contamination and environmental stressors.** The effects of Pb on birds are generally assessed independently of other environmental conditions. Much less is known about the extent to which sublethal Pb exposure interacts with other environmental stressors experienced by free-living birds, possibly resulting in behavioral abnormalities, decreased clutch sizes, reduced growth rates (Burger and Gochfeld 1994, 2000), reduced hematocrit levels (Redig et al. 1991), reduced $\delta$-ALAD activity (Hoffman et al. 1985, Finkelstein et al. 2012), and impaired neural development in young birds (Dey et al. 2000). Kelly and Kelly (2005) found that Pb-intoxicated swans were more prone to collisions with power lines than non-intoxicated swans, which suggests that sublethal Pb toxicosis may indirectly elevate mortality rates. Research that can address the issue of multiple stressors under field conditions will be critical for assessing the combined and relative risks of Pb and habitat conditions on bird species.

**Demographic effects.** Ascribing a direct link between Pb and population trajectories ($\lambda$) is exceedingly difficult (Kendall et al. 1996) because it requires estimates of cause-specific mortality rates that can be obtained only through intensive sampling efforts combined with necropsies and toxicological investigations. Projections have been made under varying exposure scenarios for such intensively managed species as the California Condor (Finkelstein et al. 2012), in which all individuals in the population are closely monitored and the cause of every known death is investigated. For other species, targeted and robust estimates of the influence of Pb on key demographic parameters (e.g., adult and juvenile mortality, fecundity) would be useful but generally do not exist. For example, Grand et al. (1998) found that survival of female Spectacled Eiders exposed to Pb from ingesting spent shot were substantially lower than those of unexposed females (77% vs. 44%), which may have made it difficult for some local populations to recover. Such an approach could facilitate a better understanding of Pb effects on key demographic parameters that may go into later population estimates and projections

## Current Approaches to Decrease Avian Mortality from Pb

Many approaches have been taken to reduce the availability of Pb ammunition and tackle to birds. Redistribution of shot through sediment cultivation, raising water levels in wetlands to reduce access to spent Pb shot, and providing uncontaminated food to highly endangered species are among the techniques used to reduce Pb exposure for specific species or at local scales (Snyder and Snyder 1989, Thomas et al. 2001). Approaches such as Pb-free ammunition and tackle giveaways and exchanges, and prohibitions on the use of Pb-based ammunition and tackle, are designed to reduce the amount of Pb entering the environment, can be applied at local to national scales, and can affect interests beyond the site- or species-management level. These measures can generally be separated into regulatory and voluntary approaches. The experiences described below reflect the diverse opinions surrounding legislative restriction of Pb ammunition and fishing tackle, and the broad engagement needed for voluntary approaches to be effective.

## Federal Regulatory Measures

**Ammunition.** Many countries have banned Pb shot for waterfowl hunting, yet only Sweden and Denmark have banned Pb ammunition for all forms of hunting (Avery and Watson 2009). The U.S. and Canadian governments banned Pb ammunition for waterfowl hunting in 1991 and 1999, respectively, using their jurisdictional authority under the Migratory Bird Treaty Act. Studies conducted after this ban found a substantial decline in Pb shot exposure in waterfowl (Anderson et al. 2000, Stevenson et al. 2005), resulting in a 64% decline in annual Pb poisoning in Mallards (Anderson et al. 2000). Currently, U.S. and Canadian migratory bird regulations prohibit hunting waterfowl and American Coots (*Fulica americana*) with Pb shot; all other hunted migratory birds can still be shot with Pb (D. J. Case and Associates 2006; Environment Canada: http://www.ec.gc.ca/regeng.html). The U.S. National Wildlife Refuge System requires that hunters possess and use only approved nontoxic ammunition while hunting on Waterfowl Production Areas (50 CFR 32.2(k)). Individual refuges have adopted specific rules that require the use of nontoxic ammunition outside of these areas for hunting waterfowl, upland game birds, Mourning Doves, red foxes (*Vulpes vulpes*), and coyotes (*Canis latrans*; 50 CFR 32.20–32.70). U.S. National Park Service personnel have used non-PB ammunition since 2008 (Ross-Winslow and Teel 2011). Further, the U.S. Army will issue a new Pb-free version of the 7.62-mm rounds fired from the M-14 to troops in 2014 (http://www.army.mil/article/106710/Picatinny_ammo_goes_from_regular_to_unleaded).

**Fishing tackle.** In the most sweeping reform, the European Union is on track to ban Pb in fishing tackle by June 2015 (European Fishing Tackle Trade Association; http://www.eftta.com/english/news_indepth.html?cart=&SKU=2047259450). All Pb fishing tackle has been banned in Denmark since 2002, and Pb tackle (0.6–28.4 g) has been banned in the United Kingdom since 1987 (United Nations Environment Programme 2013). It is illegal to use Pb fishing sinkers and jigs weighing <50 g in National Parks and National Wildlife Areas in Canada (SOR 96–313, 23.4 17(h)). There are some restrictions on the use of Pb fishing gear in U.S. national wildlife refuges and national parks, but these decisions have been made at the level of the individual refuge or park (50 CFR 32.20–32.70). For example, Yellowstone National Park banned most Pb tackle because of concerns regarding "alarmingly low populations" of Trumpeter Swans (*Cygnus buccinator*) and loons (http://www.nps.gov/yell/planyourvisit/upload/14FishReg.pdf). The park continues to allow Pb-core line and heavy (>2 kg) downrigger weights used to fish for deep-dwelling lake trout, with the rationale that these weights are too large to be ingested by waterfowl.

## State and Provincial Regulatory Measures

With the exception of hunting laws regulated under the Migratory Bird Treaty Act and on select federal lands, states and provinces have jurisdiction for establishing hunting seasons, bag limits, and limits on types of firearms, ammunition, and fishing tackle. Many states and wetland management agencies do not permit Pb ammunition in aquatic habitats, regardless of the target species. This has resulted in a patchwork of Pb regulations across the United States and Canada (D.J. Case and Associates 2006). Approximately 35 states have established areas in which waterfowl Pb-shot regulations have expanded to encompass non-waterfowl, but these regulations have typically focused on upland game-bird hunting and vary by state, by target species, and even by land ownership within a particular state (Thomas 2009).

In October 2013, California became the first U.S. state to prohibit the use of all Pb ammunition for hunting (Assembly Bill 711). The new law will not be fully enacted until 2019. Previously, the State of California passed the Ridley-Tree Condor Preservation Act, which called for use of non-Pb ammunition for all hunting (including big game) in the range of the California Condor (Assembly Bill 821, 2007). A study that examined Pb levels before and after the ban found that Golden Eagle and Turkey Vulture blood Pb levels declined following the ban (Kelly et al. 2011), although this study was of short duration and lacked replicate study sites (Box 2). A significant effect in reducing California Condor Pb exposure has not yet been realized in California in the short time of the ban (Finkelstein et al. 2012). Inadequate compliance, exposure to other sources of Pb, home ranges that extend beyond the area where Pb ammunition has been banned, and feeding on contaminated marine-mammal carcasses are among the possible factors contributing to the persistence of Pb in condors despite the Pb prohibition.

The requirements for nontoxic fishing gear also vary considerably by state, with more restrictions in areas with sizable populations of loons and swans. Currently, 6 states regulate the sale and/or use of Pb fishing tackle (Maine, Massachusetts, New Hampshire, New York, Vermont, and Washington); 4 states have explicit recommendations for voluntary use of non-Pb fishing tackle (Illinois, Iowa, Minnesota, and Montana; http://joomla.wildlife.org/documents/positionstatements/lead.and.wildlife.pdf). These efforts focus primarily on small Pb sinkers and are aimed at reducing Pb exposure to swans, loons, and other piscivorous birds.

## Voluntary Approaches

Voluntary approaches to decreasing the use of Pb ammunition and tackle can be as successful as, or more successful than, legislated requirements, and sportsmen are indicating buy-in by supporting the suggested change. Ross-Winslow and Teel (2011) provide a detailed accounting of voluntary Pb reduction programs by state. Voluntary approaches fall under two general categories: (1) giveaways or exchanges of nontoxic ammunition and tackle and (2) education and outreach efforts.

Pb fishing-tackle exchange programs have been implemented in several states, largely to protect loon and swan populations (Ross-Winslow and Teel 2011). More than 40,000 Pb sinkers were collected from anglers in state parks and fishing stores in 1 yr in New Hampshire and Vermont (http://www.nwf.org/news-and-magazines/

national-wildlife/news-and-views/archives/2001/getting-the-lead-out.aspx). This effort was used to introduce anglers to the toxicity of Pb in their gear.

Several state fish-and-game agencies no longer use Pb in internal agency operations (e.g., Oregon Department of Fish and Wildlife). The U.S. Department of Agriculture Animal and Plant Health Inspection Service Wildlife Services have adopted non-Pb ammunition for some of their control programs for nuisance wildlife species. The use of education and outreach as part of voluntary programs to reduce Pb exposure in wildlife has received the support of several groups (Box 4). Outreach activities are already occurring in many areas as a result of efforts by states, provinces, nongovernmental organizations, federal agencies, and tribes (reviewed by Ross-Winslow and Teel 2011).

For example, the Yurok Tribe in northwestern California educates citizens about Pb ammunition risks and promotes non-Pb ammunition alternatives as part of an effort to restore California Condors to the region (http://www.yuroktribe.org/news&issues/news/documents/november_2010.pdf; D'Elia and Haig 2013). Partnering with Bullets and Brass, an ammunition reloading company, and the Institute for Wildlife Studies, this group launched the "Hunters as Stewards" program to educate hunters and to build on their cultural stewardship ideals (http://www.yuroktribe.org/departments/selfgovern/wildlife_program/condor/condorproject.htm). The Yurok Tribe also purchased 8,900 ha of potential condor habitat, which is managed as Pb-free. Similarly, the Arizona Game and Fish Department has developed strategies for educating hunters to improve their understanding of the negative consequences of Pb exposure on California Condors in Arizona (Sullivan et al. 2007). Several conservation organizations (e.g., Arizona Antelope Foundation, Arizona Desert Bighorn Sheep Society, Arizona Chapter of the National Wild Turkey Federation, and others in the Kaibab Plateau region) have formed a coalition supporting voluntary efforts to reduce Pb available to condors (http://www.arizonadailyindependent.com/2013/08/29/arizonas-voluntary-lead-reduction-program-helps-condor/). There was >80% hunter compliance, and no birds were found with Pb poisoning the following year (Sieg et al. 2009).

These education programs have clearly generated support among hunters. Results from Arizona hunters indicated that 93% ($n = 380$) of successful hunters believed the nontoxic bullets performed as well as or better than Pb ammunition, and 97% ($n = 796$) of participants reported the accuracy of the ammunition as average to excellent on a 4-point scale (Sieg et al. 2009). In 2013, 88% of hunters in the condors' core range voluntarily used non-Pb ammunition or took other Pb-reduction efforts like removing affected gut piles from the field. Hunters in this area have supported the voluntary use of non-Pb ammunition at rates >80% for the past 7 yr. Results of these efforts show that 16% of birds trapped and tested in September 2013 revealed blood-Pb levels indicating extreme exposure, compared with 42% of birds last season. The number of birds treated with Pb-reducing chelation therapy dropped to 11 birds, compared with 28 in 2012 (https://www.peregrinefund.org/news-release/286).

**Alternatives to Pb.** An increasing number of Pb-free ammunition options are available for hunters and recreational shooters. A recent study of 37 corporations that produce non-Pb bullets and shot for the international market found no major difference in the retail price of equivalent Pb-free and Pb-core ammunition for many popular rifle calibers and shotgun gauges (Thomas 2013). Further, the study found that there were a minimum of 35 calibers and 51 rifle-cartridge configurations available. One caveat to the use of non-Pb ammunition is that manufacturers currently produce smaller quantities of these ammunition types compared with Pb-based ammunition, so availability may limit access to these alternatives unless production volume is increased. To explore this, we conducted an Internet market search of the 3 major resale distributers in the United States for each of the non-Pb centerfire bullets and shotgun slugs identified in Thomas (2013). In October 2013, only 18%, 27%, and 10% of the Pb-free options were available from Cabela's (http://www.cabelas.com), Cheaper Than Dirt (http://www.cheaperthandirt.com), and Bass Pro Shops (http://www.basspro.com), respectively. This general lack of availability could hamper efforts to transition to Pb-free ammunition. However, it is not clear whether the lack of Pb-free options results from lack of market demand or lack of production by ammunition manufacturers.

To our knowledge, only 2 peer-reviewed studies have assessed the effectiveness of non-Pb ammunition under traditional hunting conditions. Trinogga et al. (2012) assessed wound size and morphology between Pb-free and Pb-core rifle cartridges. In that study, wild ungulates ($n = 34$) were shot, and the authors found that the killing potential assessed via wound diameters and maximum cross-sectional area were similar between Pb-core and Pb-free bullets. Similarly, Knott et al. (2009) shot ungulates ($n = 153$) using Pb-core and Pb-free bullets and assessed the lethality of the bullets on the basis of accuracy and killing power, finding no difference in either assessment between bullet types. Although these studies indicate that the use of non-Pb ammunition is unlikely to affect hunting success, additional peer-reviewed research is needed to more fully explore non-Pb ammunition performance across a range of hunting applications.

Anglers can use a variety of materials for non-Pb fishing weights and sinkers, including bismuth, tin, tungsten, steel, and brass (http://water.epa.gov/scitech/swguidance/fishshellfish/animals.cfm). Natural stone is also an option for some fishing applications (http://www.recycledfish.org). We have not found a formal review of the effectiveness of various types of fishing tackle or comparisons among Pb and non-Pb weights and sinkers. Given that these materials vary in density, malleability, and cost, a careful review of the performance of these materials in different fishing applications would be helpful.

## Pathways to Decrease Avian Exposure to Pb

One approach to decrease avian mortality from Pb poisoning would be a federal ban on Pb ammunition and fishing tackle. On the other hand, lessons learned from environmental decision-making suggest taking an approach that recognizes the interests and concerns of a diverse group of stakeholders across multiple levels of governance (Walker et al. 2006, Walker 2007). Further, despite the success of federal regulations for non-Pb ammunition for waterfowl hunting, legislative approaches to protect additional species of birds are more likely to occur on a state-by-state or province-by-province basis. Even where federal agencies maintain control (e.g., migratory and ESA-listed species, EPA regulations), there may be reason to defer to state, provincial, or local oversight. Below, we discuss potential incentive-based and regulatory approaches that might be considered in conjunction with current programs and regulations.

**Federal, provincial, and state leadership.** U.S. and Canadian federally mandated removal of Pb from ammunition used to hunt waterfowl resulted in a significant and rapid reduction in Pb exposure in waterfowl and prevented the loss of birds to Pb poisoning (U.S. Fish and Wildlife Service 1976, 1986, 1988, Anderson et al. 2000, Samuel and Bowers 2000, Stevenson et al. 2005), thus demonstrating the efficacy of legal restrictions on the use of Pb ammunition for hunting. For example, by 1996–1997, only 1.1% of 1,318 ducks collected on the Mississippi flyway had apparently been shot using Pb ammunition (Anderson et al. 2000).

The efficacy of laws restricting the use of Pb tackle has not been well tested because there are few and they are relatively new. However, analyses comparing pre- and post-restriction (1989–1999 vs. 2000–2011) mortality in New Hampshire loons found that the rate of Pb fishing-tackle mortalities fell marginally by 3% (preban adult mortality [$\pm$ SE] = 12.5% $\pm$ 1.7; postban mortality = 9.5% $\pm$ 1.2; Grade 2011, Vogel 2013). Vogel considers the estimates of mortality to be conservative and concludes that Pb sinkers are a major cause (49% of known deaths) of mortality for Common Loons in New Hampshire.

**Voluntary approaches.** Some advocates, managers, and decision-makers have chosen to expand voluntary programs in lieu of regulatory approaches, or recommend such programs as interim steps to generate enough support for passage of a Pb ban. The National Park Service and some states have already implemented these measures (Ross-Winslow and Teel 2001, Epps 2014). The Association of Fish and Wildlife Agencies, led by the directors of state agencies, has formed a "Lead and Fish and Wildlife Health" Working Group and is an important leader on this issue. Their positions and initiatives reflect responsiveness to public sentiment and the missions of member agencies to manage for conservation, hunting, and fishing. Further, some federal, provincial, and state agencies are voluntarily switching to use of nontoxic ammunition and fishing tackle in the course of their duties (e.g., dispatching sick or wounded animals or shooting animals for depredating crops or livestock).

**Non-Pb ammunition and tackle giveaways or exchanges in key areas.** Hunters have participated in non-Pb ammunition exchange or giveaway programs in California, Utah, Wyoming, and Arizona in an effort to help conserve the California Condor and reduce Pb poisoning in wild birds (Sieg et al. 2009, Southwest Condor Review Team 2012, Ventana Wildlife Society 2012). Anglers have participated in similar programs in Maine, Massachusetts, New Hampshire, New York, and Vermont to aid waterbird conservation (Ross-Winslow and Teel 2011). Exchanges and giveaways can also serve as an important communication tool by educating hunters and anglers on the hazards of using Pb ammunition and fishing tackle and explaining the benefits of switching to nontoxic alternatives.

**Outreach and communication.** Informing decision-makers, hunters, anglers, and the general public about Pb poisoning resulting from spent ammunition and lost fishing tackle may increase support for the use of non-Pb ammunition and tackle. The utility of outreach efforts alone has been questioned (Thomas 2011; but see Sieg et al. 2009, Schroeder et al. 2012). However, from research designed to investigate which communication strategies might increase support for restrictions on Pb ammunition, Schroeder et al. (2012) suggested that messages addressing the key beliefs dividing those who support Pb restrictions from those who do not are most likely to be successful. Social scientists would be key allies in helping to define the role of education and outreach efforts and aid in crafting key messages to eliminate the use of Pb-based ammunition and fishing tackle while maintaining hunting and fishing opportunities (Ross-Winslow and Teel 2011).

## Summary

We have highlighted a substantial problem that continues to cause significant morbidity and mortality for many bird species in North America and beyond. Sufficient information is available to adequately document the issue and provide a range of potential approaches and research priorities for the future. The challenge for decision-makers seeking to conserve bird populations is to use past experience and existing scientific information to efficiently and effectively reduce Pb exposure. Successful approaches are most likely to come from wildlife professionals, hunters, anglers, and other stakeholders working together to recognize a collective long-term interest in the sustainability of wildlife resources and society's hunting-and-angling heritage.

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## LITERATURE CITED

Alfano, D. P., and T. L. Petit (1981). Behavioral effects of postnatal lead exposure: Possible relationship to hippocampal dysfunction. Behavior and Neural Biology 32:319–333.

Alfonso, S., F. Grousset, L. Massé, and J.-P. Tastet (2001). A European lead isotope signal recorded from 6000 to 300 years BP in coastal marshes (SW France). Atmospheric Environment 35:3595–3605.

Anderson, W. L., S. P. Havera, and B. W. Zercher (2000). Ingestion of lead and nontoxic shotgun pellets by ducks in the Mississippi flyway. Journal of Wildlife Management 64:848–857.

Avery, D., and R. T. Watson (2009). Regulation of lead-based ammunition around the world. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 161–167.

Bedrosian, B., D. Craighead, and R. Crandall (2012). Lead exposure in Bald Eagles from big game hunting, the continental implications and successful mitigation efforts. PLoS ONE 7(12):e51978.

Bellinger, D. C., J. Burger, T. J. Cade, D. A. Cory-Slechta, M. Finkelstein, H. Hu, M. Kosnett, P. J. Landrigan, B. Lanphear, M. A. Pokras, P. T. Redig, B. A. Rideout, et al. (2013). Health risks from lead-based ammunition in the environment. Environmental Health Perspectives 121:A178–A179.

Bellrose, F. C. (1959). Lead poisoning as a mortality factor in waterfowl populations. Illinois Natural History Survey Bulletin 27:235–288.

Bennett, J. R., C. A. Kaufman, I. Koch, J. Sova, and K. J. Reimer (2007). Ecological risk assessment of lead contamination at rifle and pistol ranges using techniques to account for site characteristics. Science of the Total Environment 374:91–101.

Best, T. L., T. E. Garrison, and C. G. Schmitt (1992). Availability and ingestion of lead shot by Mourning Doves (*Zenaida macroura*) in southeastern New Mexico. Southwestern Naturalist 37: 287–292.

Beyer, W. N., J. Dalgarn, S. Dudding, J. B. French, R. Mateo, J. Miesner, L. Sileo, and J. Spann (2004). Zinc and lead poisoning in wild birds in the Tri-State Mining District (Oklahoma, Kansas, and Missouri). Archives of Environmental Contamination and Toxicology 48:108–117.

Beyer, W. N., J. C. Franson, J. B. French, T. May, B. A. Rattner, V. I. Shearn-Bochsler, S. E. Warner, J. Weber, and D. Mosby (2013). Toxic exposure of songbirds to lead in the Southeast Missouri Lead Mining District. Archives of Environmental Contamination and Toxicology 65:598–610.

Blus, L. J. (2011). DDT, DDD, and DDE in birds. In Environmental Contaminants in Biota: Interpreting Tissue Concentrations, second edition (W. N. Beyer and J. P. Meador, Editors). CRC Press, Boca Raton, FL, USA. pp. 425–444.

Blus, L. J., C. J. Henny, D. J. Hoffman, L. Sileo, and D. J. Audet (1999). Persistence of high lead concentrations and associated effects in Tundra Swans captured near a mining and smelting complex in northern Idaho. Ecotoxicology 8:125–132.

Boggess, W. R. (Editor) (1977). Lead in the environment. Report NSF/RA-770214. National Science Foundation, Washington, DC, USA.

Brennan, L. A. (1991). How can we reverse the Northern Bobwhite population decline? Wildlife Society Bulletin 19: 544–555.

Buekers, J., E. S. Redeker, and E. Smolders (2009). Lead toxicity to wildlife: Derivation of a critical blood concentration for wildlife monitoring based on literature data. Science of the Total Environment 407:3431–3438.

Burger, J., and M. Gochfeld (1994). Behavioral impairments of lead-injected young Herring Gulls in nature. Fundamental and Applied Toxicology 23:553–561.

Burger, J., and M. Gochfeld (2000). Effects of lead on birds (Laridae): A review of laboratory and field studies. Journal of Toxicology and Environmental B 3:59–78.

Burger, J., and M. Gochfeld (2004). Metal levels in eggs of Common Terns (*Sterna hirundo*) in New Jersey: Temporal trends from 1971 to 2002. Environmental Research 94:336–343.

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

Carpenter, J. W., O. H. Pattee, S. H. Fritts, B. A. Rattner, S. N. Wiemeyer, J. A. Royle, and M. R. Smith (2003). Experimental lead poisoning in Turkey Vultures (*Cathartes aura*). Journal of Wildlife Diseases 39:96–104.

Carr, E., M. Lee, K. Marin, C. Holder, M. Hoyer, M. Pedde, R. Cook, and J. Touma (2011). Development and evaluation of an air quality modeling approach to assess near-field impacts of lead emissions from piston-engine aircraft operating on leaded aviation gasoline. Atmospheric Environment 45:5795–5804.

Castrale, J. S. (1989). Availability of spent lead shot in fields managed for Mourning Dove hunting. Wildlife Society Bulletin 17:184–189.

Centers for Disease Control (2013). Blood lead levels in children aged 1–5 years—United States, 1999–2010. Morbidity and Mortality Weekly Report 62 (April 5):245–248.

Chen, I. (2013). Overlooked: Thousands of Americans exposed to dangerous levels of lead in their jobs. Scientific American 309(3). http://www.scientificamerican.com

Church, M. E., R. Gwiazda, R. W. Risebrough, K. Sorenson, C. P. Chamberlain, S. Farry, W. Heinrich, B. A. Rideout, and D. R.

Smith (2006). Ammunition is the principal source of lead accumulated by California Condors re-introduced to the wild. Environmental Science and Technology 40:6143–6150.

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

Cruz-Martinez, L., P. T. Redig, and J. Deen (2012). Lead from spent ammunition: A source of exposure and poisoning in Bald Eagles. Human–Wildlife Interactions 6:94–104.

Cryer, M., J. J. Corbett, and M. D.Winterbotham (1987). The deposition of hazardous litter by anglers at coastal and inland fisheries in South Wales. Journal of Environmental Management 25:125–135.

D'Elia, J., and S. Haig (2013). California Condors in the Pacific Northwest. Oregon State University Press, Corvallis, OR, USA.

DeMichele, S. J. (1984). Nutrition of lead. Comparative Biochemistry and Physiology A 78:401–408.

Dermody, B. J., C. J. Tanner, and A. L. Jackson (2011). The evolutionary pathway to obligate scavenging in *Gyps* vultures. PLoS ONE 6(9):e24635.

Dey, P. M., J. Burger, M. Gochfeld, and K. R. Reuhl (2000). Developmental lead exposure disturbs expression of synaptic neural cell adhesion molecules in Herring Gull brains. Toxicology 146:137–147.

D.J. Case and Associates (2006). Non-toxic shot regulation inventory of the United States and Canada. Final Report to the Ad Hoc Mourning Dove and Lead Toxicosis Working Group. D.J. Case and Associates, Mishawaka, IN, USA.

Donázar, J. A., C. J. Palacios, L. Gangoso, O. Ceballos, M. J. González, and F. Hiraldo (2002). Conservation status and limiting factors in the endangered population of Egyptian Vulture (*Neophron percnopterus*) in the Canary Islands. Biological Conservation 107:89–97.

Duerr, A. E. (1999). Abundance of lost and discarded fishing tackle and implications for waterbird populations in the United States. M.S. thesis, School of Renewable Natural Resources, University of Arizona, Tucson, AZ, USA.

Edens, F. W., and J. D. Garlich (1983). Lead-induced egg production decrease in leghorn and Japanese Quail hens. Poultry Science 62:1757–1763.

Eisler, R. (1986). Polychlorinated biphenyl hazards to fish, wildlife, and invertebrates: A synoptic review. U.S. Fish and Wildlife Service Biological Report 85(1.7).

Eisler, R. (1988). Lead hazards to fish, wildlife, and invertebrates: A synoptic review. U.S. Fish and Wildlife Service, Biological Report 85(1.14).

Epps, C. W. (2014). Considering the switch: challenges of transitioning to non-lead hunting ammunition. Condor 116: 429–434.

European Commission (2004). Advantages and drawbacks of restricting the marketing and use of lead in ammunition, fishing sinkers, and candle wicks. Final Report. European Commission, Enterprise Directorate-General. http://ec.europa.eu/enterprise/sectors/chemicals/files/studies/ehn_lead_final_report_en.pdf

Fair, J. M., and O. B. Myers (2002). The ecological and physiological costs of lead shot and immunological challenge to developing Western Bluebirds. Ecotoxicology 11:199–208.

Fair, J. M., and R. E. Ricklefs (2002). Physiological, growth, and immune response of Japanese Quail chicks to the multiple stresses of immunological challenge and lead shot. Archives of Environmental Contamination and Toxicology 42:77–87.

Ferrandis, P., R. Mateo, F. R. López-Serrano, M. Martínez-Haro, and E. Martínez-Duro (2008). Lead shot exposure in Red-legged Partridge (*Alectoris rufa*) on a driven shooting estate. Environmental Science and Technology 42:6271–6277.

Finkelstein, M. E., D. F. Doak, D. George, J. Burnett, J. Brandt, M. Church, J. Grantham, and D. R. Smith (2012). Lead poisoning and the deceptive recovery of the critically endangered California Condor. Proceedings of the National Academy of Sciences USA 109:11449–11454.

Finkelstein, M. E., D. George, S. Scherbinski, R. Gwiazda, M. Johnson, J. Burnett, J. Brandt, S. Lawrey, A. P. Pessier, M. Clark, J. Wynne, J. Grantham, and D. R. Smith (2010). Feather lead concentrations and (207)Pb/(206)Pb ratios reveal lead exposure history of Califonia Condors (*Gymnogyps californianus*). Environmental Science and Technology 44:2639–2647.

Finkelstein, M. E., R. H. Gwiazda, and D. R. Smith (2003). Lead poisoning of seabirds: Environmental risks from leaded paint at a decommissioned military base. Environmental Science and Technology 37:3256–3260.

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

Flint, P. L., and J. L. Schamber (2010). Long-term persistence of spent lead shot in tundra wetlands. Journal of Wildlife Management 74:148–151.

Flora, S. J. S., G. Flora, and G. Saxena (2006). Environmental occurrence, health effects and management of lead poisoning. In Lead: Chemistry, Analytical Aspects, Environmental Impacts and Health Effects (S. B. Cascas and J. Sordo, Editors). Elsevier, Amsterdam, The Netherlands. pp. 158–228.

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

Franson, J. C., and D. J. Pain (2011). Lead in birds. In Environmental Contaminants in Biota: Interpreting Tissue Concentrations, second edition (W. N. Beyer and J. P. Meador, Editors). Taylor & Francis, Boca Raton, FL, USA. pp. 563–593.

Frey, S. N., S. Majors, M. R. Conover, T. A. Messmer, and D. L. Mitchell (2003). Effect of predator control on Ring-necked Pheasant populations. Wildlife Society Bulletin 31:727–735.

Gerstenberger, S., and D. D. Divine (2006). Lead shot deposition and distribution in southern Nevada. Journal of the Nevada Public Health Association 3:8–13.

Goddard, C. I., N. J. Leonard, D. L. Stang, P. J. Wingate, B. A. Rattner, J. C. Franson, and S. R. Sheffield (2008). Management concerns about known and potential impacts of lead use in shooting and in fishing activities. Fisheries 33:228–236.

Goyer, R. A. (1996). Toxic effects of metals. In Casarett and Doull's Toxicology: The Basic Science of Poisons, fifth edition (C. D. Klaassen, M. O. Amdur, and J. Doull, Editors). McGraw-Hill, New York, NY, USA. pp. 691–736.

Grade, T. (2011). Effects of lead fishing tackle on Common Loons (*Gavia immer*) in New Hampshire. M.S. thesis, University of Wisconsin, Madison, WI, USA.

Grand, J. B., P. L. Flint, M. R. Petersen, and C. L. Moran (1998). Effect of lead poisoning on Speckled Eider survival rates. Journal of Wildlife Management 62:1103–1109.

Hall, M., J. Grantham, R. Posey, and A. Mee (2007). Lead exposure among reintroduced California Condors in southern California. In California Condors in the 21st Century (A. Mee and L. S. Hall, Editors). Nuttall Ornithological Club, Cambridge, MA, and American Ornithologists' Union, Washington, DC, USA. pp. 163–184.

Harmata, A. R., and M. Restani (1995). Environmental contaminants and cholinesterase in blood of vernal migrant Bald and Golden eagles in Montana. Intermountain Journal of Sciences 1:1–15.

Harmata, A. R., and M. Restani (2013). Lead, mercury, selenium, and other trace elements in tissues of Golden Eagles from southwestern Montana, USA. Journal of Wildlife Diseases 49: 114–124.

Heinz, G. H., D. J. Hoffman, J. D. Klimstra, K. R. Stebbins, S. L. Kondrad, and C. A. Erwin (2009). Species differences in the sensitivity of avian embryos to methylmercury. Archives of Environmental Contamination and Toxicology 56:129–138.

Helander, B., J. Axelsson, H. Borg, K. Holm, and A. Bignert (2009). Ingestion of lead from ammunition and lead concentrations in White-tailed Sea Eagles (*Haliaeetus albicilla*) in Sweden. Science of the Total Environment 407:5555–5563.

Henny, C. J. (2003). Effects of mining lead on birds: A case history at Coeur d'Alene Basin, Idaho. In Handbook of Ecotoxicology, second edition (D. J. Hoffman, B. A. Rattner, G. A. Burton, Jr., and J. Cairns, Jr., Editors). Lewis, Boca Raton, FL, USA. pp. 755–766.

Hernández, M., and A. Margalida (2009). Assessing the risk of lead exposure for the conservation of the endangered Pyrenean Bearded Vulture (*Gypaetus barbatus*) population. Environmental Research 109:837–842.

Hernberg, S. (2000). Lead poisoning in a historical perspective. American Journal of Industrial Medicine 38:244–254.

Hoffman, D. J., J. C. Franson, O. H. Pattee, C. M. Bunck, and H. C. Murray (1985). Biochemical and hematological effects of lead ingestion in nestling American Kestrels (*Falco sparverius*). Comparative Biochemistry and Physiology C 80:431–439.

Hoffman, D. J., O. H. Pattee, S. N. Wiemeyer, and B. Mulhern (1981). Effects of lead shot ingestion on δ-aminolevulinic acid dehydratase activity, hemoglobin concentration, and serum chemistry in Bald Eagles. Journal of Wildlife Diseases 17:423–431.

Holladay, J. P., M. Nisanian, S. Williams, R. C. Tuckfield, R. Kerr, T. Jarrett, L. Tannenbaum, S. D. Holladay, A. Sharma, and R. M. Gogal, Jr. (2012). Dosing of adult pigeons with as little as one #9 lead pellet caused severe δ-ALAD depression, suggesting potential adverse effects in wild populations. Ecotoxicology 21:2331–2337.

Holladay, S. D., R. Kerr, J. P. Holladay, B. Meldrum, S. M. Williams, and R. M. Gogal, Jr. (2012). Persistent increase of blood lead level and suppression of δ-ALAD activity in Northern Bobwhite quail orally dosed with even a single 2-mm spent lead shot. Archives of Environmental Contamination and Toxicology 63:421–428.

Hoogland, J. L. (2003). Black-tailed prairie dog (*Cynomys ludovicianus*) and allies. In Wild Mammals of North America: Biology, Management, and Conservation (G. A. Feldhammer, B. C. Thompson, and J. A. Chapman, Editors). Johns Hopkins University Press, Baltimore, MD, USA. pp. 232–247.

Hunt, W. G. (2012). Implications of sublethal lead exposure in avian scavengers. Journal of Raptor Research 46:389–393.

Hunt, W. G., C. N. Parish, S. C. Farry, T. G. Lord, and R. Sieg (2007). Movements of introduced California Condors in Arizona in relation to lead exposure. In California Condors in the 21st Century (A. Mee and L. S. Hall, Editors). Nuttall Ornithological Club, Cambridge, MA, and American Ornithologists' Union, Washington, DC, USA. pp. 79–96.

Hunt, W. G., R. T. Watson, J. L. Oaks, C. N. Parish, K. K. Burnham, R. L. Tucker, J. R. Belthoff, and G. Hart (2009). Lead bullet fragments in venison from rifle-killed deer: Potential for human dietary exposure. PLoS ONE 4(4):e5330.

Hunter, B. F., and M. N. Rosen (1965). Occurrence of lead poisoning in a wild pheasant (*Phasianus colchicus*). California Fish and Game 51:207.

Hwang, K.-Y., B.-K. Lee, J. P. Bressler, K. I. Bolla, W. F. Stewart, and B. S. Schwartz (2002). Protein kinase C activity and the relations between blood lead and neurobehavioral function in lead workers. Environmental Health Perspective 110:133–138.

Keel, M. K., W. R. Davidson, G. L. Doster, and L. A. Lewis (2002). Northern Bobwhite and lead shot deposition in an upland habitat. Archives of Environmental Contamination and Toxicology 43:318–322.

Kelly, A., and S. Kelly (2005). Are Mute Swans with elevated blood lead levels more likely to collide with overhead power lines? Waterbirds 28:331–334.

Kelly, T. R., P. H. Bloom, S. G. Torres, Y. Z. Hernandez, R. H. Poppenga, W. M. Boyce, and C. K. Johnson (2011). Impact of the California lead ammunition ban on reducing lead exposure in Golden Eagles and Turkey Vultures. PLoS ONE 6(4):e17656.

Kelly, T. R., and C. K. Johnson (2011). Lead exposure in free-flying Turkey Vultures is associated with big game hunting in California. PLoS ONE 6(4):e15350.

Kendall, R. J., T. E. Lacker, Jr., C. Bunck, B. Daniel, C. Driver, C. E. Grue, F. Leighton, W. Stansley, P. G. Watanabe, and M. Whitworth (1996). An ecological risk assessment of lead shot exposure in non-waterfowl avian species: Upland game birds and raptors. Environmental Toxicology and Chemistry 15:4–20.

Kenntner, N., F. Tataruch, and O. Krone (2001). Heavy metals in soft tissue of White-tailed Eagles found dead or moribund in Germany and Austria from 1993 to 2000. Environmental Toxicology and Chemistry 20:1831–1837.

Kerr, R., S. Holladay, T. Jarrett, B. Selcer, B. Meldrum, S. Williams, L. Tannenbaum, J. Holladay, J. Williams, and R. Gogal (2010). Lead pellet retention time and associated toxicity in Northern Bobwhite quail (*Colinus virginianus*). Environmental Toxicology and Chemistry 29:2869–2874.

Knopper, L. D., P. Mineau, A. M. Scheuhammer, D. E. Bond, and D. T. McKinnon (2006). Carcasses of shot Richardson's ground squirrels may pose lead hazards to scavenging hawks. Journal of Wildlife Management 70:295–299.

Knott, J., J. Gilbert, R. E. Green, and D. G. Hoccom (2009). Comparison of the lethality of lead and copper bullets in deer control operations to reduce lead poisoning; field trials in England and Scotland. Conservation Evidence 6:71–78.

Knott, J., J. Gilbert, D. G. Hoccom, and R. E. Green (2010). Implications for wildlife and humans of dietary exposure to lead from fragments of lead rifle bullets in deer shot in the UK. Science of the Total Environment 409:95–99.

Kramer, J. L., and P. T. Redig (1997). Sixteen years of lead poisoning in eagles, 1980–95: An epizootiologic view. Journal of Raptor Research 31:327–332.

Lambertucci, S. A., J. A. Donázar, A. D. Huertas, B. Jiménez, M. Sáez, J. A. Sánchez-Zapata, and F. Hiraldo (2011). Widening the problem of lead poisoning to a South-American top scavenger: Lead concentrations in feathers of wild Andean Condors. Biological Conservation 144:1464–1471.

Larsen, R. T., J. T. Flinders, D. L. Mitchell, and E. R. Perkins (2007). Grit size preferences and confirmation of ingested lead pellets in chukars (*Alectoris chukar*). Western North American Naturalist 67:152–155.

Lewis, J. C., and E. Legler, Jr. (1968). Lead shot ingestion by Mourning Doves and incidence in soil. Journal of Wildlife Management 32:476–482.

Liu, J., R. A. Goyer, and M. P. Waalkes (2008). Toxic effects of metals. In Casarett and Doull's Toxicology: The Basic Science of Poisons, seventh edition (C. D. Klaasen, Editor). McGraw-Hill Medical, New York, NY, USA. pp. 931–979.

Locke, L. N., and N. J. Thomas (1996). Lead poisoning of waterfowl and raptors. In Noninfectious Diseases of Wildlife, second edition (A. Fairbrother, L. N. Locke, and G. L. Huff, Editors). Iowa State University Press, Ames, IA, USA. pp. 108–117.

Loss, S. R., T. Will, S. S. Loss, and P. P. Marra (2014). Bird–building collisions in the United States: Estimates of annual mortality and species vulnerability. The Condor 116:8–23.

Loss, S. R., T. Will, and P. P. Marra (2013). The impact of free-ranging domestic cats on wildlife of the United States. Nature Communications 4:article 1396.

Mao, J. S., J. Cao, and T. E. Graedel (2009). Losses to the environment from the multilevel cycle of anthropogenic lead. Environmental Pollution 157:2670–2677.

Marn, C. M., R. E. Mirachi, and M. E. Lisano (1988). Effects of diet and cold weather on captive female Mourning Doves dosed with lead shot. Archives of Environmental Contamination and Toxicology 17:589–594.

Martina, P. A., D. Campbell, K. Hughes, and T. McDaniel (2008). Lead in the tissues of terrestrial raptors in southern Ontario, Canada, 1995–2001. Science of the Total Environment 391: 96–103.

Mateo, R. (2009). Lead poisoning in wild birds in Europe and the regulations adopted by different countries. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 71–98.

Mateo-Tomás, P., and P. P. Olea (2010). Anticipating knowledge to inform species management: Predicting spatially explicit habitat suitability of a colonial vulture spreading its range. PLoS ONE 5(8):e12374.

McBride, T. J., J. P. Smith, H. P. Gross, and M. J. Hooper (2004). Blood-lead and ALAD activity levels of Cooper's Hawks (*Accipiter cooperii*) migrating through the southern Rocky Mountains. Journal of Raptor Research 38:118–124.

Meretsky, V. J., N. F. R. Snyder, S. R. Beissinger, D. A. Clendenen, and J. W. Wiley (2000). Demography of the California Condor: Implications for reestablishment. Conservation Biology 14: 957–967.

Mertz, D. B. (1971). The mathematical demography of the California Condor population. American Naturalist 105:437–453.

Müller, Y. M. R., L. B. D. Rivero, M. C. Carvalho, K. Kobus, M. Farina, and E. M. Nazari (2008). Behavioral impairments related to lead-induced developmental neurotoxicity in chicks. Archives of Toxicology 82:445–451.

Newth, J. L., R. L. Cromie, M. J. Brown, R. J. Delahay, A. A. Meharg, C. Deacon, G. J. Norton, M. F. O'Brien, and D. J. Pain (2012). Poisoning from lead gunshot: Still a threat to wild waterbirds in Britain. European Journal of Wildlife Research 59:195–204.

Nriagu, J. O. (Editor) (1978). The Biogeochemistry of Lead in the Environment, part B: Biological Effects. Elsevier/North Holland Biomedical Press, Amsterdam, The Netherlands.

Ohlendorf, H. M., and G. H. Heinz (2011). Selenium in birds. In Environmental Contaminants in Biota: Interpreting Tissue Concentrations, second edition (W. N. Beyer and J. P. Meador, Editors). CRC Press, Boca Raton, FL, USA. pp. 669–701.

Pain, D. J. (1991). Lead shot densities and settlement rates in Camargue marshes, France. Biological Conservation 57:273–286.

Pain, D. J., I. J. Fisher, and V. G. Thomas (2009). A global update of lead poisoning in terrestrial birds from ammunition sources. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 99–118.

Pattee, O. H., J. W. Carpenter, S. H. Fritts, B. A. Rattner, S. N. Wiemeyer, J. A. Royle, and M. R. Smith (2006). Lead poisoning in captive Andean Condors (*Vultur gryphus*). Journal of Wildlife Diseases 42:772–779.

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

Pokras, M. A., and R. Chafel (1992). Lead toxicosis from ingested fishing sinkers in adult Common Loons (*Gavia immer*) in New England. Journal of Zoo and Wildlife Medicine 23:92–97.

Pokras, M. A., M. R. Kneeland, A. Major, R. Miconi, and R. H. Poppenga (2009). Lead objects ingested by Common Loons in New England. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 283–287.

Potts, G. R. (2005). Incidence of ingested lead gunshot in wild Grey Partridges (*Perdix perdix*) from the UK. European Journal of Wildlife Research 51:31–34.

Radomski, P., T. Heinrich, T. S. Jones, P. Rivers, and P. Talmage (2006). Estimates of tackle loss for five Minnesota walleye fisheries. North American Journal of Fisheries Management 26:206–212.

Rattner, B. A., J. C. Franson, S. R. Sheffield, C. I. Goddard, N. J. Leonard, D. Stang, and P. J. Wingate (2008). Sources and implications of lead ammunition and fishing tackle on natural resources. Technical Review 08-01. The Wildlife Society and American Fisheries Society, Bethesda, MD, USA.

Redig, P. T., E. M. Lawler, S. Schwartz, J. L. Dunnette, B. Stephenson, and G. E. Duke (1991). Effects of chronic exposure to sublethal concentrations of lead acetate on heme synthesis and immune function in Red-tailed Hawks.

Archives of Environmental Contamination and Toxicology 21: 72–77.

Reeve, A. F., and T. C. Vosburgh (2005). Recreational shooting of prairie dogs. In Conservation of the Black-tailed Prairie Dog (J. L. Hoogland, Editor). Island Press, Washington, DC, USA. pp. 139–156.

Rideout, B. A., I. Stalis, R. Papendick, A. Pessier, B. Puschner, M. E. Finkelstein, D. R. Smith, M. Johnson, M. Mace, R. Stroud, J. Brandt, J. Burnett, et al. (2012). Patterns of mortality in free-ranging California Condors (*Gymnogyps californianus*). Journal of Wildlife Diseases 48:95–112.

Riley, T. Z., and J. H. Schulz (2001). Predation and Ring-necked Pheasant population dynamics. Wildlife Society Bulletin 29: 33–38.

Ross-Winslow, D. J., and T. L. Teel (2011). The quest to eliminate lead from units of the National Park System: Understanding and reaching out to audiences. The George Wright Forum 28: 34–77.

Ruxton, G. D., and D. C. Houston (2004). Obligate vertebrate scavengers must be large soaring fliers. Journal of Theoretical Biology 228:431–436.

Saito, K. (2009). Lead poisoning of Steller's Sea-Eagle (*Haliaeetus pelagicus*) and White-tailed Eagle (*Haliaeetus albicilla*) caused by the ingestion of lead bullets and slugs, in Hokkaido Japan. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 302–309.

Samuel, M. D., and E. F. Bowers (2000). Lead exposure in American Black Ducks after implementation of non-toxic shot. Journal of Wildlife Management 64:947–953.

Sanders, T., Y. Liu, V. Buchner, and P. B. Tchounwou (2009). Neurotoxic effects and biomarkers of lead exposure: A review. Reviews on Environmental Health 24:15–45.

Sanderson, G. C., and F. C. Bellrose (1986). A review of the problem of lead poisoning in waterfowl. Special Publication 4. Illinois Natural History Survey, Champaign, IL, USA.

Scheuhammer, A. M., D. E. Bond, N. M. Burgess, and J. Rodriguez (2003). Lead and stable lead isotope ratios in soil, earthworms, and bones of American Woodcock (*Scolopax minor*) from eastern Canada. Environmental Toxicology and Chemistry 22:2585–2591.

Scheuhammer, A. M., and S. L. Norris (1995). A review of the environmental impacts of lead shotshell ammunition and lead fishing weights in Canada. Occasional Paper 88. of the Canadian Wildlife Service, Ottawa, Ontario.

Scheuhammer, A. M., C. A. Rogers, and D. Bond (1999). Elevated lead exposure in American Woodcock (*Scolopax minor*) in eastern Canada. Archives of Environmental Contamination and Toxicology 36:334–340.

Scheuhammer, A. M., and D. M. Templeton (1998). Use of stable isotope ratios to distinguish sources of lead exposure in wild birds. Ecotoxicology 7:37–42.

Schmutz, J. K., K. A. Rose, and R. G. Johnson (1989). Hazards to raptors from strychnine poisoned ground squirrels. Journal of Raptor Research 23:147–151.

Schroeder, S. A., D. C. Fulton, W. Penning, and K. Doncarlos (2012). Using persuasive messages to encourage hunters to support regulation of lead shot. Journal of Wildlife Management 76:1528–1539.

Schulz, J. H., J. Fleming, and S. Gao (2012). 2011 Mourning Dove harvest monitoring program annual report. Missouri Department of Conservation, Resource Science Division, Columbia, MO, USA.

Schulz, J. H., X. Gao, J. J. Millspaugh, and A. J. Bermudez (2007). Experimental lead pellet ingestion in Mourning Doves (*Zenaida macroura*). American Midland Naturalist 158:177–190.

Schulz, J. H., J. J. Millspaugh, A. J. Bermudez, X. Gao, T. W. Bonnot, L. G. Britt, and M. Paine (2006). Acute lead toxicosis in Mourning Doves. Journal of Wildlife Management 70:413–421.

Schulz, J. H., J. J. Millspaugh, B. E. Washburn, G. R. Wester, J. T. Lanigan III, and J. C. Franson (2002). Spent-shot availability and ingestion on areas managed for Mourning Doves. Wildlife Society Bulletin 30:112–120.

Schulz, J. H., J. J. Millspaugh, D. T. Zekor, and B. E. Washburn (2003). Enhancing sport hunting opportunities for urbanites. Wildlife Society Bulletin 31:565–573.

Seamans, M. E., R. D. Rau, and T. A. Sanders (2012). Mourning Dove population status, 2012. U.S. Department of the Interior, Fish and Wildlife Service, Division of Migratory Bird Management, Washington, DC, USA.

Sears, J. (1988). Regional and seasonal variations in lead poisoning in the Mute Swan *Cygnus olor* in relation to the distribution of lead and lead weights, in the Thames area, England. Biological Conservation 46:115–134.

Sieg, R., K. A. Sullivan, and C. N. Parish (2009). Voluntary lead reduction efforts within the northern Arizona range of the California Condor. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 341–349.

Simons, T. (1993). Lead–calcium interactions in cellular lead toxicity. Neurotoxicology 14:77–85.

Smith, M. C., M. A. Davison, C. M. Schexnider, L. Wilson, J. Bohannon, J. M. Grassley, D. K. Kraege, W. S. Boyd, B. D. Smith, M. Jordan, and C. Grue (2009). Lead shot poisoning in swans: Sources of pellets within Whatcom County, WA, USA, and Sumas Prairie, BC, Canada. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 274–277.

Snyder, N. F. R., and H. A. Snyder (1989). Biology and conservation of the California Condor. Current Ornithology 6:175–267.

Snyder, N. [F. R.], and H. [A.] Snyder (2000). The California Condor: A Saga of Natural History and Conservation. Academic Press, San Diego, CA, USA.

Southwest Condor Review Team (2012). A review of the third five years of the California Condor Reintroduction Program in the Southwest (2007–2011). Prepared for the USFWS Arizona Ecological Services Office, Phoenix, AZ, USA.

Stauber, E., N. Finch, P. A. Talcott, and J. M. Gay (2010). Lead poisoning of bald (*Haliaeetus leucocephalus*) and golden (*Aquila chrysaetos*) eagles in the U.S. inland Pacific Northwest region—An 18-year retrospective study: 1991–2008. Journal of Avian Medicine and Surgery 24:279–287.

Stendell, R. C. (1980). Dietary exposure of kestrels to lead. Journal of Wildlife Management 44:527–530.

Stevenson, A. L., A. M. Scheuhammer, and H. M. Chan (2005). Effects of nontoxic shot regulations on lead accumulation in ducks and American Woodcock in Canada. Archives of Environmental Contamination and Toxicology 48:405–413.

Strom, S. M., J. A. Langenberg, N. K. Businga, and J. K. Batten (2009). Lead exposure in Wisconsin birds. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 194–201.

Sullivan, K., R. Sieg, and C. N. Parish (2007). Arizona's efforts to reduce lead exposure in California Condors. In California Condors in the 21st Century (A. Mee and L. S. Hall, Editors). Nuttall Ornithological Club, Cambridge, MA, and American Ornithologists' Union, Washington, DC, USA. pp. 109–121.

Thomas, C. M., J. G. Mensik, and C. L. Feldheim (2001). Effects of tillage on lead shot distribution in wetland sediments. Journal of Wildlife Management 65:40–46.

Thomas, V. G. (2009). The policy and legislative dimensions of nontoxic shot and bullet use in North America. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 351–362.

Thomas, V. G. (2011). Conflicts in lead ammunition and sinker regulation: Considerations for U.S. National Parks. The George Wright Forum 28:24–33.

Thomas, V. G. (2013). Lead-free hunting rifle ammunition: Product availability, price, effectiveness, and role in global wildlife conservation. AMBIO 42:737–745.

Tranel, M. A., and R. O. Kimmel (2009). Impacts of lead ammunition on wildlife, the environment, and human health—a literature review and implications for Minnesota. In Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans (R. T. Watson, M. Fuller, M. Pokras, and W. G. Hunt, Editors). The Peregrine Fund, Boise, ID, USA. pp. 318–337.

Trinogga, A., G. Fritsch, H. Hofer, and O. Krone (2012). Are lead-free hunting rifle bullets as effective at killing wildlife as conventional lead bullets? A comparison based on wound size and morphology. Science of the Total Environment 443: 226–232.

United Nations Environment Programme (2011). Literature review: Effects of the use of lead fishing weights on waterbirds and wetlands. UNEP Agreement on the Conservation of African-Eurasian Migratory Waterbirds. UNEP/AEWA/StCInf.7.6.

U.S. Fish and Wildlife Service (1976). Final environmental statement: Proposed use of steel shot for hunting waterfowl in the United States. U.S. Department of Interior, Fish and Wildlife Service, Washington, DC, USA.

U.S. Fish and Wildlife Service (1986). Use of lead shot for hunting migratory birds in the United States. Final supplemental environmental impact statement. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC, USA

U.S. Fish and Wildlife Service (1988). Appendix 13: A synopsis of the nontoxic shot issue. In Final supplemental environmental impact statement: Issuance of annual regulations permitting the sport hunting of migratory birds (SEISS 88). U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC, USA. pp. 317–319.

U.S. Geological Survey (2013). Mineral industry surveys: Lead in January 2013. http://minerals.usgs.gov/minerals/pubs/commodity/lead/mis-201301-lead.pdf

Ventana Wildlife Society (2012). First-year results of a free non-lead ammunition program to assist California Condor recovery in Central California. Ventana Wildlife Society, Salinas, CA, USA.

Vogel, H. (2013). Effects of lead fishing tackle on loons in New Hampshire, 1989–2011. http://www.loon.org/ingested-lead-tackle.php

Vyas, N. B., J. W. Spann, and G. H. Heinz (2001). Lead shot toxicity to passerines. Environmental Pollution 111:135–138.

Walker, G. B. (2007). Public participation as participatory communication in environmental policy decision-making: From concepts to structured conversations. Environmental Communication 1:99–110.

Walker, G. B., S. L. Senecah, and S. E. Daniels (2006). From the forest to the river: Citizens' views of stakeholder engagement. Human Ecology Review 13:193–202.

Walters, J. R., S. R. Derrickson, D. M. Fry, S. M. Haig, J. M. Marzluff, and J. M. Wunderle, Jr. (2010). Status of the California Condor and efforts to achieve its recovery. The Auk 127:969–1001.

Watson, R. T., M. Fuller, M. Pokras, and W. G. Hunt (Editors) (2009). Ingestion of Lead from Spent Ammunition: Implications for Wildlife and Humans. The Peregrine Fund, Boise, ID, USA.

Wayland, M., and T. Bollinger (1999). Lead exposure and poisoning in Bald Eagles and Golden Eagles in the Canadian prairie provinces. Environmental Pollution 104:341–350.