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A comparison of lead-based and lead-free bullets for shooting sambar deer (*Cervus unicolor*) in Australia

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ABSTRACT

Context. In response to the toxic health threats posed by lead (Pb), there is currently a focus on transitioning to lead-free bullets for shooting wild animals. **Aim.** We aimed to quantify the killing efficiency and animal welfare outcomes of lead-based and lead-free (copper-based) bullets for ground-based shooting of sambar deer (*Cervus unicolor*) in Victoria, south-eastern Australia. **Methods.** We used shooter-collected data from recreational diurnal hunting and professional nocturnal culling during 2020–2021. Shooters recorded rifle calibre, cartridge type, bullet mass, bullet type, shooting outcomes (miss, wound or kill), shooting distance, flight distance (the distance between where the animal was shot and where it died) as an assumed positive correlate of time to incapacitation, anatomical zones struck by bullets, and frequency of bullet exit wounds. We used flight distance as our response variable, assuming that it is positively correlated with time to incapacitation. To examine the role of several predictor variables (including bullet type) potentially influencing flight distance, the dataset was reduced to those deer killed with a single thoracic shot. **Key results.** Our data captured shooting events involving 276 deer, with 124 deer shot at with lead-based bullets and 152 with copper-based bullets. Most (87%) of the deer were killed with a single shot. The frequency of non-fatal wounding was <4% for both bullet types and there was no distinct difference in the probability of a single shot kill for deer shot with either bullet type. For those deer killed with a single thoracic shot ($n = 198$), there was no evidence that bullet energy or shooting distance influenced flight distance. After accounting for differences in terminal kinetic energy, the mean flight distance of deer shot with lead-free bullets (35 m) was 56% greater than that of deer shot with lead-based bullets (22 m). **Conclusions.** Lead-based and lead-free bullets produced similar animal welfare outcomes for shooting sambar deer. **Implications.** A transition to lead-free ammunition for shooting sambar deer would have minimal impact on efficiency or animal welfare outcomes.

Keywords: animal welfare, culling, human dimensions, invasive species, population control, recreational hunting, toxicology, wildlife management.

Introduction

Ground-based shooting, either on foot or from vehicles, is a widely used method of killing non-native deer in Australasia (Bennett *et al.* 2015; Bengsen *et al.* 2020; Nugent and Forysth 2021; Moloney *et al.* 2022). Recreational ground-based shooters kill large numbers of deer annually in Australia (Moloney *et al.* 2022) and New Zealand (Kerr and Abell 2014). For example, approximately 40 000 licensed hunters reported killing approximately 174 000 deer in the state of Victoria during the 2019 calendar year (Moloney and Hampton 2020). Professional ground-based shooters are also employed or contracted by public and private landholders to kill deer in Australasia (Bennett *et al.* 2015; Comte *et al.* 2022*a*; Hampton *et al.* 2022*a*). Last, there are small commercial markets for wild-shot deer in New Zealand (Nugent and Forysth 2021) and Australia (Watter *et al.* 2020).

The sambar deer (*Cervus unicolor*) is Australia's largest deer species (140 kg for females, 220 kg for males), and has a large and expanding range in south-eastern Australia (Forsyth *et al.* 2022). The sambar deer is the deer species most harvested by recreational ground-based shooters in Victoria (~131 000 in 2019; Moloney and Hampton 2020). Sambar deer are also culled by professional ground-based shooters with the aim of reducing their undesirable impacts in water catchments (Bennett *et al.* 2015) and national parks (Comte *et al.* 2022*b*). There is also a commercial harvest of sambar deer for pet food (Victoria State Government 2020). In Victoria, sambar deer hunters are required to use a rifle with a minimum calibre of .270 (6.85 mm) and a minimum projectile mass of 130 grains (8.45 g; Wildlife (Game) Regulations 2012). However, there are currently no restrictions on what metals can be used to make bullets that deer are shot with in Victoria, permitting the use of lead (Pb).

Lead-based bullets have been used to shoot animals for centuries, primarily because lead has been widely available, inexpensive and has excellent killing properties, being a dense and soft metal (Stokke *et al.* 2017). However, lead is a neurotoxin affecting the health of humans, animals and the environment, and has accordingly been phased out from many widely used products such as fuel and paints. The continued use of lead-based ammunition for shooting wild deer has the potential to harm several groups, including wildlife scavengers such as wedge-tailed eagles (*Aquila audax*) feeding on shot carcasses (Hampton *et al.* 2021*a*), people consuming contaminated venison (Hunt *et al.* 2009), and domestic animals fed large amounts of venison, such as hunting dogs (Fernández *et al.* 2021). The One Health threat posed by lead (Arnemo *et al.* 2022) has been a focus of international research for several decades and is gaining attention in New Zealand (Buenz and Parry 2019) and Australia (Hampton *et al.* 2022*b*).

There has been a significant global movement towards lead-free ammunition in recent decades to mitigate the numerous deleterious health impacts of lead (Cromie *et al.* 2019). The most widely researched and commonly available lead-free bullet type is copper (Cu) based (Knott *et al.* 2009; Irschik *et al.* 2013; Stokke *et al.* 2017; Hampton *et al.* 2020). Copper is a less dense and less malleable metal than is lead, and when a copper-based projectile strikes an animal, its terminal or 'wound' ballistics properties (i.e. deformation, expansion and fragmentation) differ from lead-based projectiles. Namely, copper-based bullets typically deform, expand and fragment less than do lead-based bullets (Stokke *et al.* 2017). These differences for copper-based bullets also arise with other lead-free bullets, for example, bullets made from brass (an alloy of copper and zinc; Gremse *et al.* 2014), and have manifested as doubts about the ability of lead-free bullets to achieve the same animal welfare standards as traditional lead-based bullets (Hampton *et al.* 2021*b*). This, along with the typically higher costs of lead-free ammunition (Thomas *et al.* 2016), has been a key factor in delaying moves to transition to lead-free ammunition in wildlife management (Caudell *et al.* 2012; Hampton *et al.* 2020).

To ensure that wildlife management prioritises the welfare of wildlife that are the subject of shooting practices, it is important that any products advocated in a lead-free transition are capable of maintaining, or improving, animal welfare standards (Hampton *et al.* 2021*b*). One of the most robust measures of animal welfare outcomes for killing methods is duration of suffering (Mellor and Littin 2004). The metric most commonly used in the field as a proxy for duration of suffering in studies comparing the performance of lead-based and lead-free bullets is the length of the 'escape distance', namely, the distance run after being shot and before becoming recumbent (Kanstrup *et al.* 2016; Martin *et al.* 2017; Stokke *et al.* 2018, 2019). However, this methodology has utility only for animals shot in the thorax ('chest shooting'; Stokke *et al.* 2018), and so cannot be applied to deer shooting methods used occasionally in Australasia, such as 'head shooting' of urban deer during professional culling (Hampton *et al.* 2022*a*).

Several studies have reported escape distance data associated with lead-free bullets for recreational hunting of ungulate species such as roe deer (*Capreolus capreolus*) and red deer (*Cervus elaphus*) in Scandinavia (Kanstrup *et al.* 2016), roe deer and feral pigs/wild boar (*Sus scrofa*) in Germany (Martin *et al.* 2017), and moose (*Alces alces*) in Scandinavia (Stokke *et al.* 2017, 2019). These studies have reported no significant differences in animal welfare outcomes between lead-based and lead-free bullets. Other studies to assess animal welfare outcomes between lead-based and lead-free bullets for cervid shooting have, instead, relied on quantifying the frequency of adverse animal events such as immediate insensibility and the need for repeat shooting, as for roe deer in the United Kingdom (Knott *et al.* 2009), and elk (*Cervus elaphus/canadensis*) in the United States (McCann *et al.* 2016).

In this study, we quantify the killing efficiency and animal welfare outcomes of lead-based and lead-free (copper-based) bullets for ground-based shooting of sambar deer in Victoria, south-eastern Australia. Because sambar deer are commonly killed using 'chest shooting' (Game Management Authority of Victoria 2022), we used the findings of European publications that have reported cervid flight distance from hunter-collected data (Kanstrup *et al.* 2016; Martin *et al.* 2017; Stokke *et al.* 2018, 2019) to develop our study rationale and inform how we designed our study. We also aimed to quantify the frequency of adverse animal welfare events such as non-fatal wounding. This is not the first study examining lead-free ammunition in Australia, but previous work has been restricted to rimfire ammunition and a small mammal (European rabbits; *Oryctolagus cuniculus*; Hampton *et al.* 2020) and aerial (helicopter) shooting of feral pigs (Hampton *et al.* 2021*c*).

Here, we document the range of cartridges, bullet masses, shooting distances and outcomes from samples of Victorian hunters using lead-based and lead-free bullets, and use the data to (1) compare the frequency of adverse animal welfare events for the two bullet types, (2) compare typical flight distances for the two bullet types, and (3) examine the role of other explanatory variables (namely animal mass, shooting distance and bullet kinetic energy) influencing flight distance.

Materials and methods

Study area and timing

We conducted our study in eastern Victoria (see Moloney and Hampton (2020)) from April 2020 to December 2021. In eastern Victoria, sambar deer occupies habitats ranging from coastal swamps to wet sclerophyll forests (Fig. 1*a*) to high-elevation peatlands (Gormley *et al.* 2011; Forsyth *et al.* 2015; Comte *et al.* 2022*a*; Davies *et al.* 2022). The climate is temperate, with average annual rainfall ranging from 400 to 1500 mm (Bureau of Meteorology 2021). Mean summer temperatures (December to February) vary from 23°C to 27°C and mean winter temperatures (June to August) vary from 13°C to 16°C (Bureau of Meteorology 2021).

Data collection

We adopted the methods used in recent northern European studies (Kanstrup *et al.* 2016; Stokke *et al.* 2019) to approach active deer shooters and request that they collect data from their deer shooting events. We used shooter-collected data from recreational diurnal hunting ('stalking') and professional nocturnal culling (see Comte *et al.* (2022*a*) for further details on these methods). No commercial harvesters were approached to contribute data because commercial harvesting mostly relies on 'head shooting' (Watter *et al.* 2020), which is not amenable to flight distance characterisation (Stokke *et al.* 2018). We used our professional and private networks to identify shooters who would be likely to be willing to be involved in our study. We disproportionally targeted shooters known to use lead-free bullets, given that most shooters were assumed to use lead-based bullets, in an attempt to achieve parity in sample sizes for the two bullet types.

For all deer shot at, shooters were asked to record cartridge type (including calibre), bullet mass, bullet type (lead-free or lead-based), shooting outcomes (miss, wound or kill), shooting distance, flight distance, anatomical zones struck by bullets (head, neck, thorax, abdomen, limbs), estimated body mass of deer (kg), and frequency of bullet exit wounds, as per Stokke *et al.* (2019). There can be ambiguity around whether shots miss or strike animals with certain shooting methods, particularly those using firearms that are relatively non-powerful when compared with centrefire rifles (e.g. shooting birds with shotguns; Pierce *et al.* 2015). However, shot outcomes tend to be less ambiguous when centrefire rifles that deliver relatively high kinetic energy levels are used (Table 1; Hampton *et al.* 2022*a*). Body mass was estimated visually.

Flight distance was defined as the distance moved by the deer after being shot and before becoming recumbent (Kanstrup *et al.* 2016; Martin *et al.* 2017; Stokke *et al.* 2018, 2019; Fig. 2). We collected only linear distances for flight responses, despite the fact that shot animals often follow more tortuous paths before becoming incapacitated. We also asked shooters to specify what method they use to estimate shooting and flight distances, laser range finders

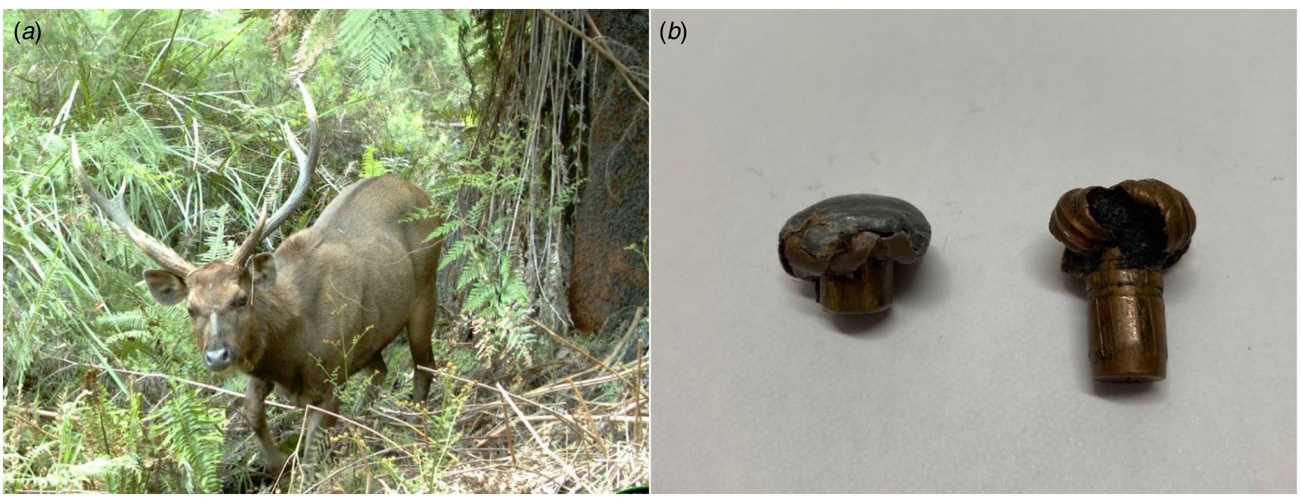

Fig. 1. (*a*) The study species, sambar deer (*Cervus unicolor*), photographed by a motion-sensitive camera (image credit: C. Davies), and (*b*) an image of typical bullets removed from sambar deer shot in eastern Victoria, Australia, in 2020–2021: a 200 g lead-based bullet (left) and a 225 g lead-free (copper-based) bullet (right). Both bullets were recovered from fired .338 Winchester Magnum cartridges (image credit: J. Hampton).

Table 1. Cartridge types, bullet masses and typical muzzle kinetic energy levels for 152 lead-free and 124 lead-based bullets fired at sambar deer (*Cervus unicolor*) in eastern Victoria, Australia, in 2020–2021.

Cartridge	Bullet mass (grains)	*n*	Typical muzzle kinetic energy (J)	Kinetic energy data source
Lead-free				
.270 Winchester	130	7	3664	www.barnesbullets.com
30-06 Springfield	150	10	3983	www.barnesbullets.com
.308 Winchester	150	15	3797	www.barnesbullets.com
8 × 64 mm S (.323)	160	3	4191	www.barnesbullets.com
.325 Winchester Short Magnum	200	26	4720	www.barnesbullets.com
.338 Winchester Magnum	225	16	5310	www.barnesbullets.com
.375 Holland & Holland Magnum	270:300	75	5826:5925	www.barnesbullets.com
Lead-based				
.270 Winchester	130:156	14	3482:3664	www.winchester.com
28 Nosler (.284)	175	1	4309	www.nosler.com
.300 Weatherby	200	9	5274	www.hornady.com
.300 Winchester Magnum	180	2	4747	www.winchester.com
.308 Winchester	135:180	17	3657:3719	www.winchester.com
.338 Lapua Magnum	250	22	6329	www.sierrabullets.com
.338 Winchester Magnum	200:225	12	5234:5275	www.winchester.com
9.3 × 62 mm (.366)	286	7	4795	www.hornady.com
.375 Holland & Holland Magnum	270:300	39	5780:5881	www.federalpremium.com
.450 Bushmaster	250	1	3642	www.hornady.com

or linear distances between saved GPS waypoints. We did not request information on the manufacturer of bullets, the angle of shots taken, or target animal movements before shooting, as some previous studies have (Kanstrup *et al.* 2016). We also requested that volunteering shooters collect and send to us any retained bullets (i.e. those that did not create exit wounds and that were found during butchering). For those bullets that were sent to us, we cleaned and weighed them to calculate their mass retention (Fig. 1*b*), as per Stokke *et al.* (2017).

Data analysis

Each shooting attempt was classified into one of the following four realised outcomes: (1) killed with the first bullet that struck; (2) killed after being struck by two or more bullets; (3) escaped wounded; and (4) missed and escaped (Hampton *et al.* 2022*a*). We used logistic regression to estimate the probability of each outcome for each bullet type.

We used the following two criteria to compare the ability of lead-based and lead-free bullets to produce rapid incapacitation: (1) the probability that a deer shot with either bullet type travelled <10 m after being shot; and (2) the effect of bullet energy or shooting distance on the distance travelled by deer after being shot (flight distance) with each bullet type. We assume that flight distance correlated with time to incapacitation (Stokke *et al.* 2018).

To evaluate the first criterion, we used logistic regression to estimate the probability that a deer shot with either bullet type travelled <10 m after being shot. Data were pooled across 13 cartridge types and various bullet calibres and masses (Table 1), and included deer shot at night with thermal scopes or in daylight hours with standard optical scopes. To reduce confounding owing to the effects of multiple shots and different shot placement, we discarded cases in which deer were shot more than once and cases in which the bullet struck outside the thorax.

To evaluate the second criterion, we used negative binomial regression to describe the effects of bullet type and either shooting distance or bullet terminal kinetic energy on deer flight distance. To estimate terminal kinetic energy, we used muzzle kinetic energy levels reported by ammunition manufacturers and assumed a drop of 1 m s^{-1} per 1 m shooting distance (Kanstrup *et al.* 2016). We also included a parameter to estimate the effect of body mass for each bullet type because we expected larger-bodied deer to travel greater distances after being shot than do smaller deer (Stokke *et al.* 2018). Shooting distance and bullet terminal kinetic energy were negatively correlated (Pearson's $r = -0.65$), so we used separate models for each variable. To improve model performance and interpretation, we mean-centred shooting distance and bullet terminal energy. The intercepts therefore represented the average flight distance of a deer shot with either bullet type. We used the same restricted dataset

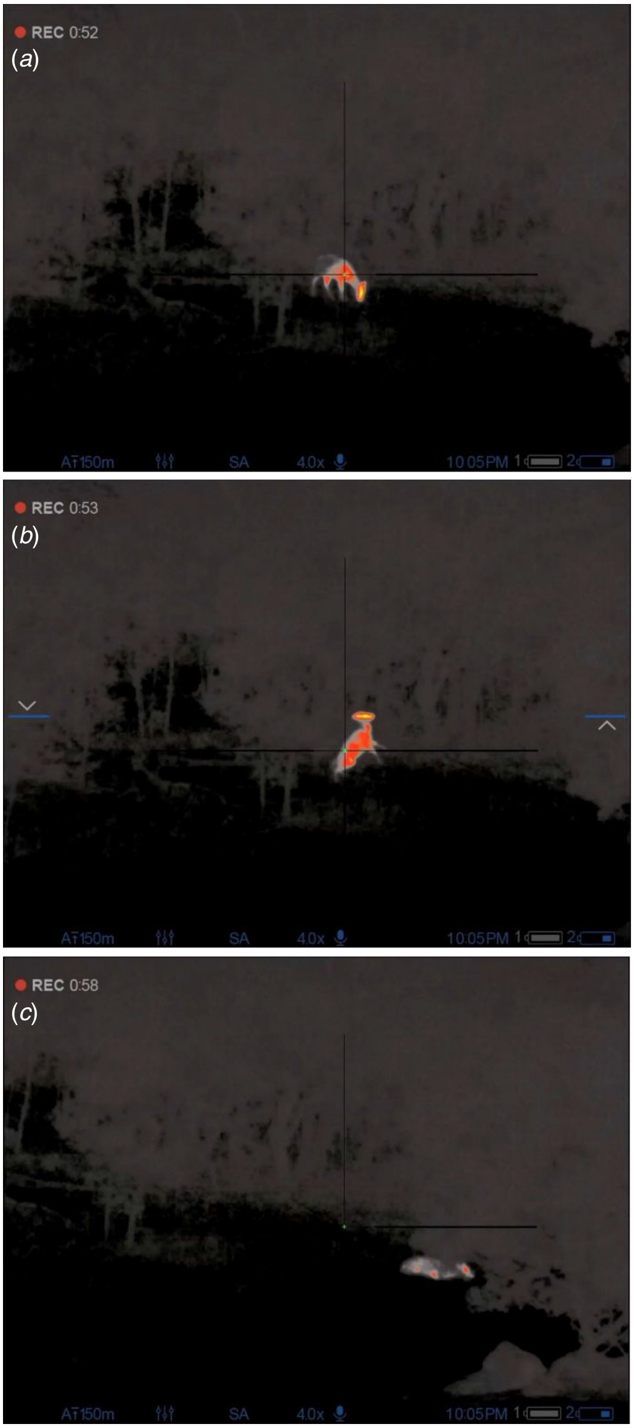

Fig. 2. Three sequential photos taken from video footage recorded by a thermal scope during night-time culling of sambar deer (*Cervus unicolor*) in eastern Victoria, Australia, in 2020–2021. The photos show (*a*) an animal about to be shot, (*b*) flight response to bullet impact and (*c*) eventual recumbency after flight response. Flight distance was <10 m. The time of each event can be seen in the top-left corner of each image.

as for the previous model and excluded a further two cases for which estimated body mass was unavailable.

All models were implemented using JAGS (Plummer 2003) called via the runjags package (Denwood 2016) in the R statistical environment (R Core Team 2020). Markov-chain Monte Carlo (MCMC) sampling used seven chains of 15 000 draws each after discarding 1000 burn-in draws. Parameter estimates are reported as posterior means and 95% credible intervals (95% CrI).

Results

Data were recorded by 15 shooters for 276 deer shooting events. Only two of the shooters were professional cullers, but they accounted for 43% of deer shot. The remaining 57% of deer were shot by recreational hunters or volunteer shooters undertaking unpaid deer control on private land (non-professionals). Professional shooters used both types of ammunition, whereas most individual non-professional shooters used only a single bullet type; lead-based bullets were used in 39% of 120 professional shooting events and 49% of 156 non-professional shooting events. In total, 152 deer were shot at with lead-free bullets and 124 with lead-based bullets.

Most (87%) of the deer in the full dataset were killed with a single shot, and there was no distinct difference in the probability of a single-shot-kill for deer shot with lead-free (0.89, 95% CrI = 0.83, 0.93) or lead-based bullets (0.85, 95% CrI = 0.78, 0.90) (Table 2). The frequency of non-fatal wounding was <4% for both bullet types, being 0.03 (95% CrI = 0.01, 0.07) for lead-free and 0.04 (95% CrI = 0.00, 0.04) for lead-based bullets (Table 2).

To examine flight distances, we discarded 36 events in which deer were shot more than once and 42 cases in which the bullet struck outside the thorax. Most (90%) of the non-thoracic killing shots struck the head or neck and were associated with low (i.e. <10 m) flight distances, with

Table 2. Posterior means and 95% credible intervals of four different outcomes for 276 sambar deer (*Cervus unicolor*) shot with lead-free or lead-based bullets in eastern Victoria, Australia, in 2020–2021.

Outcome	*n*	Posterior mean	95% CrI
Lead-free			
Killed with first hit	135	0.89	0.83, 0.93
Killed after wounding	10	0.07	0.03, 0.11
Escaped wounded	5	0.03	0.01, 0.07
Escaped unwounded	2	0.01	0.00, 0.04
Lead-based			
Killed with first hit	105	0.84	0.78, 0.90
Killed after wounding	17	0.14	0.08, 0.20
Escaped wounded	2	0.02	0.00, 0.04
Escaped unwounded	0	0.00	0.00, 0.00

87% of these head or neck shots having a flight distance of zero. The resulting dataset (n = 198) comprised 111 cases in which deer were killed with lead-free bullets and 87 cases in which lead-based bullets were used. The distribution of shooting distances and flight distances were similar for lead-free and lead-based bullets in this reduced dataset. Most deer (98%) were shot at a range of <300 m and 95% of deer travelled <100 m after being shot (Fig. 3). For those deer killed with a single thoracic shot, the proportion of bullet tracts producing exit wounds was 0.96 for lead-free and 0.58 for lead-based bullets. The numbers of retrieved lead-free and lead-based bullets returned by shooters were only n = 16 and n = 11 respectively. The mean mass retained for lead-free and lead-based bullets was 96.3% and 49.9% respectively.

Logistic regression indicated that the probability of a deer having a flight distance of <10 m after being struck by a single bullet in the thoracic region did not differ between lead-free (0.23, 95% CrI = 0.15, 0.31) or lead-based (0.25, 95% CrI = 0.17, 0.35) bullets. The terminal energy model indicated that the average flight distance for deer shot once in the thorax with lead-free bullets (34.7 m, 95% CrI = 26.3, 45.6 m) was 56% greater than for those shot once in the thorax with lead-based bullets (22.2 m, 95% CrI = 16.2, 30.5 m), after accounting for differences in terminal kinetic energy, The probability that the average flight distance was greater for deer shot with lead-free bullets than that for those shot with lead-based bullets was 0.98.

Flight distance increased with estimated body mass at a similar rate for deer shot with lead-free or lead-based bullets after accounting for the effects of terminal energy (Fig. 4). However, there was substantial uncertainty in the estimated relationship at large body masses because of the scarcity of deer >220 kg in the sample. The probability of a positive relationship between flight distance and estimated body mass was >0.99 for both bullet types. When body mass was accounted for, flight distance decreased slightly with increasing terminal energy at a similar rate for both bullet types (Table 3, Fig. 5*a*). However, the probability that flight distance decreased with increasing terminal energy was only 0.82 and 0.89 for lead-free and lead-based bullets respectively (Fig. 5*a*). The shooting distance model indicated that the range from which deer were shot had little effect on flight distance for either bullet type (Fig. 5*b*). When body mass was held constant, flight distance increased slightly with shooting distance for deer shot with lead-based bullets, but there was no evidence of any increase for deer shot with lead-free bullets (Table 3). The probability of an increase in flight distance with shooting distance was 0.93 for lead-based bullets and 0.45 for lead-free bullets.

Discussion

This is the first study assessing the performance of lead-free bullets for shooting deer in Australasia. We found that lead-free and lead-based bullets produced similar animal welfare outcomes for ground-based shooting of sambar deer in

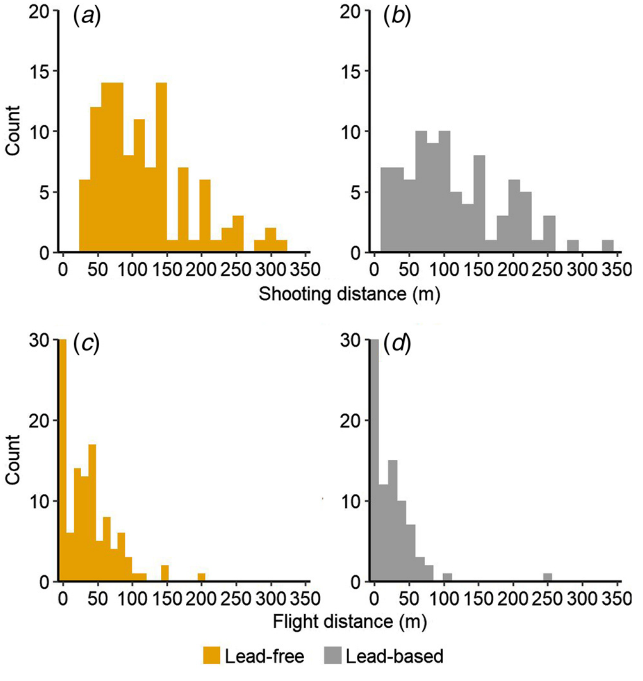

Fig. 3. Distribution of (*a*, *b*) shooting distances and (*c*, *d*) flight distances for sambar deer (*Cervus unicolor*) shot with lead-free (orange) and lead-based (grey) bullets in eastern Victoria, Australia, in 2020–2021.

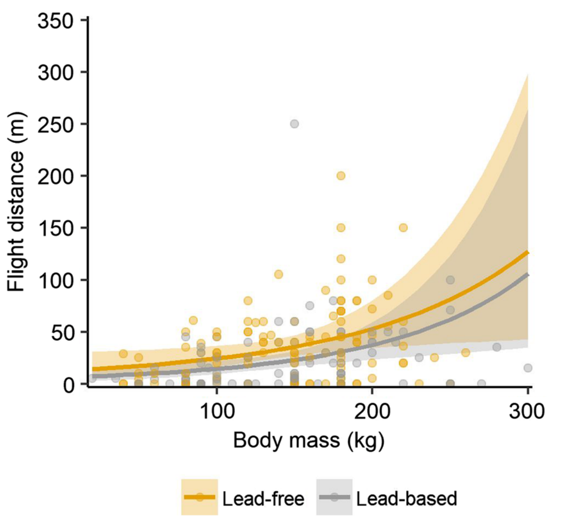

Fig. 4. Expected flight distances and observed data points for sambar deer (*Cervus unicolor*) shot with lead-free (orange) or lead-based (grey) bullets in eastern Victoria, Australia, during 2020–2021, as a function of animal body mass (kg).

Table 3. Parameter estimates (on a log scale) for two negative binomial models estimating the effects of (a) bullet terminal energy and body mass ('terminal energy model') and (b) shooting distance and body mass ('shooting distance model') on flight distance for sambar deer (*Cervus unicolor*) shot once in the thorax with lead-free or lead-based bullets in eastern Victoria, Australia, in 2020–2021.

Parameter	Bullet type	Posterior mean	95% credible interval
Terminal energy model			
Intercept	Lead-free	3.53	3.27, 3.81
	Lead-based	3.09	2.79, 3.42
β1 × terminal energy (J)	Lead-free	−0.0002	−0.0005, 0.0002
	Lead-based	−0.0002	−0.0006, 0.0001
β2 × body mass (kg)	Lead-free	0.008	0.002, 0.014
	Lead-based	0.009	0.003, 0.016
Shooting distance model			
Intercept	Lead-free	3.54	3.28, 3.83
	Lead-based	3.07	2.77, 3.40
β1 × shooting distance (m)	Lead-free	−0.0002	−0.0043, 0.0040
	Lead-based	0.0031	−0.0010, 0.0072
β2 × body mass (kg)	Lead-free	0.009	0.002, 0.015
	Lead-based	0.009	0.003, 0.015

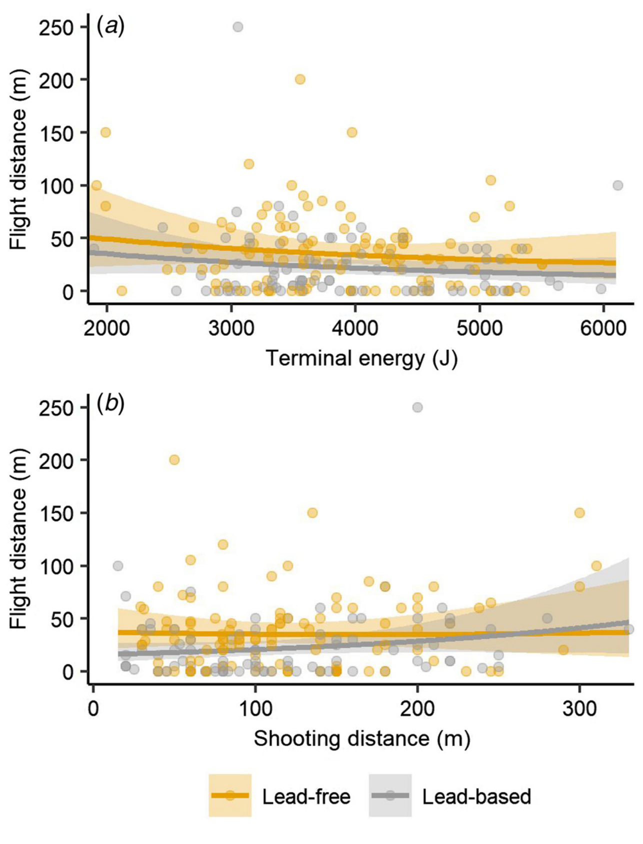

Fig. 5. Expected and observed flight distances and observed data points for sambar deer (*Cervus unicolor*) shot with lead-free (orange) or lead-based (grey) bullets, in eastern Victoria, Australia, during 2020–2021, as a function of (*a*) estimated bullet kinetic energy at point of impact and (*b*) distance from which the deer was shot.

terms of adverse event frequency. However, flight distances were, on average, 56% (13 m) longer for lead-free bullets than for lead-based bullets for deer shot once in the thorax.

For both bullet types, the frequencies of missed shots, repeat shooting (>1 shot required) and non-fatal wounding were comparable to those in other published assessments of deer shooting techniques, for example, in Hampton *et al.* (2022*a*). For both bullet types, the flight distances were within the standards reported from a model of flight distances displayed by mammals of different body size when killed via thoracic shooting (Stokke *et al.* 2018). However, the model developed by Stokke *et al.* (2018) predicted that, effects of shooting distance and ammunition type aside, average flight distances for mammals the size of sambar deer (~180 kg) would be ~50 m. The average flight distances in our study were considerably smaller than 50 m. Lead-based bullets performed better than lead-free bullets for flight distance when the effects of other variables were accounted for, but the difference was only ~13 m of flight distance for a sambar deer of average mass.

We do not suggest that the results of our study are indicative of all lead-free ammunition performance, nor of all deer shooting applications. Our study had several limitations. First, we relied on data collected by shooters rather than independent observers. Second, the shooters we relied on were self-selected volunteers rather than a random sample of all sambar deer shooters in Victoria. Third, our analysis accounted for differences in terminal kinetic energy but could not account for other sources of variability, especially potential differences among shooters in shooting accuracy. Fourth, we obtained a sample size of shooting events (n = 276) that was small relative to that in some

European studies (e.g. $n = 5255$; Stokke *et al.* 2017). Fifth, we obtained only small numbers of recovered lead-free and lead-based bullets ($n \leq 16$); so, we were unable to robustly evaluate metrics such as bullet expansion index and asymmetrical expansion, as was undertaken by Stokke *et al.* (2019). Sixth, we relied on estimated, rather than measured, body mass. It is possible that some estimates of body mass were inaccurate, but we have no way to assess this. Seventh, we looked only at ground-based shooting, and not aerial (helicopter-based) shooting (Hampton *et al.* 2021*c*). Finally, our study was restricted to one deer species. Despite these limitations, we believe that the results are representative of real-world outcomes for the shooting of sambar deer in Victoria.

The distributions of cartridge type (including caliber and bullet mass) differed between the two bullet types (Table 1). Given the importance of bullet calibre and mass in determining flight distance (Stokke *et al.* 2018), this difference could have influenced our results, but the range of calibres used were nearly identical for the two bullet types (.270–.375 for lead-free and .270–.450 for lead-based). The distributions of shooter type (i.e. professional vs recreational) also differed between the two bullet types. However, this difference was not substantial (lead-based bullets were used in 39% and 49% of professional and non-professional shooting events respectively), and both professional and some non-professional shooters used thermal scopes for nocturnal shooting.

Terminal velocity is thought to have an important influence on how bullets expand. Bullet velocity and mass determine kinetic energy, with velocity having the greatest influence (Hampton *et al.* 2016). It is thought that lead, being softer, can expand at lower terminal velocities than does copper, being a harder metal (Caudell *et al.* 2012). Greater expansion is expected to produce more rapid incapacitation because of larger wound channels, increased haemorrhage and faster exsanguination (Stokke *et al.* 2017, 2018). If this effect were widely observable, we would have expected our results to show a stronger relationship between flight distance and terminal kinetic energy for lead-free than for lead-based bullets, but this was not what we observed in our study. This effect has also been reported to be inconsistent in other published studies (see Kanstrup *et al.* 2016).

The finding that lead-based bullets lost approximately half (50%) of their mass, whereas lead-free bullets retained 96% of theirs, is similar to comparable data from European deer species (Stokke *et al.* 2017), and confirms that deer shooting is a potential pathway for lead exposure to scavenging wildlife, human consumers and domestic animals in Australia (Hampton *et al.* 2018). This finding was based on small sample sizes for each bullet type returned, but is consistent with the findings of multiple published studies that lead-based bullets tend to fragment much more than do copper-based bullets, such as, for example, Menozzi *et al.* (2019).

Our results indicated a substantially higher frequency of exit wounds for lead-free (96%) than lead-based (58%) bullets. This finding is unsurprising, given that lead-free bullets designed for deer shooting tend to be monolithic and are prone to fragment less than do lead-based bullets (Stokke *et al.* 2017). Bullets that deform and/or fragment to a lesser degree or more slowly tend to achieve deeper penetration of animal tissues (Caudell 2013). Our findings are in contrast to those of Kanstrup and Balsby (2021), who reported that the two bullet types did not show differences in the probability of exit wounds ('through-shots'). However, some lead-free bullet types are designed to fragment (Hampton *et al.* 2021*c*) and the majority of lead-free bullets used by Kanstrup and Balsby (2021) were designed to fragment and lose almost half of their mass.

Lead-free bullets available for shooting large mammals in Australia at the time of our study produced animal welfare outcomes comparable to those produced by commonly used lead-based bullets, but produced a 56% increase in flight distances. A wide diversity of lead-based bullets is currently commercially available and is used for deer shooting. We pooled a range of bullets with different manufacturers, constructions (e.g. bonded vs lead core; Stokke *et al.* 2017) and masses into the category of 'lead-based', which could have influenced our results. However, few lead-free bullet types are currently commercially available in Australia (J. Hampton, unpubl. data), and even fewer are available in factory-loaded ammunition, i.e. sold as complete cartridges rather than as bullets that require hand-loading. This contrasts to other parts of the world such as Europe (Thomas *et al.* 2016), where the availability of lead-free products has been greatly increased in recent years (Kanstrup and Thomas 2020).

Finally, there is also a substantial cost difference between lead-based and lead-free factory-loaded ammunition in Australia (Hampton *et al.* 2020), with the latter generally more than twice as expensive. This is likely to act as a barrier for uptake for many recreational deer hunters (Thomas 2019), until such time that increased demand lowers the price of lead-free ammunition (Thomas *et al.* 2016). However, the cost of ammunition is typically a trivial component of the total cost of deer hunting (Kanstrup *et al.* 2018) or culling (Bengsen *et al.* 2022). Culling programs paid for with taxpayer funds may be more willing to mandate the use of lead-free ammunition despite higher purchase costs, given the environmental costs of failing to do so (Pain *et al.* 2019).

Conclusions

Lead-based and lead-free bullets produced similar outcomes for ground-based thoracic shooting of sambar deer. However, flight distances were, on average, longer for lead-free bullets for deer shot once in the thorax. Our results emphasise the importance of considering efficacy and animal welfare when contemplating a transition to lead-free ammunition in any wildlife management context (Hampton *et al*. 2020). A transition to lead-free ammunition could be considered for sambar deer shooting without markedly affecting efficiency or animal welfare outcomes.

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Data availability. The data that support this study are not publicly shared due to privacy reasons but may be shared upon reasonable request to the corresponding author if appropriate.

Conflicts of interest. David Forsyth is a guest Associate Editor of *Wildlife Research* but was blinded from the peer-review process for this paper. Three authors are employees of government agencies involved with the management of deer shooting activities in the state of Victoria, Australia: Jason Flesch and Simon Toop are employed by the Game Management Authority, and Chris Davies is employed by Parks Victoria. Their employment could not reasonably have interfered with the full and objective presentation of this research.

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