Eur J Wildl Res
DOI 10.1007/s10344-016-1044-7

REVIEW

Non-lead rifle hunting ammunition: issues of availability and performance in Europe

Vernon G. Thomas[1] · Carl Gremse[2] · Niels Kanstrup[3]

Received: 31 May 2016 / Revised: 9 August 2016 / Accepted: 22 August 2016

Abstract Non-lead hunting rifle bullets were developed to make superior quality ammunition, and the need to reduce lead exposure of wildlife and humans. European and US hunters' concerns about non-lead bullets involve perceptions of availability, costs, efficacy, accuracy, toxicity, and barrel fouling. These concerns are politically powerful and, if not addressed, could thwart greater use of non-lead ammunition. Product availability (i.e. that which is made) of non-lead rifle ammunition in a wide range of calibres is large in Europe and is suited for all European hunting situations. At least 13 major European companies make non-lead bullets for traditional, rare, and novel rifle calibres. Local retail availability is now a function of consumer demand which relates, directly, to legal requirements for use. Costs of non-lead and equivalent lead-core hunting bullets are similar in Europe and pose no barrier to use. Efficacy of non-lead bullets is equal to that of traditional lead-core bullets. Perceptions of reduced accuracy and greater barrel fouling must be addressed by industry and hunter organizations and, if verified, resolved. Non-lead bullets are made in fragmenting and non-fragmenting versions, but there is no advice to hunters yet given on the use of these two bullet types. The non-toxicity of ingested metallic copper, the principal component of non-lead bullets, is scientifically well-established.

Keywords Bullets · Ballistics · Concerns · Efficacy · Fragmenting · Fouling

✉ Vernon G. Thomas
vthomas@uoguelph.ca

Carl Gremse
carl.gremse@hnee.de

Niels Kanstrup
nk@danskjagtakademi.dk

[1] Department of Integrative Biology, College of Biological Science, University of Guelph, Guelph, Ontario N1G 2W1, Canada

[2] Leibniz-Institute for Zoo and Wildlife Research, Berlin, and Eberswalde-University, Wildlife Department, Schicklerstrasse 5, 16225 Eberswalde, Germany

[3] Danish Academy of Hunting, Skrejrupvej 31, 8410 Rønde, Denmark

Introduction

A growing body of scientific evidence indicates that a transition to non-lead (synonymous with lead-free) rifle bullets is advisable to reduce lead exposure in wildlife and humans from ingested lead in spent hunting ammunition (Krone and Hofer 2005; Watson et al. 2009; Delahay and Spray 2015; Kanstrup et al. 2016a). What began in the state forests of Germany and, now, a total ban on use of lead-based ammunition in three German states (Gremse and Rieger 2015) has spread (beginning 2019) to California, USA, as a practice to protect endangered birds of prey, especially the California condor (*Gymnogyps californianus*) (Thomas 2013). The rationale for this transition is based on reducing lead exposure in scavenging species of wildlife (Berny et al. 2015; Helander et al. 2009; Madry et al. 2015; Nadjafzadeh et al. 2013) and humans who consume game meat containing lead bullet fragments (Dobrowolska and Melosik 2008; Fachehoun et al. 2015; Knutsen et al. 2015). Non-lead bullets were developed, initially, to produce non-fragmenting, high quality expanding ammunition capable of deep penetration. Over 30 US companies manufacture, or load, non-lead bullets into rifle ammunition, as do13 of the major European arms companies, and there is international trade in these products (Thomas 2013). Most companies produce loaded cartridges by assembling

Published online: 21 September 2016

components made by others: only a few major companies make all of the components for their rifle cartridges.

Compared to the different types of lead-core rifle ammunition, little has been written about the transition to, and use of, non-lead bullets in hunting, despite the advertising claims of manufacturers. Consequently, concerns have arisen among hunters and their representative organizations about the mandatory use of non-lead bullets (Epps 2014). These concerns are mainly oral, anecdotal, statements made at government-public hearings on the possible adoption of non-lead ammunition in hunting, or listed in survey questions to hunters (Chase and Rabe 2015). While these concerns are not based on the scientific literature, they are able to influence public attitudes and the course of government policy.

This paper addresses the principal and valid concerns of European hunters about using non-lead rifle ammunition that are impediments to making this transition. They pertain, mainly, to the retail availability and prices of lead substitutes in Europe; their accuracy and efficacy in killing game humanely; whether to use fragmenting or non-fragmenting non-lead types; toxic concerns of copper-based bullets; and issues of greater barrel fouling.

Definition of non-lead bullets

There are no international or national regulations that define the composition of non-lead bullets. California states only that they contain less than 1 % by mass of lead (California Department of Fish and Wildlife 2015a). They are, currently, made from solid pure copper or gilding metal (approx. 95 % copper and approx. 5 % zinc) and may include inserts made from tin or tungsten alloys (Oltrogge 2009; Paulsen et al. 2015). Lead-core[1] and non-lead bullets do not have identical properties, despite both having the same surface material of copper. Copper has a density of 8.96 g/cm^3, but the lead-antimony core of a bullet is approximately 11.0 g/cm^3, so lead-core bullets have a density approx. 20 % greater than copper bullets. Thus, for a given rifle calibre, and given bullet mass and shape, non-lead bullets are longer, which in some cases will demand a faster twist in the rifle barrel to achieve a sufficient stabilization to ensure accuracy. They also need to be driven at a higher velocity to achieve the same ballistic effects as the equivalent lead-core bullet (Thomas 2013). Non-lead bullets are designed to be expanding and may be made as either fragmenting[2] or non-fragmenting types. The production of non-lead bullets is currently represented mainly by US companies who either make and/or load non-lead rifle ammunition (California Department of Fish and Wildlife 2015a) and a growing number (Table 1) of European ammunition makers who offer lines of non-lead bullets for stalking and driven game hunting.

Availability of non-lead rifle ammunition in Europe

As of 2014, all of the major US rifle ammunition makers featured non-lead rifle ammunition, both centre-fire and rim-fire, in an array of popular calibres. These same companies[3] also produced non-lead slugs for shotguns, bullets for muzzle-loading rifles, non-lead bullets in bulk for hand-loaders (Thomas 2013), and export to European-Scandinavian markets (Knott et al. 2009). In 2013, 37 US and foreign on-line ammunition distributors collectively advertised non-lead ammunition in 51 different rifle calibres (Thomas 2013). Although no European country has yet regulated the use of non-lead rifle ammunition for all hunting on a national basis, the principal 13 European rifle ammunition makers have already developed their own brands. This is in response to the ongoing demand for and evaluation of non-lead rifle ammunition in Germany (Gremse and Rieger 2015), and possibly, for export into the growing North American market. The European ammunition makers may also be preparing their business for possible future European state-wide transitions to non-lead ammunition and are developing their own non-lead products to have an established market presence. The levels of production can always be geared up to future projected demand.

The major companies, Blaser, Brenneke, Fiocchi, Geco, Lapua, Norma, Rottweil, RWS, Sako, Sellier & Bellot, Sax, Sauvestre, Schnetz, and Hornady International, list calibres suitable for hunting every European game species and for every commonly used rifle (Table 1). A large range of rifle calibres (.223 to .500 Jeffrey) is listed across these 13 companies (Table 1), and they are made for both bolt-action and break-action rifles. Thus, the product availability (i.e. that which is manufactured, as opposed to what is commonly available at the retail level) of non-lead rifle ammunition is not limiting in Europe. The bullets in these non-lead calibres are listed as either fragmenting or non-fragmenting, and the company RWS lists both types of bullets in its catalogue (Table 1). For the hunting of very large (e.g. African plains) game, the companies Sako, Sauvestre, and Sax also offers a line of non-lead bullets in calibres from 9.3 × 74R to .500 Jeffery (Table 1). The company Schnetz offers lead-free ammunition in calibres that are not commonly used for hunting (Table 1) and so precludes the obsoletion of rarer European calibres and older rifles during a potential transition.

[1] A lead-core bullet has a copper (or gilding metal) jacket that surrounds the lead-alloy core which extends to an open tip in semi-jacketed bullets (conventional ammunition).

[2] The anterior part of fragmenting bullets breaks into three to four large pieces on entry, penetrating adjacent tissues, while the residual part of the bullet continues along its initial route of entry.

[3] Barnes Bullets LLC, Hornady, Federal, Remington, and Winchester.

Table 1 European manufacturers and major importers of non-lead hunting rifle ammunition, indicating the assembled rifle ammunition produced. This list is not an exclusive listing of European makers and importers, only the principal companies. The array of cartridge calibres is from company websites as of March 26, 2016. Website addresses for the companies listed are below

Brenneke Non-lead TUG Nature+	**Brenneke Non-lead TAG**	**RWS Evolution Green**	**RWS HIT**	**RWS Bionic Yellow**	**Blaser CDC Bullet**	**Norma Barnes TSX**	**Norma Kalahari**	**Hornady International**	**Hornady Super-performance**	**Sako Powerhead Barnes TSX**
7 × 57 7 × 57R 7 × 64 7 × 65R .308 Win .30–06 .30R Blaser .300 Win Mag 8 × 57JS 8 × 57JRS 8 × 68S 9.3 × 62 9.3 × 74R	.308 Win .30–06 .300 Win Mag 8 × 57JS 8 × 57JRS 9.3 × 62 9.3 × 74R	.270 Win .308 Win .30–06 .300 Win Mag .30R Blaser 7 × 57R 7 × 64 7 × 65R 7 mm Rem Mag 8 × 57JS 8 × 57JRS 9.3 × 62 9.3 × 74R	.308 Win .30–06 .300 Win Mag 7 mm Rem Mag 7 × 64 7 × 65	.308 Win .30–06	7 × 64 7 × 65R 7 mm Rem Mag .308 Win .30–06 .300 Win Mag .30R Blaser 8 × 57JS 8 × 57JRS 8 × 68S 9.3 × 62 9.3 × 74R	7 mm Rem Mag .300 Win Mag .375 H&H	.270 Win .270WSM .280 Rem 7 × 64 7 mm Rem Mag .308 Win .30–06 .300Win Mag .300 WSM	6.5 × 55 7 × 64 7 × 57 7 × 65R 8 × 57JS 8 × 57JRS 9.3 × 62 9.3 × 74R	.223 Rem .243 Win .25–06 Rem .270 Win 7 mm Rem Mag 7 mm–08 .308 Win .30–06 .300 Win Mag .338 Win Mag .375 H&H	270 Win .308 Win .30–06 9.3 × 62 9.3 × 66 Sako 9.3 × 74R .375 H&H
Nickel-plated steel jacket, tin core	Copper	Tin core nickel-plated	Copper nickel-plated	Brass	Copper	Copper	Gilding metal nickel-plated	Copper	Copper	Copper
Fragmenting	Partially fragmenting	Partially fragmenting	Non-fragmenting	Partially fragmenting	Non-fragmenting	Non-fragmenting	Partially fragmenting	Non-fragmenting	Non-fragmenting	Non-fragmenting

Sako Powerhead II Barnes TTSX	**Sako DGS Solid**	**Fiocchi Freccia Nera**	**Sellier & Bellot eXergy**	**Geco Zero**	**Sauvestre**		**Sax KGJ**		**Schnetz KG**	**Lapua Naturalis**
.222 Rem .243 Win 6.5 × 55SE .30–06 .308 Win .300 Win Mag 7 × 64 7 mm Rem Mag 8 × 57JS	9.3 × 62 9.3 × 74R .375 H&H .416 Rigby .450 Rigby .500 Jeffery	308 Win .30–06	6.5 × 55SE .270 Win 7 × 57 7 × 57R 7 × 64 7 × 65R 7 mm REM Mag .308 Win .30–06 .300 Win Mag 8 × 57JS 8 × 57JRS 9.3 × 62 9.3 × 74R	.300 Win Mag .30–06 .308 Win 7 mm Rem Mag 7 × 57 7 × 57R 7 × 64 7 × 65R 8 × 57JRS 8 × 57JS 9.3 × 62 9.3 × 74R	.243 Win 6.5 × 57 .270 Win .270 WSM .280 Rem 7 mm ’08 Rem 7 × 57R 7 × 64 7 × 65R 7 mm Rem Mag .30–06 .308 Win .300 Win Mag .300 WSM .300 Wby Mag	….cont. .30 R Blaser 8 × 57JRS 8 × 68S 35 Whelen 9.3 × 62 9.3 × 74R .338 Win Mag .375 H&H .404NE .458 Win Mag .458 Lott	.223 Rem .22–250 .243 Win 6.5 × 55 6.5–284 6.5 × 57R 6.5 × 68 .270 Win .270 WSM 7 × 57 7 × 57R 7 × 64 7 × 65R 7 mm Rem Mag 7 mm WSM 7.5 × 55 Swiss .308 Win .30–06	….cont. .300 Win Mag .300 WSM 8 × 57JS 8 × 57JRS 8 × 68S .338 Lap Mag 8.5 × 63 8.5 × 65R 9.3 × 62 9.3 × 72R 9.3 × 74R .375 H&H 10.3 × 60R .416 Rem Mag	22 Hornet 5.6 × 50R .222 Rem 5.6 × 52R 6 × 62 6 × 62R 6.5 × 57 6.5 × 63 mm 6.5 × 65 6.5 × 65R 7 × 66 7 × 75R .30R Blaser .300 Wby Mag .300 RUM 8 × 75RS .338 Win Mag	.243Win 6.5 × 55SE .308 Win .30–06 8 × 57JS .338 Lapua 9.3 × 62
Copper, plastic tip	Brass	Copper	Copper	Copper, tin core	Copper, plastic tip		Copper, plastic tip		Copper, plastic tip	Copper
Non-fragmenting	Non-expanding, Non-fragmenting	Non-expanding	Non-expanding	Fragmenting	Non-fragmenting		Fragmenting		Fragmenting	Non-fragmenting

URLs: www.brenneke-ammunition.de, https://rws-munition.de, www.blaser.de, www.norma.cc, www.hornady.com, www.sako.fi, www.fiocchigfl.it, www.sellier-bellot.cz, www.geco-munition.de, www.sauvestre.com, www.sax-munition.de, www.schnetz.at, www.lapua.com

Regulation will be the most important factor determining both the product availability and, especially, the local retail availability of non-lead ammunition, besides influencing competitive prices (Thomas 2015). This was the case when the US federal government banned nationally the use of lead shotgun ammunition for waterfowl hunting in 1991 and ushered in the rapid transition to the mandatory use of lead-free shot. However, it is interesting to note the large product availability of non-lead bullets among the 13 European companies (Table 1) even though there is, comparatively, very little regulation requiring their use in European hunting.

Non-lead bullets are made in fewer bullet weights per calibre

This concern arises, partly, from the lower density of copper and gilding metal non-lead bullets compared to equivalent lead-core bullets, resulting in their being of greater length. The constraint applies across all calibres and means that non-lead bullets have to be seated deeper in the cartridge case to prevent their extending into the rifled bore of the barrel. Thus, makers may not produce the largest mass non-lead bullets per rifle calibre. For example, lead-core bullets of 150 grains (9.72 g) mass, and heavier, are typical for the calibre .270 Winchester, but non-lead copper bullets are available mainly in 130 grains (8.42 g) and less. This does not preclude the use of non-lead bullets of this mass, consistent with energy delivered and shooting distance. However, a given bullet mass may be excluded by national regulation setting the minimum allowable bullet mass, e.g. in Denmark, where 9.0 g (138.9 grains) is legally required to hunt deer larger than roe deer. Hence, for this reason, or if hunters insist on using heavier mass non-lead bullets, they need to use ammunition and rifles of larger calibre.

Another factor relates to only the most commonly used non-lead bullet weights and shapes being made currently, and in smaller production batches or runs, in the absence of an established, regulated, market for non-lead bullets. This could result in the appearance of scarcity and unavailability of preferred bullet weights and types to hunters.

Costs of non-lead rifle ammunition

Hunters commonly feel that costs play a large role in this form of recreation and that any increase in the projected price of ammunition may cause them to leave the sport. This fear was amplified by a report commissioned for the US hunting/shooting community (Southwick Associates Inc 2014). This concern also relates to a regulated requirement for use, and to the local demand factor. Small retailers cannot compete with large specialty stores on a volume of sales/price basis. Similarly, it may cost more to import a particular, uncommon, brand or calibre and bullet type from a distant supplier. Purchase of ammunition on-line may result in lower costs (where allowed) compared to local store purchases. However, concerns about the cost of rifle ammunition used in hunting are exaggerated, especially when related to the total cost of rifle hunting (see Thomas (2015) for a UK comparison). A comparison of prices for lead-core and non-lead rifle ammunition was presented in Thomas (2013). That study compared the retail prices of nine commonly used calibres (from .223 to .416) of assembled rifle ammunition in different weights, types, and brands available across the USA. It found that prices for the two types of ammunition were generally comparable, and where the non-lead products cost more, the relatively small increase was not enough to deny purchase and use. The same result applies to bulk purchase of bullets for ammunition hand-loaders: lead-core and non-lead bullets cost about the same at the retail level. An economy of scale effect is likely to lower the price of non-lead ammunition further, as more hunters adopt this ammunition. A regulated use of non-lead rifle ammunition in hunting would increase an economy of scale effect across the most widely used bullet calibres. Kanstrup (2015) concluded that non-lead rifle ammunition is largely available in all normal calibres (particularly 6.5 × 55, 308 Win. and 30–06) in Danish hunting stores at prices comparable to equivalent lead products. The lowest range of availability was found in the small calibres (<6 mm). In Germany, Gremse and Rieger (2012) found non-lead rifle ammunition in adequate supply across the range of hunting calibres typically used, with ammunition for small calibres (≤6 mm) being offered mostly by specialty manufacturers. Pricing comparisons in Germany mirror the conclusions of Thomas (2013).

The above consideration applies only to ammunition used in hunting. Rifle target shooters may fire many more rounds during training and practice, and should the price of their selected non-lead ammunition exceed that of the lead equivalent, an extra cost is realized, unless economy of scale effects eventually render differences slight or non-existent.

Performance of non-lead rifle bullets fired through traditional rifle barrels

Accuracy of bullets

The accuracy of a rifle bullet (i.e. the technical ability of the rifle in combination with the actual cartridge to achieve a consistent hitting point independently of the shooters' skills) is a product of an array of different factors including length, quality and state of the rifle barrel, the pressure and speed of the powder burning, the velocity of the bullet, and not least how the bullet is introduced to and led by the rifling of the barrel. Most of these factors apply equally to lead-core and non-lead bullets. However, due to their lower density, copper bullets contain a greater volume to achieve an equal bullet mass; hence, they are longer than equivalent lead types. This effect is more pronounced (second power) for small calibres than for greater calibres. It may be counteracted by reducing bullet weight which, again, may result in a need for higher velocity to satisfy demands for striking power.

A longer and/or lighter bullet creates two basic challenges. The first is to avoid increasing the total length of the cartridge and prevent the bullet from extending into the rifling of the barrel. This is normally solved by seating the bullet deeper in the cartridge case and/or using more pointed bullets to ensure that the bullet still has sufficient "free bore", which is crucial for pressure and accuracy. The second concerns the barrel rifling twist rate, which is key to stabilizing the bullet and optimizing accuracy. The twist rate is designed to stabilize the range of bullets and their respective velocities used in a particular calibre, and, in most existing rifles, is designed for lead-core bullets. The twist rate is normally expressed as the number of inches per turn (e.g. 10 ipt—also noted as 1:10 in the literature). Twist rates in hunting rifles range from approx. 1:6 to approx. 1:14. The twist in a rifle barrel of a given length is designed to stabilize the range of bullets normally used in that particular calibre. The basic rule is that, at the same velocity in the same calibre, longer bullets require lower (faster) twist rates than shorter bullets of the same weight. A change from using lead-core bullets to non-lead bullets may therefore challenge the twist construction of the particular rifle. This is particularly the case in small calibres and most pronounced in older rifle models. The twist in a given rifle cannot be modified. However, change of the barrel is a realistic solution; hence, the rifle can be modified to optimized use of non-lead ammunition. In a Danish case (Niels Kanstrup, personal testing and observation, 2016) and rifle (Sako cal. .222 REM, Twist Rate 1:16) that regularly showed great accuracy with lead-core bullets, the rifle was tested for accuracy at 100 m with non-lead bullets. In no case was the accuracy acceptable, and non-lead bullet groupings were 10.0+ cm in diameter. The stabilization was unacceptable and could not be improved by changing bullet shape or powder loads. The barrel was changed to a Lothar Walther barrel .222 REM Twist Rate 1:9 and tested. Stabilization and accuracy were then found acceptable (Table 2). Total price for the change is 650 Euros.

The bullet spin rate is an essential factor determining accuracy. It is undesirable to spin a bullet faster than necessary, as this can reduce accuracy and increase pressure, barrel wear, and the strain on the bullet jacket resulting in fouling.

Professional gun smiths can give the needed advice on the optimal twist rate based on the formula,

$$\mathrm{TW} = \frac{3.5\sqrt{V}\,D^2}{L}$$

where

TW Twist rate [inches per turn]
V Muzzle velocity [feet per second]
D Diameter (cal.) [inches]
L Total bullet length [inches], (Miller 2006)

Perceptions of increased barrel fouling from non-lead bullets

Every copper-jacketed bullet fired from a barrel leaves some copper residue (fouling) on the rifling of the barrel. It builds up with every bullet fired and, if not removed, may interfere with bullet placement accuracy and pressure. This applies also to non-lead bullets, and some shooters report greater copper fouling with these bullets than with similar lead-core bullets, thus requiring more frequent barrel cleaning.

Copper fouling is already recognized by different makers of non-lead bullets who have created shallow rings in the mid-posterior section of the bullet into which copper is displaced during its contact with the rifling. In this way, copper build-up is theoretically reduced. This is a feature of the non-lead bullets made by Barnes Bullets, Hornady, RWS, Cutting Edge Bullets, and others. The last-named company actually reduces the length of the bullet's region that engages the rifling, both to increase velocity and to reduce the amount of copper fouling in barrels. The nature of the material used to make the non-lead bullet may vary among companies. Thus, "pure copper", "annealed copper", "gilding metal", and "brass" are listed as choice materials to enhance ballistic performance. Annealing copper softens the metal made hard by shaping in die-made (swaged) bullets. Perhaps the greater extent of fouling (if real) can be attributed to the different metal types used. By way of comparison, the composition of non-lead bullets should be compared to the material used for jackets of lead-core bullets, for which metal fouling affecting accuracy does not appear to be a concern. In theory, the pure copper surface of non-lead bullets and that of copper-jacketed lead-core bullets should leave the same amount of fouling in a given barrel. The same consideration applies to bullets made from copper-zinc alloys (gilding metals).

Repeated firing with non-lead bullets during range practice can be expected to produce copper residue in the barrel bore, and it is customary to remove it after such practice. Under typical European hunting conditions in which a hunter uses a sighted-in rifle with a cleaned bore, many cartridges are not expected to be fired during a day's hunt, so the issue of extensive barrel fouling and reduced accuracy may not arise. This may be a simple issue of raising awareness and instructing hunters in proper gun maintenance. In the German field studies (Gremse and Rieger 2012), the average bag per person per

Table 2 Bullet grouping diameters for .222 Rem calibre lead-core and copper bullets fired from a Sako rifle after re-barrelling with a Lothar Walther barrel, twist rate 1:9. Grouping diameters are the means of three consecutive shots. Cartridges were hand loaded with the same primers, but varying amounts of Norma 200 rifle powder. Shooting distance was 100 m. The data show that the Lothar Walther barrel produced equally acceptable bullet groupings with copper or lead-core bullets. Results show that small diameter groups with the small calibre Barnes copper bullets can be produced, and that accuracy is influenced by powder charge

Barrel type	Barnes TSX 55 grain Copper bullets	Sierra 55 grain Lead-core bullets
Lothar Walther Twist rate 1:9	18 grains Norma 200 Velocity 877 m/s Group size 20 mm	19.0 grains Norma 200 Velocity 865 m/s Group size 25 mm
	18.5 grains Norma 200 Velocity 870 m/s Group size 37 mm	19.5 grains Norma 200 Velocity 860 m/s Group size 21 mm
	19.0 grains Norma 200 Velocity 877 m/s Group size 34 mm	

year was between 3.2 and 11.2 animals. Regular gun care during the hunting seasons and a thorough cleaning twice a year have become the norm during these 6-year-field trials with over 1300 participants. These practices have shown themselves suited to ensure rifle accuracy.

Complete penetrance of shot animals by non-lead bullets: the “through and through”

Lead-core bullets frequently loose lead (often about 50 % of the initial mass (Grund et al. 2010)) from the anterior region of the bullet as their anterior region expands (or “mushrooms”) during penetration. This effect is greater if the bullet strikes bone, and if the bullet’s lead core is “unbonded” as opposed to “bonded”. In the latter case, fusion of the lead core to the copper jacket results in a greater retention of the lead core during expansion. The recent development of lead-core bullets has emphasized “bonding” so that less lead is lost during penetration, resulting in greater bullet retained mass and greater penetration depth. The lead fragments that are released travel throughout the body and continue to wound tissues at some distance (approx. 30 cm diameter (Hunt et al. 2006)) from the entry point and away from the bullet’s initial trajectory (Caudell 2013; Gremse et al. 2014). Some hunters view this bullet core fragmentation as a positive adjunct to a swift kill (Caudell et al. 2012) and view negatively the performance of bullets that pass through the entire animal intact (a “through and through”). However, an exit wound with the consequent blood trail may allow easier pursuit of a wounded animal (Gremse and Rieger 2012).

The depth of penetration of an expanding bullet is a simple function of its energy at the point of entry relative to the total resistance provided by the carcass along the route of penetration. This applies to both lead-core and non-lead bullets. Lead-core bullets that loose much of their mass during penetration will dissipate fragments and their energy within the adjacent tissues and are so less inclined to exit the body. Much of the rationale behind the development of expanding non-lead bullets was to enhance bullet mass retention during entry to maximize depth of penetration and increase the amount of wounding in vital regions. Some of the modern types of non-lead bullets are constructed to retain 95+ % of their initial mass during penetration (e.g. Barnes TSX and TTSX, Nosler E-tip, Hornady, and RWS HIT) (Grund et al. 2010; Gremse et al. 2014). Non-lead bullets are now made in both fragmenting and non-fragmenting types (Table 1), with the non-fragmenting type designed to reduce the incidence of complete penetration.

Use of fragmenting versus non-fragmenting non-lead bullets

Lead-free, non-fragmenting, bullets are designed not to disintegrate during passage through animal tissues, despite expansion of the anterior region. Bullet manufacturers in the USA and Europe (Table 1) now produce non-lead bullets whose anterior region is engineered to fragment deliberately into four to six large pieces upon entry. Each piece assumes its own trajectory in the animal and continues to wound, while the intact posterior remnant of the bullet continues along its initial trajectory. These bullets are advertised for their lethality, presumably by providing a bullet that behaves in much the same way as unbonded lead-core bullets. Trinogga et al. (2013) evaluated the performance of three partially fragmenting, non-lead bullets (RWS Bionic Yellow, Moeller KJG, and Reichenberg HDBoH) used to kill German game. Their results showed the same killing efficiency as traditional lead-core bullets and the non-fragmenting non-lead bullets (Barnes TSX and Lapua Naturalis). However, the wounds caused by the partially fragmenting bullets were smaller in diameter than the wounds made by the non-fragmenting bullets. An analysis carried out for this review paper on bullet performance data obtained from German field trials using 5842 hunter reports with non-lead, non-fragmenting bullets ($n = 2892$) and non-lead, fragmenting bullets ($n = 2950$) showed the average distance run by the targeted animal to be significantly higher for non-fragmenting bullets compared to fragmenting bullets (24.1 m versus 21.9 m; two-tailed $t = 2.18$; $p = 0.02929$; $df = 5743$). This difference, while statistically significant at the 5 % level, had no practical relevance in German hunting practices.

Table 1 indicates the array of fragmenting and non-fragmenting bullets that are available in Europe. For the hunter desiring to use non-lead bullets, there is need to understand the ballistic advantages of using non-fragmenting or fragmenting bullet types, regardless of bullet calibre, bullet mass, and profile. This is where the hunting and ammunition industry should take the initiative in explaining under what circumstance each could be used to greatest effect. Another concern related to consumption of game meat is the question of fragmenting bullets leaving metal fragments in the carcass, which could abrade the mucosa and gingiva of animals and humans that ingest them. Nadjafzadeh et al. (2015) concluded from studies on white-tailed sea eagles (*Heliaeetus albicilla*) that only pure deforming non-fragmenting bullets are suited to prevent ingestion of bullet fragments. In this respect, expanding, but non-fragmenting, non-lead bullets are preferred to fragmenting types.

Lethality of non-lead bullets

The immediate lethality of a given bullet depends on where and at what angle it strikes the animal (determined by the shooter and dependent on his experience and shooting skills), the mass of the animal as a determinant of its physical size, and its terminal energy (determined by bullet construction and by the shooters choice of ammunition and shooting distance) (Gremse 2015). The present paper cannot deal with the first three parameters. However, it can assess the relative performance of expanding non-lead bullets that retain much of their mass and their ability to kill animals outright. British wild red deer (*Cervus elaphus*) and roe deer (*Capreolus capreolus*) were shot using either Barnes non-lead TSX bullets or traditional lead-core bullets in a comparative study (Knott et al. 2009). These authors reported that there was no significant difference between the two bullet types in terms of accuracy or observed killing power. This result was supported by the study of Trinogga et al. (2013), in which German wild deer and boar were shot with non-fragmenting non-lead bullets made by Barnes and Lapua. These authors found these bullet types as effective in killing as traditional lead-core bullets when used by German hunters. The maximum cross-sectional areas of the wound channels were independent of the type of bullet used, whether lead-core or non-lead, as was the gross morphology of the wound. Kanstrup et al. (2016b) performed an extensive comparison of the efficacy of traditional lead-core bullets and non-fragmenting copper bullets for taking roe and red deer under field conditions by Danish hunters. There was no practical difference in the performance of the two bullet types in producing rapid, one-shot, kills, based on the distances run by deer after being struck. In a lab study using ballistic soap as the target, Gremse et al. (2014) found that the Barnes TSX bullets showed very similar ballistic behaviours as traditional lead-core bullets across all measured parameters, except for their much lower fragmentation. Thus, if the shot is taken responsibly, non-lead fragmenting and non-fragmenting bullets are able to produce rapid and humane kills.

The non-toxicity of ingested non-lead bullet components

There is no national or international regulative process for determining the non-toxicity of lead bullet substitutes. The US Fish and Wildlife Service legal process of toxicity evaluation applies only to lead gunshot substitutes used for the hunting of migratory waterfowl in the USA (USFWS US Fish and Wildlife Service 1997). Only California has stipulated a maximum content of 1 % lead by mass in non-lead bullets (California Department of Fish and Wildlife 2015b). The non-toxicity of ingested metallic copper pellets to birds and mammals has been established scientifically (Thomas et al. 2007; Thomas and McGill 2008; Franson et al. 2013). The levels of copper residues remaining in carcass and meat of wild European game killed with non-lead bullets have been measured by Irschik et al. (2013) and Schuhmann-Irschik et al. (2015) and shown to pose no health risks to humans. Paulsen et al. (2015) measured the amount of metals released from fragmenting non-lead bullets under simulated conditions of meat storage and human ingestion. These authors compared the release of copper, iron, zinc, tin, and aluminium to recommended daily maximum intake levels for humans and reported that the amounts of these metals released were below the limits set by health agencies. Thus, there is no risk of metal toxicosis should birds or mammals ingest copper pieces released from spent non-lead bullets.

Paulsen et al. (2015) did indicate that one brand of non-lead bullet, Bionic Black, made by the company RWS, contained 1.9 % lead by mass, so exceeding the 1 % maximum level set by California. The other brands of non-lead bullets in the same study were found not to contain lead.

Actions suggested for the ammunition industries, hunting organizations, and governments

- Evaluate concerns of poorer “impact groupings” with non-lead bullets particularly in small calibres. If real, then determine their cause, especially as it may relate to twist rates of rifle barrels (Caudell 2013).
- Evaluate concerns of greater copper residues (fouling) in barrels from using non-lead bullets. If they are valid, relate to impact group size, and the composition of metal(s) used to make various non-lead bullets. Provide information to hunters on proper barrel maintenance.

- Provide information to hunters on the optimal non-lead bullet choice for accuracy and lethality for common calibres, including the use of fragmenting versus non-fragmenting bullets for hunting, and recommended twist rates for rifle barrels.
- Regulation has to be the basis of any transition to use of lead-free bullets and the basis of regulatory enforcement and hunter compliance. Regulation provides the ammunition makers with the assurance of markets for the new products, and leads to greater availability as manufacturers meet new demands that otherwise might not exist.

Acknowledgments We thank the reviewers for their constructive comments and improvements to this paper. We acknowledge the support to N. Kanstrup from 15 Juni Fonden, Arboretet, Kirkegårdsvej 3A, DK-2970 Hørsholm (grant number 2013-A-88). Research of C. Gremse was supported by the German Federal Ministry for Food and Agriculture, Rochusstraße, 1, 53123 Bonn (grant number 09HS023), the State of Mecklenburg West Pomerania Ministry for Agriculture, Environment and Consumer Protection, and the State of Brandenburg Ministry of Rural Development, Environment and Agriculture. Lars Thune Anderson kindly performed the shooting tests with copper and lead-core bullets detailed in Table 2.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Funding The authors are not funded by any ammunition maker, government department, university, or agency promoting an end to use of lead ammunition.

References

Berny P, Vilagines L, Cugnasse J-M, Mastain O, Chollet J-Y, Concour G, Razin M (2015) Vigilance poison: illegal poisoning and lead intoxication are the main factors affecting avian scavenger survival in the Pyrenees (France). Ecotoxicol Environ Saf 118:71–82. doi:10.1016/j.ecoenv.2015.04.003

California Department of Fish and Wildlife (2015a) Certified nonlead ammunition information. URL: http://www.dfg.ca.gov/wildlife/hunting/lead-free/certifiedammo.

California Department of Fish and Wildlife (2015b) Nonlead certification information for ammo manufacturers. URL: http://www.dfg.ca.gov/wildlife/hunting/lead-free/certification.html

Caudell J (2013) Review of wound ballistic research and its applicability to wildlife management. Wildl Soc Bull 37:824–831. doi:10.1002/wsb.311

Caudell JN, Stopak SR, Wolf PC (2012) Lead-free, high-powered rifle bullets and their applicability in wildlife management. Human-Wildlife Interac 6:105–111

Chase L, Rabe MJ (2015) Reducing lead on the landscape: anticipating hunter behavior in absence of a free nonlead ammunition program. PLoS ONE 10(6):e128355. doi:10.1371/journal.pone.128355

Delahay RJ, Spray CJ (eds) (2015) Proceedings of the Oxford lead symposium. Lead ammunition: understanding and minimising the risks to human and environmental health. Edward Grey Institute, Oxford

Dobrowolska A, Melosik M (2008) Bullet-derived lead in tissues of the wild boar (*Sus scrofa*) and red deer (*Cervus elaphus*). Eur J Wildl Res 54:231–235. doi:10.1007/s10344-007-0134-y

Epps CW (2014) Considering the switch: challenges of transitioning to non-lead hunting ammunition. Condor 116:429–434. doi:10.1650/CONDOR-14-78.1

Fachehoun RC, Lévesque B, Dumas P, St-Louis A, Dubé M, Ayotte P (2015) Lead exposure through consumption of big game meat in Quebec, Canada: risk assessment and perception. Food Addit Contam 32:1501–1511. doi:10.1080/19440049.2015.1071921

Franson JC, Lahner LL, Meteyer CU, Rattner BA (2013) Copper pellets simulating oral exposure to copper ammunition: absence of toxicity in American kestrels (*Falco sparverius*). Arch Environ Contam Toxicol 62:145–153. doi:10.1007/s00244-011-9671-1

Gremse C (2015) "Tierschutz im Jagdbetrieb" (in German). The German Veterinary Society (DVG) Friedrichstraße 17, 35392 Gießen, Germany. Summary in English pg. 90. ISBN 978-3-86345-300-8

Gremse C, Rieger S (2012) Bericht zu Entscheidungshilfevorhaben "Ergänzende Untersuchungen zur Tötungswirkung bleifreier Jagdgeschosse (09HS023) In German., Federal Ministry for Food and Agriculture, Available at https://www.researchgate.net/publication/271190631

Gremse C, Rieger S (2015) Lead from hunting ammunition in wild game meat: research initiatives and current legislation in Germany and the EU. In: Delahay RJ, Spray CJ (eds) Proceedings of the Oxford lead symposium. Lead ammunition: understanding and minimising the risks to human and environmental health. Edward Grey Institute, Oxford, pp 51–57

Gremse F, Krone O, Thamm M, Kiessling F, Tolba RH, Rieger S, Gremse C (2014) Performance of lead-free versus lead-based hunting ammunition in ballistic soap. PLoS ONE 9(7):e.102015. doi:10.1371/journal.pone.0102015

Grund MD, Cornicelli L, Carlson LT, Butler EA (2010) Bullet fragmentation and lead deposition in white-tailed deer and domestic sheep. Human-Wildl Interact 4:257–265

Helander B, Axelsson H, Borg H, Holm K, Bignert A (2009) Ingestion of lead from ammunition and lead concentrations in white-tailed sea eagles (*Heliaeetus albicilla*) in Sweden. In: Sci Total Environment 407:5555–5563. doi:10.1016/j.scitotenv.2009.07.027

Hunt WG, Burnham W, Parish CN, Burnham KK, Mutch B, Oaks JL (2006) Bullet fragments in deer remains: implications for lead exposure in avian scavengers. Wildl Soc Bull 34:167–170

Irschik I, Bauer F, Sager M, Paulsen P (2013) Copper residues in meat from wild artiodactyls hunted with two types of rifle bullets manufactured from copper. Eur J Wildl Res 59:129–136. doi:10.1007/s10344-012-0656-9

Kanstrup N (2015) Non-lead rifle ammunition—availability in Danish gun stores. Report 1508–2. Danish Academy of Hunting, Rønde

Kanstrup N, Thomas VG, Krone O, Gremse C (2016a) The transition to non-lead rifle ammunition in Denmark: national obligations and policy considerations. AMBIO 45:621–628. doi: 10.1007/s13280-016-0780-y

Kanstrup N, Balsby TJS, Thomas VG (2016b) Efficacy of non-lead rifle ammunition for hunting in Denmark. Eur J Wildl Res 62(3):333-340. doi: 10.1007/s10344-016-1006-0

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

Knutsen HK, Brantsæter AL, Alexander J, Meltzer HM (2015) Associations between consumption of large game animals and blood lead levels in humans in Europe: the Norwegian experience. In: Delahay RJ, Spray CJ (eds) Proceedings of the Oxford lead symposium. Lead ammunition: understanding and minimising the risks to human and environmental health. Edward Grey Institute, Oxford, pp 44–50

Krone O, Hofer H (2005) Bleihaltige Geschosse in der Jagd–Todesursache von Seeadlern? Institute for Zoo and Wildlife. Research, Berlin

Madry MM, Kraemer T, Kupper J, Naegeli H, Jenny H, Jenni L, Jenny D (2015) Excessive lead burden among golden eagles in the Swiss Alps. Environ Res Lett 10:034003. doi:10.1088/1748-9326/10/3/034003

Miller D (2006) Where did Grennhill's twist rule come from? Int J Impact Eng 32(11):1786–1799. doi:10.1016/j.ijimpeng.2005.06.001

Nadjafzadeh M, Hofer H, Krone O (2013) The link between feeding ecology and lead poisoning in white-tailed eagles. J Wildl Manag 77:48–57. doi:10.1002/jwmg.440

Nadjafzadeh M, Hofer H, Krone O (2015) Lead exposure and food processing in white-tailed sea eagles and other scavengers: an experimental approach to simulate lead uptake at shot mammalian carcasses. Eur J Wildl Res 61:763–774. doi:10.1007/s10344-015-0953-1

Oltrogge V (2009) Success in developing non-lead, expanding-nose centre fire bullets. In: Watson RT, Fuller M, Pokras M, Hunt WG (eds) Ingestion of lead from spent ammunition: implications for wildlife and humans. The Peregrine Fund, Boise, pp 310–315. doi:10.4080/ilsa.2009.0305

Paulsen P, Bauer F, Sager M, Schumann-Irschik I (2015) Model studies for the release of metals from embedded rifle bullet fragments during simulated meat storage and food ingestion. Eur J Wildl Res 61:629–633. doi:10.1007/s10344-015-0926-4

Schuhmann-Irschik I, Sager M, Paulsen P, Tichy A, Bauer F (2015) Release of copper from embedded solid copper bullets into muscle and fat tissues of fallow deer (*Dama dama*), roe deer (*Capreolus capreolus*), and wild boar (*Sus scrofa*) and effect of copper content on oxidative stability of heat-processed meat. Meat Sci 108:21–27. doi:10.1016/j.meatsci.2015.05.008

Southwick Associates Inc (2014) Effects of the ban on traditional ammunition for hunting in California on hunting participation and associated economic measures. Prepared for the national shooting sports foundation. Fernandina beach, Florida

Thomas VG (2013) Lead-free rifle ammunition: product availability, price, effectiveness, and role in global wildlife conservation. AMBIO 42:737–745. doi:10.1007/s13280-012-0361-7

Thomas VG (2015) Availability and use of lead-free shotgun and rifle cartridges in the UK with reference to regulations in other jurisdictions. In: Delahay RJ, Spray CJ (eds) Proceedings of the Oxford lead symposium. Lead ammunition: understanding and minimising the risks to human and environmental health. Edward Grey Institute, Oxford, pp 85–95

Thomas VG, McGill IR (2008) Dissolution of copper and tin from sintered tungsten-bronze shot in a simulated gizzard, and an assessment of their potential toxicity to birds. Sci Total Environ 394:283–289. doi: 10.1016/j.scitotenv2008.01.049

Thomas VG, Santore R, McGill IR (2007) Release of copper from sintered tungsten-bronze shot under different pH conditions and its potential toxicity to aquatic organisms. Sci Total Environ 374:71–79. doi: 10.1016/j.scitotenv.2006.10.004

Trinogga A, Fritsch G, Hofer H, Krone O (2013) Are lead-free hunting rifle bullets as effective at killing wildlife as conventional bullets? A comparison based on wound size and morphology. Sci Total Environ 443:226–232. doi:10.1016/j.scitotenv.2012.10.084

USFWS (US Fish and Wildlife Service) (1997) Migratory bird hunting: revised test procedure for nontoxic shot approval procedure for shot and shot coatings. Fed Register 62(320):63607–63615

Watson RT, Fuller M, Pokras M, Hunt WG (eds) (2009) Ingestion of lead from spent ammunition: implications for wildlife and humans. The Peregrine Fund, Boise