CSIRO PUBLISHING

SPECIAL ISSUE | RESEARCH PAPER
https://doi.org/10.1071/WR22030

WILDLIFE RESEARCH

Cost-effectiveness of volunteer and contract ground-based shooting of sambar deer in Australia

Sebastien Comte[A,*], Elaine Thomas[B], Andrew J. Bengsen[A], Ami Bennett[C], Naomi E. Davis[C,D], Daniel Brown[E] and David M. Forsyth[A]

For full list of author affiliations and declarations see end of paper

***Correspondence to:**
Sebastien Comte
Vertebrate Pest Research Unit, NSW Department of Primary Industries, 1447 Forest Road, Orange, NSW 2800, Australia
Email: sebastien.comte@dpi.nsw.gov.au

Handling Editor:
Tony Pople

Received: 17 February 2022
Accepted: 11 October 2022
Published: 12 December 2022

Cite this:
Comte S et al. (2023)
Wildlife Research, **50**(8–9), 642–656.
doi:10.1071/WR22030

ABSTRACT

Context. Introduced sambar deer (*Cervus unicolor*) are increasing in south-eastern Australia, and both volunteer and contract ground-based shooters are being used by management agencies to control their undesirable impacts. However, little is known about the effectiveness and costs of volunteer and contract shooters for controlling deer populations in Australia. **Aims.** We evaluated the effectiveness and costs of volunteer and contract ground-based shooters for controlling sambar deer and their impacts in a 5-year management program conducted in and around alpine peatlands in Alpine National Park, Victoria. **Methods.** Ground-based shooting operations were organised in two blocks. Within each block, four ~4200-ha management units were delimited, of which two were randomly assigned as treatment (ground-based shooting) and two as non-treatment (no organised ground-based shooting). In the treatment units, ground-based shooting was conducted using either volunteers or contractors. Each shooting team recorded their effort and the numbers of deer seen and shot, and used a GPS to record their track log and the time and locations of deer shot. Key costs were recorded for both shooter types. **Key results.** The catch per unit effort of contract shooters was four times greater than that of volunteer shooters. Both shooter types were most effective during the first half of the night and prior to sunrise, and when using a vehicle with a spotlight or walking with thermal-vision equipment. During the day, the use of gundogs to indicate deer significantly increased the success rate of volunteer shooters. Both volunteer and contract shooters used roads and tracks to move in the landscape, but contractors covered more ground than did volunteers. After accounting for key operational costs, the cost per deer killed was 10.1% higher for contract than volunteer shooters. **Conclusions.** The effectiveness of ground-based shooters is increased by operating at night using vehicles, spotlights and thermal-vision equipment. Contract shooters kill sambar deer at a faster rate, but are slightly more expensive per deer killed, than are volunteer shooters. **Implications.** Ground-based shooting is likely to be most effective when conducted at night with thermal-vision equipment, and in areas with a high density of roads and tracks.

Keywords: biological invasions, catch per unit effort, *Cervus unicolor*, contract shooters, CPUE, culling, GPS, invasive species, ungulates, volunteer shooters, wildlife management.

Introduction

Overabundant deer can have significant undesirable impacts on native biodiversity, primary industries and human health (Côté *et al.* 2004; Martin *et al.* 2020; Spake *et al.* 2020; Carpio *et al.* 2021), including in Australia (Moriarty 2004; Davis *et al.* 2016; Cripps *et al.* 2019; Davies *et al.* 2020*a*). Mitigating the undesirable impacts of deer often involves reducing their density using ground-based shooting (Caughley 1983; Frost *et al.* 1997; Bennett *et al.* 2015; Bengsen *et al.* 2020). Ground-based shooting for population control (as distinct from harvesting) can be undertaken by volunteers (i.e. unpaid) or professionals (i.e. contractors or government/agency employees; Burt *et al.* 2011;

Warren 2011; Bengsen *et al.* 2020). Volunteer shooters give their time and experience without financial return, although non-monetary compensations (e.g. accommodation, fuel and food) are sometimes provided to them. Volunteers are generally local recreational hunters motivated by the experience of hunting in areas that might otherwise be unavailable (Gidlow *et al.* 2009), the opportunity to collect meat (Grilliot and Armstrong 2005), social interactions (Black *et al.* 2018), or by the satisfaction of being part of management programs (e.g. pest management, conservation; Woods *et al.* 1996; Finch *et al.* 2014). In addition to those motivations, contract shooters are motivated by financial incentives (usually a fee per unit of time). Contract shooters generally have more experience in control operations and already possess the licences and insurances required to participate in management programs. A recent systematic review reported that only 30% of mammalian control operations that relied only on volunteer shooters or recreational hunters achieved their management objectives (Bengsen *et al.* 2020). However, the effectiveness of different types of ground shooter (i.e. the number of animals killed per unit of time) have not been compared *within* a management program in Australia.

The equipment used for ground-based shooting can improve efficiency of operations through increased shooting opportunities and reduced shooting distances. Since deer are often most active when it is dark (Bentley 1998; Leslie 2011), white-light spotlights (Hampton *et al.* 2022) and thermal-vision equipment (Logan *et al.* 2019) can make ground-based shooters more effective. Sound suppressors reduce the peak noise level of a gunshot away from the line of fire, potentially reducing the fleeing behaviour of peripheral animals and hence providing the shooter with additional shooting opportunities (Williams *et al.* 2018). Sound suppressors also reduce the peak pressure at the shooter's ear, providing safer conditions for long and repetitive shooting operations (Murphy *et al.* 2018). In dense vegetation, an indicator dog can greatly increase the success of deer hunters (Novak *et al.* 1991; Godwin *et al.* 2013). A dog can also reduce the time to find deer that have been shot (i.e. to confirm the death of the animal), further increasing efficiency.

The efficiency of ground-based shooting operations can be measured as the number of animals killed per unit of time or catch per unit effort (CPUE), a widely used index to monitor deer population dynamics (Batcheler and Logan 1963; Haskell 2011; Gürtler *et al.* 2018). When deer densities increase, CPUE will increase until the system eventually reaches saturation, i.e. the effort required to process each kill limits the number of deer shot per unit of time. Conversely, when deer density decreases, CPUE will decrease because it becomes more difficult for the shooter to find a deer (Van Deelen and Etter 2003). This relationship between density and CPUE depends on the landscape and the environment (Fraser and Sweetapple 1992; Nugent and Choquenot 2004). Increasing road density was associated with increasing probability of success for white-tailed deer (*Odocoileus virginianus*) hunters in the United States (Lebel *et al.* 2012), and low temperatures and rain limited red deer (*Cervus elaphus*) hunting effort in Norway (Rivrud *et al.* 2014). Most studies have focused on recreational hunting, and little information is available for contract and volunteer shooters involved in management of invasive or overabundant deer.

Managers seeking to manage deer populations by ground shooting want to know how the costs of removing deer differ between contract and volunteer shooters (i.e. the cost per unit outcome). If effort and cost are standardised, then CPUE can be transformed into the cost per unit outcome (i.e. the cost of removing one individual from the population; *sensu* Cook *et al.* 2017), which can then be compared between shooter types. The costs of management programs using ground-based shooting should include the administrative and organisational costs, the operating costs (i.e. supervision, financial and in-kind compensations), and the equipment purchased for the program (e.g. ammunition, vehicle, night-vision equipment). Reporting of transparent and standardised cost per unit effort have been limited for ground-based shooting of deer. DeNicola *et al.* (2000) reported costs of US$91–310 per white-tailed deer across several management programs for white-tailed deer by using professional shooters in urban areas in the United States, but did not detail how those values were calculated. Hubbard and Nielsen (2011) used a transparent costing tool to show that the cost per deer for volunteer shooters (peri-urban white-tailed deer) varied from US$37 to US$122 depending on the management strategy used. In Australia, the standardised costs and effectiveness of ground-based shooting have not been documented for any of the six deer species present.

Sambar deer (*Cervus unicolor*), the largest species of deer in Australia (220 kg for males, 140 kg for females), have colonised a wide variety of landscapes since they were first released in 1860 (Bentley 1998; Moriarty 2004). In Victoria, sambar deer are listed as a key threatening process for the biodiversity of native vegetation (Victorian *Flora and Fauna Guarantee Act 1988*) because of herbivory, antler rubbing, trampling and wallowing. There is a long history of recreational ground-based shooting of sambar deer in Victoria (Bentley 1998; Harrison 2010). For example, during our 5-year study period (see below), an average of 88 849 sambar deer were reported killed annually across the state by licenced hunters (range: 55 094–131 258; Moloney and Flesch 2021). Despite these sustained, large recreational hunter harvests, the Victorian sambar deer population is increasing (Forsyth *et al.* 2018; Watter *et al.* 2020). Professional ground-based shooters are increasingly used to reduce the abundance of deer in Australia (e.g. sambar deer management in one of Melbourne's water catchments; Bennett *et al.* 2015), but the costs of such programs are not reported. There is substantial interest in using recreational hunters as volunteer shooters in organised Victorian deer control programs, from both hunters and public land management agencies, partly because of perceived cost-effectiveness benefits over professional shooters. However, it is recognised that co-ordinating volunteer shooters has a cost for the co-ordinating agency (New South Wales Natural Resources Commission 2017; Parliament of Victoria Environment, Natural Resources and Regional Development Committee 2017).

In this study, we compare the cost-effectiveness of volunteer and contract ground-based shooters in a 5-year management program that aimed to reduce the impacts of sambar deer in Alpine National Park, Victoria. On the basis of prior knowledge from the literature, we tested the following four hypotheses: (1) that the higher kills per unit time of contract shooters than of volunteer shooters outweighs their higher cost-per-unit-time; (2) that contract shooters cover larger areas per unit time than do volunteer shooters, resulting in more shooting opportunities; (3) that supporting equipment, particularly a vehicle with a spotlight or thermal vision when walking, improves the effectiveness of volunteer ground-based shooting; and (4) that ground-based shooting is most cost-effective around dusk, when sambar deer are most active in this environment (Comte *et al.* 2022).

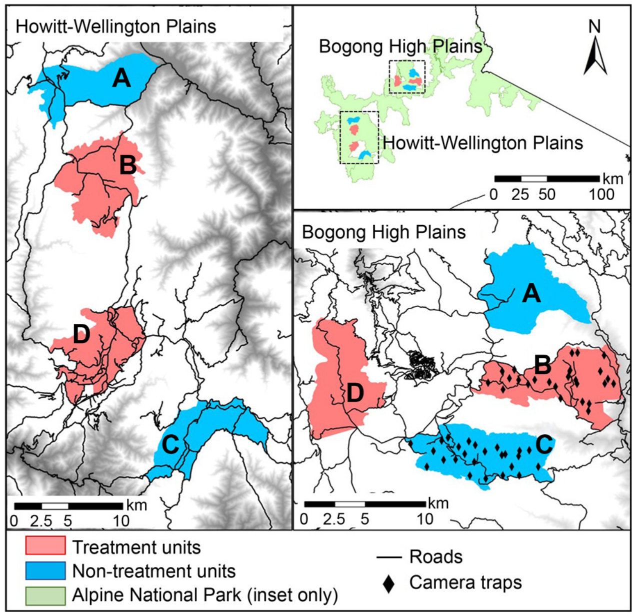

Fig. 1. Map of the two blocks with treatment (organised ground-based shooting) and non-treatment (no organised ground-based shooting) management units in Alpine National Park, Victoria, Australia, 2015–2020.

Materials and methods

Alpine National Park deer control trial

The Alpine National Park deer control trial was implemented in two blocks in Alpine National Park, the Bogong High Plains (BHP) and the Howitt-Wellington Plains (HWP). Each block consisted of four management units (Fig. 1) randomly assigned to treatment (organised ground-based shooting) or non-treatment (no organised ground-based shooting). The proposed design included the deployment of motion-sensitive cameras in each management unit for the duration of the program (Davis *et al.* 2015); however, owing to financial constraints, only two units in BHP were monitored, one treatment and one non-treatment (Fig. 1). The two blocks were selected to be spatially independent (>50 km apart) but similar in terms of landscape and habitat. Both blocks were especially chosen for the presence of alpine sphagnum bogs and associated fens dominated by *Sphagnum subsecundum* and *S. cristatum* (hereafter referred to as alpine peatlands), a nationally endangered community notably threatened by sambar deer (Australian Department of the Environment 2015). Alpine peatlands were generally present on flat areas surrounded by alpine and subalpine woodlands dominated by snow gums (*Eucalyptus pauciflora*). Montane wet forests (dominated by alpine ash *E. delegatensis*) were the dominant community in steeper slopes near watercourses, usually with a dense understorey (Conn 1993).

The BHP block surrounded the Falls Creek ski resort (36.87°S, 147.28°E). The four management units within this block were 3956–4422 ha in area, with the two treatment units separated by >7 km (Fig. 1). The road network in the two treatment units consisted of unsealed fire trails and management vehicle-only tracks (i.e. four-wheel-drive tracks closed to the public by locked gates). All roads were open to mountain biking and hiking, and there were several campgrounds and walking tracks in each treatment unit. Elevations within the four units ranged from 720 to 1882 m asl. The mean annual rainfall was 1302 mm, with monthly maximum and minimum temperatures ranging from 8.3°C and 16.9°C in February to −3.2°C and 0.9°C in July (Australian Bureau of Meteorology Falls Creek weather station, 1765 m asl). Snow was present between June and October, with a maximum mean monthly depth of 167 cm (Daily Snow Depth Records Falls Creek, Department of Environment, Land, Water and Planning, https://discover.data.vic.gov.au). Recreational hunting was prohibited in this block.

The HWP block (37.33°S, 146.77°E) was ~60 km south-west of the BHP block (Fig. 1). The four management units ranged from 3842 to 4681 ha, with the two treatment units being separated by >6 km (Fig. 1). The road network in the two treatment units consisted of unsealed two-wheel drive roads and four-wheel-drive tracks that were accessible to the public, and several management vehicles-only tracks closed to the public. There were several campgrounds in each treatment unit. Elevations within the four units ranged from 524 to 1709 m asl. The mean annual rainfall was 1622 mm and the minimum and maximum daily temperatures ranged from −7.4°C to 0.4°C and from 6.1°C to 27.0°C in August and January, respectively (Australian Bureau of Meteorology Mount Buller weather station, 1707 m asl.). There were no snow-depth data for this block. In contrast to the BHP block, recreational hunting of sambar deer was authorised annually from 15 February to 15 December, and was restricted to stalking on foot during the day without a dog (Victoria Game Management Authority, https://www.gma.vic.gov.au/hunting/deer).

This paper focuses on the ground-based shooting operations conducted in the four treatment units (two in each block). We have previously shown, using images of sambar deer activity from motion-sensitive cameras deployed in BHP, that during this management program the modal sambar deer group size was one and that a maximum of eight deer were detected together (Comte *et al.* 2022). Sambar deer detections were higher in dense woody vegetation and nearer to roads and tracks, which, owing to low vehicle traffic, may act as movement corridors. The diel activity pattern of sambar deer was mostly crepuscular (higher activity at dusk and dawn) with a larger peak of activity at sunset. The annual accumulation of snow between July and September was associated with a strong decrease in detections as sambar deer moved to lower elevations (Comte *et al.* 2022).

Ground-based shooting

During the management program, all ground-based shooting was restricted to time-limited operations ($n = 32$ operations in BHP, $n = 9$ in HWP). Because both blocks remained open to outdoor activities (including hiking, horse riding and cross-country skiing) during the shooting operations, potential visitors were advised of scheduled shooting operations by signs erected at key access points. Each operation was divided into shifts (median = 8; range: 1–16), defined by a start and end time (median = 5.5 h; range: 0.8–12.0 h), during which teams of shooters (up to four people) were given access to one management unit (Table 1). For each shift, the teams of shooters recorded the number of deer seen and killed by sex–age classes defined as adult male, adult female, yearling male, yearling female, or calf (no sex assigned). Shooters used a hand-held GPS (Garmin GPSMAP 78s, Garmin Ltd, Olathe, KS, USA) to record their movement track-log during the shift and the location and time that each deer was killed.

The 75 volunteer shooters were members of the Australian Deer Association and/or the Sporting Shooters' Association of Australia. Each volunteer shooter possessed valid firearm and game licences for the state of Victoria as well as an authorisation to possess, carry and use a firearm in a National Park (Section 37 of the *National Parks Act 1975 Victoria*). Volunteer shooters were accredited by their respective organisation to participate in deer management

Table 1. Ground-based shooting operations for sambar deer management in Alpine National Park, Victoria, Australia.

Summary statistics	BHP year 1		BHP years 2–4				HWP			
	Unit B	Unit D	Unit B (4423 ha)		Unit D (4093 ha)		Unit B (4682 ha)		Unit D (4214 ha)	
	Volunteers	Contractors	Volunteers	Contractors	Volunteers	Contractors	Volunteers	Contractors	Volunteers	Contractors
Number of operations	8	1	11	9	–	12	5	6	5	6
Number of shifts	75	11	92	35	–	83	24	28	20	27
Mean team size	2.2	1.4	1.8	1.2	–	1.5	1.9	1.8	2.0	1.5
Total deer seen	108	40	151	105	–	342	34	77	96	110
Total deer killed	26	17	62	78	–	219	9	66	26	70
Duration (h)	273.4	47.1	546.3	191.2	–	511.6	132.6	166.7	98.5	167.5
Effort (people hours)	590.8	72.3	1004.5	240.2	–	771.9	250.0	285.8	197.1	262.0

For locations of units, see Fig. 1. BHP, Bogong High Plains; year 1, 2015–2016; years 2–4, 2016–2019; HWP, Howitt-Wellington Plains 2017–2020.

programs after the completion of a theoretical and practical course. In Victoria, sambar deer hunters are legally required [Wildlife (Game) Regulations 2012] to use a minimum calibre of 0.270 (6.85 mm) with a minimum projectile weight of 130 grains (8.45 g). Eligible volunteer shooters were recruited for each operation on a first-come, first-served basis. For all operations, volunteer shooters used their own hunting equipment including rifle, ammunition, four-wheel-drive vehicles and spotlights. Shooting teams were provided with a hand-held GPS unit (as above) and Victorian StateNet Mobile Radio Network radios. Volunteer shooters had access to two thermal hand-held monoculars (Helion XQ, Yukon Advanced Optics Ltd, Lithuania) and two detachable thermal scopes (Pulsar Trail XP50 LRF, Yukon Advanced Optics Ltd, Lithuania).

In the first year of the program (May 2015–May 2016), the contract shooters were selected by a market-based expression of interest and merit-based procurement process. One company was selected (Strathbogie Wildlife Pty Ltd, Holbrook, New South Wales), and their contract was renewed for subsequent years. There were six contract shooters, all with considerable experience in ground-based shooting of sambar deer in south-eastern Australia. They possessed a valid corporate firearm licence for Victoria, including public liability insurance (*Firearms Act 1996 Victoria*). The contract shooters used the following three calibres: 0.338 Winchester Magnum, 0.308 Winchester and 0.300 Winchester Magnum. All contract shooters held an authorisation to possess, carry and use a firearm in a National Park (Section 37 of the *National Parks Act 1975 Victoria*) and a permit for using sound suppressors (Section 57 of the *Firearms Act 1996 Victoria*). For all their operations, contract shooters used their own hand-held GPS, hand-held thermal monoculars and thermal scopes (makes and models similar to those provided to the volunteer shooters). Contract shooters occasionally used vehicles (four-wheel drive or all-terrain vehicle) or horses to move within management units. Two of the contract shooters used gundogs to find shot deer.

Costing tool

Following Iacona *et al.* (2018) and Bengsen *et al.* (2022), we grouped costs on the basis of their scaling potential (Supplementary Table S1). The 'organisational costs' represent fixed annual labour time and therefore scale down with increased ground-shooting effort during the year. The 'operational costs' were calculated as the labour time and financial compensations for each ground-based shooting operation. These costs varied between volunteer and contract shooters and between blocks. Operational costs scale up with increased effort because they are proportional to the number of management operations. Finally, the 'equipment costs' summarise the purchase of assets necessary for the ground-based shooting operations. These one-off costs scale down with the amount of effort. All costs are reported in 2021 Australian dollars (A$). The labour time included different staff salary levels plus on-costs, so we used an average hourly rate of A$57.0 (Parks Victoria Enterprise Agreement 2016, https://www.fwc.gov.au/documents/documents/agreements/fwa/ae423611.pdf).

Statistical analyses

Catch-per-unit-effort for volunteer and contract shooters

During the first year of the program, all shooting operations (75 shifts within eight operations) were conducted in BHP Unit B by volunteer shooters only. Only one operation was performed by contract shooters, in BHP Unit D in May 2016, and this operation was excluded from our analysis. During this first year, volunteer shooters used different methods for ground-based shooting. The majority of shifts consisted of stalking on foot during daytime (n = 51), of which 12 used a gundog to indicate sambar deer (Table 2). An additional 21 shifts were conducted at night, shooting from a vehicle with a spotlight (n = 13) or stalking on foot using spotlight or thermal-vision equipment (n = 3 and n = 7 respectively). Two shifts consisted of static glassing (i.e. long-distance shooting during the day from one location) and one shift consisted of a drive (i.e. people flushing deer toward waiting shooters) involving 12 shooters. These three shifts were removed from analyses because of insufficient replication. We compared the CPUE (i.e. the number of deer killed per hour of shooting operation) of each method by using a Bayesian negative binomial generalised linear mixed model (GLMM). We used the number of deer killed (i.e. the catch) as the response variable C_i, with p_i the success parameter and r the dispersion parameter:

$$C_i \sim \mathrm{NB}(p_i, r)$$

$$p_i = \frac{r}{r + \lambda_i}$$

$$\log(\lambda_i) = \alpha + \textstyle\sum_a \beta_a X_{ai} + \log(\mathrm{duration}_i) + \theta_{\mathrm{operation}\,i}.$$

We included the effort (i.e. duration of the shift in hours) as log (duration$_i$), an offset (i.e. parameter fixed at 1.0) such that λ_i was the expected (mean) CPUE. The linear predictors included five shooting methods (Table 2, excluding glassing and day drive) as dummy variables (0 or 1), with spotlighting from a vehicle as the reference level (i.e. the intercept α). We included the size of the team and the duration of the shift (hours) as linear predictors and $\theta_{\mathrm{operation}\,i}$ was the random effect of the operation (n = 8).

In subsequent years (December 2016–February 2020), the ground-based shooting operations on both blocks were organised annually between November and May (spring–autumn), with volunteer and contract shooters alternately accessing the treatment units (with the exception of BHP Unit D, which was restricted to contract shooters).

Table 2. Ground-based shooting methods and equipment used by volunteer shooters in BHP Unit B in Alpine National Park, Victoria, Australia, during May 2015–May 2016.

Ground-based shooting method	Number of shifts (percentage of total)	Mean team size	Mean duration in hour (range)	Deer killed	Deer killed per hour (95% CrI)[A]
Day stalking (Bradshaw and Bateson 2000): the shooter hunts on foot during daylight	39 (52)	1.8	3.7 (0.8–8.3)	0	0.000 (0.000–0.003)
Day stalking with gundog (Godwin *et al.* 2013): the shooter hunts on foot using one dog to indicate that a deer is nearby. The dog does not chase the deer	12 (16)	2.1	3.3 (1.0–6.4)	3	0.037 (0.006–0.215)
Static glassing (Harrison 2010): the shooter uses binoculars and high magnification scopes to spot and shoot deer at dusk or dawn from one location	2 (3)	1.0	1.8–2.0	0	0.000
Day drive (Herrero *et al.* 2013): shooters wait in a line for beaters to flush deer towards them	1 (1)	12.0	1.8	1	0.556
Night stalking with spotlight (Hodnett 2006): a team of two or more shooters hunt on foot during the hours of darkness. At least one person uses a white light to detect deer	3 (4)	2.7	2.3 (1.0–3.0)	0	0.000 (0.000–0.235)
Night stalking with thermal (Hodnett 2006): the shooters walk at night and use thermal-vision equipment (monocular and/or scope) to detect deer	5 (7)	2.0	4.3 (2.8–5.5)	6	0.157 (0.037–0.696)
Vehicle with spotlight (Hampton *et al.* 2022): the driver and/or a spotter uses a white light from a four-wheel drive vehicle (or all-terrain-vehicle) driven at low speed at night to detect deer. The shooter uses the vehicle (when stationary) as a shooting platform	13 (17)	3.0	4.1 (1.3–8.0)	16	0.158 (0.005–2.684)

[A]Mean and 95% credible intervals (CrI) of the posterior distributions of the model parameters.

Ground-based shooting ceased in BHP in February 2019, and in HWP in February 2020. On the basis of the experience gained during the first year of the program, all ground-based shooting operations were conducted during night-time by stalking on foot using thermal-vision equipment or from a vehicle with spotlight or thermal vision equipment. We used a negative binomial GLMM, as previously described, to model the temporal trends in number of deer killed (the catch) with an offset of the duration of the shift (the effort). The model was fitted with different intercepts for contract and volunteer shooters, and with different slopes for those two shooter types for each block (n = 4, i.e. contractors and volunteers on BHP and HWP, respectively) over time (days since first shooting operation). We added the cumulative number of deer killed during each annual shooting period (November–May), and the number of deer seen during each shift as linear predictors. The shooting operations were undertaken on four different units; we therefore used a nested random effect of the operations (n = 35) within units (n = 4).

We implemented both models in a Bayesian framework by using gamma priors for the dispersion parameters $r_m \sim$ Gamma (0.01,0.01) and diffuse normal priors α_m, $\beta_m \sim N(0,10)$ for intercepts and linear predictors, respectively. We modelled the random effects by using normal priors for the group-level mean $\theta_n \sim N(0,\sigma_n)$ and a uniform distribution for the group-level variance $\sigma_n \sim$ U(0,20). The models were fit using the packages runjags ver. 2.0.4-6 (Denwood 2016) and coda ver. 0.19-3 (Plummer *et al.* 2006). We ran four Markov-chain Monte Carlo (MCMC) chains with a thinning of 10 for a total sample size of 100 000, with 5000 adaptation runs and 5000 burn-in runs. We assessed the mixing of the MCMC chains visually and with the Gelman–Rubin diagnostic ($\hat{R}$; Gelman and Rubin 1992).

Space use by volunteer and contract shooters

We visually inspected all track-logs and discarded any track-log with GPS malfunction or loss of satellite, that is, inconsistencies in the frequency of fixes or multiple gaps in the track log larger than 30 min. Because each hand-held GPS unit recorded the location of the shooter at different frequencies (<5 to >120 s), we standardised the tracking data by discretising all track-logs with a 5-min step duration. For each team of shooters, we calculated the total distance (m) covered during the shift (sum of all step lengths) and the mean speed (metres per second) during the shift by using ArcGIS (ver. 10.6.1.9270, Esri, Redlands, CA, USA; www.esri.com) and the R-package adehabitatLT ver. 0.3.25 (Calenge 2006).

A high frequency of fixes can produce serial autocorrelation of the relocations in tracking data (Boyce *et al.* 2010). We therefore used the biased random bridge (BRB; Benhamou and Cornélis 2010; Benhamou 2011) approach to estimate the shooters' utilisation distribution (UD). Instead of considering each new step in a trajectory as a random decision (purely diffusive movement) as in the Kernel

Brownian bridge estimators (Horne et al. 2007), the BRB incorporates a directional drift parameter (advection) between relocations. This approach is therefore more realistic when modelling movements of animals, including people (Papworth et al. 2012). We pooled the UDs for volunteers and contract shooters separately on each of the four treatment units using a 1-ha grid. Because of the difference in equipment and strategy (i.e. time of day and duration of the shifts), we discarded the UDs from the first year of the program on BHP Units B and D. As commonly used for mammal space use (Pellerin et al. 2008), we considered the core area (UD50, the smallest area containing 50% of the space-use probability) and the main space use during the study (UD95). We also defined an extended space use (UD99) including the least-used areas (Horne et al. 2007). Any cell not included in one of the categories was considered as not used by shooters during the study. We measured the overlap between the space use of volunteer and contract shooters for each level of UD on each management unit (BHP-B, HWP-B and HWP-D) as the number of grid cells (ha) common to both shooter types' UDs. All space use calculations were performed with the R-package adehabitatHR ver. 0.4.18 (Calenge 2006). We used the UDs to fit separate resource utilisation functions (RUF; Rowland et al. 2021) for volunteer and contract shooters. We restricted the RUF to BHP-B because it was the only unit on which sambar deer activity was simultaneously monitored using camera traps (Comte et al. 2022) and was also the unit with the highest combined effort for volunteer and contract shooters (Table 1), therefore remaining representative of each shooter type. To reduce the spatial autocorrelation of UD between proximal grid cells, we randomly selected two sets of 100 grid cells (one set for volunteers and one set for contractors) across the management unit. We created our response variable as the UD value (i.e. the UD probability value) extracted from the randomly sampled grid cells. For each sampled grid cell, we calculated the distance (m) from its centre to the nearest road and to the nearest watercourse, the mean slope (decimal degrees) on the grid cell and the mean probability of the grid cell being covered by woody vegetation (scaled as 0–100). We also calculated the distance (m) to the nearest alpine peatland as the main ecological asset targeted by the ground-based shooting. Last, we included the predicted sambar deer activity previously modelled on camera-trap detections (i.e. predicted monthly detections of sambar deer in the absence of snow cover; Fig. 2c). Detailed descriptions of the environmental covariates and their sources are given in Comte et al. (2022).

The UD probabilities in our response variable included true zeros. We therefore fitted a zero-inflated beta regression (Ospina and Ferrari 2012) to the UD probabilities y_i, as follows:

$$f(y_i) = \begin{cases} p_i & \text{if } y_i = 0 \\ (1 - p_i)\ \mathrm{Beta}(\mu_i, \vartheta_i) & \text{if } y_i \in (0,1) \end{cases},$$

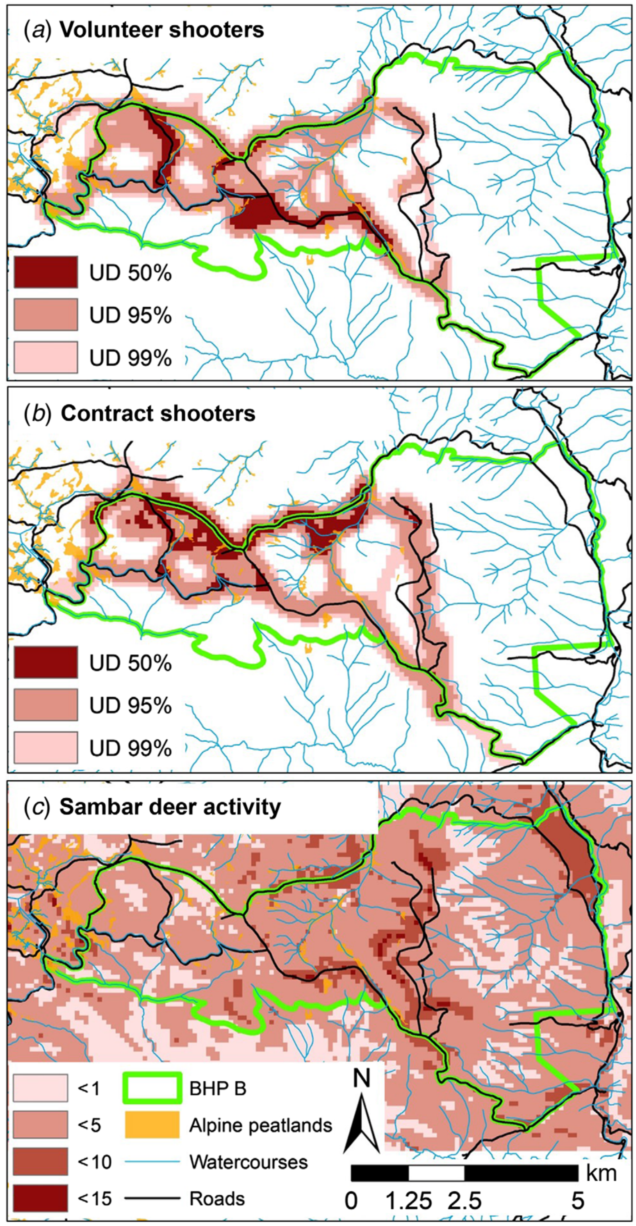

Fig. 2. Space use of (a) volunteer and (b) contract deer shooters (79 and 32 shifts between 2016 and 2019, respectively), and (c) predicted sambar deer activity (monthly detections) based on camera-trap monitoring, 2015–2019, in unit BHP-B, Alpine National Park, Victoria, Australia. Shooters' utilisation distributions (UD) were calculated using the biased random bridge method (BRB) with GPS locations collected every 5 min. See Supplementary Fig. S1 for the shooters' space use in the other treatment units.

where p_i is the probability of $y_i = 0$; μ_i and ϑ_i are the mean and dispersion parameter of the beta distribution when $y_i \in (0,1)$. We assumed a constant dispersion parameter for the beta distribution $\log(\vartheta_i) = c$, such that:

$$\mathrm{logit}(\mu_i) = \beta_1 X_{1i}$$
$$\mathrm{logit}(p_i) = \beta_2 X_{2i},$$

with $\beta_m X_{mi}$ the linear predictors. The mean UD on grid cell i was therefore:

$$E(y_i) = (1 - p_i)\mu_i = \left(1 - \frac{\exp(\beta_2 X_{2i})}{1 + \exp(\beta_2 X_{2i})}\right)\left(\frac{\exp(\beta_1 X_{1i})}{1 + \exp(\beta_1 X_{1i})}\right).$$

As we used all six explanatory variables described previously for both the mean and the zero probability of the beta distribution, $X_1 = X_2$ in our model. We fitted the model in a Bayesian framework by using diffuse normal priors $\beta_m \sim N(0,10)$ for all model parameters. We ran three MCMC chains of 50 000 samples each, with 1000 burn-in runs. We assessed the mixing of the MCMC chains visually and with the Gelman–Rubin diagnostic ($\hat{R}$). The regression analyses were performed using the packages zoib ver. 1.5.5 (Liu and Kong 2015), runjags ver. 2.0.4-6 and coda ver. 0.19-3.

Hourly catch per unit effort for volunteer and contract shooters

Deer are potentially more easily detected by shooters when they are more active (Little *et al.* 2014; Rivrud *et al.* 2014). Therefore, we expected a higher CPUE at dusk and dawn, when sambar deer were most active in our study area (Comte *et al.* 2022). We calculated the daily distribution of effort for both volunteer and contract shooters as the number of shifts active during each hour of the day across all treatment units and blocks. We then calculated the CPUE for each type of shooter as the total number of deer killed each hour divided by the total effort. We considered CPUE only for hours with at least five shifts. We scaled the times to sunrise (06:00) and sunset (18:00) by using the function sunTime in the R-package overlap ver. 0.3.3 (Ridout and Linkie 2009).

Ethical approval

The Alpine National Park deer control trial was conducted by Parks Victoria as part of a pest management program under Section 28A of the *Wildlife Act 1975* (Victoria), and therefore did not require additional Animal Ethics Approval for the ground-shooting operations. For the Bogong High Plains, the Department of Environment, Land, Water and Planning granted Parks Victoria annual 'Authorisation to destroy, possess, and dispose of protected wildlife and to use a gun to gain possession of protected wildlife' (reference numbers: 14433193, 14484589, 14567926, 14637928, 14709708, 14733000). For the Howitt-Wellington Plains, the Game Management Authority issued Parks Victoria with an 'Authority to control or destroy game' (reference numbers: GMA/2017/07, GMA/2017/01). The use of motion-sensitive cameras was approved by the Northern Melbourne Institute of TAFE Animal Ethics Committee (approval numbers: 01/14 and 03/17).

Results

Between May 2015 and February 2020, 573 sambar deer, in total, were killed during 2135 h of ground-based shooting in the four management units (total area: 17 412 ha), 21% (during 1051 h) by the volunteer shooters and 79% (during 1084 h) by the contract shooters (Table 1). More male (61%; 49% adults and 12% yearlings) than female (39%; 35% adults and 4% yearlings) sambar deer were killed, but the sex–age classes of the sambar deer killed were similar for both shooter types (Chi-squared test: $\chi^2 = 4.11$, d.f. = 3, $P = 0.25$). Seven calves (sexes not recorded) were killed, and sex–age class information was not recorded for 56 other deer (50 killed by contract shooters and six by volunteer shooters). On average, contract shooters moved faster ($n = 143$ shifts with complete GPS track logs, mean = 0.76 m/s, 95% CI: 0.67–0.86) than did volunteer shooters ($n = 140$ shifts, mean = 0.41 m/s, 95% CI: 0.35–0.46) during the shooting operations.

Catch-per-unit-effort for volunteer and contract shooters

During the first year of the program, 26 sambar deer were shot by volunteer shooters in unit BHP-B. Most sambar deer were killed at night from a vehicle by using a white-light spotlight ($n = 16$) or on foot using thermal-vision equipment ($n = 6$). Three deer were killed during daylight stalking, all while using gundogs. The last deer was killed during the 1-day drive that involved 12 volunteer shooters for 1.82 h, and this datum was not included in our analysis. Considering a mean effort (duration = 3.72 h and shooting team size = 2), the CPUE for ground-based shooting of sambar deer was highest at night when using a spotlight from a vehicle or stalking with thermal-vision equipment, both being four times more effective than day stalking with gundogs (Table 2). All three methods were significantly more effective than day stalking without gundogs. No deer were killed by night stalking (on foot) using a white-light spotlight, but because of the small sample size, the credible intervals were large (Table 2). Each additional hour of ground-based shooting resulted in a 56% (95% credible interval (CrI): 7–147) increase in CPUE, and the size of the shooting team did not have a significant effect on CPUE (Table S2).

During the following years (December 2016–February 2020), while using similar methods (equipment and schedule), the CPUE was 4.58 (95% CrI: 2.07–8.64) times higher for contract shooters (0.77 deer per hour, 95% CrI: 0.21–2.42) than for volunteer shooters (0.18 deer per hour, 95% CrI: 0.10–0.28; Table S3). During that time, there was no evidence of a change in CPUE for the contract shooters (credible intervals included zero for both BHP and HWP), but volunteer shooters became more effective over time in HWP (annual CPUE increase of 55%; 95% CrI: 15–97%; Table S3), a trend not observed in BHP. For both shooter types, the CPUE increased by 20% (95% CrI: 16–26%) with each additional deer seen but was not affected by the cumulative number of sambar deer removed during each annual shooting period.

Space use by volunteer and contract shooters

Of the 309 shifts between November 2016 and February 2020, 236 (76%) provided GPS track-log data suitable for analysis (75% for volunteer shooters and 77% for contract shooters). Both volunteer and contract shooters exhibited highly heterogenous space use in the four treatment units (Figs 2*a*, *b*, S1*a*, *b*), with core areas (UD50) corresponding to 14% (range 10–17%) of the total area used (UD99). In all four treatment units, the area used by contract shooters was greater than that used by volunteer shooters. There was 80% (range 66–92%) overlap between contract and volunteer shooters space use for the UD99, but only 40% (range 26–58%) for the UD50 (Table 3).

The RUF for ground-based shooting in the treatment unit BHP-B showed that the space use of both volunteers and contractors was significantly influenced by the landscape. The zero-inflation component of the RUF (Fig. 3*a*, Table S4) showed that both shooter types were more likely to use areas close to alpine peatlands and roads. Volunteer shooters also preferentially used flatter areas, whereas contract shooters used areas closer to watercourses. In addition, the beta distribution component of the RUF (Fig. 3*b*, Table S4) showed that within the areas of the treatment units that were used, volunteers used flatter areas and areas closer to roads and watercourses more intensively than they did steeper slopes and areas further away from roads and watercourses. However, contract shooters showed no significant associations with spatial covariates within the areas that they used.

Hourly catch per unit effort for volunteer and contract shooters

The time of shooting was recorded for 451 (79%) of the 573 deer shot during the program (volunteers: 100 of 123; contractors: 351 of 450). Contrary to our hypothesis, the efficiency of ground-based shooting did not peak at sunset when sambar deer were most commonly detected with camera-traps. For both volunteer and contract shooters, CPUE was highest in the hours between sunset and midnight (Fig. 4), before declining and then peaking again before sunrise. CPUE was lowest during daylight hours.

Table 3. Pooled utilisation distribution (UD) of volunteer and contract deer shooters, and their overlap, in four management units in Alpine National Park, Victoria, Australia, 2016–2020.

Treatment unit	Volunteers (ha)			Contractors (ha)			Overlap (ha)		
	UD50	UD95	UD99	UD50	UD95	UD99	UD50	UD95	UD99
BHP-B	262	1359	1930	354	1448	2028	89	1074	1616
BHP-D	–	–	–	343	1500	1930	–	–	–
HWP-B	236	1162	1573	295	1644	2403	65	713	1031
HWP-D	174	838	1244	404	2753	4063	101	729	1139

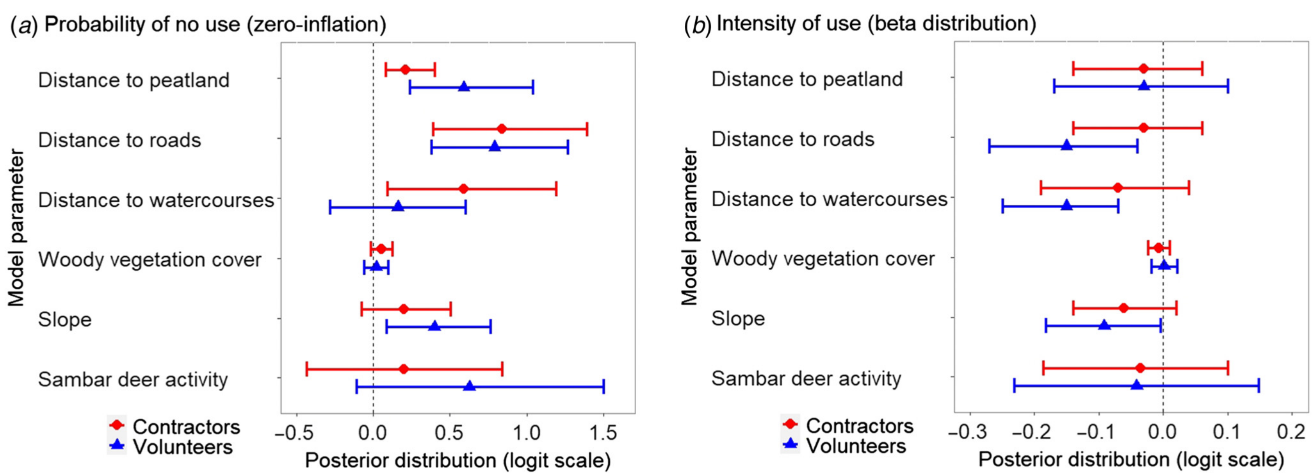

Fig 3. Posterior distributions of the parameters of the (*a*) zero-inflated and (*b*) beta distribution model for the resource utilisation function (RUF) for space use of volunteer (blue) and contract (red) shooters in Alpine National Park, Victoria, Australia, 2016–2020. For clarity of the figure, posterior distributions of distance parameters are expressed for 100 m. See Table S4 for full model outputs. Circles and triangles are means, bars are 95% CrIs.

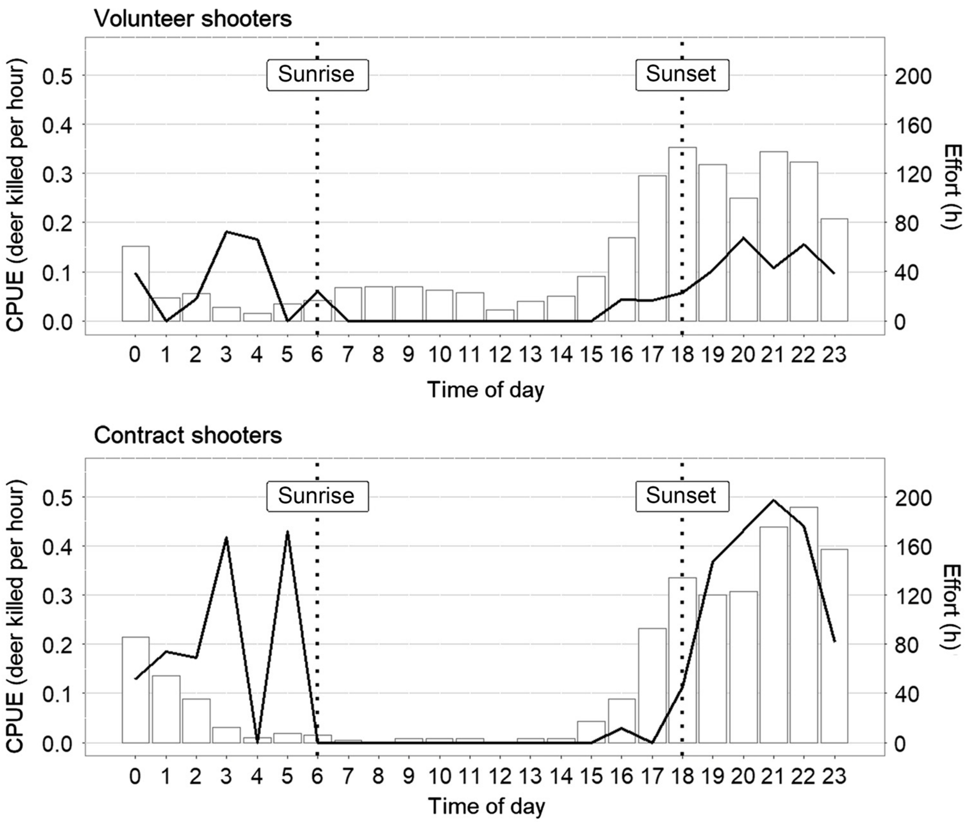

Fig. 4. Hourly catch per unit effort (CPUE; solid line) and effort (bars) for ground-based shooting of sambar deer by volunteer and contract shooters in Alpine National Park, Victoria, Australia, 2015–2020.

Cost-effectiveness of volunteer and contract shooters

After accounting for all key expenses, the cost per hour for volunteer shooters was three to four times lower than that for contract shooters (Table 4). The contract shooters' fees accounted for more than 75% of their cost per hour. As hypothesised, the higher effectiveness of contract shooters (i.e. less hours per deer killed than volunteer shooters) compensated for most of the cost per hour difference. However, across the 5-year program on both blocks, the cost per deer killed was higher for contract shooters than for volunteer shooters (12% in BHP and 10% in HWP; Table 4).

Discussion

Empirical data collected during a 5-year management program showed that, given the same access opportunities and similar equipment, contract ground-based shooters killed four times more sambar deer per hour than did volunteer shooters in and around alpine peatlands in south-eastern Australia. This higher CPUE compensated for most, but not all, of the greater cost per unit effort of contract shooters. Hence, contract shooters were, on average, 10.1% more expensive per deer killed than were volunteer shooters. The CPUE and hence cost-effectiveness of volunteer shooters was strongly influenced by shooting method and was highest when shooting at night from a vehicle with a spotlight or when stalking with thermal-vision equipment. During the day, the use of gundogs to indicate deer significantly increased the CPUE of volunteer shooters. Both contract and volunteer shooters had a higher CPUE during the first half of the night and just before sunrise. Contractors and especially volunteer shooters relied on roads and tracks to move within the treatment units to shoot sambar deer close to alpine peatlands. Although contract shooters covered more area than did volunteer shooters, there were still large parts of the treatment units with little or no shooting effort after 5 years.

In our study area, the preference of sambar deer for denser wooded habitats and their crepuscular activity (Comte *et al.* 2022) is likely to explain why no sambar deer were killed by volunteer shooters during daylight stalking unless gundogs were used to detect deer. Gundogs have long been companions of deer hunters and have been associated with higher success in reducing overabundant mammalian species by

Table 4. Cost-effectiveness of ground-based shooting of sambar deer for volunteer and contract shooters in Alpine National Park, Victoria, Australia, 2015–2020.

Item	BHP year 1		BHP years 2–4		HWP	
	Volunteers	Contractors	Volunteers	Contractors	Volunteers	Contractors
Ground-based shooting operations						
Hours expended	273.4	47.1	546.3	702.8	231.1	334.2
Area covered (km^2)	–	–	19.3	45.0	28.2	64.7
Number of deer killed	26	17	62	297	35	136
Cost per hour of ground-based shooting (A$)						
Organisational	28	120	21	40	63	115
Operational	118	34	41	27	93	29
Contract shooters' fees	–	531	–	427	–	449
Accommodation	21	–	11	–	–	–
Equipment	17	11	48	11	48	11
Cost-effectiveness of ground-based shooting						
Hours per km^2	–	–	28.3	15.6	8.2	5.2
Cost per km^2 (A$)	–	–	3427	7895	1673	3119
Deer killed per km^2	–	–	3.21	6.60	1.24	2.10
Cost per hour (A$)	184	696	121	505	204	604
Hours per deer killed	10.5	2.8	8.8	2.4	6.6	2.5
Cost per deer killed (A$)	1935	1927	1067	1195	1346	1483

Costs are in 2021 A$, rounded to nearest dollar. See Table S1 for detailed costing tool for each category.

ground-based shooters (89% and 47% success with and without dogs respectively; Bengsen *et al.* 2020). During our study, the highest CPUE was achieved at night, likely owing to deer feeding in more open areas where they are more easily detected by shooters using spotlights or thermal-vision equipment. Shooting from a vehicle with a spotlight has been associated with a decrease in sambar deer faecal pellet deposition in a flat open grassland adjacent to dense forest (Bennett *et al.* 2015). Even if using four-wheel-drive vehicles, this shooting method is restricted to the limited roads and tracks within the rugged study area. Using thermal-vision equipment should provide more shooting opportunities owing to improved detection rates compared to walking with binoculars during the day (Logan *et al.* 2019) or spotlights from vehicles during the night (Focardi *et al.* 2001).

On the basis of the results from the first year of shooting in the Bogong High Plains block, subsequent ground-shooting operations for volunteers were scheduled at night and with access to thermal-vision equipment, which was the primary method used by the contractors when they started shooting. Hunting deer on Victorian public land at night is prohibited [Wildlife (Game) Regulations 2012], and hence most volunteer shooters would have had less experience of night-shooting methods than would the contract shooters. During the management program, the CPUE of volunteer shooters increased over time in the treatment block HWP. This result suggests that volunteer ground-based shooters learnt to use new equipment, as has been described in the United States for volunteer shooters during a peri-urban white-tailed deer management (Hygnstrom *et al.* 2011). The difficulty of walking at night with a firearm in a rugged and often wooded landscape probably explains why volunteer shooters relied more on roads and flat areas to move than did contract shooters. The presence of roads has commonly been associated with increased deer hunting activity and CPUE (Lebel *et al.* 2012; Pauli *et al.* 2019; Rowland *et al.* 2021). By moving faster and covering more ground during their shifts, contract shooters may have been able to create more shooting opportunities than did volunteer shooters. According to the six contract shooters in the program, the key to successfully shooting sambar deer was to target deer emerging from wooded areas into open areas at night. Hence, during their shifts, contract shooters typically covered multiple feeding grounds with low wooded vegetation cover (K. Stone, pers. comm.).

Another factor potentially contributing to the higher CPUE of contractors than of volunteer shooters is that only the former had access to sound suppressors. This equipment is commonly used by contractors in ground-based shooting of deer in Australia (Hampton *et al.* 2022) and is likely to increase their CPUE by reducing the recoil and minimising the flight behaviours of non-targeted animals, thus creating more shooting opportunities when shooting individuals within a group (MacCarthy *et al.* 2011; Williams *et al.* 2018).

There is much interest in involving recreational hunters as volunteer shooters in deer control programs in Australia (Boyle and Henderson 2007; Bengsen and Sparkes 2016; New South Wales Natural Resources Commission 2017; Parliament of Victoria Environment, Natural Resources and Regional Development Committee 2017; Game Services Tasmania 2022). The Alpine National Park deer control trial used a mix of volunteer and contract shooters. If all the ground-based shooting was conducted by volunteer shooters (i.e. same number of shooting hours), then the cost of the program would have been 62% lower, but there would have been a 55% reduction in deer killed (315 fewer deer shot). In contrast, if contract shooters were used with the same effort, then the costs would have been 11% higher for a 52% increase in deer killed (300 more deer shot). Alternatively, contract shooters could have achieved the same outcome (i.e. total number of deer killed) with a 45% reduction in effort (20 fewer operations) and a 5% increase in costs. Volunteer shooters, to achieve the same outcome, would cost 43% less but require an additional 62 operations (40% increase) over the 5 years. However, the latter might not be possible because of limited human resources to organise the operations. There might also be a shortage of volunteer shooters because there is a limited amount of time that most volunteers can contribute during the seasons in which deer are present in and around the alpine peatlands. This was already apparent during the Alpine National Park deer control trial, with volunteer shooters showing a higher motivation to participate in ground-based shooting operations in BHP than HWP because recreational hunting was prohibited in the former (E. Thomas, pers. obs.). Our results support the general findings of Bengsen *et al.* (2020) that contract shooters are more likely to achieve population reduction, and within a shorter time, than are volunteer ground-based shooters.

Cost-effectiveness is a major aspect of successful management of overabundant deer populations, but community support is also important (Kilpatrick *et al.* 2007). There will often be greater community support for lethal control of overabundant deer when local people can contribute to the program (Martínez-Jauregui *et al.* 2020). Involving local hunters as volunteer shooters in a deer control program can therefore provide benefits to those individuals (i.e. the experience of hunting in a new area and meeting new like-minded people, taking home meat and/or a trophy and contributing to conservation programs) and increase community support for the program (Parliament of Victoria Environment, Natural Resources and Regional Development Committee 2017). Future studies of volunteer shooting programs in Australia could assess the motivations and experiences of the volunteers.

The differences in cost-effectiveness between volunteer and contract shooters during the Alpine National Park deer control trial were within the range of those observed during a peri-urban white-tailed deer ground-shooting program in Bloomington (Minnesota, USA) during 1991–1994 (Doerr *et al.* 2001). There, the cost per deer killed for volunteer shooters (US\$117 per deer in 1994; A\$304 in 2021) was 3% lower than for park rangers (US\$121 per deer in 1994; A\$314 in 2021) but 8% higher than for conservation officers (US\$108 per deer in 1994; A\$280 in 2021). Both categories of professional shooters had a much higher CPUE (4.7 h-per-deer for conservation officers and 2.1 h per deer for park rangers) than did volunteer shooters (30.9 h per deer). The costs per hour reported in the United States were much lower than in our study (accounting for inflation and currency rates) for both the organisational costs (A\$39 compared with A\$57 in our study) and for the professional shooters' fees (A\$39 compared with A\$470 in our study). These large differences reflect the difference in salary between the two countries but could also result from different costing methods (e.g. inclusion or exclusion of overhead costs, insurances, vehicles and equipment). This highlights the importance of reporting detailed costing tools for deer management programs because costs vary greatly with local socioeconomic context.

The CPUE of ground-based shooters is expected to decline at an increasingly rapid rate as deer density declines (Batcheler and Logan 1963; Van Deelen and Etter 2003; Masters *et al.* 2018). An independent index of deer abundance (camera-trap detections per month) is available for one of the four pairs of treatment and non-treatment units (Comte *et al.* 2022; see Materials and methods), but that treatment unit received the greatest ground shooting effort. After accounting for seasonal and environmental factors, the sambar deer detection rate at BHP-B (treatment unit) decreased by 14% annually (2015–2019) but increased by 7% annually at the non-treatment unit BHP-C (Comte *et al.* 2022). In contrast to expectations, the apparent stability of the CPUE at both blocks during the program suggests that the ground shooting effort did not remove a sufficiently large proportion of the population to cause it to decline, but may have succeeded in locally preventing the general increase in sambar deer population observed at a larger scale across the eastern part of Victoria (Forsyth *et al.* 2018; Watter *et al.* 2020). Our analysis of the shooters' GPS track-logs showed that the areas subject to intensive ground-shooting (combined UD50 for volunteers and contractors) represented only 10% (range 8–12%) of each treatment unit. This very localised shooting pressure may have meant that sambar deer killed by ground-based shooting may have been compensated for by local immigration (Porter *et al.* 2004; Putman 2012) from adjacent areas subject to no (BHP block) or less (HWP block) ground-based shooting. A management-scale experiment conducted in New Zealand to assess how forests responded to ground- and helicopter-based shooting of non-native deer was unable to consistently and substantially reduce deer densities at treatment relative to non-treatment areas (Forsyth *et al.* 2013), highlighting the difficulties of reducing deer populations in rugged and remote wooded landscapes.

Management implications

If there is a limited time frame for deer control then contract shooters can be expected to remove more deer than volunteer shooters, but at a (slightly) greater cost. A limited time frame for control would occur when deer seasonally migrate outside the management boundaries (Jarnemo 2008), when frequent adverse climatic conditions limit the shooting opportunities (Baur *et al*. 2021), or when access to sites is temporally limited by health and safety concerns (e.g. areas used by the public; Reis and Higham 2009). If there is more than a small window of time to conduct the control, then involving local recreational hunters as volunteer shooters could decrease the cost of the program and increase community support for it.

The timing of the shooting and the supporting equipment that can be used greatly affects shooter effectiveness and hence cost. Ground-based shooting of deer is likely to be most effective when conducted at night (when deer are most active in open areas) and with thermal vision equipment (which maximise the probability of detecting deer without the shooter being detected by deer).

Last, ground-based shooting is likely to be most effective in areas with a high density of roads and tracks (Fraser and Sweetapple 1992; Rowland *et al*. 2021), which facilitate the movement of the shooters on foot and enable rapid movement around the landscape using vehicles.

Supplementary material

Supplementary material is available online.

References

Australian Department of the Environment (2015) 'National recovery plan for the Alpine Sphagnum Bogs and Associated Fens ecological community.' (Australian Department of the Environment: Canberra) Available at https://www.awe.gov.au/environment/biodiversity/threatened/publications/recovery/alpine-sphagnum-bogs-associated-fens [Verified 10 December 2021]

Batcheler CL, Logan PC (1963) 'Assessment of an animal-control campaign in the Harper-Avoca catchment.' New Zealand Forestry Research Notes 27. pp. 1–27. (Forest Research Institute, New Zealand Forest Service)

Baur S, Peters W, Oettenheym T, Menzel A (2021) Weather conditions during hunting season affect the number of harvested roe deer (*Capreolus capreolus*). *Ecology and Evolution* **11**, 10178–10191. doi:10.1002/ece3.7825

Bengsen AJ, Sparkes J (2016) Can recreational hunting contribute to pest mammal control on public land in Australia? *Mammal Review* **46**, 297–310. doi:10.1111/mam.12070

Bengsen AJ, Forsyth DM, Harris S, Latham ADM, McLeod SR, Pople A (2020) A systematic review of ground-based shooting to control overabundant mammal populations. *Wildlife Research* **47**, 197–207. doi:10.1071/WR19129

Bengsen AJ, Forsyth DM, Pople A, Brennan M, Amos M, Leeson M, Cox TE, Gray B, Orgill O, Hampton JO, Crittle T, Haebich K (2022) Effectiveness and costs of helicopter-based shooting of deer. *Wildlife Research*. doi:10.1071/WR21156

Benhamou S (2011) Dynamic approach to space and habitat use based on biased random bridges. *PLoS ONE* **6**, e14592. doi:10.1371/journal.pone.0014592

Benhamou S, Cornélis D (2010) Incorporating movement behavior and barriers to improve kernel home range space use estimates. *The Journal of Wildlife Management* **74**, 1353–1360. doi:10.1111/j.1937-2817.2010.tb01257.x

Bennett A, Haydon S, Stevens M, Coulson G (2015) Culling reduces fecal pellet deposition by introduced sambar (*Rusa unicolor*) in a protected water catchment. *Wildlife Society Bulletin* **39**, 268–275. doi:10.1002/wsb.522

Bentley A (1998) 'An introduction to the deer of Australia, with special reference to Victoria.' (The Australian Deer Research Foundation: Melbourne, Vic., Australia)

Black KE, Jensen WF, Newman R, Boulanger JR (2018) Motivations and satisfaction of North Dakota deer hunters during a temporal decline in deer populations. *Human–Wildlife Interactions* **12**, 427–443. doi:10.26077/zb6s-4m87

Boyle B, Henderson C (2007) The game council NSW and its emerging role in game and feral animal management in NSW. In 'Pest or guest: the zoology of overabundance'. (Eds D Lunney, P Eby, P Hutchings, S Burgin) pp. 76–78. (Royal Zoological Society of New South Wales: Sydney, NSW, Australia)

Boyce MS, Pitt J, Northrup JM, Morehouse AT, Knopff KH, Cristescu B, Stenhouse GB (2010) Temporal autocorrelation functions for movement rates from global positioning system radiotelemetry data. *Philosophical Transactions of the Royal Society B: Biological Sciences* **365**, 2213–2219. doi:10.1098/rstb.2010.0080

Bradshaw E, Bateson P (2000) Welfare implications of culling red deer (*Cervus elaphus*). *Animal Welfare* **9**, 3–24.

Burt MD, Miller C, Souza D (2011) The use of volunteer hunting as a control method for feral pig populations on O'ahu, Hawai'i. In 'Island invasives: eradication and management'. (Eds C Veitch, MN Clout, DR Towns) pp. 402–406. (IUCN: Gland, Switzerland)

Calenge C (2006) The package 'adehabitat' for the R software: a tool for the analysis of space and habitat use by animals. *Ecological Modelling* **197**, 516–519. doi:10.1016/j.ecolmodel.2006.03.017

Carpio AJ, Apollonio M, Acevedo P (2021) Wild ungulate overabundance in Europe: contexts, causes, monitoring and management recommendations. *Mammal Review* **51**, 95–108. doi:10.1111/mam.12221

Caughley G (1983) 'The deer wars: the story of deer in New Zealand.' (Heinemann: Auckland, New Zealand)

Comte S, Thomas E, Bengsen AJ, Bennett A, Davis NE, Freney S, Jackson SM, White M, Forsyth DM, Brown D (2022) Seasonal and daily activity of non-native sambar deer in and around high-elevation peatlands, south-eastern Australia. *Wildlife Research* **49**, 659–672. doi:10.1071/WR21147

Conn BJ (1993) Natural regions and vegetation of Victoria. In 'Flora of Victoria. Vol. 1'. (Eds DB Foreman, NG Walsh) pp. 79–158. (Inkata Press)

Cook CN, Pullin AS, Sutherland WJ, Stewart GB, Carrasco LR (2017) Considering cost alongside the effectiveness of management in evidence-based conservation: a systematic reporting protocol. *Biological Conservation* **209**, 508–516. doi:10.1016/j.biocon.2017.03.022

Côté SD, Rooney TP, Tremblay J-P, Dussault C, Waller DM (2004) Ecological impacts of deer overabundance. *Annual Review of Ecology, Evolution, and Systematics* **35**, 113–147. doi:10.1146/annurev.ecolsys.35.021103.105725

Cripps JK, Pacioni C, Scroggie MP, Woolnough AP, Ramsey DSL (2019) Introduced deer and their potential role in disease transmission to livestock in Australia. *Mammal Review* **49**, 60–77. doi:10.1111/mam.12142

Davies C, Wright W, Hogan F, Visintin C (2020*a*) Predicting deer–vehicle collision risk across Victoria, Australia. *Australian Mammalogy* **42**, 293–301. doi:10.1071/AM19042

Davis NE, Bennett A, Forsyth DM (2015) Monitoring changes in deer density/abundance and habitat use associated with the Parks Victoria deer control trial in the Alpine National Park: survey design and rationale. Unpublished Report for Parks Victoria.

Davis NE, Bennett A, Forsyth DM, Bowman DMJS, Lefroy EC, Wood SW, Woolnough AP, West P, Hampton JO, Johnson CN (2016) A systematic review of the impacts and management of introduced deer (family Cervidae) in Australia. *Wildlife Research* **43**, 515–532. doi:10.1071/WR16148

DeNicola AJ, VerCauteren KC, Curtis PD, Hyngstrom SE (2000) 'Managing white-tailed deer in suburban environments.' (Cornell Cooperative Extension: Ithaca, NY, USA)

Denwood MJ (2016) runjags: an R package providing interface utilities, model templates, parallel computing methods and additional distributions for MCMC models in JAGS. *Journal of Statistical Software* **71**, 1–25. doi:10.18637/jss.v071.i09

Doerr ML, McAninch JB, Wiggers EP (2001) Comparison of 4 methods to reduce white-tailed deer abundance in an urban community. *Wildlife Society Bulletin* **29**, 1105–1113.

Finch N, Murray P, Hoy J, Baxter G (2014) Expenditure and motivation of Australian recreational hunters. *Wildlife Research* **41**, 76–83. doi:10.1071/WR13171.

Focardi S, De Marinis AM, Rizzotto M, Pucci A (2001) Comparative evaluation of thermal infrared imaging and spotlighting to survey wildlife. *Wildlife Society Bulletin* **29**, 133–139.

Forsyth DM, Ramsey DSL, Veltman CJ, Allen RB, Allen WJ, Barker RJ, Jacobson CL, Nicol SJ, Richardson SJ, Todd CR (2013) When deer must die: large uncertainty surrounds changes in deer abundance achieved by helicopter- and ground-based hunting in New Zealand forests. *Wildlife Research* **40**, 447–458. doi:10.1071/WR13016

Forsyth DM, Caley P, Davis NE, Latham ADM, Woolnough AP, Woodford LP, Stamation KA, Moloney PD, Pascoe C (2018) Functional responses of an apex predator and a mesopredator to an invading ungulate: dingoes, red foxes and sambar deer in south-east Australia. *Austral Ecology* **43**, 375–384. doi:10.1111/aec.12575

Fraser KW, Sweetapple PJ (1992) Hunters and hunting patterns in part of the Kaimanawa recreational hunting area. *New Zealand Journal of Zoology* **19**, 91–98. doi:10.1080/03014223.1992.10422313

Frost HC, Storm GL, Batcheller MJ, Lovallo MJ (1997) Whitetailed deer management at Gettysburg National Military Park and Eisenhower National Historic Site. *Wildlife Society Bulletin* **25**, 462–469.

Game Services Tasmania (2022) Tasmanian Wild Fallow Deer Management Plan 2022-27. Department of Natural Resources and Environment Tasmania, Hobart, Tasmania, Australia. Available at https://nre.tas.gov.au/agriculture/game-services-tasmania/wild-fallow-deer-management-plan [Verified 31 October 2022]

Gelman A, Rubin DB (1992) Inference from iterative simulation using multiple sequences. *Statistical Science* **7**, 457–511. doi:10.1214/ss/1177011136

Gidlow B, Cushman G, Espiner S (2009) Recreational hunters, fishers and divers in north Canterbury: outdoor enthusiasms in social contexts. Land environment and people research report no. 8. Lincoln University, Canterbury, New Zealand. Available at https://researcharchive.lincoln.ac.nz/handle/10182/870 [Verified 10 December 2021]

Godwin C, Schaefer JA, Patterson BR, Pond BA (2013) Contribution of dogs to white-tailed deer hunting success. *The Journal of Wildlife Management* **77**, 290–296. doi:10.1002/jwmg.474

Grilliot AL, Armstrong JB (2005) A comparison of deer hunters with disabilities and nondisabled hunters in Alabama: motivations and satisfactions in deer hunting. *Wildlife Society Bulletin* **33**, 243–250. doi:10.2193/0091-7648(2005)33[243:ACODHW]2.0.CO;2

Gürtler RE, Rodríguez-Planes LI, Gil G, Izquierdo VM, Cavicchia M, Maranta A (2018) Differential long-term impacts of a management control program of axis deer and wild boar in a protected area of north-eastern Argentina. *Biological Invasions* **20**, 1431–1447. doi:10.1007/s10530-017-1635-6

Hampton JO, MacKenzie DI, Forsyth DM (2022) Animal welfare outcomes of professional vehicle-based shooting of peri-urban rusa deer in Australia. *Wildlife Research*. doi:10.1071/WR21131

Harrison M (2010) 'Sambar the magnificent deer.' (The Australian Deer Research Foundation: Melbourne, Vic., Australia)

Haskell SP (2011) Validity of hunter surveys for daily effort and deer sightings in Vermont. *Wildlife Society Bulletin* **35**, 438–444. doi:10.1002/wsb.86

Herrero J, Torres RT, Prada C, García-Serrano A, Giménez-Anaya A, Fernández O (2013) Sustainable monitoring of roe deer in public hunting areas in the Spanish Pyrenees. *Forest Systems* **22**, 456–462. doi:10.5424/fs/2013223-02820

Hodnett EL (2006) Three-man Thermal Team (TTT): an advanced technique for control of overabundant or nuisance wildlife. Available at https://escholarship.org/uc/item/0b99f5s1 [Verified 10 December 2021]

Horne JS, Garton EO, Krone SM, Lewis JS (2007) Analyzing animal movements using Brownian bridges. *Ecology* **88**, 2354–2363. doi:10.1890/06-0957.1

Hubbard RD, Nielsen CK (2011) Cost–benefit analysis of managed shotgun hunts for suburban white-tailed deer. *Human–Wildlife Interactions* **5**, 13–22.

Hygnstrom SE, Garabrandt GW, Vercauteren KC (2011) Fifteen years of urban deer management: the fontenelle forest experience. *Wildlife Society Bulletin* **35**, 126–136. doi:10.1002/wsb.56

Iacona GD, Sutherland WJ, Mappin B, Adams VM, Armsworth PR, Coleshaw T, Cook C, Craigie I, Dicks LV, Fitzsimons JA, McGowan J, Plumptre AJ, Polak T, Pullin AS, Ringma J, Rushworth I, Santangeli A, Stewart A, Tulloch A, Walsh JC, Possingham HP (2018) Standardized reporting of the costs of management interventions for biodiversity conservation. *Conservation Biology* **32**, 979–988. doi:10.1111/cobi.13195

Jarnemo A (2008) Seasonal migration of male red deer (*Cervus elaphus*) in southern Sweden and consequences for management. *European Journal of Wildlife Research* **54**, 327–333. doi:10.1007/s10344-007-0154-7

Kilpatrick HJ, Labonte AM, Barclay JS (2007) Acceptance of deer management strategies by suburban homeowners and bowhunters. *Journal of Wildlife Management* **71**, 2095–2101. doi:10.2193/2007-058

Lebel F, Dussault C, Massé A, Côté SD (2012) Influence of habitat features and hunter behavior on white-tailed deer harvest. *The Journal of Wildlife Management* **76**, 1431–1440. doi:10.1002/jwmg.377

Leslie DM Jr (2011) *Rusa unicolor* (Artiodactyla: Cervidae). *Mammalian Species* **43**, 1–30. doi:10.1644/871.1

Little AR, Demarais S, Gee KL, Webb SL, Riffell SK, Gaskamp JA, Belant JL (2014) Does human predation risk affect harvest susceptibility of white-tailed deer during hunting season? *Wildlife Society Bulletin* **38**, 797–805. doi:10.1002/wsb.449

Liu F, Kong Y (2015) Zoib: an R package for Bayesian inference for beta regression and zero/one inflated beta regression. *The R Journal* **7**, 34–51. doi:10.32614/RJ-2015-019

Logan TW, Ashton-Butt A, Ward AI (2019) Improving daytime detection of deer for surveillance and management. *European Journal of Wildlife Research* **65**, 83. doi:10.1007/s10344-019-1318-y

MacCarthy M, O'Neill M, Cripps H (2011) 'An investigation into the use of sound moderators on firearms for game and feral management in New South Wales.' (Game Council for NSW: NSW, Australia) Available at https://ro.ecu.edu.au/ecuworks2011/858/ [Verified 10 December 2021]

Martin J-L, Chamaillé-Jammes S, Waller DM (2020) Deer, wolves, and people: costs, benefits and challenges of living together. *Biological Reviews* **95**, 782–801. doi:10.1111/brv.12587

Martínez-Jauregui M, Delibes-Mateos M, Arroyo B, Soliño M (2020) Addressing social attitudes toward lethal control of wildlife in national parks. *Conservation Biology* **34**, 868–878. doi:10.1111/cobi.13468

Masters P, Markopoulos N, Florance B, Southgate R (2018) The eradication of fallow deer (*Dama dama*) and feral goats (*Capra hircus*) from Kangaroo Island, South Australia. *Australasian Journal of Environmental Management* **25**, 86–98. doi:10.1080/14486563.2017.1417166

Moloney PD, Flesch JS (2021) Estimates of the 2020 deer harvest in Victoria: results from surveys of Victorian game licence holders in 2020. Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Melbourne, Vic., Australia. Available at https://www.gma.vic.gov.au/_data/assets/pdf_file/0020/803207/Victorian-deer-harvest-Estimates-2020.pdf [Verified 10 December 2021]

Moriarty A (2004) The liberation, distribution, abundance and management of wild deer in Australia. *Wildlife Research* **31**, 291–299. doi:10.1071/WR02100

Murphy WJ, Flamme GA, Campbell AR, Zechmann EL, Tasko SM, Lankford JE, Meinke DK, Finan DS, Stewart M (2018) The reduction of gunshot noise and auditory risk through the use of firearm suppressors and low-velocity ammunition. *International Journal of Audiology* **57**, S28–S41. doi:10.1080/14992027.2017.1407459

New South Wales Natural Resources Commission (2017) Supplementary pest control trial: final evaluation. NSW Natural Resources Commission, Sydney. Available at https://www.nrc.nsw.gov.au/SPC%20-%20Final%20report%20-%20February%202017.pdf?downloadable=1 [Verified 10 December 2021]

Novak JM, Scribner KT, Dupont WD, Smith MH (1991) Catch-effort estimation of white-tailed deer population size. *The Journal of Wildlife Management* **55**, 31–38. doi:10.2307/3809238

Nugent G, Choquenot D (2004) Comparing cost-effectiveness of commercial harvesting, state-funded culling, and recreational deer hunting in New Zealand. *Wildlife Society Bulletin* **32**, 481–492. doi:10.2193/0091-7648(2004)32[481:CCOCHS]2.0.CO;2

Ospina R, Ferrari SLP (2012) A general class of zero-or-one inflated beta regression models. *Computational Statistics & Data Analysis* **56**, 1609–1623. doi:10.1016/j.csda.2011.10.005

Papworth SK, Bunnefeld N, Slocombe K, Milner-Gulland EJ (2012) Movement ecology of human resource users: using net squared displacement, biased random bridges and resource utilization functions to quantify hunter and gatherer behaviour. *Methods in Ecology and Evolution* **3**, 584–594. doi:10.1111/j.2041-210X.2012.00189.x

Parliament of Victoria Environment, Natural Resources and Regional Development Committee (2017) Inquiry into the control of invasive animals on Crown land. Victorian Government Printer. Available at https://www.parliament.vic.gov.au/435-enrrdc/inquiry-into-the-control-of-invasive-animals-on-crown-land [Verified 10 December 2021]

Pauli BP, Sun ER, Tinkle ZK, Forbey JS, Demps KE, Heath JA (2019) Human habitat selection: using tools from wildlife ecology to predict recreation in natural landscapes. *Natural Areas Journal* **39**, 142–149. doi:10.3375/043.039.0202

Pellerin M, Saïd S, Gaillard J-M (2008) Roe deer *Capreolus capreolus* home-range sizes estimated from VHF and GPS data. *Wildlife Biology* **14**, 101–110. doi:10.2981/0909-6396(2008)14[101:RDCCHS]2.0.CO;2

Plummer M, Best N, Cowles K, Vines K (2006) Coda: convergence diagnosis and output analysis for MCMC. *R News* **6**, 7–11.

Porter WF, Underwood HB, Woodard JL (2004) Movement behavior, dispersal, and the potential for localized management of deer in a suburban environment. *Journal of Wildlife Management* **68**, 247–256. doi:10.2193/0022-541X(2004)068[0247:MBDATP]2.0.CO;2

Putman RJ (2012) Effects of heavy localised culling on population distribution of red deer at a landscape scale: an analytical modelling approach. *European Journal of Wildlife Research* **58**, 781–796. doi:10.1007/s10344-012-0624-4

Reis AC, Higham JES (2009) Recreation conflict and sport hunting: moving beyond goal interference towards social sustainability. *Journal of Sport & Tourism* **14**, 83–107. doi:10.1080/14775080902965025

Ridout MS, Linkie M (2009) Estimating overlap of daily activity patterns from camera trap data. *Journal of Agricultural, Biological, and Environmental Statistics* **14**, 322–337. doi:10.1198/jabes.2009.08038

Rivrud IM, Meisingset EL, Loe LE, Mysterud A (2014) Interaction effects between weather and space use on harvesting effort and patterns in red deer. *Ecology and Evolution* **4**, 4786–4797. doi:10.1002/ece3.1318

Rowland MM, Nielson RM, Wisdom MJ, Johnson BK, Findholt S, Clark D, Didonato GT, Hafer JM, Naylor BJ (2021) Influence of landscape characteristics on hunter space use and success. *The Journal of Wildlife Management* **85**, 1394–1409. doi:10.1002/jwmg.22107

Spake R, Bellamy C, Gill R, Watts K, Wilson T, Ditchburn B, Eigenbrod F (2020) Forest damage by deer depends on cross-scale interactions between climate, deer density and landscape structure. *Journal of Applied Ecology* **57**, 1376–1390. doi:10.1111/1365-2664.13622

Van Deelen T, Etter D (2003) Effort and the functional response of deer hunters. *Human Dimensions of Wildlife* **8**, 97–108. doi:10.1080/10871200304306

Warren RJ (2011) Deer overabundance in the USA: recent advances in population control. *Animal Production Science* **51**, 259–266. doi:10.1071/AN10214

Watter K, Thomas E, White N, Finch N, Murray PJ (2020) Reproductive seasonality and rate of increase of wild sambar deer (*Rusa unicolor*) in a new environment, Victoria, Australia. *Animal Reproduction Science* **223**, 106630. doi:10.1016/j.anireprosci.2020.106630

Williams W, McSorley A, Hunt R, Eccles G (2018) Minimising noise disturbance during ground shooting of pest animals through the use of a muzzle blast suppressor/silencer. *Ecological Management & Restoration* **19**, 172–175. doi:10.1111/emr.12311

Woods GR, Guynn DC, Hammitt WE, Patterson ME (1996) Determinants of participant satisfaction with quality deer management. *Wildlife Society Bulletin* **24**, 318–324.

Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest. David Forsyth was a guest Associate Editor for this special issue. Despite this relationship, he did not at any stage have editor-level access to this manuscript while in peer review, as is the standard practice when handling manuscripts submitted by an editor to this journal. *Wildlife Research* encourages its editors to publish in the journal and they are kept totally separate from the decision-making process for their manuscripts. The authors have no other conflicts of interest to declare.

Declaration of funding. The Victorian Alpine Peatland Protection Program is an initiative jointly funded through Parks Victoria, the West Gippsland Catchment Management Authority, the Australian Government's National Landcare Programme (via North East, West Gippsland and East Gippsland Catchment Management Authorities) and the Victorian Government through the Alps Intensive Management Program. The analysis of these data, and the writing of the manuscript, were funded by the Centre for Invasive Species Solutions project 'Cost-effective management of wild deer' (PO1-L-001).

Acknowledgements. We thank all the Parks Victoria staff, with a special mention for Mick Keenan, Anthony Thomas and Conor Wilson, that were involved in the planning and organisation of the ground-shooting operations and data collation. We thank all the volunteer and contract deer shooters that participated in the program. We acknowledge the constructive comments from two anonymous reviewers that greatly improved the manuscript.

Author affiliations

[A]Vertebrate Pest Research Unit, NSW Department of Primary Industries, 1447 Forest Road, Orange, NSW 2800, Australia.

[B]Parks Victoria, Mt Beauty, Vic. 3699, Australia.

[C]School of BioSciences, The University of Melbourne, Melbourne, Vic. 3010, Australia.

[D]Parks Victoria, 535 Bourke Street, Melbourne, Vic. 3000, Australia.

[E]Parks Victoria, Bright, Vic. 3741, Australia.