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Weight retention and expansion of popular lead-based and lead-free hunting bullets

Michael McTee [a,*], Chris N. Parish [b], Craig Jourdonnais [a], Philip Ramsey [a]

[a] MPG Ranch, 19400 Lower Woodchuck Road, Florence, MT 59833, USA
[b] The Peregrine Fund, 5668 West Flying Hawk Lane, Boise, ID 83709, USA

HIGHLIGHTS

- Testing the performance of rifle bullets is critical as more hunters go lead-free.
- We fired popular lead-free and lead-based bullets into water at 91 m and 238 m.
- Copper bullets exhibited >98 % weight retention, compared to 13–97 % for lead-based.
- Many bullets expanded consistently at 91 m and 238 m, but some showed variability.
- Subtle modifications in bullet design can yield drastic differences in performance.

GRAPHICAL ABSTRACT

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ABSTRACT

Hunting bullets are often comprised of a lead core covered with a copper alloy jacket. When the bullet collides with an animal, particles—sometimes millions—can shed from the projectile and embed in animal tissues. Those lead fragments can persist in game meat and remain in the discarded viscera that many wildlife species scavenge. Bullets often differ in design, so it is vital to assess their weight retention and expansion, which affects how much metal they deposit in tissue and how effectively they kill animals. We fired 12 types of hunting bullets into water to measure their weight retention and expansion at 91 m and 238 m (100 and 260 yards). Bullet constructions included copper, tin, bonded lead, partitioned lead, and cup-and-core lead. On average, copper bullets retained >98 % of their weight, whereas cup-and-core lead bullets retained <13–55 %, depending on the brand and shot distance. One brand of bonded lead bullet retained mass (≥96 %) nearly as well as copper bullets, while another brand retained much less (~71 %). Two types of copper bullets expanded similarly between test distances, while a third expanded less at 238 m. Cup-and-core lead bullets often experienced a separation between their copper alloy jacket and lead core. Our data emphasize that lead-based bullets of similar construction can drastically differ in weight retention and expansion.

* Corresponding author.
E-mail address: mmctee@mpgranch.com (M. McTee).

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1. Introduction

Hunters worldwide have shot copper-jacketed, lead-core bullets for much of the last century (Caudell et al., 2012; Hampton et al., 2018; Ishii et al., 2017; Stokke et al., 2017). Compared to other common metals, lead is inexpensive, dense, and malleable, which has made it a suitable choice for hunting bullets (Caudell et al., 2012; Stokke et al., 2017; Stroud and Hunt, 2009). When a typical lead-core bullet collides with an animal, the projectile expands, increasing the bullet's cross-sectional area to maximize tissue damage. As a bullet continues through tissue, fragments of metal shed, sometimes embedding at least 45 cm from the main wound channel (Grund et al., 2010; Stewart and Veverka, 2011). Millions of the particles can be too small to see (Kollander et al., 2017; Leontowich et al., 2022), making it nearly impossible to detect and extract. As a result, lead fragments can persist in game meat and the offal and unrecovered carcasses that scavengers ingest (Haig et al., 2014; Hunt et al., 2009). Hunters can interrupt this pathway of lead into food chains by removing lead-containing remains from the field (Chase and Rabe, 2015), using bullets that have higher weight retention (McTee et al., 2017), or shooting lead-free bullets (Bedrosian et al., 2012; Kelly et al., 2011).

With all bullets, it is vital to assess their precision and terminal ballistics to ensure they rapidly kill animals (Hampton et al., 2020). Hunters can easily test the precision of bullets at the shooting range (McCann et al., 2016; McTee and Ramsey, 2022), but evaluating weight retention, expansion, and other aspects of terminal ballistics requires more rigorous study. Weight retention influences a bullet's ability to penetrate and informs the shooter of how much metal may be deposited in tissue (Caudell, 2013; Stokke et al., 2017). Expansion measures a bullet's ability to increase its frontal area and cause tissue damage (Caudell, 2013; Stokke et al., 2017). Most practical data come from hunts and culling efforts (Hampton et al., 2022; Hampton et al., 2021; McCann et al., 2016; Stokke et al., 2019), but collecting enough data from live animals to perform statistical analysis can be difficult (Caudell, 2013). For instance, shooters often use different cartridges and bullets (Epps, 2014). Shots can also vary in angle, target species, point of impact, and distance, which affects kinetic energy, expansion, and the corresponding tissue damage (Caudell, 2013; Gremse et al., 2014). Without those factors held constant, the performance of two or more individual bullets is difficult to compare (Caudell, 2013). Consequently, many studies have grouped bullets into broad categories (e.g., lead vs. lead-free or copper; Hampton et al., 2022; Kanstrup et al., 2016). Although these types of studies yield invaluable ballistics comparisons, bullets within the lead and lead-free categories may have been constructed differently. Slight variations in bullet design have the potential to affect weight retention and expansion (Gremse et al., 2014; Stokke et al., 2017).

Copper comprises many lead-free bullets, although there are other lead-free options, including fragmenting rifle bullets made of tin. Monolithic copper bullets became commercially available in the early 1980s (Zent and Barnes, 2014). Compared to lead, the market price of raw copper is roughly four times higher (https://markets.businessinsider.com, Accessed 1 May 2023), although copper bullets are often priced comparably or only slightly higher than lead bullets (Thomas, 2013). Copper is also less ductile, so bullet manufacturers mill an opening at the tip of the projectile to help ensure expansion upon impact (Caudell et al., 2012; Stokke et al., 2017). Many of the copper bullets available in factory ammunition in the U.S. are designed to retain >95 % of their weight, but some copper bullets are designed to shed metal to maximize energy transfer (Gremse et al., 2014). As opposed to lead, which has no known biological function, copper is a micronutrient for many species, although insufficient or excessive intake can cause health problems (Stern, 2010). A study that orally administered copper pellets to American kestrels (*Falco sparverius*) did not observe increases in copper blood concentrations (Franson et al., 2012).

Most of the lead-based bullets hunters shoot fall into three categories: cup-and-core, bonded, and partitioned. Cup-and-core bullets are likely the most popular, where a copper alloy jacket surrounds the lead core (Caudell et al., 2012; Massaro, 2015). Bonded bullets have copper alloy jackets chemically bonded to the lead core to enhance weight retention. Lastly, partitioned bullets are jacketed with copper alloy as well, but they contain two tandem lead cores separated by a strip of copper. Stokke et al. (2017) found that bonded bullets retained more weight than other lead-based bullets after striking soft tissue on moose (*Alces alces*). Yet, the opposite held true on bone hits, highlighting the potential variability of bullet performance based on bullet construction and the medium it strikes.

To overcome the logistical limitations of collecting data from live animals, researchers often shoot bullets into homogenous simulants that have densities similar to muscle ($\rho = 1.06$ g/cm^3). Common simulants include gelatin blocks and ballistics soaps (Kneubuehl et al., 2011). However, these two simulants are costly, with pre-made ballistics gelatins often priced >80 USD (www.clearballistics.com, Accessed 1 May 2023). Shooting bullets into water ($\rho = 1.00$ g/cm^3) offers an inexpensive alternative for testing bullet weight retention and expansion. Essentially, a rain barrel is placed on its side, strapped to a table, and a series of water containers are placed inside. The shooter then fires a bullet into the barrel (termed “water trap,” hereafter; Fig. 1). The water containers stop the projectile, and the bullet material settles to the bottom, where it can be poured out and collected. This simple and inexpensive method has allowed biologists to conduct ballistics demonstrations that compare lead-based and lead-free bullets (Dickson, 2020; McCormick, 2014; Wallowa County Chieftain, 2017). Water traps are seldom employed in wildlife research (but see Sanchez et al., 2016), although forensic scientists use them (Werner et al., 2018; www.emtforensics.com, Accessed 28 April 2023).

We tested the weight retention and expansion of 12 common bullets by firing them into water traps set 91 m and 238 m away. They included: monolithic copper, fragmenting tin, bonded lead, partitioned lead, and cup-and-core lead. We hypothesized that weight retention and expansion would be more consistent for copper, fragmenting tin, bonded lead, and partitioned lead bullets due to their design features compared to cup-and-core lead. Additionally, we expected bonded bullets to have a higher weight retention than partitioned lead bullets because of their copper jacket being chemically bonded to the core. We also hypothesized that different copper bullets would exhibit similar weight retention and expansion due to their homogenous, monolithic designs. Further, we hypothesized that the copper bullets would expand less at 238 m than at 91 m due to their lower ductility than lead, whereas those distances might not influence the expansion of lead-based bullets. Lastly, to visually show the differences in bullet design and performance, we photographed each type of bullet, their cross sections, and their typical shapes and associated fragments after being fired into water at 91 m and 238 m.

2. Material and methods

2.1. Bullet selection, water traps, and ballistics testing

We selected the .270 Winchester cartridge (.270 Win) for testing, a rifle that was introduced in the 1920s and continues to be a popular cartridge for big game (Massaro, 2015; Van Zwoll, 2022). We chose 12 types of ammunition that encompassed the main rifle bullet constructions hunters in the U.S. would encounter at sporting goods stores and while shopping online (Table 1).

Ballistics testing occurred at MPG Ranch in the Bitterroot Valley of western Montana (elevation ~1000 m; McTee and Ramsey, 2022). We shot bullets at 91 m in mid-late April and at 238 m in early August 2022. We measured the 91 m distance by both tape measure and laser rangefinder. We measured the 238 m distance by laser rangefinder. We chose 91 m because it is a common distance for target shooters in the U. S. The 238 distance was roughly the longest distance we could reliably

Fig. 1. We constructed three water traps to capture rifle bullets. Each trap held a row of six 3.8-L water containers.

Table 1
Description of the ammunition used to evaluate bullet weight retention and expansion after being fired into water containers at 91 m and 238 m with a .270 Winchester rifle. BC represents the bullet's ballistic coefficient.

Bullet	Ammunition	Construction	Grains	G1 BC	Velocity[a] (m s^{-1} [ft s^{-1}])		
					0 m	91 m	238 m
Barnes TTSX	Choice ammunition	Copper	130	0.392	970 [3184]	902 [2958]	799 [2621]
Barnes LRX	Choice ammunition	Copper	129	0.463	950 [3117]	892 [2928]	806 [2644]
Federal Copper	Federal power shok	Copper	130	0.287	891 [2923]	803 [2635]	674 [2212]
Hornady CX	Hornady outfitter	Copper	130	0.403	895 [2937]	832 [2730]	737 [2418]
Norma Evostrike	Norma	Tin	96	0.292	1044 [3424]	947 [3107]	806 [2644]
Federal Trophy Bonded Tip	Federal premium	Bonded lead	130	0.440	920 [3017]	860 [2823]	771 [2531]
Nosler Accubond	Choice ammunition	Bonded lead	150	0.500	891 [2923]	840 [2756]	763 [2502]
Nosler Partition	Federal premium	Partitioned lead	130	0.416	927 [3042]	864 [2836]	770 [2527]
Berger VLD	Choice ammunition	Cup and core lead	130	0.462	960 [3149]	902 [2958]	814 [2671]
Core-Lokt Tipped	Remington	Cup and core lead	130	0.447	912 [2993]	854 [2803]	767 [2517]
Hornady Interlock	Choice ammunition	Cup and core lead	130	0.409	945 [3099]	880 [2887]	783 [2569]
Hornady SST	Choice ammunition	Cup and core lead	140	0.495	901 [2956]	849 [2786]	771 [2528]

[a] We measured muzzle velocity (0 m) with a chronograph and entered the average velocity ($n = 3$) into a ballistics calculator to estimate velocity at 91 m and 238 m.

hit the water trap with the different ammunition. We used three 238-L plastic rain barrels (56 cm diameter and 104 cm long; Mirainbarrel; Taylor, MI, USA). At the bottom edge of each barrel, we cut a rectangular hole (8 cm × 8 cm) from which we could decant excess water and retrieve bullet fragments, which sink to the bottom. We cut an opening in the lid (~24 cm tall) to expose the region where we would later fire bullets (see Fig. 1). We lay rain barrels on separate tables and secured each setup with a ratchet strap. We slid an HDPE textured cutting board (1 × 30 × 122 cm; SIBE-R-Plastic Supply; Ocala, FL) into each barrel. We elevated the cutting boards on two Camco 4414 Wheel Chocks (21 × 15 × 13 cm; Camco Manfacturing LLC; Greensboro, NC). We set six 3.8-L (1-gal) HDPE containers with caps in place on each cutting board (Fig. 1). The containers are sold ubiquitously in the U.S. to hold milk and water. We adjusted each table to ensure all six water containers were in-line with the shooter.

One shooter fired the .270 Win (Tikka T3x Superlite; Sako Limited, Accokeek, MD, USA) equipped with a 4-12× riflescope (Swarovski Z3; Absam, Austria) from a Caldwell The Lead Sled Solo Recoil-Reducing Shooting Rest (Battenfeld Technologies, Inc., Columbia, MO, USA). Bullets were first fired at a paper target to determine their approximate point of impact. The shooter then shot once into each of the three water traps ($n = 3$), with bullets penetrating between two to six water containers before coming to rest (Fig. S1; water does not sustain a sheer force, so we felt that our penetration data were inadequate for statistical analysis). We experienced precision issues with the Hornady CX at 238 m, so we did not collect data at that distance.

We carefully removed the shredded and intact water containers. When visible bullet fragments clung to the water containers and cutting board, we washed them into the barrel with a 7.6-L garden sprayer. For water containers that held bullet particles inside, we removed the lids and emptied the contents into the barrel. We then reached into the barrel to collect the largest mass of the bullet, which we placed on a paper coffee filter. In several instances, copper bullets pierced all the water jugs, struck the rear of the barrel, exited the front of the barrel, and landed at the base of the table. We included those bullets. We unstrapped the barrel from the table and decanted the water while bullet fragments sank to the bottom. We then washed the inside of the barrel with the garden sprayer and poured the bullet fragments out the lower hole onto paper coffee filters. We dried the bullet material indoors at approximately 20 °C to be included in photographs.

2.2. Velocity measurements and calculations

We measured bullet velocity at the rifle muzzle with a LabRadar doppler radar chronograph (Infinition Inc., Trois-Rivières, Quebec, Canada) with a LabRadar Trigger Gen 2 (JKL Precision, Christiansburg, Virginia, USA). The LabRadar is advertised to measure velocity with an accuracy of ±0.1 %. We measured bullet velocity separately from other testing because the heterogeneous profiles of the water traps and their location among vegetation at MPG Ranch made measurements with the chronograph extremely difficult. Instead, we measured muzzle velocity at the Deer Creek Shooting Center in East Missoula, Montana (elevation ~1000 m) on May 30, 2023. We calculated velocity at 91 m and 238 m using the Berger Ballistics Calculator (bergerbullets.com, Accessed 5 June 2023), using the measured muzzle velocity, the G1 ballistics coefficient, and weight of each bullet, while setting the ambient temperature to 15.6 °*C*.

2.3. Measuring weight retention and expansion

We weighed the heaviest mass of each bullet with a Sartorius Entris 4202 Precision Balance (Sartorius Lab Instruments, Göttingen, Germany). To calculate expansion ratios, we measured each bullet's expanded frontal area using the FIJI image analysis software (Schindelin et al., 2012). To set the measurement scale, we measured U.S. pennies stacked to the height of each bullet. We divided expanded areas by the area of an unfired .270 Win bullet (38.88 mm^2). The Berger VLD Hunting and Norma Evostrike bullets might be best classified as fragmentation bullets following the criteria set forth in Kneubuehl et al. (2011), where the bullet's purpose is to break into many smaller particles. We still attempted to measure the expanded area of all bullets, assuming we recovered at least the shank.

We measured bullet lengths as an auxiliary measure of how projectiles transformed in shape after impact (termed *lengthwise deformation*, hereafter). Using Neiko Tools Digital Calipers (Neiko Tools, Corona, CA, USA), we measured the longest distance from the base of the bullet to the expanded frontal area, turned the bullet 90°, measured again, and calculated the average. We divided that average by the bullet's unfired length, excluding the length of the polymer tip when present. We measured lengths only for bullets where we had data for both 91 m and 238 m and the projectile reliably expanded without the core separating from the jacket, excluding the Nosler Partition, where at least one of the two lead cores remained within the bullet jacket. Consequently, we excluded bullets having tin and cup and core lead constructions.

2.4. Photographing bullets

We photographed each bullet to visually show the variability in bullet construction, weight retention, and expansion before and after impact with the water trap. We included bullet fragments in the photos, which were weighed with the main bullet mass to indicate how well our water trap recovered bullet particles (Fig. S2). We also photographed cross sections of the bullets to show their internal constructions. We cut cross-sections using a Vertical Milling Center (Fadal VMC4020fx; Vorteque, LLC.; Missoula, MT). The tip of the Norma Evostrike disintegrated while being cut. For the fired bullets, we selected those that best reflected the results. For instance, if the core separated from the jacket for two out of three bullets, we photographed a bullet with core separation. For bullets that had similar weight retention, we selected the projectile with the median value. All photos were taken with an iPhone SE 12 cm from the bullets.

2.5. Statistical analysis

We tested for an interaction between type of bullet and shot distance in predicting weight retention and expansion ratios using two-way analysis of variance (ANOVA; $\alpha = 0.05$ for all analysis). If we observed significant interactions, we then ran two-sample *t*-tests between shot distances for each bullet, both for weight retention and expansion ratios. To test for differences within bullet constructions having more than two bullets in the grouping, we used a one-way ANOVA and Tukey post-hoc test (copper and cup-and-core lead; Table 1). For groupings having two bullets, we ran two-sample t-tests (bonded). To compare each bonded bullet to the copper bullets, we individually added one type of bonded bullet to the copper dataset, ran a one-way ANOVA, and if $P \leq 0.05$, we ran a Dunnett's test (Signorell, 2017), where each copper bullet was compared to the bonded bullet. We repeated this methodology to compare the partitioned bullet to each of the bonded bullets and to the copper bullets. We calculated coefficients of variation (CV; SD $mean^{-1}$) for weight retention and expansion ratios to examine the variability of our results. We compared bullet lengths between distances using two-sample t-tests. We created graphics and analyzed data in Program R (version 4.2.1; R Core Team, 2022) using the RStudio platform (version 2022.07.1; RStudio Team, 2022).

3. Results

3.1. Weight retention

For weight retention, we observed an interaction between bullet type and shot distance ($F = 17.33$, $P < 0.001$). On average, the copper bullets retained >98 % of their mass at 91 m and 238 m, and we observed no statistical difference among copper bullets (Fig. 2A). A portion of that weight loss can be accounted for by the loss of the polymer tip, except for the Federal Copper, which did not have a polymer tip (Fig. 3). Several bullets lost visible copper fragments (Fig. 3). Overall, each type of copper bullet exhibited consistent weight retention, having low coefficients of variation (≤3 %; Table 2.)

Unlike many lead-free bullets that maintain nearly all their mass, the tin Norma Evostrike retained only 58 % of its mass at both distances. In all cases, the front portion of the bullet fragmented, leaving a shank intact (Fig. 3).

The two models of bonded lead bullets differed in weight retention. On average, the Federal Trophy Bonded Tip retained 96 % and 97 % of its mass at 91 m and 238 m, respectively. In contrast, the Nosler Accubond retained 71 % at both distances. For each type of bullet, their weight retention was consistent between shots at both distances (Table 2). Perhaps most notable, the weight retention of the Federal Trophy Bonded Tip did not differ from two types of copper bullets at 91 m (Barnes TTSX and Hornady CX; $P = 0.157$ and $P = 0.270$, respectively; Table S1).

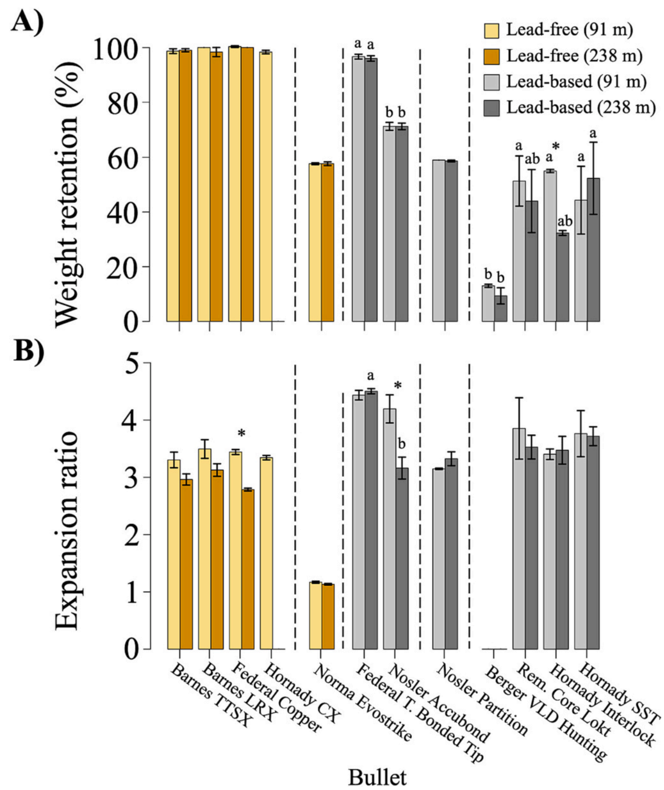

Fig. 2. The mean A) weight retention (%; n = 3) and B) expansion ratios (n = 3) of lead-free and lead-based bullets at 91 m and 238 m. Error bars represent standard error. The vertical dashed lines separate statistical analysis between and among bullets. Different letters above bars signify statistical groupings ($P \leq 0.05$) for specific shot distances based on one-way ANOVA and two-samples *t*-test. Asterisks denote differences ($P \leq 0.05$) between 91 m and 238 m for specific bullets based on two-samples *t*-tests.

The lead-based Nosler Partition had consistent weight retention at both distances (59 %; Table 2) but lost more mass than both bonded lead bullets (Fig. 2A; Table S1). When the bullets struck the water trap, the first lead core separated from the main bullet mass while the second core remained intact.

The cup-and-core lead bullets often separated from their copper jackets, causing substantial variability in weight retention (Table 2; Figs. 2A, 4). While the coefficient of variation for the lead-free, bonded lead, and partitioned lead bullets was always ≤4 %, it was often >30 % for the cup-and-core lead bullets (Table 2). Most of the bullets had similar but low (< 60 %) weight retention values. Weight retention for the Hornady Interlock was higher at 91 m than at 238 m (Fig. 2A), due to core separation. The Berger VLD Hunting had the lowest weight retention, with 13 % at 91 m and 9 % at 238 m. At the longer distance, however, we recovered an average of 60 % of the Berger VLD Hunting (Fig. S2), meaning bullet material heavier than what we found could have exited the barrel, driving down our weight retention value.

3.2. Bullet expansion

We observed an interaction between bullet type and shot distance for expansion ratios ($F = 14.36$, $P < 0.001$). Copper bullets tended to expand similarly to one another, although the Federal Copper expanded less at 238 m than at 91 m (Fig. 2B). Copper bullets were longer after impacting water containers at 238 m than at 91 m, meaning they exhibited less lengthwise deformation (Fig. 5A; Fig. 6). Specifically, the Barnes TTSX was 14 % longer, the Barnes LRX 10 %, and the Federal Copper 19 %.

By design, the frontal area of the tin Norma Evostrike fragmented instead of expanding. Its diameter after impact equaled its unfired diameter at both 91 m and 238 m (Fig. 2B).

The expansion ratios between the bonded lead bullets did not differ at 91 m (Fig. 2B). At 238 m, however, the Federal Bonded Tip had a larger expansion ratio than the Nosler Accubond. The Federal Bonded Tip also maintained its expansion ratio at the longer distance, whereas the expansion ratio decreased for Nosler Accubond (Figs. 2, 4, 5B). Yet, the Nosler Accubond had consistent lengthwise deformation, with jacket material peeling around the base of the bullet (Figs. 4B; 5B). Both bonded bullets deformed to <50 % of their initial lengths, regardless of distance.

We compared the bonded lead bullets individually to the copper bullets and found multiple differences (Table S2). The Federal Trophy Bonded Tip expanded more than the copper bullets at 91 m ($F = 19.89$, $P < 0.001$) and 238 m ($F = 101.9$, $P < 0.001$), whereas the Nosler Accubond had a higher expansion ratio than copper bullets only at 91 m ($F = 6.12$, $P = 0.009$).

The lead-based Nosler Partitions had similar expansion ratios at both 91 m and 238 m, while the bullet's average length was 8 % longer at 238 m. The Nosler Partitions expanded less than both bonded lead bullets at 91 m ($F = 20.82$, $P = 0.002$; Table S2) and less than the Federal Trophy Bonded Tip at 238 m ($P = 0.001$). The Nosler Partitions did not have significantly different expansion ratios compared to copper bullets, besides at 238 m, where the Federal Copper expanded less (Table S2).

For many cup-and-core lead bullets, the lead core often separated from the bullet jacket and expansion ratios were variable (Table 2). The Berger VLD Hunting fragmented so extensively that we were never able to record expansion (Fig. 4). For the Hornady SST, the core and jacket stayed intact for one-third of the shots at 91 m, compared to two-thirds at 238 m. Two-thirds of the Remington Core Lokt bullets did not experience core and jacket separation at 91 m, although their expansion ratios were highly dissimilar (1.9 vs. 2.6). At 238 m, only one bullet held its core to the jacket. Lastly, the Hornady Interlock always kept its mushroomed shape at 91 m but never at 238 m.

4. Discussion

4.1. Main findings

We observed drastic differences in weight retention and expansion among bullets, demonstrating why hunters and researchers should not assume bullets of similar construction perform alike. The lead-based Federal Bonded Tip retained ≥96 % of its weight on average, rivaling the weight retention of copper bullets (>98 %). Other lead-based bullets varied considerably in their weight retention, with one bullet (Berger VLD Hunting) retaining an average of ≤13 % of its mass. The weight retention of cup-and-core lead bullets was inconsistent due to frequent separation of the lead core from the copper jacket. Copper bullets tended to expand similarly, but the expansion ratio for the Federal Copper decreased at 238 m, suggesting that long-range shooters wishing to hunt with lead-free must carefully select their bullet, a practice that also applies with lead-based bullets. The fragmenting tin bullet (Norma Evostrike) retained only 58 % of its weight and highlights the importance of communicating exactly which lead-free bullets are expected to maintain their weight. Testing ammunition from different manufacturing lots, at different powder loads, or for various calibers could have influenced the results, particularly with regard to bullet expansion, as expansion ratios can decrease with increasing caliber (Stokke et al., 2019). Although we tested bullets for only one cartridge (.270 Win), our results demonstrate how differences in bullet construction can yield highly variable performance.

4.2. Unequal performance of bonded lead bullets

Bullet manufacturers design bonded lead bullets to retain their weight better than traditional cup-and-core lead bullets (Massaro,

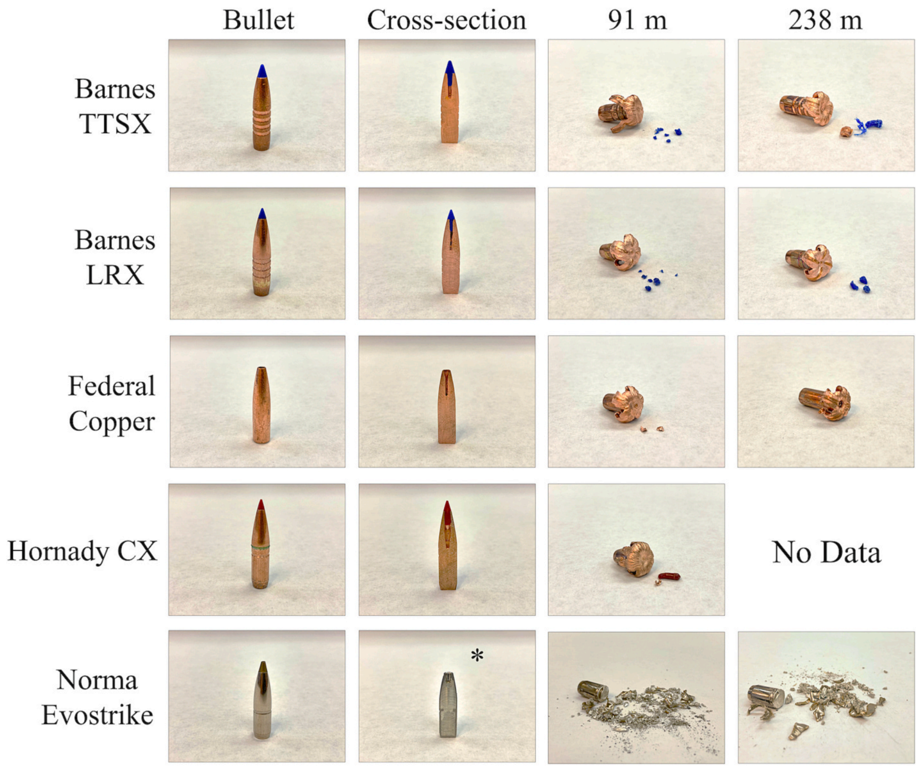

Fig. 3. The first two columns show the lead-free bullets and their cross-sections. The second two columns show their expansion and fragmentation at 91 m and 238 m after being fired into water containers. On average, we recovered >99 % of the mass from each copper bullet from the water trap and 92 % of the Norma Evostrike (Fig. S2). *The bullet's polymer tip disintegrated while being cut into a cross-section.

Table 2
Coefficient of variation (SD mean^{-1}) for weight retention ($n = 3$) and expansion ratios ($n = 3$) of bullets fired into water containers at 91 m and 238 m.

		Coefficient of variation (%)			
		Weight retention		Expansion ratio	
Bullet	Construction	91 m	238 m	91 m	238 m
Barnes TTSX	Copper	2	1	7	6
Barnes LRX	Copper	0	3	8	6
Federal Copper	Copper	1	0	2	2
Hornady CX	Copper	1		2	
Norma Evostrike	Tin	1	2	3	2
Federal Trophy Bonded Tip	Bonded lead	2	2	3	2
Nosler Accubond	Bonded lead	4	3	10	10
Nosler Partition	Partitioned lead	0	1	1	6
Berger VLD Hunting	Cup and core lead	8	55		
Core-Lokt Tipped	Cup and core lead	31	45	24	10
Hornady Interlock	Cup and core lead	2	5	5	12
Hornady SST	Cup and core lead	48	44	19	8

2015). Indeed, the Federal Trophy Bonded Tip had a higher average weight retention (≥96 %) than all other lead-based bullets shot in this study. Hunting with this bullet may decrease but not eliminate lead deposition in animal tissue. But a bonded construction does not guarantee high weight retention, especially with bone contact, a potentially significant factor we did not test. The Nosler Accubond retained an average of 71 % of its mass, shedding more mass than what Stokke et al. (2017) observed with bonded lead bullets used to hunt moose (*Alces alces*) in Fennoscandia (10–25 % mass loss). Unlike our study results, those authors noted that bonded lead bullets experienced jacket and core separation as often as other lead-core bullets, which they considered a serious functional failure. The difference in bullet performance might be explained by impact medium (water containers vs. moose) or bullet constructions. Additionally, their data were collected between 2004 and 2006, and it is possible the bonded bullet technologies have changed.

4.3. *Less weight retention by design*

Bullet fragmentation can maximize energy transfer from the bullet to its living target (Coupland, 1999; Fackler et al., 1984; Spencer, 1908). Consequently, our observation of the lead-based Berger VLD Hunting retaining ≤13 % of its weight implies the bullet released a significant amount of energy within the testing medium. Conversely, penetration depth can be negatively correlated with bullet expansion in that violent fragmentation reduces momentum and limits penetration (Wolberg, 1991). We observed anecdotal evidence in support of this when the Berger VLD Hunting tended to penetrate an average of only 2.7 and 3.7 water containers at 91 m and 238 m, respectively, compared to ≥4 water containers for all other bullets (Fig. S1).

Based on our experience purchasing ammunition in the U.S., the fragmenting nature of the Norma EvoStrike is uncommon for lead-free bullets intended for big game hunting. Its tin composition is also unusual. Some copper bullets are designed to expand and shed their petals (Gremse et al., 2014), but many options we have encountered in the U.S. require handloading (e.g., ER Raptor, Cutting Edge Bullets, Accessed 28 April 2023). These fragmenting lead-free options may fill a niche for hunters seeking maximum energy transfer. However, fragmenting bullets may deposit a significant amount metal into animal tissue, although both tin and copper are only marginally toxic (Franson et al., 2012; Rüdel, 2003). Additionally, some government entities require expanding bullets for big game hunting (e.g., Norway; https://www.miljodirekt

Fig. 4. The first two columns show the lead-based bullets and their cross-sections. The second two columns show their expansion and fragmentation at 91 m and 238 m. after being fired into water containers. On average, we recovered >99 % of the Federal Trophy Bonded Tip and > 90 % of the mass from the other bullets besides the Berger VLD Hunting at both shot distances and Hornady SST at 238 m (60 % and 82 %, respectively; Fig. S2).

oratet.no, Accessed 19 July 2023), so fragmenting bullets such as Norma Evostrike would be prohibited. When hunters kill animals with any new bullet, such as a fragmenting projectile, they should examine the tissue damage and determine whether the bullet performed as intended.

4.4. Distance-dependent performance

A bullet's ability to expand depends largely on its construction and impact velocity, which is affected by shot distance and the projectile's ability to resist air resistance in flight (i.e., ballistic coefficient; Gremse et al., 2014; Litz, 2015). Only the bonded-lead Nosler Accubond and copper Federal Copper had lower expansion ratios at 238 m compared to 91 m (Figs. 2B; 5A), although the Nosler Accubond had consistent lengthwise deformation at both distances. Differences for other bullets may also emerge at longer shot distances, perhaps most often with copper constructions. Copper is less ductile than lead (Stokke et al., 2017), which is why manufacturers drill deep hollow points and often add polymer tips that increase the ballistic coefficient (Caudell et al., 2012). Barnes Bullets designed their copper LRX projectile specifically for extended range (www.barnesbullets.com, Accessed 1 May 2023). The Federal Copper expanded similarly to the Barnes LRX at 238 m, although differences may become pronounced at longer shot distances. For example, the ballistic coefficient (BC; Table 1) of the Federal Copper is much lower than the BC of the Barnes LRX (0.287 vs. 0.463; Table 1). The higher a bullet's BC, the better it resists air drag and conserves downrange velocity and kinetic energy (Table 1; Litz, 2015). When we stood expanded copper bullets on their bases and viewed them from the side, the bullets shot at 238 m appeared taller (Fig. 5A), which we verified with length measurements (Fig. 6). So even if we did not detect a statistical difference in expansion between shot distances, we observed a shift in lengthwise deformation in copper bullets that were absent for the bonded lead bullets (Figs. 5B; 6).

Higher velocities often enhance fragmentation (Gremse et al., 2014). However, we noted a distance-dependent change in weight retention only for the Hornady Interlock, where the lead core always separated from the jacket at 238 m. Future studies could adjust the powder loads of each round to achieve incrementally slower velocities (Gremse et al., 2014) and fire from a set distance while using a chronometer.

4.5. Water traps as a reproducible simulant

Water traps collected some bullets better than others. We always collected >99 % of the copper bullets (Fig. S2), while our recovery of lead-based bullets was poorer, particularly with those of cup-and-core constructions. We collected ≤53 % of two Berger VLD Hunting bullets at 238 m, possibly because fragments exited the mouth of the barrel with

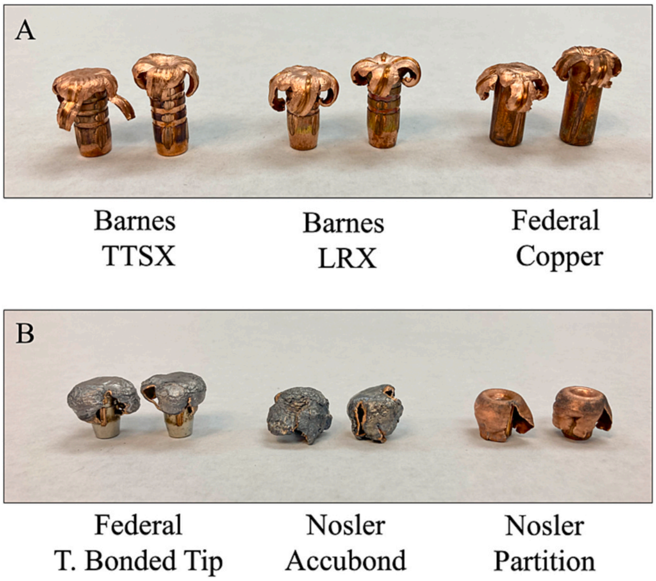

Fig. 5. Examples of expanded A) copper and B) lead-based bullets, depending on distance after being fired into water containers. The first projectile for each bullet grouping was fired at 91 m while the second was fired at 238 m.

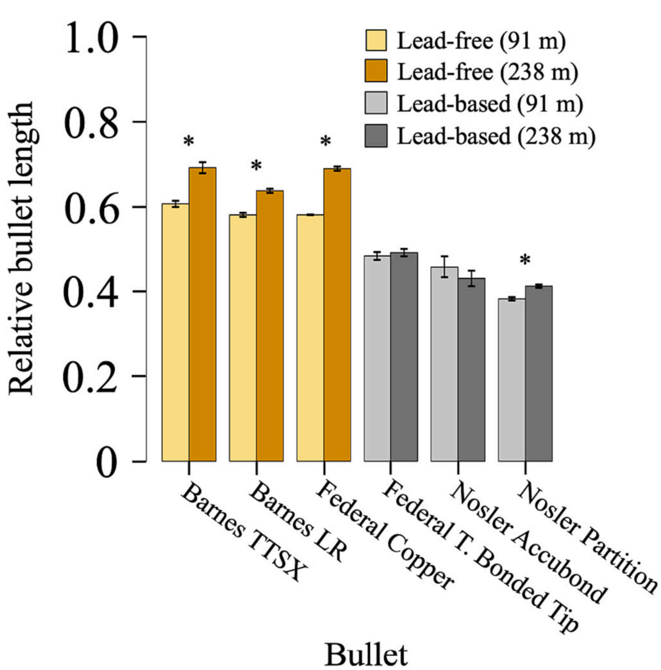

Fig. 6. Lengths of expanded bullets relative to their unfired lengths, excluding polymer tips (when present). Bullets were fired into water at 91 m and 238 m from a .270 Winchester rifle. Asterisks denote differences ($P \leq 0.05$) between 91 m and 238 m for specific bullets based on two-samples *t*-tests.

turbulent water or bounced out, as seen with several copper bullets that we picked off the ground. Cutting a smaller hole in the mouth of the barrel may remedy the issue, but doing so would require greater precision and accuracy from the firearm and the shooter. Reducing the length of the HDPE cutting board may also prevent it from becoming pathway for particles to exit the barrel.

The homogenous nature of the water trap does not capture the variability in bullet performance associated with shooting into a heterogeneous profile of hair, hide, bone, and other living tissues. For example, the density of cortical bone is often >1.6 g/cm^3 compared to <0.6 g/cm^3 for lung tissue (Kieser et al., 2014; Zhou and Zhang, 2018). Further, Wolberg (1991) found that penetration and expansion of pistol bullets were more uniform in gelatin blocks than in human tissue. Despite water traps lacking the complexities of living tissue, they are easy to operate and inexpensive to construct, with most of the supplies being available at hardware and grocery stores. Our weight retention results for copper bullets corroborated values advertised by bullet manufacturers (often >95 %), demonstrating that water traps can offer practical baseline information to hunters, shooters, biologists, and wildlife managers.

5. Conclusions

Shooting bullets into a water trap offered a consistent and reproducible test medium for comparing weight retention and expansion. Copper bullets generally performed similarly to one another, with their frontal areas expanding into petals that peeled back. On average, copper bullets always retained >98 % of their weight. Lead-based bullets as a group, however, showed drastic differences that included: consistent expansion, separation of the copper jacket from the core, and explosive fragmentation. One type of bonded bullet exhibited a surprising ≥96 % weight retention, but the other lead-based bullets retained ≤71 %, with one retaining ≤13 %. Hunters should be aware that bullets of different designs sometimes yield extreme disparities in terminal ballistics.

CRediT authorship contribution statement

Michael McTee: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Chris N. Parish:** Conceptualization, Methodology, Validation, Writing – review & editing. **Craig Jourdonnais:** Methodology, Writing – review & editing. **Philip Ramsey:** Methodology, Writing – review & editing, Funding acquisition.

Declaration of competing interest

Michael McTee is the author of Wilted Wings: A Hunter's Fight for Eagles. Chris Parish is the co-founder of the North American Non-Lead Partnership. All remaining authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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