IMPACTS OF LEAD AMMUNITION ON WILDLIFE, THE ENVIRONMENT, AND HUMAN HEALTH – A LITERATURE REVIEW AND IMPLICATIONS FOR MINNESOTA

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ABSTRACT.—The Minnesota Department of Natural Resources (MDNR) has been investigating non-toxic shot regulations for upland small game hunting because there is considerable evidence that the use of lead ammunition impacts the health of wildlife, the environment, and humans. In 2006 MDNR established a Non-toxic Shot Advisory Committee (NSAC) to provide citizen input on restricting lead shot for small game hunting. To support the NSAC discussions, we summarized available literature regarding lead ammunition and its effects on wildlife, the environment, and human health. This literature review includes more than 500 citations on lead and non-toxic ammunition related issues worldwide and summarizes studies regarding ingestion of lead shot, bullets, and fragments by wildlife species and the impacts of lead poisoning on wildlife, the environment, and humans. We found over 130 species of animals (including upland birds, raptors, waterfowl, and reptiles) have been reported in the literature as being exposed or killed by ingesting lead shot, bullets, bullet fragments, or prey contaminated with lead ammunition. The impacts of ingested lead on wildlife included decreased survival, poor body condition, behavioral changes, and impaired reproduction. We found 15 recent studies that demonstrated the impacts of lead ammunition on human health. Studies in Canada, Greenland, and Russia linked lead shot found in game animals to higher levels of lead in people who eat those game animals, and recent evidence shows that meat far from entry wounds may contain lead fragments. Effective non-toxic alternatives to lead shot are available, and at costs comparable to lead. The results of our review demonstrate the effects of lead ammunition on wildlife, the environment, and human health and support the need for the use of non-toxic alternatives to lead ammunition.
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Key words: Hunting, lead ammunition, lead poisoning, lead shot, non-toxic shot, Pb, Minnesota.

THE MINNESOTA DEPARTMENT OF NATURAL RESOURCES (MDNR) has been investigating non-toxic shot regulations for upland small game hunting because there is considerable evidence that lead shot impacts the health of wildlife, the environment, and humans. Currently, Minnesota's non-toxic shot regulations beyond federal waterfowl regulations are for managed dove fields, which included four wildlife management areas for 2007. In May 2006, MDNR established a Non-toxic Shot Advisory Committee (NSAC) to provide citizen input on whether to restrict lead shot for upland small game hunting. The NSAC included constituents with interests in hunting, the environment, human health, and the ammunition industry. The committee unanimously agreed restrictions on the use of lead

shot were needed for hunting beyond current federal and state regulations, and that lead shot will inevitably have to be restricted for all shotgun hunting at some future time. However, opinions varied on a timetable for implementing various regulations for Minnesota (NSAC 2006). To support the NSAC discussions, we summarized available literature regarding lead ammunition and its effects on wildlife, the environment, and human health. The literature review includes more than 500 citations on lead and non-toxic ammunition-related issues worldwide (Tranel and Kimmel 2008).

IMPACTS OF LEAD AMMUNITION ON WILDLIFE

Wildlife mortality from ingestion of lead shot was first reported more than 100 years ago. In 1876, H. S. Calvert published "Pheasants Poisoned by Swallowing Shot" (Calvert 1876), and a second article about pheasants poisoned by lead shot appeared in 1882 (Holland 1882). In 1894, G. B. Grinnell published an article, entitled "Lead Poisoning," in *Forest and Stream* (Grinnell 1894). Since that time, professional journals have published literature that provides scientific evidence of lead ingestion by wildlife, lead toxicity to wildlife, and lead accumulation in wildlife and human tissues resulting from lead shot (Tranel and Kimmel 2008). The literature documents over 130 species of wildlife that have ingested lead shot, bullets, or bullet fragments (Table 1). Some wildlife species, such as raptors (e.g., hawks, eagles, and condors), are "secondarily poisoned" by consuming animals that either ate or were shot with lead ammunition.

Impacts of lead shot on wildlife include decreased survival, poor body condition, behavioral changes, and impaired reproduction. Tavecchia et al. (2001) reported decreased survival of Mallards (*Anas platyrhynchos*) from lead ingestion in France. Sileo et al. (1973) reported 25–45% reduction in body weight followed by death for Canada Geese (*Branta canadensis*) dosed with lead shot. Death as a result of poisoning from lead shot has been demonstrated for many species, including doves (Schulz et al. 2006a, Schulz et al. 2007), Mallards (Finley and Dieter 1978, Anderson and Havera 1989), and Canada Geese (Cook and Trainer 1966). Fisher et al. (2006) suggested that behavioral changes resulting from lead poisoning might influence susceptibility to predation, disease, and starvation, which increases the probability of death. Mallards experimentally dosed with lead shot had reduced immunologic cells (Rocke and Samuel 1991) and depressed antibody production (Trust et al. 1990). Experimental evidence has demonstrated impaired reproduction from lead shot ingestion in captive doves (Buerger et al. 1986) and domestic Mallards (Elder 1954).

Lead shot impacts on wildlife were most obvious in heavily hunted areas, such as wetlands that were popular waterfowl hunting areas. Because grit is essential for the digestive systems of waterfowl (and most upland game birds), and birds do not differentiate between lead shot and grit of a similar size, wildlife feeding and gathering grit in these wetlands also pick up lead shot (Osmer 1940). Wilson (1937) reported lead poisoning in ducks, geese, and swans discovered in Back Bay, Virginia, and Currituck Sound, North Carolina. He analyzed gizzards, some of which contained more than 100 full-sized No. 4 lead shot and partly ground remains. Osmer (1940) noted that "ingestion of six No. 5 shot by a duck is fatal. Even two or three shot are often fatal." Bellrose (1959) summarized historic information on duck die-offs from lead poisoning ranging from hundreds of ducks in Indiana (1922) and in Louisiana (1930) to as many as 16,000 birds in Missouri (1945–1957) and Arkansas (1953–1954).

Studies in Minnesota documented lead shot problems for Bald Eagles (*Haliaeetus leucocephalus*) and Canada Geese (Minnesota Department of Natural Resources 1981, Bengston 1984, Hennes 1985). Problems were considered severe enough at that time for a steel shot zone to be established for Canada Goose hunting at Lac Qui Parle Wildlife Management Area (Bengston 1984). Hennes (1985) noted that lead shot poisoning of Bald Eagles decreased, but wasn't eliminated. A Trumpeter Swan (*Cygnus buccinator)* die-off in 2007 at Grass Lake in Wright County, Minnesota was attributed to poisoning from lead shot (Minnesota Department of Natural Resources 2007).

Table 1. Species documented as ingesting lead shot, bullets, fragments, or contaminated prey, and species with elevated lead bone, tissue, or blood levels from lead ammunition. Due to the large amount of literature for some species, only selected references are listed.

Species	References	Location
Birds		
American Black Duck (*Anas rubripes*)	White & Stendell (1977); Zwank et al. (1985)	North America
American Coot (*Fulica americana*)	Jones (1939); Anderson (1975)	North America
[c] American Crow (*Corvus brachyrhynchos*)	NYDEC (2000) as read in Golden & Rattner (2002)	New York, USA
[b] Andean Condor (*Vultur gryphus*)	Locke et al. (1969)	Captive
[b] Bald Eagle (*Haliaeetus leucocephalus*)	Jacobson et al. (1977); Clark & Scheuhammer (2003)	North America
[b]Barn Owl (*Tyto alba*)	Mateo et al. (2003)	Spain
Black-bellied Whistling Duck (*Dendrocygna autumnalis*)	Estabrooks (1987)	Sinaloa, Mexico
Black-necked Stilt (*Himantopus mexicanus*)	Hall & Fisher (1985)	Texas, USA
Black Scoter (*Melanitta nigra*)	Lemay et al. (1989) as translated in Brown et al. (2006)	Quebec, Canada
Black Swan (*Cygnus atratus*)	Koh & Harper (1988)	Australia
Black-tailed Godwit (*Limosa limosa*)	Pain (1990)	France
Blue-headed Vireo (*Vireo solitarius*)	Lewis et al. (2001)	Georgia, USA
Blue-winged Teal (*Anas discors*)	Bellrose (1959); Zwank et al. (1985)	North America
Brant Goose (*Branta bernicla*)	National Wildlife Health Laboratory (1985)	North America
Brown Thrasher (*Toxostoma rufum*)	Lewis et al. (2001)	Georgia, USA
Brown-headed Cowbird (*Molothrus atar*)	Vyas et al. (2000)	North America
Bufflehead (*Bucephala albeola*)	Scanlon et al. (1980); Sandersen and Belrose (1986)	North America
[a] California Condor (*Gymnogyps californianus*)	Church et al. (2006); Cade (2007)	North America
California Gull (*Larus californicus*)	Quortrup & Shillinger (1941)	North America
Canada Goose (*Branta canadensis & B. hutchinsii*)	Bellrose (1959); Szymczak & Adrian (1978)	North America
Canvasback (*Aythya valisineria*)	Bellrose (1959); Havera et al. (1992)	North America
Chukar (*Alectoris chukar)*	Walter & Reese (2003); Larsen (2006)	Oregon, USA
Cinnamon Teal (*Anas cyanoptera*)	Bellrose (1959)	North America
Clapper Rail (*Rallus longirostris*)	Jones (1939)	North America
[b] Common Buzzard (*Buteo buteo*)	MacDonald et al. (1983); Battaglia et al. (2005)	France; Italy
Common Coot (*Fulica atra*)	Mateo et al. (2000)	Spain
Common Eider (*Somateria mollissima*)	Franson et al. (1995); Flint et al. (1997)	Alaska, USA
Common Goldeneye (*Bucephala clangula*)	Bellrose (1959); Anderson (1975)	North America
Common Moorhen (*Gallinula chloropus*)	Jones (1939); Locke & Friend (1992)	North America
Common Pheasant (*Phasianus colchicus*)	Hunter & Rosen (1965); Butler et al. (2005)	North America; England
Common Pochard (*Aythya ferina*)	Mateo et al. (1998); Mateo et al. (2000)	Spain

Species	References	Location
[b, a] Common Raven (Corvus corax)	Scheuhammer & Norris (1995); Craighead & Bedrosian (2008)	Canada; Wyoming, USA
Common Snipe (*Gallinago gallinago*)	Pain (1990); Olivier (2006)	France
Common Teal (*Anas crecca*)	Mateo et al. (2000)	Spain
Common Wood-pigeon (*Columba palumbus*)	Clausen & Wolstrop (1979)	Denmark
[c] Cooper's Hawk (*Accipiter cooperii*)	Martin & Barrett (2001)	Canada
Dark-eyed Junco (*Junco hyemalis*)	Vyas et al. (2000)	North America
Dunlin (*Calidris alpina*)	Kaiser et al. (1980)	British Columbia, Canada
[b] Egyptian Vulture (*Neophron percnopterus*)	Donazar et al. (2002)	Canary Islands
[b] Eurasian Eagle Owl (*Bubo bubo*)	Mateo et al. (2003)	Spain
[b] Eurasian Griffon (*Gyps fulvus*)	Mateo et al. (2003); Garcia-Fernandez et al. (2005)	Spain
[b] Eurasian sparrowhawk (*Accipiter nisus*)	MacDonald et al. (1983)	France
[c, b] European Honey-buzzard (*Pernis apivorus*)	Lumeij (1985)	The Netherlands
Gadwall (*Anas strepera*)	Bellrose (1959); Mateo et al. (2000)	North America; Spain
Glaucous-winged Gull (*Larus glaucescens*)	National Wildlife Health Laboratory (1985)	North America
[a, b] Golden Eagle (*Aquila chrysaetos*)	Craig et al. (1990); Kenntner et al. (2007)	Idaho, USA; Switzerland
[c] Gray-headed Woodpecker (Picus canus)	Mörner and Petersson (1999)	Sweden
[b] Great Horned Owl (*Bubo virginianus*)	Clark & Scheuhammer (2003)	Canada
Greater Flamingo (*Pheonicopterus ruber*)	Schmitz et al. (1990); Mateo et al. (1997)	Yucatan, Mexico; Spain
Greater Scaup (*Aythya marila*)	Bellrose (1959)	North America
Greater White-fronted Goose (*Anser albifrons*)	Zwank et al. (1985)	Louisiana, USA
Green-winged Teal (*Anas carolinensis*)	Bellrose (1959); Zwank et al. (1985)	North America
Greylag Goose (Anser anser)	Mudge (1983); DeFrancisco (2003)	England; Spain
Hardhead (*Aythya australis*)	Baxter et al. (1998)	Australia
Herring Gull (*Larus argentatus*)	National Wildlife Health Laboratory (1985)	North America
Hungarian Partridge (*Perdix perdix*)	Keymer & Stebbings (1987); Kreager et al. (2007)	England; Canada
Jack Snipe (*Lymnocryptes minimus*)	Olivier (2006)	France
Japanese Quail (*Coturnix coturnix*)	Yamamoto et al. (1993)	Japan
King Rail (*Rallus elegans*)	Jones (1939)	North America
[b] King Vulture (*Sarcorhampus papa*)	Decker et al. (1979)	Captive
[b] Laggar Falcon (*Falco jugger*)	MacDonald et al. (1983)	Captive
Lesser Scaup (*Aythya affinis*)	Bellrose (1959); Havera et al. (1992)	North America
Long-billed Dowitcher (*Limnodromus scolopaceus*)	Hall & Fisher (1985)	Texas, USA
[b] Long-eared Owl (*Asio otus*)	Brinzal (1996) as read in Fisher et al. (2006)	Spain
Long-tailed Duck (*Clangula hyemalis*)	Flint et al. (1997); Skerratt et al. (2005)	Alaska, USA; North America
Magpie Goose (*Anseranas semipalmata*)	Harper & Hindmarsh (1990); Whitehead & Tschirner (1991)	Australia

Species	References	Location
Mallard (*Anas platrhynchos*)	Bellrose (1959), Mateo et al. (2000)	North America; Spain
Maned Duck (*Chenonetta jubata*)	Kingsford et al. (1994)	Australia
Marbled Godwit (*Limosa fedoa*)	Hall & Fisher (1985); Locke et al. (1991)	Texas, USA; North America
Marbled Teal (*Marmaronetta angustirostris*)	Mateo et al. (2001); Svanberg et al. (2006)	Spain
Merganser (*Mergus spp*)	Bellrose (1959); Skerratt et al. (2005)	North America
Middendorff's Bean Goose (*Anser fabalis middendorffii*)	Chiba et al. (1999)	Japan
Mottled Duck (*Anas fulvigula*)	Merendino et al. (2005)	Texas, USA
Mourning Dove (*Zenaida macroura*)	Lewis & Legler (1968); Schulz et al. (2006a)	North America
Musk Duck (*Biziura lobata)*	Department of Sustainability and Environment (2003)	Australia
Mute Swan (*Cygnus olor*)	Bowen & Petrie (2007)	Great Lakes, Canada
Northern Bobwhite Quail (*Colinus virginianus*)	Westemeier (1966); Keel et al. (2002)	Illinois, USA
[a, b] Northern Goshawk (*Accipiter gentillis*)	Martin & Barrett (2001); Pain & Amiard-Triquet (1993)	Canada; France
Northern Pintail (*Anas acuta*)	Bellrose (1959); Mateo et al. (2000)	North America; Spain
Northern Shoveler (*Anas clypeata*)	Bellrose (1959); Mateo et al. (2000)	North America; Spain
Pacific Black Duck (*Anas superciliosa*)	Baxter et al. (1998)	Australia
Pacific Loon (*Gavia pacifica*)	Wilson et al. (2004)	Alaska, USA
[b] Peregrine Falcon (*Falco peregrinus*)	MacDonald et al. (1983); Pain et al. (1994)	Captive; England
Pink-footed Goose (*Anser brachyrhynchus*)	Mudge (1983)	England
[b] Prairie Falcon (*Falco mexicanus*)	Redig (1980); MacDonald et al. (1983)	Captive
[b] Red Kite (*Milvus milvus*)	Mateo et al. (2003); Pain et al. (2007)	England
Red-tailed Hawk (*Buteo jamaicensis*)	Sikarskie (1977); Clark & Scheuhammer (2003)	Canada
Red-crested Pochard (*Netta rufina*)	Mateo et al. (2000)	Spain
Red-legged Partridge (*Alectoris rufa*)	Butler (2005)	England
Redhead (*Aythya americana*)	Bellrose (1959); Zwank et al. (1985)	North America
Ring-necked Duck (*Aythya collaris*)	Anderson (1975); Havera et al. (1992)	North America
Rock Dove (*Columba livia*)	DeMent et al. (1987)	New York, USA
Rough-legged Hawk (*Buteo lagopus*)	Locke & Friend (1992)	North America
Ruddy Duck (*Oxyura jamaicensis*)	Perry & Artmann (1979); Sanderson & Bellrose (1986)	North America
Ruffed Grouse (*Bonasa umbellus*)	Rodrigue et al. (2005); Kendall et al. (1984)	Virginia, USA; Canada
Sandhill Crane (*Grus canadensis*)	Windingstad et al. (1984); Franson & Hereford (1994)	North America
Scaled Quail (*Callipepla squamata*)	Campbell (1950); Best et al. (1992)	New Mexico, USA
Snow Goose (*Anser caerulescens*)	Bellrose (1959); Zwank et al. (1985)	North America
[a] Snowy Owl (*Nyctea scandiaca*)	MacDonald et al. (1983)	Captive
Sora Rail (*Porzana carolina*)	Artmann & Martin (1975); Stendell et al. (1980)	Maryland, USA
Spanish Imperial Eagle (*Aquila adalberti*)	Mateo et al. (2000); Pain et al. (2005)	Spain

Species	References	Location
Spectacled Eider (*Somateria fischeri*)	Franson et al. (1995); Grand et al. (1998)	Alaska, USA
[a] Steller's Sea Eagle (*Haliaeetus pelagicus*)	Kurosawa (2000)	Japan
Trumpeter Swan (*Cygnus buccinator*)	Bellrose (1959); Blus (1994)	North America
Tufted Duck (*Aytha fuligula*)	Mudge (1983); DeFrancisco et al. (2003)	England; Spain
Tundra Swan (*Cygnus columbianus*)	Trainer & Hunt (1965); Blus (1994)	North America
[b] Turkey Vulture (*Cathartes aura*)	Clark & Scheuhammer (2003); Martin et al. (2008)	North America
Virginia Rail (*Rallus limicola*)	Jones (1939)	North America
[b] Western Marsh Harrier (*Circus aeruginosus*)	Pain & Amiard-Triquet (1993); Mateo et al. (1999)	France; Spain
[c] White-backed Woodpecker (*Dendrocopus leucotos*)	Mörner and Petersson 1999	Sweden
White-faced Ibis (*Plegadis chihi*)	Hall & Fisher (1985)	Texas, USA
White-fronted Goose (*Anser albifrons*)	Bellrose (1959); Ochiai et al. (1993)	North America; Japan
White-headed Duck (*Oxyura leucocephala*)	Mateo et al. (2001); Svanberg et al. (2006)	Spain
White Pekin (wild) (Anas platyrhychos)	Schwab & Padgett (1988)	Virginia, USA
[a] White-tailed Eagle (*Haliaeetus albicilla*)	Kurosawa (2000); Krone et al. (2004)	Japan; Greenland
White-throated Sparrow (*Zonotrichia albicollis*)	Vyas et al. (2000)	North America
Whooper Swan (*Cygnus cygnus*)	Ochiai et al. (1992); Honda et al. (2007)	Japan
Whooping Crane (*Grus americana*)	Hall & Fisher (1985)	North America
American Wigeon (*Anas americana*)	Zwank et al. (1985); Mateo et al. (2000)	Louisiana, USA; Spain
Wild Turkey (*Meleagris gallopavo*)	Stone & Butkas (1972); Kreager et al. (2007)	New York, USA; Canada
Wood Duck (*Aix sponsa*)	Bellrose (1959); Sanderson & Bellrose (1986)	North America
[b] Woodcock (*Scolopax minor*)	Scheuhammer et al. (2003)	Canada
Yellow-rumped Warbler (*Dendroica coronata*)	Lewis et al. (2001)	Georgia, USA
Mammals		
Bank vole (*Clethrionomys glareolus*)	Ma (1989)	The Netherlands
[b] Domestic cattle (*Bos taurus*)	Rice et al. (1987)	
Gray squirrel (*Sciurus carolinensis*)	Lewis et al. (2001)	Georgia, USA
Humans (*Homo sapiens*)	Engstad (1932); Larsen and Blanton (2000)	
Shrew (*Sorex araneus*)	Ma (1989)	The Netherlands
White tailed deer (*Odocoileus virginianus*)	Lewis et al. (2001)	Georgia, USA
Reptiles		
[a, b] American alligator (*Alligator mississippiensis*)	Camus et al. (1998); Lance et al. (2006)	North America; Captive
[b] Crocodile (*Crocodylus porosus*)	Hammerton et al. (2003); Orlic et al. (2003)	North America; Australia

[a] Evidence of secondary poisoning from lead bullets.
[b] Evidence of secondary poisoning from lead shot.
[c] Source of lead unknown, lead ammunition suspected.

Impacts of lead shot at a population level are variable. Butler et al. (2005) noted that 3% of pheasants on shooting estates in Great Britain had lead in their gizzards. Kreager et al. (2007) examined gizzards from upland game birds harvested in Ontario, Canada and found lead pellets ingested by 8% of the Chukars (*Alectoris chukar*) and 34% of the pheasants. They found that 13% of the livers from Chukars, Common Pheasants (*Phasianus colchicus*), Wild Turkey (*Meleagris gallopavo*), and Hungarian Partridge (*Perdix perdix*) had elevated lead concentrations. Ingestion rates may vary by species, feeding behavior, and availability of lead shot in the habitat.

Fisher et al. (2006) suggested that a lack of evidence of poisoned species does not suggest a lack of poisoning. Schulz et al. (2006a) found that Mourning Doves (*Zenaida macroura*) may expel lead shot pellets after ingesting them, indicating incidence of lead exposure in wildlife may be higher than reported. In a similar study, one in three birds that expelled all shot exhibited measurable effects of lead poisoning (Schulz et al. 2007). Die-offs and evidence of lead poisoning may not be apparent, because wildlife affected by lead poisoning may seek isolation and protective cover (Friend and Franson 1999). Furthermore, it is unknown if mortality due to non-lethal effects such as reproductive problems, lowered immunity, anemia, and weakened muscles could be higher than losses from direct lead poisoning (Michigan Department of Natural Resources 2002).

Lead shot ingestion and toxicity problems for wildlife have been documented worldwide. Table 1 documents lead ingestion or secondary lead exposure for wildlife species in more than 10 countries and several continents. Tavecchia et al. (2001) found lead pellets in the muscles and gizzards of 11% of the Mallards captured in France. Mateo et al. (1998) found lead pellets in 87.5% of Common Pochards (*Aythya ferina*) and 33% of Mallards and Northern Shovelers (*Anas clypeata*) in Spain. Mörner and Petersson (1999) found lead poisoning in two woodpecker species in forested areas in Sweden suggesting that the woodpeckers searching for food removed lead pellets shot into trees.

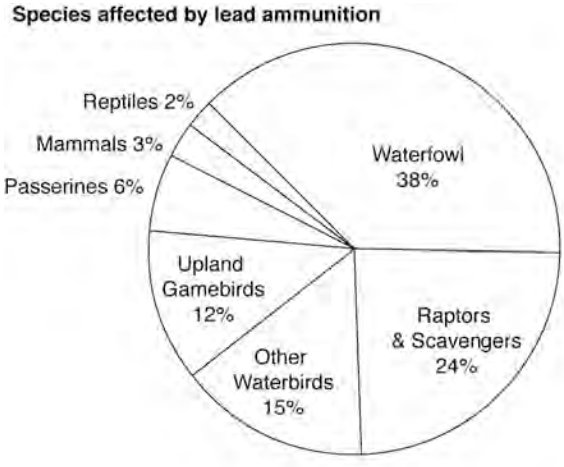

Figure 1. Categories of species reported in the literature as ingesting lead shot, bullets, fragments, or prey contaminated with lead ammunition, and species with elevated lead levels in bone, tissue, or blood from exposure to lead ammunition.

There is sufficient evidence that the problem of lead poisoning in birds extends to upland birds and raptors. Sixteen species of upland game birds, and 29 species of raptors were reported in the literature as being affected by lead ammunition (Figure 1). Butler et al. (2005) reported lead exposure over a number of years (1996–2002) for Common Pheasants in Great Britain. Fisher et al. (2006) provided a review of 59 (9 threatened) terrestrial bird species that have been documented to have ingested lead or suffered lead poisoning from ammunition sources. Exposure of lead shot on some upland game birds such as doves could rival the problem in waterfowl (Kendall et al. 1996). Ingestion of lead by wildlife, other than waterfowl and birds of prey, "appears to be extensive" (Harradine 2004). Current use of lead shot for small game hunting (such as pheasants) potentially continues to deposit lead in wetlands and expose waterfowl to lead shot.

Lead ammunition can secondarily poison wildlife that feed on hunted species. Studies have linked the likelihood of a species ingesting lead shot to feeding habits, with scavengers and predators that take game species being the most susceptible (Pain and Amiard-Triquet 1993). In Spain, Mateo et al. (2003) reported lead poisoning from exposure to lead shot in prey species in eight upland raptor spe-

cies. Clark and Scheuhammer (2003) examined lead exposure in 184 dead raptors (16 species) found across Canada. They determined that, of the three most commonly encountered species, 3–4% died as a result of lead poisoning. They concluded that upland birds of prey and scavengers that eat game birds and mammals are at risk for lead poisoning from ingestion of lead shot and bullet fragments used in upland hunting. They suggested that use of non-toxic ammunition for hunting upland game would effectively remove the only serious source of high lead exposure and lead poisoning for upland-foraging raptors.

Knopper et al. (2006) reported that carcasses from squirrel populations managed by shooting had lead levels lethal to raptors and suggested either collection of carcasses shot with lead or the use of non-toxic shot. Similar to the lead shot problems described by Clark and Scheuhammer (2003), deer carcasses containing lead fragments from bullets impact California Condors (*Gymnogyps californianus*) (Cade 2007) and Bald Eagles (Franson 2007). Hunt et al. (2006) examined the remains of 38 deer killed with rifles and found that all deer killed with lead-based bullets contained bullet fragments. Mateo et al. (2003) analyzed bones from 229 birds of prey in Spain (11 species) and diagnosed lead poisoning in 8 raptor species that feed on wildlife targeted by hunters in upland habitats.

LEAD AMMUNITION IMPACTS ON THE ENVIRONMENT

The Minnesota Pollution Control Agency (1999) estimated that 1,184,202 kg of lead shot were used annually in Minnesota in hunting and shooting ranges. In their legislative report on sources and effects of lead, they state, "The fact that lead ammunition is estimated to be the single largest source of lead released to the environment qualifies it as a concern that should be examined more closely."

De Francisco et al. (2003) estimated that lead shot can take 100 to 300 years to disappear from a site, allowing for concentration of large amounts of lead in areas of heavy hunting pressure. Although the breakdown is slow, lead shot pellets accumulating in the environment are not inert and ultimately the lead will be deposited as particles in soil and water (Scheuhammer and Norris 1995). Mozafar et al. (2002) found a high degree of bioavailability in heavy metals (including lead) in soils at a shooting range in Switzerland. Uptake of this lead by terrestrial and aquatic plants and animals can occur, leading to elevated lead concentrations (Ma 1989, Manninen and Tanskanen 1993, Rooney et al. 1999).

Guitart et al. (2002) reported that a single lead shot could raise 12,000 liters of water to the European Union threshold guideline for lead in drinking water. Surface water contamination by lead shot from shooting ranges has been well documented (Stansley et al. 1992, Dames and Moore Canada 1993, Emerson 1994, United States Environmental Protection Agency 1994). Strait et al. (2007) found that shooting ranges contained areas where lead occurred at "concentrations significantly in excess of the Michigan Department of Environmental Quality criteria and therefore pose a potential risk to the human users of the land as well as to the native wildlife." While shooting ranges contain far more spent shot than typical hunting areas, these studies demonstrate the ability of lead to accumulate over time and contaminate the surrounding environment and wildlife. Areas with acidic waters or soils are at particularly high risk for contamination from lead shot, as lead is more easily mobilized at a lower pH (Stansley et al. 1992).

Contamination of human and livestock food sources due to lead shot deposition has also been documented. Guitart et al. (2002) suggested that the high lead content of rice produced in Spain was a result of hunting with lead shot near rice fields. Rice et al. (1987) reported lead poisoning of cattle from ingestion of silage contaminated with lead shot. In addition, milk production decreased and stillbirths increased in cattle (*Bos taurus*) ingesting lead contaminated hay cut from a field used for clay pigeon shooting (Frape and Pringle 1984).

IMPACTS OF LEAD AMMUNITION ON HUMANS

Lead poisoning in humans has occurred for at least 2,500 years (Eisler 1988). Today, it is widely known that lead is toxic to humans and can cause permanent learning disabilities, behavioral prob-

lems, and even death. Haldimann et al. (2002) concluded that frequent consumption of wild game meat had no significant effect on blood lead levels. However, studies in Canada, Greenland, and Russia have linked lead shot found in game animals to higher levels of lead in people who eat those game animals (Table 2). Levesque et al. (2003) stated, "Lead shots may be a major source of lead exposure to humans that consume hunted game animals." This study found that lead shot was a source of lead exposure in the Inuit population; blood lead concentrations in 7% of Inuit newborns were higher than government-recommended levels. Studies linking game meat containing lead shot and elevated blood lead levels in children (Odland et al. 1999, Smith and Rea 1995) and newborns (Dewailly et al. 2000, Hanning et al. 2003) are of particular concern.

Breurec et al. (1998) diagnosed lead poisoning in an adult patient who had frequently eaten game birds containing lead shot. Professional medical literature contains many references of humans carrying lead shot in their digestive tracts (Engstad 1932, Horton 1933, Hillman 1967, Reddy 1985, Madsen et al. 1988, Spitale and D'Olivo 1989, Moore 1994, Tsuji and Nieboer 1999, and Larsen and Blanton 2000). Lead from shot may accumulate in tissues of game animals. In upland game birds and waterfowl killed by hunters using lead shot, 40% of 123 livers (Kreager et al. 2007) and 9% of 371 gizzard tissue samples (Tsuji et al. 1999) showed lead levels greater than Health Canada's guidelines for fish.

In animals shot for human consumption, meat far from the entry wound may contain lead. Scheuhammer et al. (1998) found fragments of lead in game birds far from wounds from shotgun pellets. Hunt et al. (2006) found lead fragments in meat 15 cm away from rifle bullet wounds in game animals. Lead fragments, likely from bullets, were found in ground venison in North Dakota and Minnesota. This prompted North Dakota Health, Game and Fish, and Agriculture Departments to advise food pantries not to distribute or use donated ground venison because of the potential for lead contamination (North Dakota Department of Health 2008). Minnesota Department of Agriculture found lead fragments in 76 of 299 tested samples of ground venison donated to food shelves, prompting disposal of all remaining donated venison (Minnesota Department of Agriculture 2008).

Tsuji et al. (1999) reported that, "People who consume *any* game species harvested with lead shot risk exposure to this metal by way of ingestion of tissue-embedded lead pellets and fragments." With alternatives to lead shot readily available (Sanborn 2002), human exposure to lead through game meat is unnecessary (Rodrigue et al. 2005). Levesque et al. (2003) showed significant decreases in lead concentrations in umbilical cord blood after a public health intervention to reduce the use of lead shot by the Inuit population.

NON-TOXIC AMMUNITION

Substituting non-toxic shot for lead shot could reduce lead shot impacts on the health of wildlife, the environment, and human health. Alternatives to lead shot were not readily available in the past, especially prior to the 1991 federal ban on lead shot for waterfowl hunting in the United States. However, other types of shot, particularly steel shot, are now available at a cost comparable to lead shot ammunition (Sanborn 2002). Non-toxic shot is now also available for safe use in vintage and older shotguns (Cabela's 2008). Scheuhammer and Norris (1995) found that, while non-toxic alternatives to lead shot are more expensive than lead, they represent only a 1–2% increase in the average hunter's yearly expenses. There are currently 11 types of shot approved as non-toxic by the US Fish and Wildlife Service (US Fish and Wildlife Service 2006). Studies have demonstrated the effectiveness of steel shot. For example, Schulz et al. (2006b) evaluated crippling rates in waterfowl prior to and following implementation of non-toxic shot regulations in the US. They found that, after a five-year phase-in period, crippling rates for ducks and geese were lower after non-toxic shot restrictions were implemented.

Despite numerous reports of negative impacts of lead shot on wildlife worldwide, restrictions on the use of lead shot have been minimal (Thomas 1997). Interest in non-toxic shot regulations has resulted in discussions on restricting lead ammunition and some legislation on different continents. Denmark and the Netherlands have banned all uses

Table 2. Selected literature regarding elevated lead levels in humans consuming game meat harvested with lead shot.

Author	Country	Findings
Bjerregaard et al. (2004)	Greenland	Blood lead adjusted for age and sex was found to be associated with the reported consumption of sea birds.
Breurec et al. (1998)	Not reported	Patient diagnosed with adult lead poisoning by ingestion of game birds with small lead shots.
Dewaily et al. (2000)	Arctic Canada	Ingestion of lead shot/fragments in game meat may be responsible for higher lead levels found in Inuit newborns. Lead isotopes of shotgun cartridges were similar to those of Inuit newborns.
Dewailly et al. (2001)	Quebec, Canada	Evaluated 492 blood levels of lead and mercury in Inuit adults, revealed that smoking, age, and consumption of waterfowl were associated with lead concentrations ($r^2 = 0.30$, $p < 0.001$).
Guitart et al. (2002)	Spain	Approximately 30,000 waterfowl hunters and their families, especially children, are at risk of secondary lead poisoning from lead poisoned birds in Spain.
Hanning et al. (2003)	Canada	Traditional animal food intake, especially wild fowl, correlated significantly with umbilical cord blood lead, and reflected the legacy of using lead-containing ammunition.
Johansen et al. (2001)	Ontario, Canada	Breast meat lead values in birds killed with lead shot were 10 times higher than birds not killed with lead shot. Shot is a significant source of lead in many people in Greenland.
Johansen et al. (2004)	Greenland	Lead intake of Greenland bird eaters can largely exceed the tolerable lead intake guidelines, and the shot is a more important source of lead than previously estimated.
Johansen et al. (2006)	Greenland	Found clear relationship pointing to lead shot as the dominating lead source to people in Greenland.
Levesque et al. (2003)	Quebec, Canada	Lead from game hunting was a major source of human exposure to lead. Calls for international ban on lead shotgun ammo.
Mateo et al. (2007)	Spain	Consumption of half a pickled quail/week with embedded shot may cause the provisional tolerable weekly intake of lead by the Spanish consumer to be exceeded.
Odland et al. (1999)	Russia	Suggests lead shot as the main source of lead in population in the Kola Peninsula, Russia.
Smith and Rea (1995)	Canada	Elevated lead blood levels in children probably due to consumption of birds containing lead shot, suggest use of alternative shot.
Trebel and Thompson (2002)	Canada	Young child exhibited elevated blood lead levels after ingesting spent air rifle pellets.
Tsuji et al. (1999)	Ontario, Canada	Consumption of any game species harvested with lead shot risks exposure by way of ingestion of tissue-embedded lead pellets and fragments.

of lead shot (Thomas 1997). Broad regulatory action to restrict lead shot across Europe has been discussed by various cross-continental groups, such as the European Council, the Bonn and Bern Conservations, and by the European Union (Thomas and Owen 1996). In Australia, lead shot restrictions vary by state from a total ban, to restrictions for waterfowl hunting similar to those in the USA, or suggesting non-toxic alternatives and leaving the choice of shot up to the hunters (Green 2004).

The most significant non-toxic shot regulation in the USA was the federal ban on the use of lead shot for hunting waterfowl in 1991. This ban has been demonstrated to have a positive impact on wildlife. For example, Anderson et al. (2000) attributed an estimated 64% reduction in mortality from lead poisoning to the switch to non-toxic shot. They estimated that 1.4 million ducks in the 1997 fall continental flight of 90 million were spared from fatal lead poisoning due to the ban on lead shot. Stevenson et al. (2005) found that lead concentrations in the bones of two species of ducks decreased after the ban, but in comparison, they noted that bone lead concentrations showed no change for American Woodcock (*Scolopax minor*), a migratory upland species not impacted by the lead shot ban for waterfowl hunting.

Some small game hunters have already begun to switch to non-toxic shot. In Minnesota, a recent survey, conducted by Schroeder et al. (2008) found that 40% of pheasant hunters reported they are currently using non-toxic shot voluntarily. Case et al. (2006) surveyed USA states and Canadian provinces regarding non-toxic shot regulations and found that 45% of surveyed states and provinces have non-toxic shot regulations beyond federal waterfowl regulations. Nine states and provinces that have non-toxic shot regulations were discussing additional regulations.

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