Human–Wildlife Interactions 10(2):268–282, Fall 2016

Efficacy of non-lead ammunition for culling elk at Theodore Roosevelt National Park

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Abstract: During 2010 to 2013, park staff and public volunteers culled 983 elk (*Cervus elaphus*) from Theodore Roosevelt National Park (United States) utilizing non-lead rifle ammunition as part of a sanctioned herd management operation. Because there is little empirical evidence available on the performance of non-lead ammunition, staff recorded information on tools and techniques relevant to the scenarios under which elk were culled and the outcome of each engagement. We also conducted a firing range experiment to evaluate the precision of non-lead ammunition used in park firearms. Specific objectives were to identify program factors predicting efficient destruction of elk with non-lead ammunition and to evaluate the precision of non-lead ammunition in National Park Service (NPS) firearms to facilitate accurate shot placement. To address these objectives, we conducted multivariate ordinal regression analyses of 13 variables, including bullet type, marksman type, shot distance, initial shot impact location, number of shots fired, and need for a killing shot, as predictors of distance traveled by elk after being shot. Among 921 elk removals evaluated, mean shot distance was 182 meters, and the median and mode of distance traveled were 46 m and 0 m, respectively. Multivariate analyses revealed that shots to the head and neck were most effective, followed by those striking the shoulder and chest. Heavier bullets should be used whenever practical. Mean group size for non-lead ammunition fired through NPS firearms was 50 mm at 91 m, with minimum and maximum group sizes of 18.8 and 98.6 mm, respectively. We found that non-lead ammunition provided the necessary precision for accurate shot placement in spot and stalk hunting conditions and that these bullets typically accomplished instantaneous or near-instantaneous incapacitation of elk whenever vital areas of the body were impacted. We conclude that non-lead bullets are effective for wildlife management and hunting scenarios.

Key words: ammunition, bullets, efficacy, elk, lead-free, management, non-lead, NPS

Elk (*Cervus elaphus*) were extirpated from southwest North Dakota during the late 1800s (Seabloom 2011; Figure 1). In 1985, 47 elk were reintroduced to the South Unit of Theodore Roosevelt National Park (TRNP), joining bison (*Bison bison*), pronghorn (*Antilocapra americana*), and bighorn sheep (*Ovis canadensis*) as restored elements of the native biotic community (Harmon 1986). With low natural mortality and few natural predators, management intervention to prevent overpopulation and resource degradation was anticipated. A forage allocation study was conducted during the 1980s and early 1990s to determine population management objectives for elk and other large ungulates inhabiting the park (Irby et al. 2002). When elk numbers exceeded the maximum determined population objective of 400 individuals in 1993 and 2000, helicopter-assisted roundups were conducted and live elk were removed and transferred to other government agencies, nonprofit organizations, and Native American tribes. However, in 2002, when the population was again approaching its upper limit, a moratorium was placed on translocation of elk due to concerns regarding chronic wasting disease (CWD; Natl. Park Serv. 2010*a*).

In the absence of an authorized reduction tool, and with the elk population growing unchecked, the National Park Service formally initiated the development of an Environmental Impact Statement in 2004 to identify alternative management methods for elk population control. Ultimately, direct reduction with firearms was selected as the primary tool in the Record of Decision (Natl. Park Serv. 2010*b*). It was stipulated that for the initial reduction phase, a period expected to take 4–5 years, park staff would lead teams of volunteers to decrease the population below the established upper limit.

Volunteer shooters were required to comply

Figure 1. Elk in the badlands of North Dakota at Theodore Roosevelt National Park. (*Photo courtesy of R. and L. Honeyman*)

with directives related to federal firearms laws and use of non-lead ammunition in national parks. Meat (quarters, backstraps, and tenderloins) was recovered from culled animals, packed out of backcountry locations to a centrally located facility, then distributed to project volunteers, state food pantries across North Dakota, and various Native American organizations. Brain stem and lymphatic tissue were collected from all animals and screened for CWD. Remaining portions of carcasses were left to recycle into the environment.

Non-lead ammunition was required for use by staff and volunteers at TRNP to comply with agency policy and to prevent exposure of lead by meat recipients and animals scavenging carcasses (Ross-Winslow and Teel 2011). Secondary consumption of lead projectiles has been implicated in mortality of birds of prey and several game and non-game species (Fisher et al. 2006, Hunt et al. 2006, Pauli and Buskirk 2007, Rogers 2010). Further, lead fragments pose a human health risk where wild game harvested with lead ammunition is consumed (Hunt et al. 2009, Kosnett 2009). However, the general public and some wildlife professionals have resisted the use of non-lead ammunition, citing the added expense, a limited variety of loadings, and reputed accuracy and performance problems (Friend et al. 2009, Knott et al. 2009, Caudell et al. 2012). Issues of expense and variety are indisputable, as non-lead projectiles are typically loaded in premium ammunition products, and the vast array of lead projectile offerings largely outnumbers non-lead options (Knott et al. 2009, Thomas 2013). However, there is little empirical evidence pertaining to precision and performance of non-lead rifle ammunition in field conditions (Caudell et al. 2012, Caudell 2013).

Gremse et al. (2014) compared lead and non-lead ammunition performance when fired into ballistic soap and reported similar terminal ballistic behavior. In Germany, comparison of thoracic wound channels in 34 large ungulates produced by lead and non-lead projectiles revealed no detectable difference between bullet types (Trinogga et al. 2013). In the United Kingdom, researchers conducted qualitative analyses, where shot outcomes were ranked by professional marksmen, to evaluate ammunition performance in terms of perceived accuracy and animal incapacitation. Analysis of approximately150 deer of multiple species, removed using lead and non-lead ammunition, resulted in equal rankings for accuracy and slightly higher scores for lethality of lead bullets (Knott et al. 2009). However, the authors concluded that differences in killing power were marginal (Knott et al. 2009).

Killing power has been described as levels of incapacitation, ranging from instantaneous (i.e., a shot stopping the animal immediately), to near instantaneous (stopping the animal within 1–30 seconds), and rapid (stopping the animal within 30 seconds to 5 minutes; Caudell et al. 2012, Caudell 2013). The level of incapacitation achieved in any situation depends on the location of the bullet strike (i.e., tissue and organs impacted), the mass and shape of the bullet, velocity, depth of penetration, and other factors relevant to field conditions (Fackler et al. 1988, MacPherson 2005, Caudell 2013). Therefore, it may be challenging to identify the specific cause for ultimate incapacitation outcomes without close examination of field tools and the scenarios under which they are employed. However, where field data describing tools and techniques for destruction of hundreds of animals are available, much may be learned through objective analysis. The elk reduction program at TRNP provides one such scenario.

Here, we present a quantitative analysis of elk reduction program data and a firing range experiment aimed at evaluating the efficacy of non-lead ammunition to serve as a basis from which field procedures may be refined. Our specific objectives are to identify program factors predicting efficient destruction of elk with non-lead ammunition and to evaluate the precision of non-lead ammunition in NPS firearms to facilitate accurate shot placement.

Figure 2. Staff member (right) and volunteer (left) engaged in elk reduction activities at Theodore Roosevelt National Park during 2010. (*Photo courtesy of J. Powers, Natl. Park Serv.*)

Methods

Elk reduction operations were conducted in the South Unit of Theodore Roosevelt National Park, which encompasses 18,756 ha in the badlands of southwest North Dakota (centroid coordinates: 46°57′12″ N, 103°27′33″ W). Park staff led teams of volunteers in field activities to cull elk during the first 2 years of the reduction (during October 2010 to January 2011 and October to December 2011) to lower herd numbers to <400 animals (Figure 2). NPS employees alone conducted maintenance-level removal operations subsequently (during October to December 2012 and November to December 2013). Volunteers provided their own shooting equipment and supplies, representing a variety of firearm makes, models, calibers, and ammunition types. However, volunteers primarily used 3 brands of projectiles: (1) Barnes Bullets Inc. (Mona, UT), (2) Hornady Manufacturing Company (Grand Island, NE), and (3) Nosler Inc. (Bend, OR; Table 1). Prior to field work, the park required volunteers to score 3 of 5 shots within a 200 mm diameter circle at 183 m to qualify rifles and ammunition for use on the project. We then recorded the chambering, caliber, type of bullet, and bullet weight used by each individual, and we subsequently categorized rifle chamberings as "standard" or "magnum" velocity for our analysis (Table 1). With few exceptions, park staff used rifles chambered in .308 Winchester, firing 150 grain and 165 grain Barnes TSX bullets.

We used marked animals fitted with combination radio-telemetry and satellite tracking collars to locate groups of elk. When elk were located, team leaders attempted to maneuver marksmen to within 183 m of targeted animals, though longer shots were occasionally taken when distances could not be reduced and

Table 1. Fourteen variables collected during elk reduction activities at Theodore Roosevelt National Park from 2010 to 2013; TSX® = triple shock X; TTSX® = tipped triple shock X; GMX® = gilding metal expanding; and ETIP® = energy-expansion-cavity tipped.

Variable	Type	Description
Distance traveled	Ordinal/categorical	0, 46, 91, 183, 274, 366+ m
Year	Categorical	Years 1, 2, 3, and 4
Marksman type	Categorical	Volunteer or staff[a]
No. elk in group	Categorical	1, 2–10, 11–25, 26–50, 51–100, >100
Shot distance	Continuous	Estimated: using laser range finder; 27–366 m
No. shots fired	Continuous	Shots fired at elk; not striking elk
Killing shot required	Categorical	Yes or no
Initial shot impact	Categorical	Location of first bullet strike: head, neck, shoulder, chest, abdomen, leg
Rifle caliber	Categorical	0.257, 0.277, 0.284, 0.308, and 0.338
Velocity rank	Categorical	Standard or magnum judged ad hoc by belting and case capacity
Bullet type	Categorical	Barnes (TXS, TTSX), Hornady (GMX), and Nosler (ETIP)
Bullet weight	Continuous	115–225 grains
Sex of elk	Categorical	Male or female
Age of elk	Categorical	Calf (<1 yr), yearling (>1 yr), adult (≥2 yr); estimated by size and dentition

[a] In few instances, staff returning as volunteers during later project years were still considered "staff" in statistical analyses.

where environmental conditions (e.g., wind speed) allowed. Typically, 1 marksman was designated the primary shooter, and the team leader provided a follow-up shot if necessary. Marksmen would engage 1 animal at a time, targeting the shoulder and chest, and confirm that the elk was down before firing at a second animal in the group.

Identification of factors contributing to efficient kills

For each elk dispatched, we recorded animal and herd demographics, marksman type (i.e., volunteer or staff), initial shot distance, number of shots fired, distance traveled after shot, and initial shot impact location (Table 1). We measured initial shot distance to the nearest meter with Nikon Rifle Hunter 550, laser rangefinders (Nikon, Inc., Melville, NY), and we recorded distance traveled by elk as an ordinal variable ranging from 0 to 366+ m, based on manual estimates, visually judged and paced on foot (Table 1). We partitioned initial shot impact into 6 anatomical categories: (1) head: shots to the crania and mandible; (2) neck: shots striking cranial to the shoulder but caudal to the head; (3) shoulder: bullet impacts to the upper front leg, scapula, spine, and associated musculature cranial to the exposed rib cage; (4) chest: shots penetrating the rib cage, sternum, and spine, cranial to the abdomen; (5) abdomen: bullet strikes to the musculature, organs, and bones of the body caudal to the chest; and (6) leg: shots striking distal portions of limbs extending below the abdomen and chest. Finally, we included project year as a predictor variable to account for variance associated with changes in operational intensity and animal behavior over time as a work-environment factor. In total, we recorded 14 variables relevant to the scenarios under which elk were culled and the outcome of each engagement (Table 1).

Quantitative analyses. We conducted statistical analyses using Statistica (Statsoft, Inc., Tulsa, OK) and program R (R Foundation for Statistical Computing, Vienna, Austria). We identified "distance traveled" as our response variable, because distance moved by animals after bullet

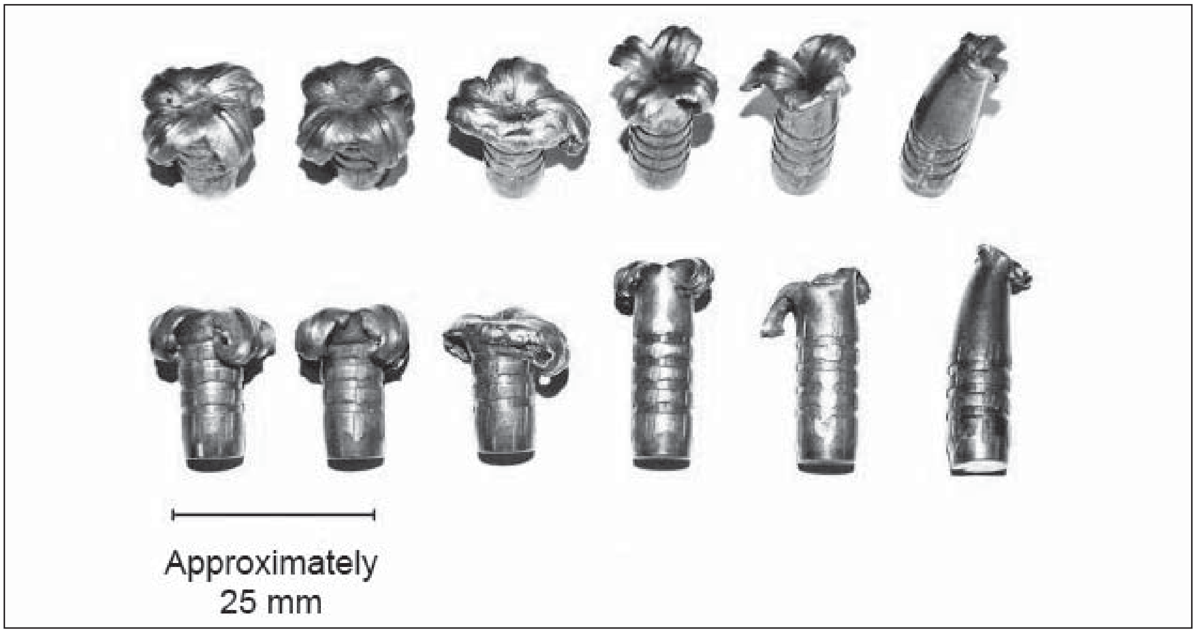

Figure 3. A sample of 6 non-lead bullets recovered from elk carcasses at Theodore Roosevelt National Park, viewed from the side (at bottom) and above (at top), demonstrating commonly observed controlled expansion (2 bullets at left) versus less frequent intermediate expansion (center right), occasional fragmentation (center left and second from right), and rare instances of non-expansion and bullet tumbling (at right). (*Photo courtesy of Blake McCann*)

impact has been previously identified as a measure of shot efficacy, and time associated with animal movements is directly related to levels of incapacitation (Ruth and Simmons 1999, Maiden 2009, Caudell 2013). The top speed of elk has been reported as 72 km per hour on flat land, though 48 km per hour is a more typical pace, and we expect that speed would be reduced where steep slopes and thick vegetation must be navigated (Willoughby 1974, Ballard 2012). Given an ad hoc speed of 24 to 32 km per hour, to account for complexity of terrain at TRNP, an elk could traverse 200–267 m within 30 seconds. Therefore, our response variable categories generally correspond to previously defined levels of incapacitation as follows: instantaneous (0 m), near instantaneous (46, 91, 183 m), and rapid (274 and 366+ m; Caudell et al. 2012, Caudell 2013).

We performed multiple exploratory analyses to detect trends in the dataset and to identify potential areas of covariance and interaction among predictors. We conducted Spearman rank correlation of continuous and ordinal variables, correspondence analyses between categorical variables, and Analysis of Variance (ANOVA) of continuous variables by categorical variable groupings. We then evaluated variance in distance traveled in a series of logit-based, univariate ordinal regression analyses to detect significant relationships and identify candidate predictor variables for multivariate analysis. Next, we performed an ordinal regression of all candidate predictors on distance traveled under all effects and best subsets parameters, employing model building using the Akaike Information Criterion (AIC). We then conducted model-averaged, multi-model inference using package MuMIn in program R to elucidate the most parsimonious regression model through evaluation of sample size corrected AIC scores across all models with weights summing to ≥95%. Finally, we calculated descriptive statistics to examine relationships further explaining independent effects of categorical predictor variables.

Precision of non-lead ammunition

We performed a shooting test of 8 rifles and factory-loaded ammunition used for elk reduction operations at TRNP. We conducted the test at a firing range near Belfield, North Dakota on October 18, 2013. Area weather records indicate that ambient temperature was between 0.6-8.3°C, wind speed was 21–40 km per hour from the west-northwest, and barometric pressure was 762 mm of mercury (<http://www.wunderground.com>, September 3, 2015, unpublished data). The firing range was situated with targets positioned to the north

Table 2. Univariate regression results of 13 individual predictor variables on "distance traveled," representing elk reduction data collected at Theodore Roosevelt National Park during 2010 to 2013. Significance at $\alpha = 0.05$ used to screen variables for multiple regression analysis.

Effect	df	Wald stat.	*P*	Included in multiple regression analysis?
All intercepts			≤0.001***	
Year	3	83.12	≤0.001***	Yes
Marksman type	1	0.05	0.82	No
No. elk	5	5.82	0.32	No
Killing shot required	1	16.64	≤0.001***	Yes
Initial shot impact	5	103.97	≤0.001***	Yes
Velocity rank	1	4.13	0.04*	Yes
Bullet type	3	19.0001	0.0003**	Yes
Rifle caliber	4	5.58	0.23	No
Bullet weight	1	5.35	0.02*	Yes
Sex of elk	1	0.53	0.47	No
Age of elk	2	0.06	0.97	No
Shot distance	1	7.21	0.007**	Yes
No. shots fired	1	74.72	≤0.001***	Yes

*$P \leq 0.05$
**$P \leq 0.01$
***$P \leq 0.001$

of the shooter, which presented a substantial crosswind during our evaluation period.

Firearms were Remington Model 700 rifles (Remington Arms Company, Ilion, NY), equipped with sporter-weight barrels, and chambered in .308 Winchester. All rifles were fitted with Nikon Monarch (model #8421) 4–16 variable-power scopes with 42 mm objective lenses (Nikon, Inc., Melville, NY). However, 2 rifles were equipped with aftermarket, adjustable triggers, and one was glass bedded. To maintain consistency of loaded rounds, we used a single case of Federal Premium® Ammunition loaded with 150-grain Barnes TSX bullets for all courses of fire. We cleaned the bore of each rifle and ensured that actions were clear of debris and in good working condition prior to the test. We then mounted each rifle in a Hyskore Model 30185 machine rest (Hyskore, Huntington Station, NY) and fitted a hydraulic trigger release (Hyskore, Huntington Station, NY) to actuate the firing mechanism.

For each rifle, we fired a fouling round and then performed a 5-round course of fire at 91 m, aligning the crosshairs at target center between shots. We allowed rifle barrels to cool to perceived ambient temperature and then completed a second 5-round course of fire with each rifle. We recorded the velocity of each round using a Beta Master chronograph (Shooting Chrony Inc., Amherst, NY). We then measured the maximum spread of bullet strikes to the nearest 0.03 mm from the visually estimated center of bullet holes with a dial caliper for each rifle across both courses of fire. Finally, we performed a Student's *t*-test to detect variation in pattern size and velocity between courses of fire and conducted linear regression of mean velocity of 5-shot strings on pattern size to test for variation in precision associated with differential charging of ammunition.

Results

Efficiency of kills

Prior to initiation of reduction activities in November 2010, the elk herd was estimated at approximately 1,200 individuals (Natl. Park Serv., unpublished data). During 2010 to 2013, park staff and volunteers shot 1,000 elk. Among these, 983 animals were recovered and 17 were wounded and lost, resulting in a 98.3% recovery rate overall. Notably, 279 elk were dispatched with a single shot. Dozens of bullets were recovered from elk carcasses over the course of the program, with most exhibiting deep, controlled expansion (Figure 3). All elk tested negative for CWD, and 67,170 kg of meat were distributed to qualified recipients.

After filtering records to remove cases

Table 3. All effects (top) and best subset (bottom) multiple regression analysis results for elk reduction data collected at Theodore Roosevelt National Park during 2010–2013.

Model	Effect	df	Wald stat.	*P*
All effects:				
	Intercept	5	621.00	≤0.001***
	Shot distance	1	0.09	0.77
	No. shots	1	33.15	≤0.001***
	Bullet Weight	1	2.57	0.11
	Year	3	67.91	≤0.001***
	Killing shot required	1	5.17	0.02*
	Initial shot impact	5	88.60	≤0.001***
	Velocity rank	1	0.75	0.39
	Brand acronym (bullet type)	3	4.04	0.26
Best subset:				
	Intercept	5	621.83	≤0.001***
	No. shots	1	36.16	≤0.001***
	Bullet weight	1	4.12	0.04*
	Year	3	88.04	≤0.001***
	Killing shot required	1	5.18	0.02*
	Initial shot impact	5	88.95	≤0.001***

*$P \le 0.05$
**$P \le 0.01$
***$P \le 0.001$

Table 4. Covariate relative importance values derived from analysis of all models with Akaike Information Criterion (AIC) weights summing to 95% or greater (n = 22) in model-averaging, multi-model inference analysis of eight variables pertaining to elk reduction activities at Theodore Roosevelt National Park during 2010 to 2013. Presented are the weights of models including each variable, divided by the sum of the AIC weights of all averaged models, with a highest possible score of 1.00.

Variable	Importance value	No. models containing variable
Initial shot impact	1.00	22
No. shots fired	1.00	22
Year	1.00	22
Killing shot required	0.85	16
Bullet weight	0.72	12
Velocity rank	0.27	9
Shot distance	0.26	9
Brand acronym	0.10	10

missing data (n = 29), records with inconsistent information (n = 5), and instances where chamberings or projectile types were represented <5 times (n = 28), we retained 921 cases for analysis. Among these, mean shot distance was 182 m, and the median and mode of distance traveled were 46 m and 0 m, respectively. Volunteers were the primary shooter for 502 cases, whereas park staff shot 419.

Exploratory analyses of field data revealed covariation among multiple continuous and categorical variables, suggesting considerable potential for interaction among predictors (results not presented). Eight of the 13 independent variables were significant individual predictors (Table 2). Multivariate ordinal regression of these 8 variables revealed that "initial shot impact," "killing shot required," "number of shots," and "year" were significant predictors of the efficiency of kills in terms of distanced traveled (Table 3). Model building with best subsets supported the inclusion of these four variables and "bullet weight" in the most parsimonious regression model (Table 3). Model averaging analyses confirmed the importance of all 5 aforementioned variables in predicting distance traveled (Table 4; Appendix A).

Parameter estimates of the regression indicated that differences in levels of effect for initial shot impact between marginal shots in the legs and abdomen, shots striking the shoulder and chest, and those shots impacting the neck are driving the significance of this variable for predicting distance traveled (Appendix B). Descriptive statistics for initial shot impact generally supported a hierarchy of effectiveness for shot placement, with short distances resulting from head and neck shots, intermediate distances following chest and shoulder wounds, and the longest distances resulting from abdomen and leg impacts (Table 5). Animals requiring a killing shot traveled farther than those that did not, and number of shots was positively correlated with distance traveled (r = 0.27, P < 0.05). The distance traveled by elk after being shot was different for year 1 and all other years (Table 5; Appendix B). Finally, the weight of bullets was negatively correlated with distance traveled (r = -0.07, P < 0.05), suggesting that heavier bullets may be more effective at incapacitating elk. However, when compared to other significant factors, bullet weight was of lower importance (Table 4; Appendix B).

Range evaluation of ammunition

Muzzle velocity was successfully recorded for 78 of 80 shots taken during two 5-shot courses of fire with 8 rifles. Mean velocity was 851 m per second, and mean group size was 50 mm, with minimum and maximum group sizes varying 2-fold from the mean (Table 6). Between courses of fire, mean group size did not vary (t_{14} = 0.13, P = 0.90), though muzzle velocity was significantly different (t_{76} = -3.01, P = 0.004), with mean velocity 5 m per second faster for the second course of fire. However, mean muzzle velocity was not a significant predictor of 5-shot group size (R^2 = 0.1801, $F_{1,14}$ = 3.08, P = 0.10).

Discussion

Program factors contributing to efficient culling of elk

The successful removal of 983 elk at TRNP with minimal wounding loss suggests that the tools and techniques employed were highly effective. Our structured approach to field operations, with a team leader directing the actions of reduction team members, generally resulted in efficient kills. Program policies, such as range qualification of rifles and ammunition, targeting of the shoulder and chest, stalking to within 183 m, and directing the fire of multiple marksmen on individual elk maximized recovery of animals. Individual efforts of staff and volunteers to coordinate actions and facilitate scenarios leading to success should not be overlooked when considering the efficacy of non-lead bullets.

Regardless of bullet design, shot placement is an important factor for effective destruction of animals (Ruth and Simmons 1999, Caudell et al. 2013). Intentional targeting of the shoulder and chest by marksmen often resulted in near instantaneous incapacitation of elk during our program, similar to that observed by Ruth and Simmons (1999) for whitetail deer (*Odocoileus virginianus*). However, our analyses indicate that shots to the neck are more likely to result in instantaneous incapacitation of animals. Ruth and Simmons (1999) also observed that shots to the neck immediately immobilized animals, but the neck of whitetail deer was considered a problematic target due to its small size. In contrast, the relatively large size of an elk's neck may present a reasonable target for precision kills at close or intermediate ranges. Notably, at TRNP, 75% of shots to the neck resulted in instantaneous incapacitation, versus 40% for shots to the chest and 46% for shots striking the shoulder. This disparity in bullet strike outcomes is likely due to the concentration of vascular and central nervous system organs in the neck (Caudell et al. 2012). Knott et al. (2009) reported that sika deer (*Cervus nippon*) shot in the chest with non-lead ammunition had to be tracked and concluded that head shots were most practical for that study site. At TRNP, the few recorded shots to the head of elk were mostly unintentional, but also generally resulted in instantaneous incapacitation. However, the small size of the crania made the head an impractical target for dynamic field conditions at our site, where animals were typically engaged at 183 m and required shooter precision at that distance was a 200-mm pattern for 60% of shots. Further, shots to the head with non-lead ammunition often result in bullet pass-through, which could result in injury to other animals or ricochets (Caudell et al. 2012). Thus, we infer that the shoulder is the best aiming point for future operations at the park because it provides the greatest margin of error. Shots striking the shoulder will typically result in quick kills, whereas shots flying wide will impact the heart and lungs caudally or the neck cranially. In all cases instantaneous or near-instantaneous incapacitation may be expected.

Mass, velocity, and bullet configuration have been identified as critical factors in the wounding potential of projectiles (Bellamy and Zajtchuk 1999, MacPherson 2005, Caudell et al. 2013). Further, the importance of matching bullet type with animal type and shooting scenarios is well understood (DeMuth 1966, Caudell et al. 2009, Litz 2011). Therefore, it makes sense that bullet weight was included in our top regression model. Though an ideal bullet weight or configuration cannot be gleaned from our analysis, a general recommendation is to use heavier bullets for elk whenever practical in terms of availability and accuracy in the rifles utilized. Additionally, accuracy and velocity are inversely related to distance, and the range at which marksmen can deliver accurate shots depends on individual skill level and knowledge of ballistics (DeMuth 1966, Vaughn 2000, Litz 2011). Significant covariance among shot distance and number of shots fired (r = 0.18, $P < 0.05$) and between shot distance and initial shot impact ($F_{1,5} = 2.83$, $P = 0.02$) indicates that shot distance has impinged directly on the variance of other important factors in the model. Thus, we infer indirectly that closer shots will be more effective at dispatching elk.

The relationship for number of shots fired and the need for a killing shot with longer distances traveled by elk is easily understood. Wounded animals were fired upon until they were incapacitated or out of sight and were the most likely to require a killing shot. The significance of year on distance traveled may be explained in part by heavy snowfall during the first year of the project. During October 2010 to January 2011, snow drifted and accumulated to heights of >1 m in some locations at TRNP, possibly causing difficulties for elk to traverse the landscape. Additionally, large herds of elk existed in the park at the beginning of the project, and they had not previously experienced hunting pressure within the park boundary. Therefore, elk were naïve to removal activities and faced environmental difficulties when attempting to escape during the first year, resulting in short distances traveled. Conversely, distance traveled by elk during subsequent years may have been increased by conditioning of radio-collared animals to removal operations (Bender et al. 1999).

Though our analysis has provided useful insights, several factors were not addressed in our investigation due to the physical challenges and complexity of operations required to accomplish management objectives. Specifically, (1) we did not attempt to evaluate wound channel pathology, (2) we did not consistently record the number of shots striking elk or the impact locations for bullets subsequent to the initial shot, and (3) we did not record precise measurements or spatial variables (i.e., direction, slope, elevation gradients) pertaining to movement of elk after being shot. Evaluation of wound channels and the number and order of bullet impacts would allow for determination of the series of vital organs affected and identification of

Table 5. Descriptive statistics for response variable "distance traveled" (m) across significant categorical predictor variables in the most parsimonious regression model obtained from elk reduction data collected during 2010 to 2013.

Grouping variable	Level	*n*	Mean	SD	Median	Mode	Mode frequency	Min	Max
Initial shot impact									
	Abdomen	71	79.2	80.6	46	91	25	0	366
	Chest	332	36.2	38.8	46	46	167	0	274
	Head	5	9.1	20.4	0	0	4	0	46
	Leg	18	147.3	138.9	91	46/91/366[a]	4	0	366
	Neck	67	15.7	32.4	0	0	50	0	183
	Shoulder	428	36.1	51.5	46	0	195	0	366
Year									
	One	371	27.5	52.3	0	0	228	0	366
	Two	438	50.1	58.7	46	46	224	0	366
	Three	67	38.2	37.0	46	46	30	0	183
	Four	45	47.7	56.8	46	46	25	0	274
Killing shot required									
	Yes	186	62.2	85.1	46	0	68	0	366
	No	735	34.4	43.8	46	0	324	0	366

[a] Denotes that multiple modes were observed.

central nervous system strikes that would help explain ultimate outcomes in terms of levels of incapacitation (Caudell et al. 2012, Caudell 2013, Trinogga et al. 2013). Field necropsies might also provide information regarding bullet and bone fragmentation, which may be an important factor in killing power (DeMuth 1966, Fackler et al. 1984, Cruz-Martinez et al. 2015; Figure 3). Spatial information, such as GPS track logs retracing the course traveled by elk, would provide more accurate and informative metrics as response variables for multivariate analyses. Future efforts to understand the efficacy of bullets in context of field operations should be designed to better measure these variables.

Utility of non-lead ammunition for precise shot placement

In a meta-analysis of accuracy tests for sporting arms, Vaughn (2000) reported that the typical maximum group size for 5 shot strings of fire for hunting cartridges was roughly 50.8 mm and the typical mean group size was 38.1 mm. In most cases, rifles and non-lead ammunition used on our project yielded comparable levels of precision. In fact, when our worst performing rifle was excluded, mean minimum group size was 35.8 mm and mean maximum group size was 51.1 mm at 91 m, falling well within the range of precision described for most sporting arms firing lead-based projectiles (Vaughn 2000). Range evaluations of non-lead ammunition performed elsewhere generally support this finding (C. Batha and P. Lehman, Wisconsin Department of Natural Resources, unpublished data). The Barnes Ballistics Lab reported mean 5-shot group size of 12.7 mm and 17.8 mm at 91 m for their TTSX bullets fired through rifles chambered in 7mm Winchester Short Magnum and .300 Weatherby Magnum, respectively (Barnes Bullets Inc., unpublished data). Therefore, the accuracy potential for non-lead ammunition is clearly sufficient for dispatching large ungulates in typical hunting scenarios.

Variable accuracy of rifles may be explained by a number of factors, including differences

Table 6. Velocity (m per second) at muzzle and group size (spread in mm) at 91 m recorded during a shooting test of NPS rifles firing non-lead ammunition near Belfield, ND on October 18, 2013.

Statistic	Velocity (n = 78)	Group size (n = 16)
Mean	851	50
SD	7.9	22.5
Min	824.5	18.8
Max	874.2	98.6
Range	49.7	79.8

in machining of receivers and barrels, the fitting of rifle stocks, the quality of optical sights and mounts, the materials used during production, levels of wear and cleanliness of the barrel, and the conditions under which the firearm was discharged (Vaughn 2000, Litz 2011). Variation in ammunition, such as seating depth, powder charge, case neck uniformity, and case length, may also affect consistency of shots. Additionally, the physical properties of non-lead bullets vary from that of lead-core projectiles, for which most modern arms are designed. Due to lower density, non-lead bullets are typically longer than lead bullets, potentially causing accuracy problems related to standard twist rates of rifles (Caudell et al. 2012).

We worked to minimize variability in our analysis by utilizing the same model of rifle, mounts, and optics and using a single case of ammunition. Despite wind effects, variable velocities, and minor modifications to 3 rifles, a lack of detectable variation in pattern size between courses of fire suggests that our techniques were reliable. In fact, the observed variation in recorded muzzle velocities is within the range of error for many chronographs, perhaps explaining the lack of change in group size between courses of fire (Litz 2014). Further, it is well established that different rifles will fire a particular brand of ammunition or projectile type with different levels of precision, as evidenced by the poor performance of one of our rifles that scored 98.6 and 94.2 mm groupings at 91 m across courses of fire. Therefore, additional tests of our rifles with different ammunition are warranted. To improve the matching of rifles and ammunition for optimal accuracy, custom ammunition providers with government contracting authority may be utilized to prepare smaller quantities of cartridges for specific firearms. This custom loading approach has been employed by managers at Pinnacles National Park to produce minute-of-angle accuracy with non-lead ammunition fired through NPS rifles (S. Scherbinski, Natl. Park Serv., personal communication).

Management implications

Recent changes in NPS policy mandating the use of non-lead ammunition in all park units as of 2011 have caused some uncertainty among managers and the public regarding the efficacy of this tool. Therefore, our evaluation of non-lead ammunition performance during a sanctioned NPS lethal removal operation is timely and will serve to inform management actions on federal lands and elsewhere. We conclude that non-lead bullets are an effective tool as an alternative to lead projectiles for wildlife management operations where post-cranial vital areas of animals are targeted, supporting and validating the aforementioned NPS policy. Non-lead ammunition provides the necessary precision for accurate shot placement, which we have identified as a key factor for incapacitating animals. Further, the bullets used in our program typically produced lethal wounds, as evidenced by the high rate of carcass recovery. Finally, non-lead ammunition facilitated our donation of large amounts of untainted (i.e., free of lead fragments) meat to public recipients. Given the potential environmental and human health benefits, managers and sportsmen alike should be encouraged to try the growing array of non-lead ammunition available today. However, individuals should always experiment with cartridge components to identify loadings that will meet performance expectations for specific shooting scenarios.

Considering the nature in which non-lead ammunition was employed during our program, with staff and volunteers utilizing spot and stalk hunting techniques, we infer that non-lead ammunition is a practical alternative tool for sporting pursuit of large game. An after-action survey of project volunteers requesting "Rate your experience using non-lead ammunition" revealed that 88% of the 186 respondents viewed the ammunition as average or above average, and 42% gave it the highest possible rating (Natl. Park Serv., unpublished data). This high approval rating generally agrees with results of a hunter survey conducted by Arizona Game and Fish Department, which revealed that 75% of participants would recommend non-lead ammunition to other hunters (P. T. Seng et al., D. J. Case and Associates, unpublished data). Therefore, the opinions of elk reduction participants at TRNP regarding non-lead ammunition are well aligned with experienced public opinion elsewhere. Additional opportunities for development of firsthand experience among public stakeholders should be facilitated to improve awareness and encourage use of alternative ammunition.

Though we did not directly evaluate human performance, initial shot impact and number of shots fired may be viewed as proxy variables, with the assumption that shooter performance is key to the successful harvesting of animals with firearms and ammunition of all types. Moreover, our analysis has demonstrated that lead-free rifle ammunition of various brands and calibers can produce rapid kills of elk within 183 m of shooters, whenever vital tissues are impacted.

Acknowledgments

We thank our NPS colleagues for their assistance in developing and implementing procedures unprecedented in terms of scope and intensity in the National Park system. It is remarkable that few human injuries resulted from this strenuous activity and annual elk reduction goals were consistently exceeded. A cooperative effort involving North Dakota Sportsman Against Hunger, North Dakota Community Action Partnership, and North Dakota Game and Fish Department provided the mechanisms by which the recovered elk meat was provided to the volunteer shooters and the people of North Dakota. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Appendix A. Best subsets regression model building results (top 10 models) with Akaike Information Criterion (AIC) as selection factor for 8 variables (Var.) pertaining to the elk reduction program at Theodore Roosevelt National Park during 2010 to 2013. Note: KSR (killing shot required), ISI (initial shot impact), BT (bullet type), NS (number of shots), VR (velocity rank), SD (shot distance), and BW (bullet weight).

Model No.	Var. 1	Var. 2	Var. 3	Var. 4	Var. 5	Var. 6	Var. 7	df	AICc	Delta	Weight
1	NS	BW	Year	KSR	ISI			11	1900.9	0.00	0.244
2	SD	NS	BW	Year	KSR	ISI		12	1902.8	1.89	0.095
3	NS	BW	Year	KSR	ISI	VR		12	1902.9	2.00	0.09
4	NS	Year	KSR	ISI				10	1903	2.07	0.087
5	NS	BW	Year	KSR	ISI	BT		14	1903.6	2.68	0.064
6	NS	BW	Year	ISI				10	1903.8	2.83	0.059
7	NS	Year	KSR	ISI	BT			13	1904.6	3.65	0.039
8	SD	NS	BW	Year	KSR	ISI	VR	13	1904.8	3.87	0.035
9	NS	BW	Year	KSR	ISI	VR	BT	15	1904.9	3.95	0.034
10	NS	Year	KSR	ISI	VR			11	1904.9	3.98	0.033

Appendix B. Model-averaged parameter estimates from all effects regression on elk reduction data from Theodore Roosevelt National Park during 2010 to 2013.

Effect	Level of effect	Estimate	SE	Adj. SE	*Z* value	Pr(>|z|)
Intercept 1		–2.27	1.01	1.01	2.25	0.02*
Intercept 2		0.16	1.00	1.00	0.16	0.88
Intercept 3		1.81	1.01	1.01	1.79	0.07
Intercept 4		2.75	1.03	1.03	2.68	0.007**
Intercept 5		3.23	1.04	1.04	3.09	0.002**
Initial shot impact	Thorax	–1.41	0.27	0.27	5.20	≤0.001***
	Head	–2.81	1.20	1.20	2.34	0.02*
	Leg	0.82	0.58	0.58	1.41	0.16
	Neck	–2.83	0.38	0.39	7.36	≤0.001***
	Shoulder	–1.68	0.26	0.26	6.36	≤0.001***
Killing shot required	Yes	0.38	0.17	0.17	2.22	0.03*
Year	One	–0.92	0.32	0.32	2.89	≤0.001***
	Three	0.08	0.37	0.37	0.21	0.83
	Two	0.43	0.32	0.32	1.34	0.19
Velocity rank	Standard	0.08	0.16	0.16	0.48	0.63
Brand acronym	BTTSX	0.40	0.20	0.20	1.95	0.05
	ETIP	0.06	0.33	0.33	0.19	0.85
	HGMX	0.22	0.26	0.26	0.83	0.41
Shot distance		0.00	0.00	0.00	0.39	0.69
No. shots fired		0.33	0.06	0.06	5.67	≤0.001***
Bullet weight		–0.01	0.00	0.00	1.95	0.05

*$P \leq 0.05$
**$P \leq 0.01$
***$P \leq 0.001$

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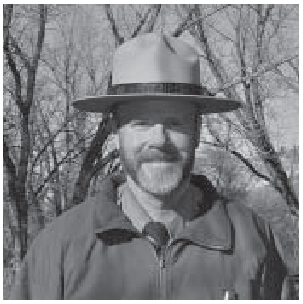

William Whitworth serves as chief of the Resource Management Division at Theodore Roosevelt National Park located in the Little Missouri River Badlands of southwestern North Dakota. Management challenges often focus on ecosystem and historic structure preservation and active management of highly productive elk, bison, and feral horse populations within the context of the surrounding Bakken shale-oil boom. Prior to his current position, he was a natural resource manager for the Natchez Trace Parkway headquartered in Tupelo, Mississippi and a wildlife ecologist with the U.S. Army Corps of Engineers in Champaign, Illinois. He received his B.S. and M.S. degrees in field biology from Fort Hays State University in 1983 and 1986, respectively.

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