NeoBiota 83: 109–129 (2023)
doi: 10.3897/neobiota.83.100993
https://neobiota.pensoft.net

RESEARCH ARTICLE

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

Aerial culling invasive alien deer with shotguns improves efficiency and welfare outcomes

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Academic editor: Sandro Bertolino | Received 25 January 2023 | Accepted 12 April 2023 | Published 25 April 2023

Citation: Bradshaw CJA, Doube A, Scanlon A, Page B, Tarran M, Fielder K, Andrews L, Bourne S, Stevens M, Schulz P, Kloeden T, Drewer S, Matthews R, Findlay C, White W, Leehane C, Conibear B, Doube J, Rowley T (2023) Aerial culling invasive alien deer with shotguns improves efficiency and welfare outcomes. NeoBiota 83: 109–129. https://doi.org/10.3897/neobiota.83.100993

Abstract

Invasive alien deer (known in Australia as 'feral deer'; hereafter, 'alien deer') are some of Australia's worst emerging pest species. Recently, the Government of South Australia launched a four-year program to reduce the populations of alien fallow deer (*Dama dama*). The program will focus on coordinating landscape-scale aerial culls and seeks to deliver the most efficient and humane approach to aerial culling. We sourced data from a recent program trialling a new approach to aerial culling that incorporated advanced thermal technology and a second shooter with a shotgun to target fallow deer. We reviewed available video and audio records of 104 deer culled in the program to assess efficiency and welfare outcomes. We collected information on the number of shotgun and rifle rounds fired per animal, time between first shot with a shotgun and apparent death, and pursuit time. We completed field dissections of 20 individuals targeted in the program to assess the lethality of wounds inflicted with shotgun pellets. We also compared program costs and efficiency against published and unpublished data from ten other aerial-culling programs for alien deer in South Australia since 2009. A total of 383 shotgun rounds and 10 rifle rounds were used on 104 fallow deer in the focal program. We documented strong improvements to animal welfare for alien deer targeted with shotguns. The mean (± standard error) time between first shot and apparent death with a shotgun was 11.1 ± 0.7 seconds; mean pursuit time between detection and apparent death was 49.5 ± 3.4 seconds. Pursuit time increased with subsequent deer controlled within a group; the maximum pursuit time for any individual was 159.0 seconds. All autopsied animals had received lethal wounds from shotgun pellets, with 100% receiving lung-penetrating damage and 70% also receiving heart-penetrating damage. While a program that uses a shotgun and rifle combined with a second shooter and thermographer can cost more to mobilise, the outcomes measured in cost deer^{-1} made it the most cost-effective approach of any program we assessed. Control options that deliver improved animal welfare outcomes and increase efficiency are desirable for managing expanding populations of alien deer in South Australia and elsewhere.

Keywords

Aerial culling, animal welfare, Australia, cost-effectiveness, costs, culling, *Dama dama*, helicopters, invasive alien species, management, non-native species, shooting, wildlife

Introduction

Invasive alien deer (known in Australia as 'feral deer'; hereafter, 'alien deer') are some of Australia's worst emerging pests. The total number of deer in Australia increased from an estimated 200,000 in 2000 (Moriarty 2004) to around 2 million animals by 2021 (i.e., a ten-fold increase) (Government of South Australia 2022). Their impacts are now severe and include damage to native plants, competition with native animals, economic losses to primary industries (crops, pastures, horticulture, plantations) (Bradshaw et al. 2021), and human safety hazards from vehicle collisions. Alien deer are reservoirs and vectors of endemic animal diseases and have the potential to transmit exotic animal diseases, such as foot-and-mouth disease (Cripps et al. 2019). If left uncontrolled, within 30 years the economic impacts of alien deer are expected to cost Australia billions of dollars annually (BDO EconSearch 2022; Frontier Economics 2022).

Australia has six species of alien deer – fallow (*Dama dama*), red (*Cervus elaphus*), hog (*Axis porcinus*), chital (*A. axis*), rusa (*C. timorensis*), and sambar (*Rusa unicolor*); of all the alien deer species in the country, fallow deer are the most abundant and widespread (Centre for Invasive Species Solutions 2022b). They are also considered one of the most difficult deer species to shoot from a helicopter during aerial control programs, because they tend to hide in dense vegetation and run fast, darting quickly from side to side when being pursued (Hampton et al. 2022). These behaviours make accurate shots with a rifle difficult and can increase pursuit times and duration of suffering relative to other deer species (Sharp et al. 2022).

Adopting new technologies could enhance the efficiency of aerial programs and welfare outcomes for target animals. Recently, Pulsford et al. (2023) concluded that thermal-assisted aerial culls were more effective than ground shooting when targeting sambar deer, and Cox et al. (2022) demonstrated improvements in both efficiency and welfare outcomes for fallow deer by incorporating thermal technology into their aerial programs. Government programs across Australia are trialling new combinations of firearms for different terrain and species of deer to improve the efficiency of culling operations. For example, programs have been trialling the use of shotguns to target alien fallow deer in New South Wales and the Australian Capital Territory (Hampton et al. 2022). While shotguns are routinely used by the New Zealand Government for aerial culling of alien deer (Forsyth et al. 2013) and in Australia for aerial culling of goats (*Capra hircus*) and pigs (*Sus scrofa*) (Sharp 2012a, b), they are not widely used for the control of alien deer in aerial culling programs in Australia.

Fallow deer are also the most abundant deer species in South Australia and the population is increasing despite the Government of South Australia supporting helicopter and ground-based shooting programs for more than 15 years. Recently, the State Government and Regional Landscape Boards launched a four-year program to reduce the populations of alien fallow deer in South Australia. The program focusses on coordinating landscape-scale aerial culls and aims to deliver the most efficient and humane approach to aerial culling. In that context, the State Government recently did a trial program (henceforth, 'P1') to test a new approach to aerial culling; it incorporated advanced thermal technology and a second shooter with a shotgun to target alien fallow deer.

Our study assessed the outcomes from P1 to examine the efficiency of the shotgun-rifle-thermal configuration compared to other configurations used in aerial culling programs delivered in the same region and across South Australia. We predicted that using the shotgun-rifle-thermal combination could: (*i*) improve animal welfare outcomes for target animals by minimising time between first shot with a shotgun and apparent death and pursuit time, and rapidly deliver fatal injuries to vital organs; and (*ii*) increase the efficiency and/or cost-effectiveness of the program compared to other programs delivered in the same region and across the State.

Methods

Program location and target species

The aerial culling trial program P1 occurred from 1–7 in October 2022, covering ~ 20,000 ha of private property in the Limestone Coast region of South Australia, about 300 km southeast of Adelaide (Fig. 1). The program targeted fallow deer – relatively small-bodied cervids with adult masses of 35–55 kg (females) and 50–97 kg (males) (West 2018). For comparison, sambar deer are Australia's largest deer and weigh around 230 kg (females) and 300 kg (males) (Centre for Invasive Species Solutions 2022a). We reasoned that the small size of fallow deer would increase the likelihood of shotgun pellets effectively penetrating the thorax compared to larger-bodied species.

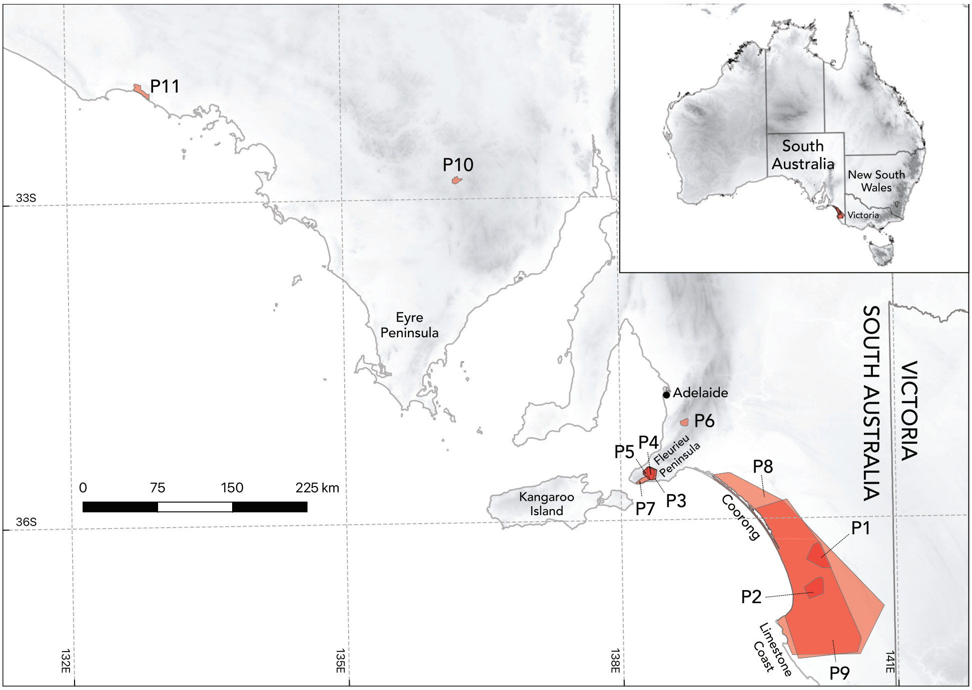

Figure 1. Location of the alien deer aerial culling programs in South Australia from 2009 to 2022 (P1–P11). See Table 1 for program descriptions. Red boxes are the minimum convex polygons enclosing all deer kills within each program (P1–P9), or the area searched by helicopters (P10–P11).

Firearms, ammunition, and crew configuration

All programs used either an AS350 B2 'Squirrel' (Airbus Helicopters, France) or Robinson R44 (Robinson Helicopter Company, U.S.A.) helicopter flown at altitudes generally below 250 m above sea level for all shooting operations. Shotguns can be used up to a maximum of 25 m from the target animal, so helicopters typically remained at 15–20 m above ground level at time of shooting. While rifles have a longer maximum range, shooters in the programs we describe do not typically take rifle shots at distances > 30 m from the target animal.

In P1, one shooter (hereafter, the 'primary' shooter) was equipped with a Benelli M2 semi-automatic shotgun with a 26" barrel and a custom choke at full extension, which created a 25-cm pellet spread at 20 m and a 45-cm spread at 30 m. The primary shooter targeted deer in open areas, within a 30-m range. The shotgun was fitted with a red-dot scope (Sightron S30-5 and Aimpoint 9000L); it had a 12-shell tube magazine and was loaded with GB SSG 21-pellet buckshot and Winchester Super-X 16-pellet buckshot. The projectiles of the 21-pellet SSG cartridges have an average weight of 1.8 g, with an average total payload of 37 g. The projectiles in the Winchester Super-X 16-pellet SSG cartridges have an average weight of 2.3 g and a total payload of 36 g. Professional shooters (Wildlife Resources Australia, Wangaratta, Victoria) did not observe any difference in the performance between the different rounds of buckshot.

Both round types were mixed into the primary shooter's ammunition bags, and we did not distinguish between ammunition type during data collection. The primary shooter was positioned in the rear right-hand side of the helicopter behind the pilot (Fig. 2), which gives that shooter the most-efficient position relative to the pilot manipulating the helicopter for optimal distance and angle relative to the target animal.

Another shooter ('secondary' shooter) was equipped with a Wedgetail WT25 semi-automatic, .308-calibre rifle with a variety of ammunition types. The ammunition included 160-grain copper projectiles used to cull deer near wetlands and creeks. Copper projectiles are being trialled in many pest-control programs in Australia because they do not contain any lead, but they could potentially increase the risk of ricochet (Steven Hess, U.S. Department of Agriculture, Animal and Plant Health Inspection Service, National Wildlife Center, Colorado, personal communication). The secondary shooter targeted deer within vegetated areas and had a range of 70 m. The secondary shooter was positioned next to a thermal camera operator ('thermographer'; Fig. 2). The thermographer operated a Vayu HD uncooled microbolometer array with the Blackmagic Video Assist and Panasonic GH5 4K video camera and used a high-powered laser to assist the secondary shooter to locate deer in forested areas. The .308-calibre rifle was also equipped with a thermal scope (Pulsar Trail 2 LRF XQ50), so wounded deer in forested areas could be located quickly for follow-up shots and the thermographer could confirm death.

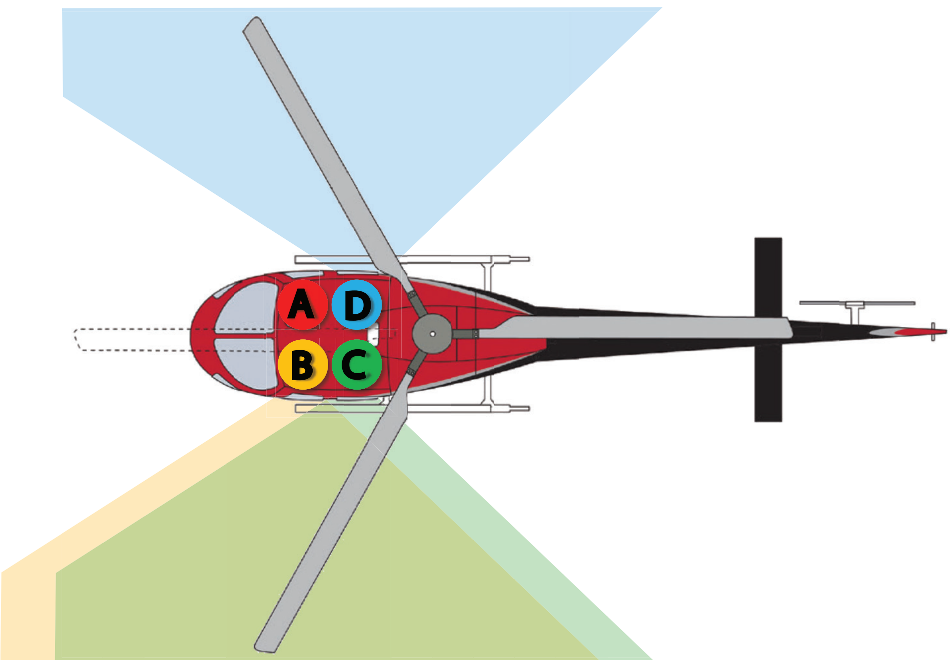

Figure 2. Seating configuration of the helicopter crew in P1 **A** pilot **B** secondary shooter with rifle and thermal scope **C** thermographer, and **D** primary shooter with shotgun and red-dot scope. Yellow and blue polygons show the indicative field of view for the shooters, and the green polygon shows the field of view for the thermographer.

Shooters made chest shots exclusively. For small deer species, especially those that move quickly and erratically such as fallow deer, chest shots are preferred for the best welfare outcomes (Sharp et al. 2022). P1 deployed a deliberate 'overkill' policy, which mandated that each deer was shot at least twice (following Hampton et al. 2022). If the target was not moving after a single shot, it would still receive at least one additional chest shot. Two crew members assessed both visually and with the thermal equipment the insensibility/death of each target animal before moving to the next target (see signs for assessing death in 'Data collection and analyses'). On average, the crew spent 5–10 seconds to determine each apparent death. The total flight time of P1 was 26.3 hours for a total of 611 alien deer culled.

All seating configurations and helicopter operational procedures are obliged to conform to the "Civil Aviation Safety Regulations 1998" and "Manual of Standards" produced and overseen by the Commonwealth of Australia's Civil Aviation Safety Authority (casa.gov.au). Safety therefore has primacy over all other considerations, including animal humaneness and efficiency/cost components of aerial shooting.

Data collection

All P1 flights were recorded on the thermal camera and with a GoPro 3 camera. The thermal camera captured all vision from the thermographer's perspective. The GoPro 3 camera was mounted to the rear firewall of the helicopter and recorded continuously; it captured the activities of all personnel in the helicopter and most of their field of view (Fig. 3). Both systems captured flight audio. The large video and audio files were overwritten every few days, so only a sub-sample of the 611 targeted deer was available for this assessment.

Figure 3. A GoPro 3 camera, mounted to the rear firewall of the helicopter, captured the seating configuration of the personnel in the helicopter, their field of view, and four deer being pursued (circled in red).

Based on the approach described by Cox et al. (2022), we reviewed all available video footage and audio from the first four hours of flight time on 2, 4, and 5 October 2022 and recorded: (*i*) number of shotgun and rifle rounds fired; (*ii*) time taken between the first shot fired at the target with a shotgun and apparent death (with shotgun or rifle); at least two helicopter personnel assessed time of apparent death based on the thermographer observing hotspots indicating that the thorax (heart and/or lungs) had been pierced, and a complete absence of movement determined by any crew member with clear vision; (*iii*) time between first detection of the target and confirmation of its death; if a deer stayed with its group under pursuit, pursuit time was cumulative for each consecutive deer (i.e., last deer killed in the group was recorded as pursued for the entire time that other deer in the group were being culled); if the group dispersed and a subset of that group had to be re-located, pursuit time was started when the group was relocated.

Analysis

To test which components of an individual kill explained the most variation in the time from the start of the pursuit to apparent death, we constructed a series of generalised linear models using the glm function in the stats R library (R Core Team 2022). Here, we tested whether the time between first and last/kill shots, number of rounds fired, and group size explained the variation in the time from the start of the pursuit to the kill (with a shotgun). We applied a gamma error distribution and a log link function to account for the non-Gaussian distribution of errors (confirmed appropriate after inspecting quantile-quantile plots), and scaled the response and explanatory variables (except group size) using the *scale* function in R. We contrasted a total of eight models, including the three additive main effects, all combinations of two additive effects, single effects, and the intercept-only model. We compared the relative probability of the five models per response variable using Akaike's information criterion corrected for small sample size (AIC_c) (Burnham and Anderson 2002). The bias-corrected relative weight of evidence for each model, given the data and the suite of candidate models considered, was the AIC_c weight (the smaller the weight, the lower the model's probability) (Burnham and Anderson 2002). We also calculated the percent deviance explained (%DE) as a measure of goodness of fit. We examined model diagnostics using the *check_model* function in the *performance* R library (Lüdecke et al. 2021). All data and R code are available at https://github.com/cjabradshaw/deerCullShotgun.

Field dissections to assess lethality of shotgun damage

After the morning flights on 4 and 5 October 2022, 20 deer carcasses were located for assessment. Field dissections were done to collect information on shotgun-pellet penetration and spread and organ damage. Shotgun injuries were determined by cutting and peeling back the pelt and visually assessing the external muscle tissue for bruising and penetration of shotgun pellets on the impact and exit sides. Because damage from multiple projectiles to either the heart or lungs is lethal, the number of projectiles that impacted the thorax was also recorded for each carcass.

Following inspection of the muscle tissue and sites of pellet impact, the chest cavity was opened below the sternum using a bone saw. The heart and lungs were removed and inspected for tissue damage, wound channels, bleeding, and blood coagulation to determine whether pellets penetrated the heart and/or the lungs. The heart and lungs were dissected to establish the extent of the wounding by shotgun pellets, if not obvious externally. The chest cavity was also inspected for pooling of blood. All damage was recorded photographically, and the sites assessed for evidence of struggle or distress (such as kicking or disturbance of surrounding ground).

Cost-effectiveness

We compared the economic costs and outcomes of P1 to those of 10 other aerial culling programs (P2–P11) completed between June and November 2022. All programs targeted deer in the same region (Limestone Coast) or elsewhere in South Australia, and varied in crew configuration, firearms, equipment, deer density, area covered, and landscape (Table 1). P3, P4 and P5 were part of one large program, but we treated them separately based on their different configurations. We compared the programs according to the following metrics: (*i*) costs associated with delivering each program, (*ii*) costs per number of deer culled, and (*iii*) costs per flight hour and area covered.

Staff costs were included in the assessment because they are necessary to plan and deliver all aerial culling programs. This approach is consistent with 'competitive neutrality' requirements for government agencies in South Australia, which ensure government businesses compete fairly in the market (Government of South Australia 2023a). Staff costs were estimated to be $150 per hour for all agencies.

To contextualise any landscape-scale differences among the programs that could have affected cost effectiveness, we also calculated the dominant landcover classes within the area of each program using the South Australia Land Cover raster (2010–2015) at a resolution of 25 m × 25 m (available from data.sa.gov.au/data/dataset/sa-land-cover). We compared the land cover classes in which kills occurred to 'available' land cover classes within a minimum convex polygon defined by the locations of all kills in the program. Additionally, we calculated the mean human population density (persons km^{-2}) within 50 km of the program's minimum convex polygon to assess the relative likelihood of human visitors to a program area during culls (when near to larger human populations, personnel costs increase – see Results).

Results

Number of rounds

We reviewed all available footage from P1, which included 20% of the 611 fallow deer culled (n = 104). Of these, 92% were killed with a shotgun only (n = 96) and 8% with a shotgun-rifle combination (n = 8). Shooters used a total of 383 shotgun rounds and 10 rifle rounds (Table 2).

Table 1. Summary details of 11 alien deer aerial culling programs, including the recent trial (P1), to compare program efficiency. F = fallow deer (F); R = red deer (R); S = sambar deer (S); TAAC = thermal-assisted aerial cull (crew has a dedicated thermographer). All programs used .308 centrefire rifles exclusively except for P1 and P5 that also used a shotgun. The lead South Australian Government agency for each program was: PIRSA (P1–P5); Hills and Fleurieu Landscape Board (P6–P7); Limestone Coast Landscape Board (P8–P9); Eyre Peninsula Landscape Board (P10–P11).

No.	Region and location	Land use	Area (km^2)	Deer species	Deer density	Helicopter	Primary shooter	Secondary shooter	TAAC	Shotgun	Notes
P1	Limestone Coast, Willalooka	rich agricultural area, isolated patches of vegetation	150	F, R, S	high	B2 Squirrel	✓	✓	✓	✓	current trial; fallow most common species
P2	Limestone Coast, Taratap	coastal agricultural area, linear vegetation remnant and dunes	100	F, R	high	B3 Squirrel	✓		✓		first trial of TAAC for deer in South Australia; fallow most common species
P3	Fleurieu Peninsula, Parawa	undulating peri-urban area mixed agricultural/rural with abundant vegetated creek lines and vegetation pockets	60	F	high	B2 Squirrel	✓		✓		Programs 3-5 delivered as part of a single program, but separated based on crew configuration, area covered, firearm type
P4	Fleurieu Peninsula, Parawa		30	F	high	B2 Squirrel	✓	✓	✓		
P5	Fleurieu Peninsula, Parawa		110	F	high	B2 Squirrel	✓	✓	✓	✓	
P6	Adelaide Hills, Mt Bold	peri-urban water reservoir, undulating land covered in native and pine forest	20	F	high	R44	✓				goats also targeted
P7	Fleurieu Peninsula, Deep Creek	national park – undulating landscape with thick vegetation	40	F	high	B2 Squirrel	✓				
P8	Limestone Coast, Salt Creek to Taratap	coastal agricultural area, linear vegetation remnant and dunes	1200	F, R, S	high	2 × R44	✓				2 helicopters, single shooter in each; fallow most common species
P9	Limestone Coast, Salt Creek to Taratap	coastal agricultural area, linear vegetation remnant and dunes	1200	F, R, S	high	2 × R44	✓				2 helicopters, single shooter in each; fallow most common species
P10	Eyre Peninsula, Buckleboo	open, dry-land cropping country, isolated vegetation patches	160	R	low	R44	✓				no individual coordinates
P11	Eyre Peninsula, Chadinga	remote conservation reserve, squat coastal vegetation	100	no deer culled	low	R44	✓				no individual coordinates

Time between first shot with a shotgun and apparent death

The mean time between first shot with a shotgun and apparent death was 11.1 seconds (± 0.7; n = 104). Individual deer, or the first deer shot in a group, had the greatest mean time between first shot and apparent death, but this time decreased with subsequent individuals targeted within the group (Fig. 4). The maximum time recorded between first shot and apparent death for any individual deer was 35.9 seconds (Table 2).

Pursuit time

Mean time between first detection and apparent death was 49.5 seconds (± 3.4; n = 104). Pursuit time increased with subsequent deer shot within a group (Fig. 4). The maximum pursuit time for any deer was 159.0 seconds. See summary data from the analysis of footage in Table 2.

Table 2. Summary statistics from footage of 104 deer killed with a combination of firearms, a secondary shooter, and thermal-imaging technology.

Summary statistic	Order of deer shot						
	First[a]	Second	Third	Fourth	Fifth[b]	Total	Mean
sample size (# deer)	45	29	21	8	1	104	–
shotgun rounds fired	169	114	64	34	2	383	–
mean ± s.e. shotgun rounds per deer	3.8 ± 0.3	3.9 ± 0.3	3.0 ± 0.4	4.3 ± 0.6	2.0	–	3.7 ± 0.2
rifle rounds fired	4	6	–	–	–	10	–
min-max time between first shot with shotgun and apparent death (seconds)	2.9–35.9	2.6–32.0	2.6–33.2	4.0–14.1	3.1	–	–
mean ± s.e. time between first shot with shotgun and apparent death (seconds)	12.5 ± 1.0	11.4 ± 1.3	9.2 ± 1.5	7.9 ± 2.4	3.1	–	11.1 ± 0.7
min-max pursuit time (seconds)	13.9–83.1	16.0–89.4	14.5–120.2	46.3–159.0	84.2	–	–
mean ± s.e. pursuit time (seconds)	34.9 ± 5.2	50.7 ± 6.5	63.1 ± 7.6	87.4 ± 12.3	84.2	–	49.5 ± 3.4

[a] first deer includes isolated individual deer as well as the first deer targeted within a group; data also collected for subsequent deer shot from the same group for up to five deer.
[b] sample size = 1, no standard error (s.e.), mean, or range calculated.

Figure 4. Mean (± standard error) time (seconds) between first shot and apparent death (black circles) and mean (± standard error) pursuit time (seconds) between first detection and apparent death (grey squares) as a function of shot order (either singularly or in groups of 1 to 5).

Model results

There was a positive effect of deer group size and number of shotgun rounds fired on the total time elapsed since start of pursuit to death (Table 3). These two variables explained ~ 43% of the variation in the response. However, there was no evidence for an effect of the time between the first and last shot and total time elapsed since start of pursuit to death.

Dissection to assess shotgun damage

The 20 carcasses were recovered and dissected within six hours of being culled in P1. All carcasses had received shotgun wounds only and were located using GPS data collected during the flight. A total of 116 shotgun pellets had penetrated the thorax of the 20 deer (5.8 ± 0.6 pellets deer^{-1}; range: 3–13 pellets deer^{-1}). Lethal lung-penetrating wounds were recorded in all 20 animals; 14 (70%) also recorded lethal heart-penetrating wounds. The wounds and their classification are shown in Suppl. material 1. Carcasses showed no indication of struggle or distress or movement from the location at which they were shot and apparent death by the helicopter crew.

Cost effectiveness

For 2022, the cost of delivering 11 aerial culling programs for alien deer in South Australia exceeded $1.1 million (Table 4); the mean ± s.e. cost per program was $100,461 ± $13,385; individual program costs ranged from $45,000 for one component of a larger program (P3) to over $160,000 for P8. As expected, the most expensive component of running any program was associated with helicopter operations, which comprised 54% of all costs.

Operating staff costs accrued by various agencies (South Australian Department of Primary Industries and Regions; Regional Landscape Boards of the Hills and Fleurieu, Limestone Coast, and Eyre Peninsula; National Parks and Wildlife Service;

Table 3. Generalised linear model results testing the effects of time between first and last/kill shots (*t1stLast*), number of rounds fired (*rnds*), and group size (*grpSize*) on the time from the start of the pursuit to the kill with a shotgun (response). *k* = number of model parameters; ℓ = -log likelihood; AIC$_c$ = Akaike's information criterion corrected for small sample size; *w*AIC$_c$ ≈ model probability; %DE = percent deviance explained.

Model	*k*	ℓ	AIC$_c$	*w*AIC$_c$	%DE
~grpsize + rnds	3	-24.770	57.945	0.529	42.7
~t1stLast + grpSize + rnds	4	-23.859	58.330	0.436	43.7
~t1stLast + grpSize	3	-27.489	63.383	0.035	39.7
~grpSize	2	-32.480	71.201	0.001	33.8
~rnds	2	-50.879	107.997	<0.001	6.9
intercept-only	1	-54.745	113.610	<0.001	-
~t1stLast + rnds	3	-50.356	109.116	<0.001	7.8
~t1stLast	2	-54.603	115.446	<0.001	0.3

Table 4. Cost summary for 11 deer culling programs completed in South Australia between June and November 2022. P3, P4, and P5 are separate components of a large program; all staff hours were costed at $150 per hour. All costs in AU$ and include goods and services tax.

Detailed costs	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
helicopter operations	81,999	46,620	52,851	28,959	83,257	28,216	27,390	104,247	106,904	28,875	14,300
ammunition	7,500	1,868	2,802	1,535	4,413	2,756	2,200	4,051	3,221	0	0
professional shooters	7,200	3,000	3,842	2,105	6,053	6,916	4,500	27,000	27,000	4,200	1,780
PIRSA costs	20,625	26,149	18,010	9,869	28,371	6,450	0	0	0	0	0
Landscape board costs	5,625	970	1,890	701	2,659	29,100	21,375	16,950	9,000	31,000	6,750
NPWS costs	0	0	750	0	900	11,600	23,415	0	0	450	750
DEW costs	0	0	0	0	0	0	655	1172	1609	0	0
SA Water costs	0	0	0	0	0	47250	0	0	0	0	0
Forestry SA costs	0	0	2,500	1,500	3,000	0	0	0	0	0	0
community engagement	2,500	2,710	2,401	1,316	3,783	1,800	2,250	0	0	2,550	1,575
other logistics (car hire, travel, food, etc.)	4,700	2,460	2,145	1,175	3,379	1,900	2,600	6,846	6,978	3,100	2,200
Total costs	**$130,149**	**$83,777**	**$87,190**	**$47,160**	**$135,816**	**$135,988**	**$84,385**	**$160,266**	**$154,712**	**$70,175**	**$27,355**

Department for Environment and Water; SA Water; Forestry SA) varied considerably among programs. These costs were largely associated with the location of the operations. P3–P7 occurred on public lands (e.g., parks) near metropolitan areas, so additional staff were required to supervise entrances and prevent public access during the operations. Staff costs for all agencies for all programs combined exceeded $330,000, or 30% of all costs. P6 had the highest staff costs, exceeding $45,000, which comprised 54% of all costs associated with the project. This program required many multi-agency staff to supervise gates and entrances to the operations area, which is a high-profile, peri-urban site on public land (Fig. 1).

From the 11 programs, a total of 3,609 deer (at least 90% fallow deer) were culled during 486 flight hours (see Table 5). In terms of the program cost per deer controlled, P1 was the most cost-effective at $199 deer^{-1}. The least cost-competitive programs were P10 and P11, which operated in areas with low deer densities (Table 1). Seven animals were culled in P10, costing more than $10,000 deer^{-1}; P11 cost $27,000 and no animal was destroyed. Excluding P1, the cost per deer controlled in areas with high deer densities (P2–P9) ranged from $210 to $447 deer^{-1}. The cost per flight hour ranged from around $1,720 (P9) to $8,440 (P7); the mean was $4,526 ± $604 flight hour^{-1}; P1 cost around $4,950 flight hour^{-1}. The cost per area covered ranged from around $130 (P9) to $6,800 (P6) km^{-2} of program delivered; the mean was $1,445 ± $570 km^{-2}; P1 cost $868 km^{-2}.

Deer were most commonly killed in native woody vegetation > 1 m in height (64% of all kill locations across all programs) (Table 5), and in all programs except P7 (Suppl. material 1: fig. S6h), this land cover class was proportionally less-available (20% of area flown) (Suppl. material 1: fig. S6). Sparse native vegetation was the second-most common land cover class in which deer were killed overall (18%), which compares to an availability of only 1% (Suppl. material 1: fig. S6a). Dryland crops was the third-most common land cover class in which deer were killed overall (11%), but

Table 5. Cost effectiveness of 11 alien deer culling programs done in South Australia between June and November 2022. P3, P4, and P5 are separate components of a large program. All costs in AU$ and include goods and services tax.

Program outcomes	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
total animals culled	655	190	195	179	645	347[a]	243	645	503	7	0
total flight hours	26	16	18	10	29	20	10	87	90	21	9
animals/flight hour	25	12	11	18	22	17	24	7	6	< 1	0
cost/animal	$198.70	$440.93	$447.13	$263.46	$210.57	$391.90[d]	$347.26	$248.47	$307.58	$10,025	-
cost/flight hour	$4,948.63	$5,404.97	$4,777.58	$4,716.00	$4,724.05	$6,799.40	$8,438.50	$1,842.14	$1,719.02	$3,341.67	$3,073.60
cost/area (km^2)	$867.66	$837.77	$1,453.17	$1,572.00	$1,234.69	$6,799.40	$2,109.63	$133.56	$128.93	$483.59	$273.55
dominant vegetation in program area	dry cropland	dry cropland	dry cropland	dry cropland	dry cropland	woody native > 1 m	woody native > 1 m	dry cropland	dry cropland	woody native[c] > 1 m	woody native[d] > 1 m
dominant vegetation in which deer were culled	dry cropland	woody native > 1 m	woody native > 1 m	woody native > 1 m	woody native > 1 m	woody native > 1 m	woody native > 1 m	woody native > 1 m	woody native > 1 m		
mean human pop density within 50 km (persons km^{-2})	0.47	0.52	69.70	75.76	68.64	58.05	59.50	4.71	3.96	0.10	negligible

[a] total animals culled for Program 6 at Mt Bold Shoot includes 61 goats
[b] the cost/animal adjusted to include the 61 goats is $333.30
[c] no individual kill locations available; value indicates dominant land cover class available (64% of area searched)
[d] no deer killed; value indicates dominant land cover class available (83% of area searched).

this was relatively low compared to an availability of 55% (Suppl. material 1: fig. S6a). Contrary to expectation, there was no apparent relationship between mean human population density within 50 km of a program and either the total personnel costs or personnel costs flight^{-1} hour^{-1} area^{-1} animal^{-1}; however, the Limestone Coast and Fleurieu Peninsula programs had separate clusters within this cost-population density relationship (Suppl. material 1: fig. S7).

Discussion

Aerial culling

Aerial culling can be an effective, rapid, and humane means for removing large numbers of alien deer (Husheer and Robertson 2005; Bengsen et al. 2022; Pulsford et al. 2023), alien pigs (Cox et al. 2022; Hamnett et al. 2023), and other pest species in vast, remote, and inaccessible landscapes. In 2020, 2021, and 2022, South Australia's aerial culling programs have removed approximately 3,000 alien deer per year (BDO EconSearch 2022). In addition to aerial culling, some programs have used ground shooting by professional shooters, volunteers and landholders, and commercial harvesting operations (Government of South Australia 2023b). Recreational hunting and culling by private landholders are estimated to remove about 8,300 alien deer annually. With all control approaches combined, approximately 11,300 alien deer are removed per year from South Australia (BDO EconSearch 2022).

Unfortunately, a large proportion of the population of alien deer must be removed each year to drive population decline. For example, at least 34% of the population of fallow deer must be removed each year just to avoid population increase, and even higher culling proportions are required for other deer species (hog: 52%; chital: 49%; rusa: 46%; sambar: 40%) (Hone et al. 2010). The number of fallow deer removed annually from the estimated population of 40,000 in South Australia is around 28% (BDO EconSearch 2022), so the population has continued to grow.

Large-scale, intensive, and coordinated control programs are therefore necessary to drive population declines of alien deer. Improved efficacy of aerial culling programs is clearly needed if management goals to arrest the impacts of deer are to be realised. However, the adoption of new approaches and technologies first requires examination to ensure high animal welfare standards are met, in addition to operational cost effectiveness. Analysis of the outcomes from a recent trial program that used shotguns and thermal equipment, in combination with a rifle, provided insight into the humaneness and effectiveness of a new approach to controlling alien deer in South Australia.

Animal welfare

In pest control operations, welfare is generally evaluated in terms of the duration and intensity of suffering (Littin et al. 2004), which inform humaneness assessments of control tools that are common practice in Australia (Sharp and Saunders 2011) and New Zealand (Littin et al. 2004). We used 'time between first shot with a shotgun and apparent death' and 'pursuit time' as indicators of duration of suffering and penetration and severity of shotgun pellets as indicators of intensity of suffering. The time recorded by Cox et al. (2022) between first shot and apparent death of deer using a rifle was 22 seconds; Hampton et al. (2022) reported that 95% of deer were dead within 57 seconds of the first shot in their program using rifles. In this trial, the average time between first shot with a shotgun and apparent death was 11 seconds, a markedly improved outcome for animal welfare.

Individual deer, or the first deer shot in a group, had the longest mean time between first shot and apparent death, and this interval decreased if targeting subsequent individuals in a group. This decrease is because of the relatively longer time taken to pursue a group of deer after first being sighted, before the first deer is shot. Once the group of deer was engaged, the pursuit time of the remaining deer in the group was usually shorter. The maximum time recorded between first shot and apparent death for any deer was 35.9 seconds, which is an improvement on programs that have used a rifle exclusively (Hampton et al. 2022).

Unlike Cox et al. (2022), our study assessed the metrics of a program that targeted deer with shotguns in relatively open terrain. Shotguns have not been trialled in densely vegetated areas, and so additional trials will be required to determine their efficacy in such habitats. Clearly, different vegetation densities and terrain will affect the outcomes of aerial culling program. The dominant vegetation class of several programs was 'dry cropland' (P1–P5, P8–P9), but only P1 also recorded this vegetation type as dominant where deer were killed. Unlike the other programs, outcomes from P1 included a subset of the overall program and selected for shotgun kills, which only occurred in open areas. We found similar proportions of available and kill-location land cover classes in P3–P4 (i.e., including P1, each had 50–60% dry cropland and deer were killed in 30–40% dry cropland; see S1), but the dominant land cover class where deer were killed for most programs was woody native vegetation (i.e., P2–P9) that harbour deer in the landscape.

Other influences such as proficiency of shooters, type of helicopter used, and weather conditions will also affect time between first shot (with shotgun or rifle) and death. In their study, Cox et al. (2022) measured the 'time from first shot impact to death', a potentially useful metric for assessing shooter proficiency. We were unable to differentiate impact shots from non-impact shots because the thermographer was not on the same side of the helicopter as the primary shooter with the shotgun. The GoPro footage was not of sufficient quality to assess individual shot impacts. However, we were able to assess overall pursuit time, and time between first shot and apparent death. Cox et al. (2022) and Hampton et al. (2022) recorded pursuit times of around 150 seconds and 90–200 seconds, respectively. The average pursuit time from 104 animals in our study was just 50 seconds, and the maximum pursuit time for any individual was 159 seconds.

In most jurisdictions, procedures and guidelines for aerial culling programs of alien deer dictate that a shot with a rifle is not taken until the shooter has a clear shot of the chest or head, and that there is no risk of a wounded animal escaping to somewhere where a follow-up shot cannot be taken. The spread pattern of the shotgun pellets requires less precision for pellets to hit the thorax of the animal. Hence, using a shotgun reduces the time required to 'line up' an accurate and humane shot.

In terms of the intensity of suffering, all animals assessed had received rapid and lethal impacts from shotgun pellets. The average number of thorax-penetrating wounds delivered with the shotgun was higher than in some autopsies of deer culled with a rifle (Hampton et al. 2022). All animals recorded lethal damage to their lungs, and most to their hearts as well. Wounds to the lungs and the pooling and/or clotting of blood in the chest cavity indicated a pneumothorax (collapse of lung) and/or a hemothorax (collapse of lung because of blood in the chest cavity). The wounds to the heart are expected to have caused rapid decrease in blood pressure, rapid loss of consciousness, and rapid death by exsanguination. In combination, these injuries lead to hypovolaemic shock, causing unconsciousness due to inadequate cerebral perfusion pressure, and resultant rapid death from lack of blood supply to the brain (Stokke et al. 2018).

A potential shortcoming of our study is that the apparent death of the target animals in P1 was assessed in the air by the pilot, and at least one other crew member, rather than landing the helicopter to have a veterinary surgeon make a formal assessment (e.g., Hampton et al. 2022). Instead, a veterinary surgeon (A.D.) and a medical doctor (J.D.) were available for consultation for our study. Future research into the use of different firearms to cull deer could benefit from additional veterinary oversight, including work to ensure that culled deer do not have spinal injuries, which could render the animal unresponsive, but alert for some time. In addition, high-resolution photos taken from the helicopter could be used to compare the exact location and position of culled deer with photos subsequently taken from the ground. These records could be used to determine whether there were any signs of movement, distress, or disturbance of the surrounding ground after each deer was killed from the helicopter.

Cost effectiveness

Helicopter-based aerial shooting is a cost-effective tool for alien deer control (Bengsen et al. 2022). However, few studies have assessed the efficiency of different crew and equipment configurations. We assessed a trial program (P1) that used the same pilots, aircraft, and thermal technology as Cox et al. (2022) in their alien pig and deer control research. The main difference was the inclusion of a second shooter armed with a shotgun; it is only the second time (after P5) a program has used a shotgun for targeting alien deer in South Australia.

The largest expense associated with aerial culling is helicopter flight time (Bengsen et al. 2022), largely driven by the cost of aviation fuel. The approximate \$2,500 cost hour^{-1} of flight time for a B2/B3 Squirrel helicopter is nearly double that of the R44 (approximately \$1,000). As such, when using the larger and more expensive helicopters in aerial culling of high-density deer populations, our results indicate that efficiency is maximised by the addition of a thermographer and second shooter with a shotgun. While cost per flight hour and area is relatively high for P1, the efficiency of the configuration was unmatched (25 deer $hour^{-1}$ at < \$200 $deer^{-1}$). Crew configurations would be amended to suit program objectives. For example, a second shooter or thermographer might not be necessary when targeting exclusively open areas where deer densities are high. However, the additional crew members reported other benefits, including (*i*) additional safety benefits because shooters had opportunities to take brief breaks during each flight; (*ii*) shooters had the opportunity to change roles when a magazine needed to be changed; (*iii*) shooters had the opportunity to alternate between using the shotgun and the rifle between flights; (*iv*) the thermographer had more opportunity to monitor welfare outcomes of targeted animals using the high-resolution thermal camera to confirm death and to locate wounded deer in forested areas; and (*v*) the thermographer provided a strategic approach to targeting alien deer and enabled searching and scanning areas harbouring deer that might otherwise be missed. The flight crew also reported an increase in the rate of detections of target animals because of the extra spotting capacity from an additional shooter equipped with thermal optics (Rob Matthews, Heli Surveys, Jindabyne, New South Wales, pers. comm.).

Program costs and efficiency will vary with location and density of deer. For example, the cost of targeting sambar deer at low densities in alpine environments exceeded \$1,000 $deer^{-1}$ (Pulsford et al. 2023). We compared 11 aerial culling programs that varied in location, planning, staffing, and logistic requirements. P10 and P11 occurred in remotes areas with low deer densities. The goal of those programs was to eradicate small satellite populations before they established. The relatively high costs of programs in areas with low deer densities should not discourage land managers, particularly where eradication is possible. Of the programs delivered in areas with high deer densities, program costs ballooned for peri-urban programs because additional staff were required to restrict public access to popular recreation areas. Programs should continue to document the inputs, configurations, and outcomes of their efforts to inform future aerial culling programs of alien deer.

Conclusions

We found that the use of a suitable shotgun could improve welfare outcomes for culled deer, compared to programs that used .308-calibre rifles only. Improved welfare outcomes included reduced pursuit time and reduced time between the first shot and death. Furthermore, all deer dissected were shot more than once, and received multiple thorax-penetrating wounds, resulting in lethal injuries to either the lungs and/or heart, and ensuring a short time until death. These findings are at least as good as the best welfare outcomes reported from aerial culling programs in Australia to date (e.g., Hampton et al. 2022).

We found that a two-shooter crew configuration, with the addition of a thermal camera operator and a primary shooter with a shotgun, resulted in increased operational efficiency and cost effectiveness when compared to more conventional crew configurations. These changes to the format of the aerial operation appeared to increase efficiency independently, but the addition of the shotgun appears to have made the biggest single difference. These results are likely to be applicable to areas with similar deer densities, canopy cover, and terrain to the Limestone Coast region of South Australia. Although thermal imagery can increase detection of control targets in denser vegetation, relative openness of the canopy will always be required for shooting to be efficient and effective. Control options that deliver improved animal welfare outcomes and increased efficiencies are urgently needed to manage expanding populations of alien deer in South Australia.

Acknowledgements

We thank M. Garrod, W. Boardman, D. Evans, I. Hough, and A. Wiebkin for reviewing and improving drafts. We also thank D. Forsyth and A. Bengsen for their leadership in assessments of cost effectiveness for deer culling through the Centre for Invasive Species Solutions (invasives.com.au), of which Primary Industries and Regions South Australia (A.S., B.P., M.T., K.F., L.A.) is a member. We thank S. C. Hess for constructive review comments. All aerial culling programs were completed as part of ongoing pest animal management operations, which do not require animal ethics approval. The Primary Industries and Regions South Australia animal ethics Teaching, Research and Experimentation licence number is 176.

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Supplementary material 1

Supplementary information

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Data type: figures

Explanation note: Deer VI, killed with the shotgun; pelt is removed to show the difference between shotgun-pellet wounds on the entry (A) and exit (B) sides of the carcase. Deer XV, showing typical wounds and mode of death for feral fallow deer culled with shotguns in this trial. Deer IX, showing typical wounds and mode of death for feral fallow deer culled with shotgun in this trial. Deer XII, showing typical wounds and mode of death for feral fallow deer culled with shotgun in this trial. Deer XIV, showing typical wounds and mode of death for feral fallow deer culled with shotgun in this trial. Proportion of feral deer killed per major land cover class (black bars) relative to availability (proportional coverage within a minimum convex polygon defined by the kill locations per program; green bars) for (a) all kill locations combined and (b–j) P1–P9. Mean human population density within 50 km of the minimum convex polygon defined from kill locations per program (top panel).

Link: https://doi.org/10.3897/neobiota.83.100993.suppl1