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MINI REVIEW

The ecotoxicology of lead shot and lead fishing weights

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Lead shot ingestion is the primary source of elevated lead exposure and poisoning in waterfowl and most other bird species. For some species (e.g. Common Loons, *Gavia immer*), lead sinker ingestion is a more frequent cause of lead poisoning. In freshwater environments where recreational angling activity and loon populations co-occur, lead poisoning from ingestion of small (<50 gram) lead sinkers or jigs accounts for 10–50% of recorded adult loon mortality, depending on the locations studied. Lead shot ingestion occurs in waterfowl, and in a wide variety of non-waterfowl species, including upland game birds, shorebirds, raptors, and scavengers. Where it has been explicitly studied in Canada and the US, lead poisoning mortality of bald (*Haliacetus leucocephalus*) and golden eagles (*Aquila chrysactos*) from eating prey animals with lead shot embedded in their tissues accounts for an estimated 10–15% of the recorded post-fledging mortality in these raptorial species. In addition to environments that experience hunting with lead shot, clay target shooting ranges, especially those in which the shotfall zones include ponds, marshes, lakes, rivers, beaches, or other aquatic-type environments, create a significant risk of shot ingestion and poisoning for waterbirds. Metallic lead pellets deposited onto soils and aquatic sediments are not chemically or environmentally inert, although tens or hundreds of years may be required for total breakdown and dissolution of pellets. Functional, affordable non-toxic alternatives to lead shot and sinkers are being currently produced, and additional such products are being developed. Several countries have successfully banned the use of small lead sinkers, and of lead shot for waterfowl and other hunting, also for clay target shooting, using a phasing-out process that gives manufacturers, sellers, and users adequate time to adjust to the regulations.

Keywords: lead shot; lead sinkers; lead poisoning; birds; toxicity; environmental fate.

Introduction

Lead (Pb) is a soft, bluish, metallic element found naturally in all environmental media. It has been mined and used in society for many hundreds of years. Pb's low melting point, malleability, ease of processing, and low cost have resulted in its use in a wide range of products, including Pb shotshell (and other) ammunition, and Pb fishing weights

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(sinkers and jigs). However, due to Pb's relatively high intrinsic toxicity, and the continual refinement of the science of Pb toxicology, which has resulted in the recognition of adverse effects of Pb at lower and lower levels of exposure, many of the traditional uses of Pb have been phased out in recent decades. Its uses in solder, plumbing pipes, paints, pottery glazes, crystal ware, and gasoline have been banned or severely reduced.

World production of Pb metal is about 4–6 million tonnes annually (OECD, 1993). Battery and pigment manufacturing together account for about 76% of the current world production of Pb. The manufacture of Pb shot and sinkers represents a relatively minor use of Pb (<1% of world Pb production).

The ingestion of Pb shot by waterfowl and other avian species, and the toxic effects of this ingestion, have been extensively studied and reviewed (e.g. Bellrose, 1959; Mudge, 1983; Sanderson and Bellrose, 1986; USFWS, 1986; Pain, 1992). Here, we briefly review the major toxic effects of Pb in birds from shot or sinker ingestion; the environmental chemistry and fate of metallic Pb pellets in the environment; and the approaches taken by different nations to deal with the problems caused by Pb shot and sinker use.

Lead shot ingestion

It has been known since the late 1800s (Grinell, 1894; Hough, 1894) that waterfowl ingest spent Pb shotgun pellets that have been deposited on the bottoms of lakes and marshes, mistaking these pellets for food items or grit. These Pb pellets often become lodged in the gizzard where ionic Pb is released due to the grinding action of the gizzard combined with its acidic environment. Acute or chronic Pb poisoning can result. If there has been ingestion of a large number (≥10) of shot, acute Pb poisoning rapidly ensues, and birds usually die within a few days. Victims of acute poisoning can appear to be in good condition, without pronounced weight loss. More commonly, birds die of chronic Pb poisoning following ingestion of a smaller number of shot pellets. In these instances, signs of Pb poisoning (distention of the proventriculus, green watery faeces, drooping wings, anaemia, weight loss) appear gradually, and affected birds die approximately 2–3 weeks post ingestion, often in a very emaciated condition (Sanderson and Bellrose, 1986; USFWS, 1986). In addition, many sublethally-exposed birds probably die even though mortality cannot be attributed directly to Pb poisoning. Pb exerts sublethal toxic effects on many tissues, primarily the central and peripheral nervous systems, the kidneys, and the circulatory/haematopoietic systems (Scheuhammer, 1987). The lesions caused in these tissues by Pb exposure result in biochemical, physiological, and behavioural impairments. These impairments contribute to an increased risk of starvation, predation, and disease in affected birds. Sublethal exposure to Pb results in an impaired ability to cope with other potential sources of mortality.

Pb shot ingestion by waterfowl has been documented in many countries including Australia (Kingsford *et al.*, 1989), Britain (Mudge, 1983), Canada (Kennedy and Nadeau, 1993; Scheuhammer and Norris, 1995), France (Pain, 1990), Spain (Guitart *et al.*, 1994), the Netherlands (Lumeij and Scholten, 1989), Japan (Honda *et al.*, 1990; Ochiai *et al.*, 1993), and the US (Sanderson and Bellrose, 1986; USFWS, 1986). Pb shot ingestion has been judged to be the primary source of elevated Pb exposure and Pb poisoning in waterfowl (Sanderson and Bellrose, 1986; Scheuhammer and Dickson, 1996). Before US restrictions on the use of Pb shot for waterfowl hunting, it was estimated that 2–3% of the continental waterfowl 'population', or about 1–3 million North American ducks and geese died yearly of Pb poisoning from shot ingestion (USFWS, 1986). Blus (1994) has reviewed Pb poisoning in swans, and found that at least 10 000 swans of six species from 14 countries have been reported to have died of Pb poisoning, most from ingestion of Pb shot or fishing weights. This was considered to be a gross underestimate of actual mortality because, in many areas, no research or monitoring activity relevant to this issue has taken place.

In addition to waterfowl, a risk for shot ingestion by a wide variety of other avian species exists wherever shot density in the environment is high, and environmental conditions are such that shot are available to be ingested. Areas of intensive upland shooting, such as for doves in the US, can result in shot ingestion and poisoning in these species. Shot ingestion or high tissue-Pb concentrations in mourning doves (*Zenaida macroura*) have ranged from 1.0–6.5% of birds sampled in Tennessee, Maryland, and New Mexico (Best *et al.*, 1992; Lewis and Legler, 1968; Locke and Bagley, 1967). Hall and Fisher (1985) observed that Texas marshbird species that typically probe sediments for food and grit were at particularly high risk for shot ingestion; 19% of a combined sample of black-necked stilt (*Himantopus mexicanus*), white-faced ibis (*Plegadis chihi*), and long-billed dowitcher (*Limnodromus scolopaceus*) gizzards contained Pb shot, whereas no sandpipers, terns, or herons had evidence of ingested shot. In Canada, Kaiser *et al.* (1980) reported that 9% of 54 dunlin (*Calidris alpina*), collected after colliding with electric power wires, contained 1–5 ingested Pb shot each. As reported by Hunter and Haigh (1978), domestic fowl have also died of Pb poisoning from shot ingestion. Flamingoes have suffered Pb poisoning from shot ingestion in Mexico (Schmitz *et al.*, 1990). Other examples of primary ingestion and/or Pb poisoning in non-waterfowl, summarized in USFWS (1986) and in Locke and Friend (1992), include various upland game bird, marshland, and shore bird species. They concluded that 'lead poisoning has been documented in a sufficiently wide variety of birds to consider all birds as being susceptible to intoxication after ingesting and retaining lead shot'.

A related problem is the 'secondary' poisoning of raptorial birds that feed on animals with Pb shot embedded in their tissues. Secondary Pb shot poisoning has now been documented in many locations in Europe and North America, in various raptorial species (Pain *et al.*, 1994; Pain *et al.*, 1993; Pain and Amiard-Triquet, 1993; Scheuhammer and Norris, 1995; USFWS, 1986). A case of Pb poisoning in a wild peregrine falcon (*Falco peregrinus*) has also been reported (Pain *et al.*, 1994), and captive falcons have died following the ingestion of Pb shot pellets in the tissues of hunter-killed game presented to the birds as food (MacDonald *et al.*, 1983). Many free-living raptorial species for which secondary poisoning has not yet been documented nevertheless risk this type of poisoning as a direct consequence of their preferred feeding habits.

The main source of Pb shot exposure in cases of secondary poisoning is embedded or ingested shot carried by waterfowl and other game animals. For waterfowl, numerous studies have been undertaken to estimate the frequency of embedded shot. Table 1 summarizes the results of these studies. For many species of waterfowl, sampled in many different locations, it is common for 20–30% of apparently healthy individuals to be carrying one or more shot pellets. Even a portion (15%) of a 'non-hunted'

Table 1. Frequency of embedded shot in free-living waterfowl

Country	Species	Frequency	Reference
Canada (Maritimes)	Black Duck	12–18%	CWS unpublished data
	Canada Goose	32%	
	Common Eider	20–35%	
Canada	Small Canada Goose	⩾25%	MacInnes *et al.*, 1974
Canada	Lesser Snow Goose	28%	Ankney, 1975
Canada	Mallard	28%	Elder, 1950
United States	Canada Goose	42%	Funk, 1951
	Mallard	13%	
	Pintail	13%	
United States	Redhead	15%	Perry and Geissler, 1980
	Lesser Scaup	10%	
	Ring-necked Duck	21%	
	Canvasback	29%	
United States	Atlantic Brant	20%	Kirby *et al.*, 1983
United States	Mallard	27%	Murdy, 1952
Netherlands	Mallard	22–68%	Lumeij and Scholten, 1989

population of trumpeter swans (*Cygnus buccinator*) has been reported to carry embedded shot (Banko, 1960). These findings indicate that literally millions of free-flying waterfowl, in addition to the millions killed or crippled with Pb shot, carry embedded shot and are a potential source of Pb poisoning in raptorial predators and scavengers. Although few studies have examined the frequency of embedded shot in non-waterfowl species, the frequency is probably high in some other species of heavily hunted game animals. Elder (1955) reported an embedded shot incidence of 27% in male ring-necked pheasants. In the New England states, about 30% of common loon carcasses examined to date carried embedded Pb shot, although gunshot was responsible for <10% of deaths (M. Pokras, personal communication, 1995).

The phenomenon of embedded shot is not restricted to birds. Although most evidence indicates that waterfowl are the most likely source of Pb shot ingestion in bald eagles, Platt (1976) reported that a population of eagles wintering in a Utah desert ingested shot by feeding heavily on hunter-killed jackrabbits (*Lepus californicus*). Hunter-killed jackrabbits may be a major source of Pb for bald eagles in the US Great Plains, Black Hills, and the High Plains of Texas (USFWS, 1986). Embedded shot in small game mammals is thus an additional source of Pb ingestion in raptors and scavengers.

Lead poisoning at clay target shooting ranges

Significant quantities of Pb shot are deposited at clay target shooting ranges. Loadings at large individual ranges can be 10–30 tonnes per year (Ordija, 1993). Shotfall areas of shooting ranges may include dryland fields, ravines, creeks, rivers, mudflats, marshes, ponds, and lakes. Spent shot generally remain within the upper 10 cm of soils, and are therefore available for ingestion by waterfowl and other birds at these sites. Ranges located over or near wetland environments pose a considerable risk to waterfowl and other waterbirds. Clay target shooting under such environmental circumstances results in a very high local rate of pellet deposition. Under these conditions, the risk of ingestion and poisoning are similar to, or even greater than, those caused by wetland hunting. Roscoe *et al.* (1989) reported poisoning of northern pintail ducks (*Anas acuta*) that ingested Pb shot from a tidal meadow within the shotfall zone of a trap and skeet club, now defunct, in New Jersey. The top 7.5 cm of affected sediments contained over 87 million pellets per acre, which was over 4 000 times the shot density recorded near hunting blinds in the same area.

The issue of establishing environmental guidelines and regulations governing the use of lead shot at gunclubs is in its infancy. In the US, approximately 12 clay target shooting ranges, at least six of which were located in wetland areas, have been either closed indefinitely or required to use non-toxic shot products by local or state governments (SAAMI, 1993; Yurdin, 1993; Ordija, 1993; Morehouse, 1992). Denmark banned target shooting over shallow water in 1981, and several trap ranges were closed as a consequence (Clausen, 1992). The Netherlands, Sweden and Norway are currently working with their respective sport shooting associations to phase out the use of lead shot for target shooting. The United States Sporting Arms and Ammunition Manufacturers (SAAMI) believes that the deposition of lead shot on outdoor shooting ranges should be controlled by more vigilant maintenance of ranges, soil and water management and periodic lead recovery (SAAMI, 1993). In the US, about 15 companies have equipment for recovering lead shot from soil, but this equipment is designed for operation on relatively flat, dry surfaces, and there is no known practical method for recovering lead shot from forested, hilly, or marshy areas. Recovery and recycling of lead from target shooting ranges is encouraged by the USEPA and the National Rifle Association (NRA) (Sever, 1993), and can actually be a source of profit for the range.

Gun clubs which do not shoot over or near water or wetland environments, and have an active programme to recover lead, are least likely to be at risk for environmental impacts. National or provincial/state site-specific environmental criteria for lead in range soils and surface waters, and regulations requiring ranges to monitor and properly maintain their shooting areas, have not been established in most countries. Such criteria are needed to ensure that lead shot deposition is isolated, is not resulting in off-site lead contamination or shot ingestion by waterbirds, that lead from waste shot is periodically recovered, and that ranges are established only on sites where deposited lead shot is capable of recovery.

Effects of lead shot ingestion in cattle

Lead poisoning from ingestion of Pb shot is primarily an avian phenomenon, mainly due to the peculiarities of the avian gizzard, an anatomical structure not shared with mammals. However, Pb poisoning from shot ingestion has been reported in ungulate mammals – in particular, cattle. It was once believed that ingestion of metallic Pb pellets did not pose a significant risk to domestic cattle, based on the failure of Allcroft (1951) to observe evidence of Pb poisoning in calves fed metallic Pb. Also, Bjorn *et al.* (1982) did not observe elevated blood-Pb concentrations of heifers grazing in pastures where upland bird hunting was common; and Clausen *et al.* (1981) reported that cattle retaining up to 100 Pb pellets in the reticulum nevertheless had normal Pb concentrations in liver and kidney tissue. Other studies, however, indicate that dairy cattle fed grass or corn silage contaminated by Pb shot can suffer from Pb poisoning (Howard and Braum, 1980;

Frape and Pringle, 1984; Rice *et al.*, 1987). Rice *et al.* (1987) reported that in 14 steers fed chopped silage prepared from a field that had been used for clay target shooting, one animal died, a second demonstrated clinical signs of Pb poisoning, and all animals had substantially inhibited δ-aminolevulinic acid dehydratase (ALA-d) enzyme activity (a sensitive biomarker of elevated Pb exposure). It was further noted that, even when Pb pellets were removed, samples of silage still contained an average of 0.23% Pb, which would have resulted in the ingestion of about 18 grams of Pb per steer per day, based on the consumption of about 8 kg of silage per animal. Rice *et al.* (1987) suggested that this concentration of Pb would have been sufficient to cause toxicity, independent of ingestion of any Pb shot pellets. The mechanical/chemical process of producing silage from material containing Pb pellets may be a more important risk factor than ingestion of Pb shot pellets *per se.*

Lead sinker ingestion

A second important source of Pb exposure and poisoning for some wild bird species is the ingestion of lost Pb fishing weights (sinkers and jigs). 'Sinkers' are weights of various sizes and shapes used to sink a fishing line below the surface of the water; 'jigs' are weighted hooks, often brightly painted or otherwise decorated, used as lures in angling.

Because sinkers and jigs are generally much larger than shot pellets, a single Pb sinker may induce acute Pb poisoning. In North America, Pb poisoning from sinker ingestion has been documented in common loons; trumpeter, tundra, and mute swans; and sandhill cranes (USEPA, 1994). Many other species of waterbird have feeding habits similar to those in which sinker ingestion has been documented (e.g. diving ducks, grebes, herons, osprey, bald eagles). These species are therefore also at risk for Pb poisoning from sinker ingestion.

The ingestion and toxicity of Pb sinkers in swans in Great Britain, and in common loons and other waterbirds in the US, has been extensively documented and reviewed (Nature Conservancy Council, 1981; Birkhead, 1982; O'Halloran *et al.*, 1988; Pokras and Chafel, 1992; USEPA, 1994). These findings have resulted in the banning of small Pb sinkers in Britain; the banning of Pb sinkers in some national parks in the US; a proposal by the USEPA to nationally prohibit the manufacture, processing, and commercial distribution of Pb sinkers of a size range known to be ingested by waterbirds; and a proposal by the USFWS to ban the use of Pb sinkers and jigs on 40 units of the US National Wildlife Refuge system. In Britain, the mute swan (*Cygnus olor*) population had declined since the 1960s, a trend that has dramatically reversed since 1986/87 when the sale of small Pb fishing weights was banned (Kirby *et al.*, 1994). Other countries have not, to our knowledge, proposed restrictions on the sale or use of Pb sinkers.

Results from Canada have documented significant mortality of common loons and other birds from sinker ingestion. We found unpublished data from Ontario, Quebec, and the Maritime provinces of Canada demonstrating that Pb sinker or jig ingestion accounts for roughly 30% (38 of 127 birds examined) of adult loon mortality in locations where loon habitat and sport angling overlap (Scheuhammer and Norris, 1995). These data are consistent with US research by Pokras *et al.* (1992), which has demonstrated that over 50% of adult common loon mortality in the New England states is attributable to Pb sinker or jig ingestion, and that this source of mortality is of greater importance than any other single mortality factor including tumours, trauma, fractures, gunshot wounds, and infections. The importance of sinker ingestion as a mortality factor is less important, but still significant, in some other locations in the US (e.g. 17% of total mortality in Minnesota; Ensor *et al.*, 1992).

Analyses at Canadian Wildlife Service's National Wildlife Research Centre (Hull, Quebec) have confirmed a direct link between sinker ingestion and loon mortality from Pb poisoning. Of 28 individual common loons for which we have completed Pb analysis, only those loons with confirmed evidence of Pb sinker or jig ingestion (six) have high (>15 ppm dry wt) liver-Pb concentrations (Scheuhammer, unpubl. data). Evidence gathered to date indicates that sinker/jig ingestion is the only significant source of elevated Pb exposure, and of Pb toxicity, for common loons. In Ontario, about four fifths of the Pb poisoning deaths in loons is from ingestion of Pb sinkers, and one fifth is from ingestion of Pb-headed jigs.

Pb poisoning from sinker ingestion has also been documented in numerous other species of waterbird in the US, including trumpeter, tundra, and mute swans; various duck species; and sandhill cranes (*Grus canadensis*) (USEPA, 1994). In Canada, documented sinker ingestion has occurred in Canada geese, several duck species, and a bald eagle, in addition to common loons (Scheuhammer and Norris, 1995). In principle, any species of bird that has feeding habits similar to that of loons, or of other species confirmed to have ingested sinkers or jigs, are also at risk of Pb poisoning from this source.

Environmental chemistry and fate of metallic lead

What happens to Pb shot pellets and sinkers deposited into the environment, if they are not ingested by waterfowl or other birds? It has often been assumed that Pb from spent shot (or sinkers) is environmentally stable or 'inert', and thus not worthy of consideration as a source of environmental Pb contamination and foodchain transfer, except as relates to the direct ingestion of pellets by animals. However, there is now sufficient evidence to conclude that, ultimately, all of the metallic Pb in shot and sinkers will be transformed into particulate and molecular Pb species, and will be dispersed through the environment to some degree. This process can result in local Pb concentrations in soils and water far in excess of normal concentrations.

When metallic Pb in the form of spent shot (or sinkers) is exposed to air or water, Pb oxides, carbonates and other compounds are produced by weathering of the pellets (Sever, 1993). Analyses of spent shot pellets collected from target shooting ranges in Canada and Denmark have shown pellets to be visibly corroded and covered with a crust of white, grey or brown material (Jorgensen and Willems, 1987; Emerson, 1994). These crusts are composed of various Pb compounds, predominantly cerussite ($PbCO_3$), hydrocerussite ($Pb(CO_3)_2(OH)_2$), and small amounts of anglesite ($PbSO_4$). Pellets from all soil samples over a wide range of pH (3.5–8.1) contained crust material; however, older pellets (Emerson, 1994), and pellets from acidic soils ($pH < 6.0$), had larger quantities of material, reflecting a more advanced state of shot breakdown.

For an uncultivated grassland with soil pH 5.5, Jorgensen and Willems (1987) calculated that half of a lead pellet's metallic lead content would be transformed into lead compounds within 54–63 years, and that total pellet transformation would occur in about 100–300 years. Under circumstances of intensive mechanical treatment, such as cultivation of the soils, these time periods may be shortened to 15–17 and 29–82 years respectively. Similar breakdown of lead shot pellets has also been reported in Finland (Tanskanen *et al.*, 1991). Fisher *et al.* (1986) also reported significant breakdown of buried lead shot. Shot pellets buried for about 20 years at the Anahuac National Wildlife Refuge on the Gulf Coast of Texas displayed highly eroded surfaces, and were much smaller than would have been expected, knowing the typical size of pellets used for waterfowl hunting.

Very few studies have examined the concentrations of Pb in biota in sites that have experienced high deposition of Pb shot. In an investigation of a skeet target shooting range located on the shores of Lake Merced, California, sediments contained up to 1200 μg per g Pb in the shotfall zone, and tule seedheads and coontails growing within these sediments exhibited Pb concentrations averaging 10.3 μg per g and 69.2 μg per g (dw), respectively, compared with concentrations of 2.3 μg per g and 11.9 μg per g (dw), respectively, at control sites (Peterson *et al.*, 1993). We are aware of only a single study in which the effects of environmental Pb shot deposition on Pb accumulation in terrestrial mammals has been examined. In an investigation 20 years after the abandonment of a clay target shooting range in the Netherlands, Pb pellets were found to be present predominantly above a depth of 5 cm. The site was characterized by sandy acidic soils (pH 3.9 $\pm$ 0.4), with total Pb concentrations of the upper soil layer (pellets included) of 360–70,000 μg per g dw (Ma, 1989). Average tissue Pb concentrations were higher in small mammals obtained from within the shooting range than from adjacent control areas (Ma, 1989). Shrews (*Sorex araneus*) had the highest kidney, liver and femur Pb levels. Pb concentrations in kidney tissue of all shrews from the shooting range exceeded the level generally considered to be diagnostic of Pb poisoning in mammals (10 μg per g wet wt.; Osweiler *et al.*, 1978).

Restrictions on the use of lead shot

Because it is generally impractical for users of Pb shot and sinkers to recover these items after discharge into the environment, other solutions to the problem must be considered. One possibility that has been explored is to produce these Pb items with a coating of another less toxic metal, such as copper, or with plastic. In general, these options have been judged to be ineffective in controlling the toxicity of Pb because the coatings wear off or are dissolved in the highly acidic environment of the avian gizzard and stomach (USFWS, 1986). A more effective solution is to manufacture shot and sinkers from metals (or other materials) that are substantially less toxic than Pb. Much research and development has occurred, and continues to occur, to produce effective, nontoxic substitutes for Pb shot and sinkers. Several such substitutes are commercially available.

When Pb shot ingestion and poisoning of waterfowl are recognized and documented, it has been usual for wildlife managers to assume, or to hope, that the issue is a relatively minor one, and is geographically local in extent (i.e. local 'hotspots' of high ingestion and poisoning). It is usually judged that the least restrictive sort of regulation will be adequate to manage the problem. Criteria, inevitably somewhat arbitrary in nature, are established to assess where the problem is unacceptably severe. Criteria may be based on the local incidence of poisoning and/or shot ingestion as measured by gizzard surveys or other indicators of ingestion rate, and may also include considerations of hunting pressure, density and availability of shot pellets in sediments, and other local conditions. As a result, several countries have established a few local zones wherein the use of Pb shot for waterfowl hunting is prohibited. This occurred in the US in the late 1970s, in Canada in 1990/91, and in some other nations. However, further research and monitoring may identify additional sites of concern, and may uncover problems not originally predicted, such as the secondary poisoning of raptors, and the transboundary export/import of Pb poisoning through embedded and ingested shot. Furthermore, the assessment of an increasing number of potential sites of concern can overwhelm available scientific personnel. Also, the enforcement of small, local Pb shot bans is problematical if Pb shot is still widely available and legal for use in the majority of hunting situations. As a result of these considerations, a gradual evolution towards larger zones can occur, combined with a greater acceptance of alternative shot types, which in turn can lead to province- or state-wide bans on Pb for waterfowl hunting. This is currently occurring in Canada, Australia and Sweden. Ultimately, a national ban on Pb shot for waterfowl hunting (as in the US and Norway, and in Canada beginning in 1997), for all wetland hunting/shooting (as in Finland), or for all hunting (as in Denmark and the Netherlands) may be established.

The regulatory restriction of Pb shot, and its replacement with non-toxic alternatives, has been the option chosen by most nations that have recognized the risks to wildlife health from the use of Pb shot. There are significant variations, however, in the kinds of regulatory actions taken by different nations. Regulations cover a range of possible options, from restricting the use of Pb shot for waterfowl hunting in certain small local zones, to a ban on Pb shot for all hunting and target shooting. Table 2 summarizes the policies of several of the OECD nations regarding the use of Pb shot.

Steel shot

Steel shot, currrently the major alternative to Pb, is required for waterfowl hunting in the US, and is approved for use in non-toxic shot zones in Canada and other countries. Several ammunition manufacturing companies have successfully converted a significant portion of their manufacture from Pb to steel. High performance Pb cartridges are approximately the same price as some steel loads, but in general, steel shot is slightly more expensive than Pb. The market for steel and other non-Pb shot will probably continue to be marginal as long as the sale and use of Pb shot is legal.

One of the most contentious aspects surrounding the phase-out of Pb shot for hunting has been the concern that, should steel shot be the only (or the major) replacement for Pb shot, the proportion of gamebirds injured but not killed by hunters (the crippling rate) would undergo a dramatic increase. The ultimate effect might be that increased losses of birds through crippling would surpass the number of birds saved due to the elimination of Pb poisoning. There is now sufficient evidence to conclude that this is probably not the case.

There is no doubt that the ballistic properties of Pb and steel shot differ. Steel shot pellets are about 30% lighter than Pb pellets of the same diameter, and are significantly harder than Pb pellets. These basic physical differences result in less pellet deformation, denser patterning, shorter shot strings, and a lower retained velocity/energy at long ranges for steel shot, compared to Pb shot. However, the development of modern steel shotshell ammunition has evolved to the point where the perceived deficiencies of steel have been largely overcome (Brister, 1992; Coburn, 1992). Increasing the size of steel

Table 2. Actions of various OECD countries for regulating the use of lead shot (as of 1994)

Country	Current lead shot policy/actions taken
Australia	established non-toxic shot zones for waterfowl hunting; state-wide ban on lead for waterfowl in effect in South Australia; considering national ban
Canada	established non-toxic shot zones for waterfowl hunting in 6 provinces; will establish national ban for all migratory game bird hunting beginning 1997
Denmark	total ban on the use of lead shot for all hunting; ban on lead shot for target shooting over water and on agricultural lands
Finland	total ban on the use of lead shot in wetlands, beginning 1996
Mexico	established non-toxic shot zone for waterfowl hunting in State of Yucatan to protect flamingos
Netherlands	total ban on the use of lead shot for all hunting; proposing phase out of lead for clay target shooting
Norway	total ban on the use of lead shot for waterfowl hunting; Norwegian Association of Hunters has agreed to a stepwise reduction in the use of lead shot for all other hunting
Sweden	established non-toxic shot zones for wetland hunting; ban on use of lead shot in all RAMSAR sites; agreement with Swedish Sport Shooting Association to phase-out lead shot for sport shooting
United States	total ban on the use of lead shot for waterfowl hunting; phasing in further bans on use of lead shot for squirrel, pheasants, etc. in wetlands of National Wildlife Refuges
United Kingdom	established voluntary switch to non-toxic shot for all wetland hunting/shooting over 2 years, starting 1995; regulatory action may follow

Information for Table 2 is from Clausen, 1992; ANZECC. 1994; OECD, 1993, Dorgelo, 1994; Jackson, 1994, Nordic Council of Ministers, 1994; USFWS, personnal communication, 1995

pellets compensates for steel's inherently lower density. (Hunters switching to steel should use shot of at least two sizes larger than the Pb loads that they are used to) Steel shot cartridges are loaded with a greater volume of shot to ensure an effective number of pellets per cartridge. A rigid, plastic wad prevents the harder steel pellets from contacting, and possibly scoring, the gun barrel upon discharge. Increasing the propellant charge, and the use of a magnum primer ensures that retained velocity of steel shot is comparable to that of a Pb load two sizes smaller. To counteract the increased chamber pressures that result from using a greater amount of powder, slower burning propellants are used in steel shot cartridges. The tighter patterns of steel loads require the use of more open chokes.

Between 1950 and 1984, approximately 15 published shooting tests comparing the effectiveness of Pb versus steel shot were conducted in the US. The results of these tests are equivocal: three of the tests favoured Pb, two favoured steel, two reported mixed results, and eight showed no statistically significant differences in crippling between the two shot types (Morehouse, 1992b). It is now generally, although not universally, accepted that modern steel shot ammunition is effective in bagging game animals within normal shotgun range, and that crippling rates are more a function of the skill of the shooter than the type of shot (lead, steel) used.

Bismuth (and other) shot

Bismuth/tin shot is about 86% the density of Pb (compared to only about 70% for steel) and thus exhibits shot patterns and downrange velocities/retained energy similar to those of Pb (Lowry, 1993). Pure bismuth (Bi), used in the original cartridges, is brittle, causing pellets to break in the gun barrel, leading to poor patterning, and causing pellets to shatter on impact. However, the addition of approximately 3% tin, and modifications in the production process, have reduced shot brittleness, resulting in improved performance. Because bismuth/tin and Pb have similar density and softness, shotshell gauges, chamber sizes and barrel designs suitable for Pb may be used without modification with bismuth/tin cartridges.

Based on oral dosing studies showing bismuth shot to be non-toxic when ingested by waterfowl (Sanderson *et al.*, 1992), bismuth/tin shot was approved on an interim basis for use in Canadian non-toxic shot zones beginning in 1993. Similarly, conditional approval of bismuth/tin for use as a non-toxic shot was granted in the US for the latter part of the 1994–95 waterfowl hunting season (USFWS, 1994), and for Australia's Northern Territory beginning in the 1993 season (King, 1993).

Zinc is also being used to manufacture shot. It is plentiful, and has satisfactory ductility and hardness. However, it is expensive, compared with either steel or Pb, and it has relatively poor ballistic qualities due to its low density (less than steel). Nevertheless, zinc shot is apparently effective for hunting over short shooting distances. Unfortunately, zinc shot (and other forms of zinc metal) can be toxic to birds when ingested, although toxicity is lower than that of Pb (Grandy *et al.*, 1968; Reece *et al.*, 1986; Droual *et al.*, 1991; Zdziarski *et al.*, 1994).

A blend of biodegradable polymers and powdered molybdenum (Mo) results in a shot (Molyshot) which closely resembles Pb in its physical and ballistic properties (Jackson, 1994). Molyshot has a density and hardness which are very close to Pb or bismuth/tin. Initial ballistics tests of molyshot have been encouraging. We are unaware of any toxicity testing of this shot type. However, chronic oral ingestion of molecular Mo can be toxic. Adverse effects include growth retardation, anaemia, bone deformities, and interference with copper metabolism (Friberg and Lener, 1986).

A new tungsten/polymer shot is being produced using powdered tungsten in a thermoplastic polymer (made from food-grade raw materials), and can be made to have a density equal to that of Pb (Marchington, 1994). The resulting pellets are hard to the touch, yet soft enough to be crushed between the teeth like Pb. Once deformed, the pellets retain their new shapes. Tungsten/polymer is also being used to produce bullets for use in indoor ranges to overcome health concerns relating to the use of Pb ammunition. The new tungsten/polymer shot is not yet being marketed, to our knowledge, but we expect that the price would be higher than steel or bismuth shot. We expect that this form of shot would be non-toxic to birds, based on the known toxicology of tungsten (Kazantzis, 1986).

Restrictions on the use of lead sinkers/jigs

There are a number of options for managing the problems created by lead sinker and jig use. The major options include limited bans on the use of lead sinkers and jigs of a specified size range known to be ingested by waterbirds in certain geographical areas where a poisoning problem has been identified (i.e. a zoning approach); a comprehensive ban on the manufacture, sale, and/or use of lead sinkers and jigs of a size range known to be ingested by waterbirds; a ban on the manufacture, sale, and/or use of certain generic types of lead weights (e.g. splitshot); a regulation restricting the lead content of all or some types of sinker and jig; and a comprehensive ban on the manufacture, sale, and/or use of all sinkers and jigs containing a significant (e.g. >0.1%) lead content.

Zoning approaches would probably suffer from compliance problems, and would be difficult to enforce effectively, as has been the case for lead shot. Lead fishing sinkers and jigs have a long history of traditional use, they perform as well or better than the alternatives, they are widely available in a wide variety of types and sizes, and they are cheaper than alternative, non-toxic products. The USEPA (1994) has rejected a geographic zoning approach for regulating lead sinkers because at-risk habitats, in which waterbirds live and in which anglers fish, essentially include the entire US. The costs associated with an extensive research and monitoring programme to identify all local areas of concern based on documented mortality of waterbirds from sinker or jig ingestion, the cost of subsequent enforcement, and the likelihood of compliance problems, makes this option unattractive. A zoning approach may be useful, however, as part of a more comprehensive phase-out plan.

A ban on only a few types of small sinkers and jigs is unjustified because many different types of these products have been found to be ingested by waterbirds. For example, loons do not ingest only splitshot; worm weights, egg sinkers, bass casting sinkers, and small lead jigs have also been found in common loons. Restricting the lead content of sinkers has been examined and rejected by the USEPA (1994) on the basis that it may be difficult to accurately measure the lead content of sinkers, making compliance by industry burdensome, and enforcement difficult.

Countries that have taken, or are taking, regulatory action to restrict lead sinkers (Britain and the US) have focused on small sinkers known to be ingested by waterbirds. We judge that banning the sale and use of lead sinkers and jigs under 2 cm in all directions, and under 50 g in mass, would virtually eliminate the risk of lead poisoning in common loons and other fish-eating birds. Such a ban, along with a concurrent ban on lead shotshell ammunition, would greatly decrease the risk of lead poisoning for all wild bird species.

Alternative fishing sinker products

Numerous non-toxic alternative materials exist for use as fishing sinkers and jigs including: tin, bismuth, antimony, steel, brass, tungsten, terpene resin putty, and polypropylene. All of the alternative products are more expensive than lead, and each differs slightly with respect to the types of uses for which it is appropriate. Fishing sinkers are diverse in shape and weight, reflecting the different fishing methods for which they are used. Alternative non-toxic products, either alone or in combination, appear to have effectively provided substitutes for all of the current lead sinkers and jigs on the market. The majority of non-toxic sinker manufacturers are located in the US, however bismuth sinkers and jigs are manufactured in Canada, and tin sinkers are manufactured in Britain. Tungsten/polymer putty compounds, popular in Britain, are relatively expensive and are not now widely available in North America.

The USEPA (1994) has estimated that the average American sport angler would incur an additional expense of about $4.00 or less per year on non-toxic sinkers, should lead sinkers be banned.

Conclusions

Based on the well-documented toxicology of Pb in general, and on numerous field and controlled dosing studies that have explicitly investigated the ingestion and toxicity of small metallic Pb items in various bird species, there is no doubt that the currently available alternative materials are safer for the environment (and for human health) than is the continued use of Pb for shot and fishing sinkers. Hunters and anglers spend relatively little of their annual budgets on shot and sinkers. We have calculated that switching to non-toxic alternatives would, in most cases, incur a $\leq 1\%$ increase in the average waterfowl hunter's or recreational angler's annual expenditure (Scheuhammer and Norris, 1995). Because of the relatively minor cost impact on consumers, the production and sale of shot and sinkers would not likely be affected negatively by a switch to alternative materials. Adequate time should be allowed for distributors to dispose of existing inventories, and for manufacturers to convert to production of non-toxic alternatives. Public relations, education, and training (in the case of hunters switching to steel shot), are also essential aspects of the phase-out of Pb. Because the production of alternative, non-toxic products does not require the development of new technologies, a 2–4 year lead time should generally be suitable. Any decreased trade in Pb metal might be offset by an increased sale of other, substitute metals.

Recreational hunting and angling are popular activities in many countries, and many of the bird species at risk for Pb poisoning from shot or sinker ingestion are migratory. Thus, the transboundary ramifications of these issues should be seriously considered. We suggest that all countries that provide habitat for migratory birds, especially waterbirds and their predators, be actively involved in discussions for phasing out those uses of lead shotshell ammunition and lead fishing weights known to be detrimental to the health of migratory birds.

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