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Original Article

Metal Deposition of Copper and Lead Bullets in Moose Harvested in Fennoscandia

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ABSTRACT Fragments from bullets used for moose (*Alces alces*) hunting contaminate meat, gut piles, and offal and expose humans and scavengers to lead and copper. We sampled bullets ($n = 1{,}655$) retrieved from harvested moose in Fennoscandia (Finland, Sweden, and Norway) to measure loss of lead and copper. Concordant questionnaires ($n = 5{,}255$) supplied ballistic information to complete this task. Hunters preferred lead-based bullets (90%) to copper bullets (10%). Three caliber classes were preferred: 7.62 mm (69%), 9.3 mm (12%), and 6.5 mm (12%). Bullets passed completely through calves (76%) more frequently compared to yearlings (63%) or adults (47%). Metal deposition per bullet type (bonded lead core, lead core, and copper) did not vary among moose age classes (calves, yearlings, and adults). Average metal loss per bullet type was 3.0 g, 2.6 g, and 0.5 g for lead-core, bonded lead-core, and copper bullets, respectively. This corresponded to 18–26, 10–25, and 0–15% metal loss for lead-core, bonded lead-core, and copper bullets, respectively. Based on the harvest of 166,000 moose in Fennoscandia during the 2013/2014 hunting season, we estimated that lead-based bullets deposited 690 kg of lead in moose carcasses, compared with 21 kg of copper from copper bullets. Bone impact increased, whereas longer shooting distances decreased, lead loss from lead-based bullets. These factors did not influence loss of copper from copper bullets. In conclusion, a significant amount of toxic lead from lead-based bullets is deposited in the tissue of harvested moose, which may affect the health of humans and scavengers that ingest it. By switching to copper bullets, Fennoscandian hunters can eliminate a significant source of lead exposure in humans and scavengers.

KEY WORDS *Alces alces*, bullet, caliber, human health, hunting, lead, moose, toxicity, wound ballistics.

Moose (*Alces alces*) hunting is an important recreational and economic activity in Fennoscandia (Finland, Sweden, and Norway; Lavsund et al. 2003). There are approximately 411,000 registered moose hunters in these countries (100,000 in Finland [Natural Resources Institute Finland 2015], 250,000 in Sweden [Swedish Hunters' Association 2008], and 61,000 in Norway [Statistics Norway 2014]). During the 2013/2014 hunting season, 166,000 moose were harvested in Fennoscandia (38,000 in Finland [Finnish Game and Fisheries Research Institute 2014], 95,000 in Sweden [Swedish Hunters' Association 2016], and 33,000 in Norway [Statistics Norway 2014]). Thus, moose meat is an important source of protein for a significant proportion of the population in these countries. Additionally, animals scavenge on gut piles and offal from harvested moose and carcasses of wounded moose.

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In all 3 countries, moose can only be hunted with rifles using centerfire cartridges with expanding bullets weighing $\geq$9 g ($\geq$139 grains). For bullets weighing 9–10 g (139–154 grains), the minimum impact energy required is 2,700 joules (275 kg/m) at 100 m. For bullets weighing $\geq$10 g ($\geq$154 grains), the minimum impact energy must be >2,200 joules (225 kg/m) at the same range. Bullets approved for big game hunting include various alloyed lead (92–96% lead, 1–2% arsenic, 3–6% antimony with traces of silver, cadmium, bismuth, tin, zinc, copper) core bullets or copper (90–95% copper) or copper–zinc alloy (5–10% zinc) bullets (Peters 2002). Lead-based bullets are semijacketed in sheaths of copper. All hunting bullets are required to expand on impact. Expansion ("mushrooming") is a highly complex process, which intends to increase the cross-sectional area of the bullet tip upon impact.

Lead is widely available, easily extracted from ore and simply purified with low energy input. Thus, lead is cheap compared with most other nonferrous metals. The density of lead is particularly high (11.3 g/cm^3) compared with other metals. Tensile strength on the other hand is approximately 12–17 MPa, which is much lower than other common metals; mild steel and cast copper are approximately 15 and 10 times stronger, respectively (Schmid and Kalpakjian 2013). Yielding occurs already at 5 MPa making lead highly ductile; thus, it can deform plastically before it fractures. This is contrary to most common metals, which have limited ability to deform before they become hard and brittle (Guruswamy 2000). Technically, lead is therefore an excellent choice for hunting ammunition. However, lead has no known biological function in vertebrates and is toxic to most physiological systems, including the nervous, renal, cardiovascular, reproductive, immune, and hematologic systems (Bellinger et al. 2013).

Copper is found in sulphide ores or in carbonate, arsenide, and chloride forms. The market price of copper is 2–3 times greater than that of lead. It has superb thermal and electrical conductivities, corrosion resistance, and alloying capability. Density of copper is relatively high ($8.96\,g/cm^3$) compared with most forms of steel ($<8.05\,g/cm^3$), but is inferior to lead. Tensile strength is approximately 210 MPa, which is similar to cast iron (200 MPa). Copper is regarded as ductile, having an elongation at rupture at approximately 20–35%. This is about the same as aluminum, but inferior to lead, which is 1.5 times more ductile than copper. Copper is an essential element required to maintain homeostasis in vertebrates, even though too high or too low dietary intake can induce adverse health effects (Stern 2010). Although copper is technically inferior to lead as a ductile component in bullets, it has lately been introduced as the sole component in nontoxic expanding rifle bullets used for big game hunting (Thomas 2013).

A fundamental characteristic of semijacketed lead-core bullets is the ability to fragment into tissues surrounding the permanent cavity or wound channel (Fackler et al. 1984, Gremse et al. 2014). Although debated, bullet fragmentation is commonly considered to be a primary cause of increasing the permanent wound cavity by weakening the tissues under tension from the temporary cavity (Fackler et al. 1984, Coupland 1999, Trinogga et al. 2013). In contrast, deforming copper bullets can withstand fragmentation and thus sustain momentum ensuring proper penetration (Hunt et al. 2009, Batha and Lehman 2010, Gremse et al. 2014). Although copper bullets are considered to be nontoxic (Thomas et al. 2007, Caudell et al. 2012, Franson et al. 2012, Irschik et al. 2013), there is a huge body of evidence showing that fragments from lead-based ammunition contaminate venison, carcasses, and offal from shot animals (Iqbal et al. 2009, Kosnett 2009, Grund et al. 2010, Lindboe et al. 2012, Bellinger et al. 2013, Arnemo et al. 2016). However, few studies have quantified lead fragments in the carcasses of big game shot with lead-based bullets (Hunt et al. 2006, 2009; Knott et al. 2010; Cruz-Martinez et al. 2015). These studies found large amounts of lead fragments using X-ray imaging. Knott et al. (2010) reported an average of 356 lead fragments in the carcass and 180 fragments in the viscera of 10 red deer (*Cervus elaphus*) and 2 roe deer (*Capreolus capreolus*) shot with lead based bullets in United Kingdom. Further, they estimated the total amount of lead residues in a carcass to be 17% of the bullet weight. All studies, however, likely missed a considerable share of smaller fragments because of the resolution limit of the radiographs. Only 3 studies have addressed fragmentation of copper bullets (Hunt et al. 2006, Irschik et al. 2013, Cruz-Martinez et al. 2015). They all found significantly less fragmentation compared with lead bullets. Irschik et al. (2013) studied fragmentation of 2 brands of copper bullets in 46 roe deer, red deer, fallow deer (*Dama dama*), and wild boars (*Sus scrofa*), and found copper fragments in all animals ($n = 10$) shot with one bullet type (Aero, Styria Arms, Zeltweg, Austria) whereas only one fragment was found in 34 animals shot with the other brand (Barnes TSX, Barnes Bullets, Mona, UT, USA).

To the best of our knowledge, no published studies have used retrieved bullets to quantify metal deposition in carcasses of big game. Here, we report loss of lead and copper from bullets collected from moose harvested in Fennoscandia.

STUDY AREA

We collected data from moose hunters in Fennoscandia (Fig. 1). The total mainland area was $1,111,127\,km^2$ and approximately 1,850 km long and 370–805 km wide. Moose occurred primarily in coniferous mixed forests dominated by Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and deciduous trees and shrubs including alder (*Alnus* sp.), birch (*Betula* sp.), willow (*Salix* sp.), and aspen (*Populus tremula*) in the boreal and boreo–nemoral zones (Ahti et al. 1968). The predominate climate in Fennoscandian moose range varied from subarctic in the north to humid continental further south.

Figure 1. Map of Fennoscandia (Norway, Sweden, and Finland), where we sampled bullets retrieved from harvested moose and concordant questionnaires during the 2004/2005 and 2005/2006 hunting seasons to estimate the amount of lead and copper deposited in carcasses.

METHODS

Data Sampling

We sent questionnaires to Swedish and Finnish moose hunters through the Swedish Association for Hunting and Wildlife Management and Finnish Wildlife Agency, respectively (2004/2005–2005/2006 hunting seasons). In addition, we provided information on where to download our survey online to Norwegian hunters through hunting magazines. We asked participants to complete a form for each harvested moose, with information on sex, age, cartridge and bullet types, and description of bone impact. In addition, respondents were asked to provide shooting distance and number of bullets impacting tissue, including euthanizing shots used to dispatch moose at close range. We also asked hunters to include bullets retrieved from the carcass together with the corresponding questionnaire. Respondents also reported whether a bullet stopped in the body or passed through the moose. This information was used to calculate the frequency of use of cartridge and bullet types and quantify weight retention and loss of lead and copper.

Bullet Inspection and Estimation of Metal Loss

In the laboratory, we submerged bullets overnight in a fat-soluble solvent. We then cleaned them by using compressed air together with a thin bodkin to remove bone and other tissue fragments. We weighed bullets on a digital scale accurate to 0.01 g (Mettler PC 440; Mettler-Toledo, Inc., Mississauga, ON, Canada). Loss of mass (i.e., amount of metal deposited in the carcass) from a bullet was the difference between the bullet mass provided by hunters on the data forms and retention mass determined in the laboratory. We discarded 384 bullets with missing jacket parts or separated lead cores from the metal loss analysis. Loss of lead was calculated for lead bullets, whereas loss of copper was quantified only for homogenous deforming bullets. We checked bullet mass given by respondents against factory mass from the manufacturers. We assumed that bullets passing through animals had similar retention mass as retrieved bullets of the same type.

Pooling of Data According to Bullet and Caliber Classification

Cartridges are classified according to the diameter measured between the raised portions of the rifling groove, or "land" of a gun bore. We converted the Anglo-American classification for bore diameters (caliber) in inches to millimeters to standardize cartridge classes. We categorized cartridges into 5 major caliber classes: 1) 6.5 mm (0.254 in.); 2) 7.62 mm (0.300 in.); 3) 8.58 mm (0.338 in.); 4) 9.3 mm. (0.354 in.); and 5) $\geq$9.52 mm ($\geq$0.375 in.; Supporting Information A). Because 9.3 mm is commonly used in Fennoscandia, we decided to classify this caliber separately.

We categorized bullets into 3 major types: 1) lead core; 2) bonded lead core; and 3) homogenous copper (Supporting Information B). The first type included a semijacketed copper mantle filled with a lead core. The second type had the same basic construction but with a lead core bonded to the copper mantle. The third type was composed of solid homogenous copper or a copper alloy. Bullet types 1) and 2) were collectively referred to as lead bullets whereas type 3) was defined as copper bullets.

Estimation of the Amount of Metal Deposited in Moose Tissue

First, we estimated average metal loss per bullet type. Then, knowing the number of bullet impacts, we could estimate metal loss per bullet type within each moose age class (calf, yearling, and adult) to see whether metal loss within bullet types differed among age classes. In the next step, we estimated the average amount of metal mass lost per bullet type and caliber class. This was estimated both as absolute values and percentages.

Our categorization of applied cartridges and bullets into 3 bullet types and 5 caliber classes meant that we had 15 combinations. We assumed that our data sample was representative for the distribution of ammunition types among moose hunters in Fennoscandia. Then, knowing the total amount of moose harvested in Fennoscandia (N_F) during the 2013/2014 hunting season, we could estimate the amount of metal deposited (M_{di}) in moose per combination (i) in Fennoscandia for the same season by using the following equation:

$$M_{di} = \frac{n_i N_F}{\sum_{i=1}^{15} n_i} m_i b_i$$

Where n_i is the number of moose harvested in combination i, m_i is the average amount of metal loss per bullet for combination i, and b_i is the average number of bullets used to dispatch moose in combination i. Thus, we could estimate the expected metal deposition in harvested moose for the whole of Fennoscandia for each combination of bullet type and caliber class. Experimentally, we substituted m_i for lead bullets with m_i for copper bullets within corresponding caliber classes to estimate the amount of copper that potentially could replace deposited lead if all users of lead bullets changed to copper bullets. Finally, we explored whether metal loss was affected by shooting distance or tissue type impacted (bone vs. soft tissue).

Statistical Approach

For simple testing among many factors, we generally used chi-square tests to determine whether differences existed at $\alpha = 0.05$ level. For correlation analyses, we used the nonparametric Spearman's rho with bootstrapping. We applied generalized linear models and 95% Wald confidence interval (Poisson distribution and log-link function) to test for differences except for shooting distances, where we used general linear model univariate analysis of variance. We used IBM SPSS Statistics Version 22 (International Business Machines Corporation, Armonk, NY, USA) for statistical analyses and Visual FoxPro 9.0 SP2 (Microsoft Corporation, Redmond, WA, USA) for storing and SQL querying of data as well as for programming to calculate M_{di} and other statistical processes.

RESULTS

Applied Calibers and Bullets Classes

We received 5,255 questionnaires and 1,655 bullets (Table 1). Hunters in Fennoscandia most commonly used the following calibers: 7.62 mm (69%), 9.3 mm (12%), 6.5 mm (12%), 9.52 mm (4%), and 8.58 mm (3%; see complete list of cartridges and caliber classes in Supporting Information A). The most commonly used bullet types were lead core (47%), followed by bonded lead core (43%) and copper (10%; see Supporting Information B for complete list of bullet types). Copper bullets were used more frequently in Finland (17%) than in either Sweden (2%) or Norway (6%; $\chi^2_4 = 50.42$, $P < 0.001$). Copper bullets were more commonly used in larger calibers (≥9.3 mm) and the least in small calibers ($\chi^2_8 = 126.46$, $P < 0.001$). Mantel and lead core separation occurred at approximately the same frequency for bonded lead-core and lead-core bullets (11% and 16% respectively: $\chi^2_1 = 2.66$, $P = 0.10$). Bullets passed completely through 47.0% of adults, 62.8% of yearlings, and 76.2% of calves ($\chi^2_2 = 402.0$, $P < 0.001$).

Metal Deposition per Bullet Type and Caliber Class

The amount of metal deposited in tissue per bullet type did not differ among moose age classes (Fig. 2; Wald $\chi^2_2 = 0.39$, $P = 0.82$). Thus, it was not necessary to account for body size in the estimation of metal loss. Average metal loss differed among bullet types: lead-core bullets 3.00 ± 0.17 g, bonded lead-core bullets 2.65 ± 0.15 g, and copper bullets 0.54 ± 0.18 g (Fig. 2; Wald $\chi^2_2 = 148.53$, $P < 0.001$).

Among bonded lead core bullets, 6.5 mm lost on average 1.38 g less lead compared to the other caliber classes (Table 2; Wald $\chi^2_8 = 50.47$, $P < 0.001$). Similarly, for lead core bullets, 6.5 mm lost on average 1.51 g less lead than bullets from larger caliber classes (Table 2). There was a weak positive correlation between lead-core bullet loss of mass and bullet diameter (Spearman's $\rho = 0.13$, $P = 0.003$). There was no such correlation for bonded lead-core bullets (Spearman's $\rho = -0.01$, $P = 0.82$). No differences were found for copper bullets (Table 2). There was a decreasing trend in the proportional (%) amount of metal loss among bullet types from lead-core to copper bullets (Fig. 3; Wald $\chi^2_2 = 176.42$, $P < 0.001$),18–27% for lead-core bullets, 10–24% for bonded lead-core bullets, and 0–15% for copper bullets (Fig. 3; Wald $\chi^2_2 = 176.42$, $P < 0.001$).

Total Metal Deposition to Moose Tissue

In total, 689.5 kg of lead was deposited in 166,000 harvested moose (Table 3), wherein lead-core and bonded lead-core bullets added 389.9 and 299.6 kg, respectively. Copper bullets deposited 20.6 kg (Table 3). All deposited lead could potentially be replaced with 169 kg of copper if all users of lead bullets changed to copper bullets.

Table 1. The number of questionnaires and bullets received from respondents to a survey that asked hunters in Fennoscandia to submit bullets retrieved from carcasses of moose harvested during the 2013–2014 hunting season, along with information about moose age and sex, cartridge and bullet types used, description of bone impact by bullets, shooting distance, and number of bullets impacting tissue.

Country	Questionnaires	Bullets
Finland	2,750	1,340
Sweden	1,543	232
Norway	962	83

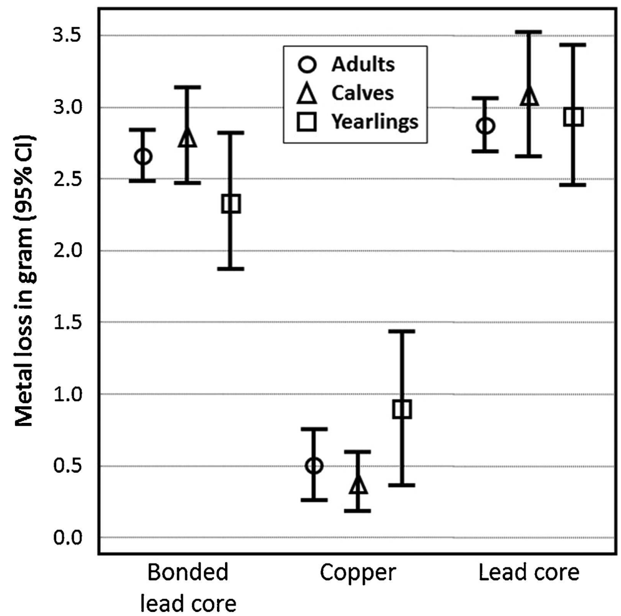

Figure 2. Metal loss (g) for bonded lead-core, copper, and lead-core bullets retrieved from adult, calf, and yearling moose harvested during the 2004/2005 and 2005/2006 hunting seasons in Fennoscandia (Norway, Sweden, and Finland).

Factors Influencing Metal Loss

Lead loss from lead bullets was greater for bone hits than for soft tissue penetration (23% vs. 29%; Fig. 4: Wald $\chi^2_1 = 12.04$, $P = 0.001$). Bonded lead-core bullets lost relatively more lead than lead-core bullets after bone hits, but lost less than lead-core bullets after soft tissue penetration (Wald $\chi^2_1 = 8.01$,

Table 2. Estimated marginal means $\bar{x}$ (SE and 95% Wald CI) for metal deposited in moose harvested in Fennoscandia (Finland, Sweden, and Norway) during the 2013/2014 hunting season. These estimates were based on retention mass of bullets retrieved from moose harvested during the 2004/2005 and 2005/2006 hunting seasons. Marginal means are shown per bullet type and caliber class.

				95% Wald CI	
Caliber class (mm)	Bullet type	$\bar{x}$ (g)	SE	Lower	Upper
6.5 mm	Lead core	2.60	0.30	2.01	3.18
	Bonded lead core	0.92	0.41	0.13	1.72
	Copper	1.99	0.70	0.61	3.37
7.62 mm	Lead core	2.74	0.09	2.57	2.91
	Bonded lead core	2.77	0.08	2.61	2.93
	Copper	0.41	0.13	0.15	0.66
8.58 mm	Lead core	4.51	0.77	3.00	6.02
	Bonded lead core	2.15	0.50	1.18	3.13
	Copper	0.30	0.65	−0.97	1.58
9.3 mm	Lead core	3.91	0.27	3.38	4.45
	Bonded lead core	2.26	0.25	1.76	2.76
	Copper	1.02	0.30	0.45	1.60
>9.52 mm	Lead core	4.27	0.34	3.59	4.94
	Bonded lead core	2.03	0.77	0.52	3.54
	Copper	0.65	0.70	−0.73	2.03

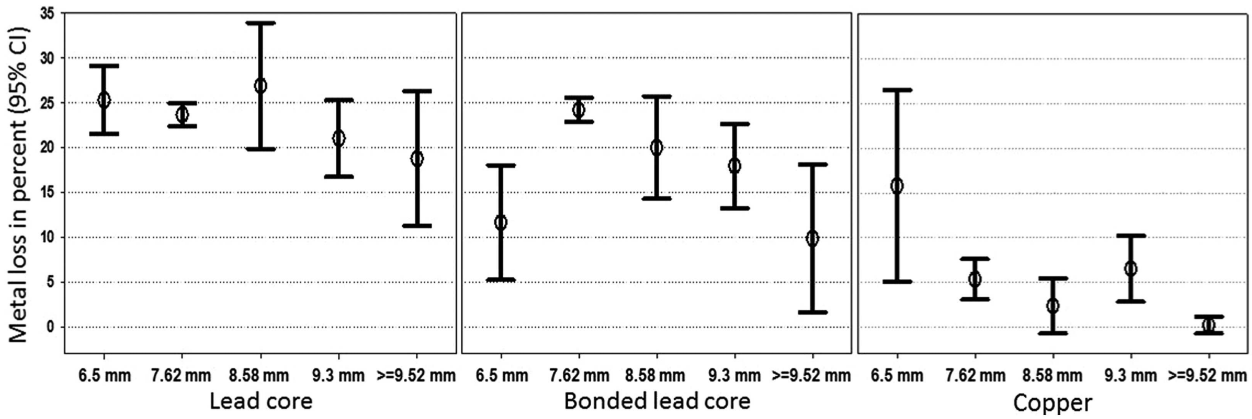

Figure 3. Metal loss (%), within 5 caliber classes, for lead-core, bonded lead-core, and copper bullets retrieved from moose harvested during the 2004/2005 and 2005/2006 hunting seasons in Fennoscandia (Norway, Sweden, and Finland).

$P = 0.005$). Shooting range varied between 2 m and 330 m with a mean distance of 65.8 m (SD = 40.3 m, SE = 0.60, 95% CI: LB = 64.8, UB = 67.0, $n = 5{,}245$ shots). There were no differences between average shooting distances (mean) for bonded lead-core (64.1 m, SD = 39.4, SE = 1.71, range = 288, 95% CI: LB = 60.8, UB = 67.5), lead-core (63.4 m, SD = 35.8, SE = 1.65, range = 225, 95% CI: LB = 60.1, UB = 66.6), and copper (65.3 m, SD = 40.5, SE = 2.8, range = 265, 95% CI: LB = 59.8, UB = 67.5) bullets ($F_{2,2} = 0.20$, $P = 0.82$). In general, there was a weak trend for mass loss from lead bullets to decrease with shooting distance (Spearman's $\rho = -0.15$, $P < 0.001$). Copper bullets lost the same amount of mass independent of tissue type (Wald $\chi^2_1 = 1.72$, $P = 0.19$) or shooting distance (Spearman's $\rho = 0.002$, $P = 0.98$).

DISCUSSION

The vast majority of hunters used lead bullets. Three caliber classes dominated cartridge choice among the hunters, 7.62 mm, 9.3 mm, and 6.5 mm. Hunters with larger calibers tended to use copper bullets more frequently. This is probably related to the poor stabilization of homogeneous bullets fired from smaller calibers because of a mismatch between bullet length and barrel twist (Caudell et al. 2012, Carlucci and Jacobson 2014). Finnish hunters used copper bullets more frequently than did hunters in Norway and Sweden.

Bullet penetration characteristics are important and many hunters believe that complete penetration (in and out) will provide a better blood trail for tracking wounded animals (Jeanneney 2006, Trinogga et al. 2013). The length of the bullet path to achieve complete penetration increases with body size, implicating that total drag on bullets will increase correspondingly. As expected, complete penetration depended on body size and was most frequent for moose calves, followed by yearlings and adults. This effect of body size is supported by Trinogga et al. (2013), who reported

Table 3. Estimated total amount (kg) of lead and copper deposited in moose harvested in Fennoscandia (Finland, Sweden, and Norway) during the 2013/2014 hunting season. Metal loss from bullets was based on retention mass of bullets retrieved from harvested moose during the 2004/2005 and 2006/2007 hunting seasons. We divided bullets into 3 types and pooled cartridges into 5 caliber classes to obtain reasonable sample sizes. We estimated the total amount of lead and copper deposited in moose carcasses during 2013/2014 hunting season by multiplying the number of harvested moose per bullet type and caliber class by the estimated deposited metal per moose (metal loss per bullet times spent bullets per moose).

Bullet type	Caliber class	*n* harvest moose in sample	Estimated *n* harvested in Fennoscandia	Metal loss per bullet (g)	Bullets per moose	Deposited lead and copper (kg)	Total lead and copper (kg)
Lead core	6.5 mm	361	13,359	2.60	1.74	61.33 ± 14.01	689.5 ± 129.5 (lead)
	7.62 mm	1,356	50,179	2.74	1.69	232.89 ± 22.35	
	8.58 mm	36	1,332	4.51	1.42	9.97 ± 6.62	
	9.3 mm	252	9,325	3.91	1.60	59.64 ± 16.51	
	≥9.52 mm	93	3,441	4.27	1.63	26.08 ± 14.89	
Bonded lead core	6.5 mm	144	5,329	0.92	1.68	9.04 ± 6.44	
	7.62 mm	1,418	52,473	2.77	1.69	246.92 ± 23.68	
	8.58 mm	68	2,516	2.15	1.43	8.66 ± 5.48	
	9.3 mm	197	7,290	2.26	1.51	26.01 ± 10.95	
	≥9.52 mm	67	2,479	2.03	1.49	8.95 ± 8.07	
Copper	6.5 mm	18	666	1.99	1.78	3.80 ± 3.7	20.6 ± 14.7 (copper)
	7.62 mm	352	13,026	0.41	1.68	9.20 ± 4.15	
	8.58 mm	22	814	0.30	1.59	0.62 ± 0.62	
	9.3 mm	80	2,960	1.02	1.58	5.54 ± 4.88	
	≥9.52 mm	22	814	0.65	1.36	1.42 ± 1.42	

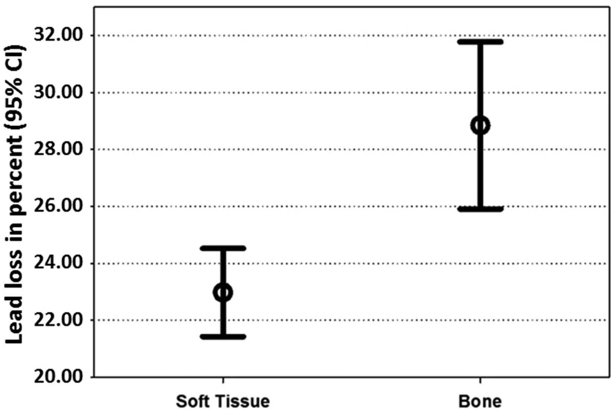

Figure 4. Lead loss (%) from bullets after penetration of bone and soft tissues, retrieved from moose harvested during the 2004/2005 and 2005/2006 hunting seasons in Fennoscandia (Norway, Sweden, and Finland).

complete penetration in 33 out of 34 shot wild boars, roe deer, chamois (*Rupicapra rupicapra*), red deer, and fallow deer. The body size of most of these species is smaller than a moose calf.

One main reason for bonding the lead core to the jacket is improved resistance to mantel separation, which is a serious functional failure. Another intended advantage is greater retention mass. Surprisingly, mantel separation occurred as frequently for bonded lead-core bullets as for lead-core bullets.

How Valid Are the Assumptions?

We made the assumptions that bullet mass loss from retrieved bullets was equal to the amount of metal deposited in the body of shot moose and metal loss from retrieved bullets were comparable to metal loss from bullets exiting the body. Lead and copper bullets deform very differently from full metal-jacketed ones, which mainly deform if they tumble and either flatten radially or break as a result of the weakening of the jacket at the cannelure (Berlin et al. 1988). Lead bullets expand because of the force acting on the exposed lead tip at impact. The drag forces generated by the stagnation pressure at the exposed bullet tip exceeds the yield limit for lead, which then behaves like an incompressible fluid (MacPherson 2005, Kneubuehl et al. 2011). Thus, pressure disperses within the floating lead and acts on the jacket from inside the bullet causing it to burst (Berlin et al. 1988, Kneubuehl et al. 2011). Deformation is extremely rapid, taking place within 0.1 ms (Berlin et al. 1988, Kneubuehl et al. 2011). As a result of the high velocity, significant deformation and fragmentation is present after 2–4 cm of tissue penetration and it continues as long as the stagnation pressure exceeds the yield limit (Berlin et al. 1988, MacPherson 2005, Kneubuehl et al. 2011).

Copper bullets expand in a similar manner because of the same mechanisms as long as the penetrated medium enters the hollowed-out tip and bursts the bullet as a result of the sudden increase of pressure in the cavity (Kneubuehl et al. 2011). Thus, it is reasonable to assume that all shed lead and copper will remain inside the animal as long as there is bullet seizure in tissue.

We cannot certainly say that bullets passing completely through moose shed the same amount of metal to tissue as bullets retrieved from moose tissue. Bullet deformation depends not only on bullet design, but also on impact velocity and the time for which the bullet tip is subjected to pressure. Penetration depth is directly proportional to sectional density and inversely proportional to energy transfer (Kneubuehl et al. 2011). Energy transfer strongly depends on the size of the frontal area; therefore, penetration depth decreases as bullet expansion increases (Wolberg 1991). It is therefore possible that we have overestimated lead deposition to tissue because exiting bullets probably possess less expansion and fragmentation of the lead core. On the other hand, we suggest a mechanism whereby bullets might lose a lot of mass and still exit from the animal. Bullets that penetrate large bones may become cylindrical in shape because bent-out jacket parts, supporting the protruding lead mushroom, are stripped off or flattened out during penetration. Even though they have lost a lot of lead, they might still pass through the moose because of a small frontal area that easily penetrates the skin on the exit side of the animal (the same applies for copper bullets). A fully expanded bullet of approximately similar retention mass will need much more energy to pass through the body. Thus, it is very difficult to determine if the estimated amount of deposited metal in the carcass is too high or too low.

Data sampling took place in 2004/2005 and 2005/2006 hunting seasons, whereas the number of harvested moose we use is derived from the 2013/2014 hunting season. Even though metal loss from fragmenting bullets probably is reasonably stable over time, we cannot assure that the distribution of rifles, cartridges and bullet types among hunters remained unchanged between the period of our study and the later hunting season. However, because hunters seem to be quite conservative and firearms tend to be retained over long periods, it is probable that no significant change in the use of calibers and bullets occurred during this period.

Because respondents in Sweden and Finland were selected randomly, but self-selected in Norway, the question of potential nonresponse bias emerges. Thus, Norwegian respondents could include hunters with certain caliber or bullet preferences or shooting habits that differ from random respondents. However, because bullets from Norway contributed only 5% of the total amount and 18% of the questionnaires, we do not expect any marked effect of this bias. Further, one might expect that metal loss from bullets is independent of origin as long as the penetrated medium is fully comparable. That said, metal loss from bullets used with recreational hunting is very complex and addressing all variables is not feasible. For example, for a given bullet, metal loss might vary with shot placement, type of cartridge, type of penetrated tissue, shooting range, length of the permanent wound cavity, and water content in fur. Thus, individual shooting habits might in fact affect metal loss from bullets, because hunters tend to prefer different points of aim. The complexity and diversity of uncontrollable factors regarding this topic will therefore raise difficulties when attempting to design replicable studies intended to represent this aspect of recreational hunting.

Deposited Metal in Moose Tissue

Surprisingly, loss of metal did not depend on body size for any of the bullet types. This suggests that there is bullet seizure in tissue after a certain loss of mass. The important difference is that copper bullets lost much less metal on average (0.7 g) compared with lead-core bullets (3.0 g) and bonded lead-core bullets (2.6 g). The superior resistance to abrasion of copper compared with lead is probably due to lower ductility, harder surface, and higher yield limit. Similar to our findings, few fragments in tissues of ungulates shot with copper bullets have been reported from other studies (Hunt et al. 2006, Irschik et al. 2013, Cruz-Martinez et al. 2015). This resistance to fragmenting applies primarily to copper bullets intended to deform. However, partially fragmenting copper bullets have recently appeared on the market. These bullets shed 4–6 relatively large fragments (petals) from the frontal area on impact where after they propagate sideways into tissue while the remaining rear shank penetrates deeply and normally exit the body. The intention of this design is increased wounding and killing efficiency due to fragments as suggested by Fackler et al. (1984). Lead-core bullets exhibited a correlated increase in lead loss with increasing caliber; this was not evident for bonded lead-core and copper bullets. Apparently, bonding of the lead core to the jacket seems to reduce lead loss to some degree.

Our results are similar to Knott et al. (2010), who estimated that 6.85-mm-caliber, 8.39-g (130 grains) lead-core bullets deposited 17% of their weight as fragments into carcasses of red deer and roe deer. Knott et al. (2010) presumed that they might have lost smaller fragments as a result of low resolution of the radiographs. Their concern seems to be relevant because our results indicate about 25% lead loss due to fragmentation.

Lead Contamination of Carcasses, Meat, and Offal

Lead residues from hunting bullets may have serious implications for human, wildlife, and environmental health. We estimated that lead bullets used to harvest 166,000 moose during the 2013/2014 hunting season in Fennoscandia deposited 690 kg of lead in the carcasses.

It is difficult to estimate the amount of lead consumed by people. According to Knott et al. (2010), 83% of the total amount of deposited lead fragments remained in the carcass (including heart, lungs, liver, and kidneys), whereas 17% were found in the viscera (stomach, intestines, and spleen). In Fennoscandia, the lungs, diaphragm, and liver are also left in the forest and we estimated that ≥30% of the lead would be in the gut pile and offal. Thus, 483 kg of lead may remain in edible parts of moose harvested in Fennoscandia. Several studies show that considerable amounts of lead are found in consumer packages of venison, especially in ground meat (Cornatzer et al. 2009, Hunt et al. 2009, Lindboe et al. 2012). According to Tsuji et al. (2009) and Falandysz et al. (2005), tissues surrounding the wound channel, embedded with fine dust particles of lead from lead bullets, are used in processed food, such as pies, stew, and sausages. Grund et al. (2010) documented with X-ray imaging that lead fragments can spread ≥45 cm from the wound channel in animals shot with lead bullets.

Other studies show that people consuming meat from game shot with lead bullets or shot have greater blood levels of lead compared with the general population (Iqbal et al. 2009, Verbrugge et al. 2009, Bjermo et al. 2013, Meltzer et al. 2013) and lead exposure from spent ammunition poses significant health risk both for human consumers (Kosnett 2009, Knott et al. 2010, Green and Pain 2012, Bellinger et al. 2013, Arnemo et al. 2016) and scavenging animals (Fisher et al. 2006, Knott et al. 2010, Bellinger et al. 2013). Madsen et al. (1988) showed that human patients with one or two lead pellets in the appendix, identified by radiography, had blood lead levels almost twice as high as matched controls. These authors did not retrieve pellets from the patients but stated that "the weight of one single lead pellet is often several hundred milligrams" (Madsen et al. 1988: pp 745). Shot #3, #4, and #5, commonly used for bird hunting, contain 237 mg, 202 mg, and 168 mg of lead, respectively. According to our estimation, moose harvested with lead bullets in Fennoscandia contain on average 4,668 mg of lead, which is up to 28 times the amount of the lead in a single pellet used for bird hunting.

Recommendations on dietary intake of meat from cervids hunted with lead bullets, butchering and trimming practices, and handling of waste tissues have been released both in Norway (Norwegian Scientific Committee for Food Safety 2013) and Sweden (Bjerselius et al. 2014, Kollander et al. 2014). The Norwegian recommendations are only based on a literature review, whereas the Swedish ones are partly based on studies of a limited number of cervids and birds killed with lead-based ammunition.

Moose harvested in Fennoscandia are eviscerated in the field and the intestinal tract, liver, spleen, kidneys, lungs, and diaphragm are left in the forest before transporting the carcass out for butchering. These remains can contain a large proportion of the lead fragments if animals were shot with lead bullets. Butchering practices and the extent of trimming vary. Some of the bones and other tissues not used for human consumption may be used to feed dogs, whereas the rest is transported back into the forest or used for baiting red foxes (*Vulpes vulpes*) or other carnivorous game species. Moose meat can be sold commercially; and these carcasses, usually together with required organs for meat inspection (kidneys, liver, spleen, lungs, and heart), are processed at small butcheries. There are no public statistics available in any of the countries in Fennoscandia, but Wiklund and Malmfors (2014) estimated that 12% of the moose harvested in Sweden are processed in this way. Professional butchers are required to send their waste for incineration.

Pattee et al. (1981) found that an initial dose of 10 #4 lead pellets (2.02 g of lead) fed to bald eagles (*Haliaeetus leucocephalus*) was lethal and that one bird had only 1 pellet (202 mg) in the stomach at the time of death 20 days later; 6 pellets had been regurgitated, but they were unable to account for 3 pellets. Carrion eaters will consume gut piles and offal and also animals fatally wounded by lead bullets and not recovered by the hunters. Our estimate is that 30% of the lead deposited by bullets in harvested moose remains in gut piles and offal (i.e., 207 kg). Assuming that 12% of the animals are handled by professional hunters (Wiklund and Malmfors 2014), we estimate the net amount of lead in gut piles and offal available to scavengers was about 182 kg during the 2013/2014 hunting season. Reports on wounding rates (cited in Stokke et al. 2012), show that the number of moose fatally wounded and not retrieved by the hunters is approximately 2% of the number of animals actually harvested. Thus, close to 3,000 carcasses are available for scavengers each year. Assuming that each of these carcasses contain $\geq$2.77 g of lead (average lead loss per bullet), this amounts to 8 kg of lead. The total amount of lead in gut piles, offal, and carcasses is 215 kg in 1 year in Fennoscandia. This constitutes >100,000 lethal lead doses for eagles. Not surprisingly, Helander et al. (2009) reported that lead poisoning from lead-based ammunition in shot game is a significant mortality factor for the white-tailed sea eagle (*H. albicilla*) in Sweden.

MANAGEMENT IMPLICATIONS

Lead bullets used for moose hunting in Fennoscandia pose a significant health risk for human consumers and scavenging animals that ingest lead deposited in moose tissue. Copper bullets are a nontoxic alternative that are readily available and already used for big game hunting. Copper bullets perform more consistently than lead bullets and retain much greater mass. Hunters and governments should consider ways to reduce the use of lead-based ammunition for hunting moose and other big game species, to protect human health and the environment.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

A. Applied cartridges in Fennoscandia, ordered by frequency of use.

B. Applied expanding hunting bullets in Fennoscandia, ordered by frequency of use.