Efficacy of aerial control of invasive animals

Results from the Bushfire Biodiversity Response and Recovery program

D.S.L. Ramsey

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Acknowledgment

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it. We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

We are committed to genuinely partner, and meaningfully engage, with Victoria's Traditional Owners and Aboriginal communities to support the protection of Country, the maintenance of spiritual and cultural practices and their broader aspirations in the 21st century and beyond.

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Context:

The Bushfire Biodiversity Response and Recovery (BBRR) program is a multi-year program that prioritises actions for fire-affected threatened species and habitats. Aerial shooting from a helicopter is a key activity being undertaken as part of the BBRR program, targeting invasive animals (deer, feral goats, feral pigs, feral cattle and foxes) in priority fire-affected and adjacent public land in the North East and East Gippsland regions of Victoria. Threatened species and habitats recovering from fire are vulnerable to impacts from invasive species, and aerial control is being used to alleviate these potential impacts.

Aims:

To undertake an analysis of the operational data collected during the aerial control program to: (1) assess the efficacy of aerial shooting from helicopters for reducing densities of invasive animals; and (2) determine how aerial control operations can best achieve target densities.

Methods:

Operational data from the aerial shooting program (locations of all shot (and killed) animals and aerial search effort by the helicopter) undertaken between February 2020 and May 2022 were analysed using a Bayesian generalised catch–effort model, which allowed for population changes between five periods of intensive control. The model was fitted to the sequence of removals and search effort within each period to estimate initial abundance, the detection rate by the helicopter and the proportion of the population removed by control activities for three invasive species – Sambar deer (*Cervus unicolor*), Fallow deer (*Dama dama*) and feral pigs (*Sus scrofa*) – across 10 operational areas (OAs). Estimates of the removal rate of the most abundant species detected, Sambar deer, were then used to recommend the aerial search intensities required to reduce population densities by various proportional amounts.

Results:

A total of 361 individual helicopter missions were undertaken within the 10 OAs between February 2020 and May 2022 with 6,264 animals shot over this period. The vast majority (92%) were Sambar deer, mostly from the Snowy River National Park (NP) (58% of all Sambar deer). The next most numerous animals shot were feral pigs (3.7%) and Fallow deer (3.5%).

Following fitting of the catch–effort model, the estimates of the detection (and removal) rate of individual Sambar deer averaged 0.11 (95% CI: 0.09–0.12) per km of search effort, per km^2 of habitat. However, the detection probability varied among OAs, and was highest in the Alpine NP–Bogong High Plains at 0.15 and lowest at Errinundra NP at 0.02 per km of search effort, per km^2 of habitat. Initial densities of Sambar deer ranged from 2.8 deer/km^2 in the Snowy River NP to less than 0.08 deer/km^2 in the Coopracambra NP.

Aerial shooting of Sambar deer over the five periods of intensive control resulted in highest population reductions in the Mt Mitta Mitta Regional Park (RP) and Snowy River NP, at 66% and 68%, respectively. Population reductions of 62% and 53% were also obtained at the Mt Buffalo NP and Alpine NP–Bogong High Plains OAs, respectively. Reductions at Burrowa–Pine Mountain NP, Wabba Wilderness Park (WP) and Coopracambra NP were uncertain, and populations exhibited increases at the remaining OAs. There were two main reasons for the variation in efficacy of the aerial shooting program among the different OAs. The main reason was that the level of population reduction achieved was strongly related to the amount of aerial search effort. The second reason was that population increases due to natural recruitment between periods of intensive aerial shooting, primarily due to deer movement, were responsible for eroding reductions due to aerial shooting. The rate of natural recruitment of Sambar deer between control periods varied with average elevation of the OA and season (winter or summer). Populations of Sambar deer in OAs at the highest elevations (e.g. above 1000 m – Alpine NP) decreased over the winter period and increased over the summer period. Conversely, populations in OAs at the lowest elevations (e.g. < 100 m – Croajingolong NP) exhibited the highest increases during the winter period and the lowest during the summer period.

The results of aerial shooting operations on Fallow deer were analysed for three OAs (Burrowa–Pine Mountain NP, Snowy River NP and Alpine NP–Eastern Alps). Initial densities of Fallow deer in these OAs were less than 0.4 deer/km^2. However, aerial shooting only resulted in the overall reduction of Fallow deer in one OA (54% – Burrowa–Pine Mountain NP), with Fallow deer density increasing in the other two OAs over the duration of the program due to natural recruitment. Despite this, aerial shooting within some periods in all three of these OAs resulted in reductions in Fallow deer densities similar to that achieved for Sambar deer, indicating that with sufficient search effort aerial shooting can effectively reduce Fallow deer densities.

The results of aerial shooting operations for feral pigs were analysed for two OAs, the Alpine NP–Eastern Alps and Snowy River NP. There was no evidence that aerial shooting resulted in overall population reductions for this species in either of these two areas, with natural recruitment offsetting any reductions due to aerial shooting. Estimates of population densities of feral pigs before the commencement of aerial shooting ranged from 0.08–0.16 pigs/km^2, but increased to around 0.26–0.29 pigs/km^2 by the final control period.

Conclusions and implications:

Analyses of the aerial shooting data across the 10 OA's between February 2020 and May 2022 indicated that sustained reductions in Sambar deer densities (mean 63%; range 53–68%) have occurred at four OA's – Mt Mitta Mitta RP, Snowy River NP, Alpine NP–Bogong High Plains and Mt Buffalo NP. Initial Sambar deer densities in these four OAs ranged from 0.6–2.8 deer/km^2 (mean 1.6 deer/km^2), with residual densities at the conclusion of the aerial shooting program ranging from 0.21–0.91 deer/km^2 (mean 0.59 deer/km^2). In the remaining OAs, population densities of Sambar deer have stayed static (two OAs) or have increased over the five control periods (four OAs) due to either low aerial shooting effort and/or natural recruitment (deer movement) between control periods.

Aerial control efficiencies differed between locations, being relatively high in some areas such as the Alpine NP–Bogong High Plains, Mt Buffalo NP, Burrowa–Pine Mt NP and the Snowy River NP, and relatively low in other areas such as the Alpine NP–Eastern Alps, Errinundra NP and Coopracambra NP. In general, reductions in Sambar deer densities of 50% could be achieved over a single period of intensive control with 7 km of search effort per km^2 of habitat. For areas with relatively high control efficiencies, this could be reduced to 5 km/km^2 of search effort. In practice, the recommended search effort for a single period would need to be undertaken over several occasions, defined as the number of missions required to undertake at least one complete search of the OA. Hence, five occasions would be equivalent to at least five complete searches of the OA, with each occasion consisting of 1.4 km/km^2 of search effort (i.e. 7 km/km^2 total). If four occasions were undertaken, then each occasion would consist of 1.75 km/km^2 of search effort. Due to the effects of deer recruitment (i.e. recolonisation) eroding reductions achieved by aerial shooting, the length of time required to complete a period of intensive control should be no more than 3 months. If high reductions (e.g. > 75%) in deer densities are required, then several such periods of intensive control would need to be undertaken with the interval between periods (i.e. where no aerial shooting occurs) also limited to no more than 3 months. Care also needs to be undertaken to ensure the size of the operational area searched by the helicopter team does not increase substantially over time.

To maintain reductions in deer densities over time, aerial shooting should be concentrated at certain times of the year to counteract the effect of natural recruitment to the population, especially due to seasonal movements of deer. Hence, in high altitude areas, aerial shooting should be undertaken mainly during the summer and autumn when the population is highest following the likely recruitment of deer as they move back into alpine regions as the temperature warms. Conversely, in low altitude areas, aerial shooting should be mainly undertaken during winter and spring to counteract the movement of deer to lower altitudes over winter due to increasing snow cover at high altitudes. Areas at intermediate altitudes can be subject to aerial control in either or both periods.

No recommendations have been provided on the aerial control effort required to achieve target densities for other invasive species (e.g. Fallow Deer, feral pigs and goats) due to the limited amount of data, which precluded a comprehensive analysis. To gain a better understanding of the effectiveness of aerial shooting on other invasive species to achieve target densities, aerial operations may need to specifically target these species to obtain sufficient data for analysis. Until then, these species can continue to be targeted opportunistically while conducting operations on Sambar deer.

1 Introduction

The 2019–20 bushfires in Victoria burnt approximately 1.5 million hectares across the state and impacted at least 50% of the habitat for 244 species of plants and animals, including 215 rare or threatened species (DELWP 2020). The Bushfire Biodiversity Response and Recovery (BBRR) program is a multi-year program funded by the Victorian and Commonwealth governments that prioritises actions for fire-affected threatened species and habitats. Aerial shooting is a key activity of Theme 4 of the BBRR program, targeting invasive animals (deer, feral goats, feral pigs, feral cattle and red foxes) in priority fire-affected and adjacent public land in the North East and East Gippsland regions of Victoria (DELWP 2021). Threatened species and habitats recovering from fire are vulnerable to impacts from invasive species, and aerial control is being used to alleviate these potential impacts. Aerial shooting operations delivered as part of the BBRR program were split into three phases:

- Emergency Response Phase: February 2020 – May 2020 (coordinated by DELWP in partnership with Parks Victoria)
- Phase 1: June 2020 – May 2021 (led by Parks Victoria)
- Phase 2: September 2021 – May 2022 (led by Parks Victoria)

These phases have been developed to implement a coordinated, strategic, and targeted aerial shooting program to reduce the impact of invasive animals on the survival and recovery of threatened flora species, habitat, and vegetation communities.

Key data captured as part of the aerial shooting operations include helicopter flight path (search) data, mission time data, location data for shot (and killed) animals, and records of animals seen but not shot. Analysis of the aerial shooting spatial data is required to assess the effectiveness of the aerial shooting operations as part of the BBRR program to help inform and guide future aerial shooting programs. Key outcomes from these analyses will include recommendations on the optimal frequency and intensity of control effort required to achieve a set management objective (i.e. target densities) for different invasive animal species. This will be achieved by using the operational data collected during each control mission to estimate pre- and post-control densities of invasive animals, their recolonisation rates between periods of intensive control and then using these results to recommend optimal control effort to achieve target densities.

The shooting of individual animals from a defined area can be viewed as a removal (or depletion) sample, which is a well-known sampling method used to estimate the size of a demographically closed population. By demographically closed, we mean that the sampled population is closed to additions or losses (i.e. no births, deaths, immigration or emigration) except those due to the removal method. The method has a long history in the estimation of animal abundance (Zippin 1958) and is regularly used to estimate the size of populations exploited by fishing or hunting (Dorazio *et al.* 2005). Recent theoretical work has also extended these types of removal models to populations where demographic closure should not be assumed (Dail and Madsen 2011; Link et al. 2018). Here, populations are assumed to be subject to additions or losses between periods of intensive control, but not during control periods. Hence, these models include parameters for estimating population growth due to natural recruitment or recolonisation between these intensive control periods (Hostetler and Chandler 2015).

This study analysed the aerial control operational data collected during the emergency response, Phase 1 and Phase 2 periods conducted between February 2020 and May 2022 from fire-affected areas in the North East and East Gippsland regions. The analysis estimated pre- and post-control densities of introduced animals within distinct geographical areas subject to aerial control operations to assess the effectiveness of the aerial shooting program at reducing invasive animal densities. By using models allowing for additions and losses to the population between intensive periods of control, the study provided an understanding of the effect of recruitment and/or recolonisation of individuals into an area following control. The fitted models were subsequently used to inform management decisions by recommending optimal timing, frequency and intensity of control effort to best achieve target densities.

2 Methods

Aerial control of invasive animals (deer, feral pigs, feral goats, feral cattle and foxes) in the North East and East Gippsland regions of Victoria occurred mainly across seven national parks (NP) (Alpine; Mt Buffalo; Burrowa–Pine Mountain; Croajingolong; Coopracambra; Errinundra; Snowy River), as well as Mt Mitta Mitta Regional Park (RP) and the Wabba Wilderness Park (WP) (Figure 1). Due to the size of the Alpine National Park, aerial control was focused within two separate areas, the Bogong High Plains and the Eastern Alps. Hence, 10 operational areas (OA) were the subject of aerial control (Figure 1). Operational data from the aerial shooting program consisted of spatial layers representing the routes flown by the helicopter while actively searching for animals ('search effort') (Figure 1), as well as the locations of all shot animals ('removals') within each OA (Figure 2). Records were also collected for animals observed where a shot was not taken. However, these were not used in the present analysis as animals observed may have been shot at a later occasion.

Aerial control conducted between February 2020 and May 2022 was grouped into five distinct periods, representing periods when intensive control occurred (Table 1). This grouping of the aerial control data allowed the analysis to consider changes to populations of invasive animals to be attributed to one of two processes. Within a period, a population could change only due to the removals from aerial shooting, while between periods, the population could change due to natural additions or losses (i.e. births, natural deaths, immigration or emigration). Hence, the data grouping facilitated estimates of the population dynamics of each species while accounting for the removal of individuals from aerial shooting. More details on these analyses are provided below.

For each notional OA, the total search area was defined by discretising the continuous search route by overlaying a 1 km grid on to the helicopter flight paths, aggregated over all periods. The total area of each OA (= total search area) used in subsequent analyses (e.g. density estimates) was then defined as the area of the combined grids cells (Figure 1a,b).

Table 1. Summary of the total amount of helicopter search effort (search km) and the number of helicopter missions (in brackets) undertaken within each operational area during the five periods of aerial control.

NP = national park, RP = regional park, WP = wilderness park.

Operational area	Feb–May 2020	Jun–Oct 2020	Mar–May 2021	Sep–Dec 2021	Mar–May 2022	Total effort
Alpine NP–Bogong	373 (5)	1734 (11)	1311 (14)	1393 (12)	2571 (19)	7382 (61)
Alpine NP–Eastern	699 (6)	0 (0)	183 (4)	602 (6)	379 (5)	1847 (21)
Burrowa NP	537 (4)	674 (6)	112 (1)	819 (13)	157 (2)	2300 (26)
Coopracambra NP	57 (1)	195 (2)	129 (1)	147 (1)	88 (1)	608 (6)
Croajingolong NP	893 (7)	591 (5)	666 (5)	167 (1)	499 (6)	2815 (24)
Errinundra NP	159 (1)	435 (4)	437 (4)	244 (2)	191 (2)	1434 (13)
Mt Buffalo NP	281 (4)	804 (6)	2020 (7)	696 (7)	1643 (10)	5443 (34)
Mt Mitta Mitta RP	223 (4)	211 (5)	92 (2)	186 (4)	82 (1)	794 (16)
Snowy River NP	3811 (35)	6632 (44)	3374 (23)	3550 (29)	1424 (13)	18791 (144)
Wabba WP	520 (4)	309 (2)	0 (0)	1250 (9)	163 (1)	2242 (16)
Totals	**7553 (71)**	**11585 (85)**	**8324 (61)**	**9054 (84)**	**7197 (60)**	**43656 (361)**

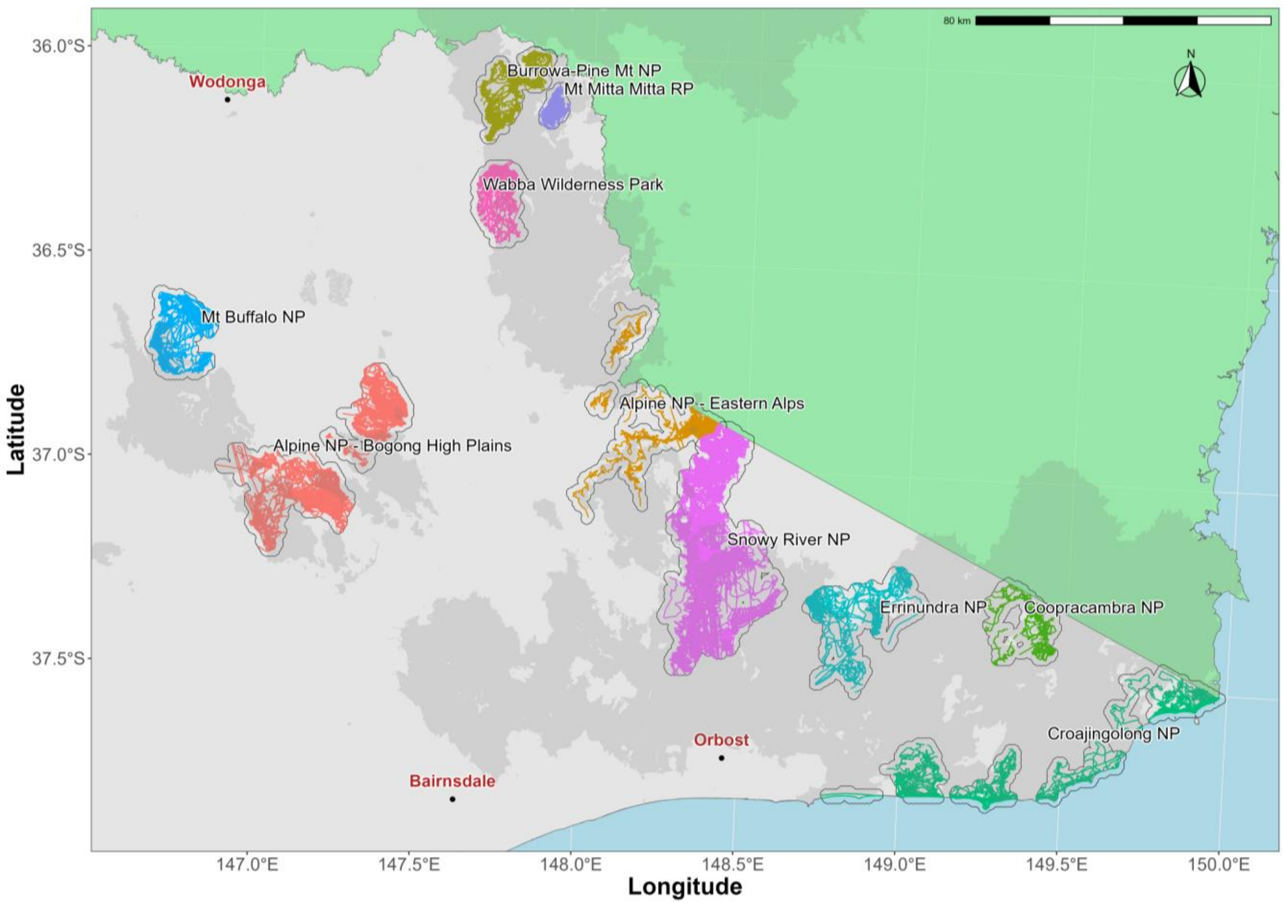

Figure 1. Locations of operational areas (OA) where aerial control of invasive animals occurred between February 2020 and May 2022.

Coloured lines indicate flight paths flown by the helicopter. Grey polygons surrounding flight paths for each OA represent the total search area. Dark shaded area shows the extent of the 2019–20 bushfires.

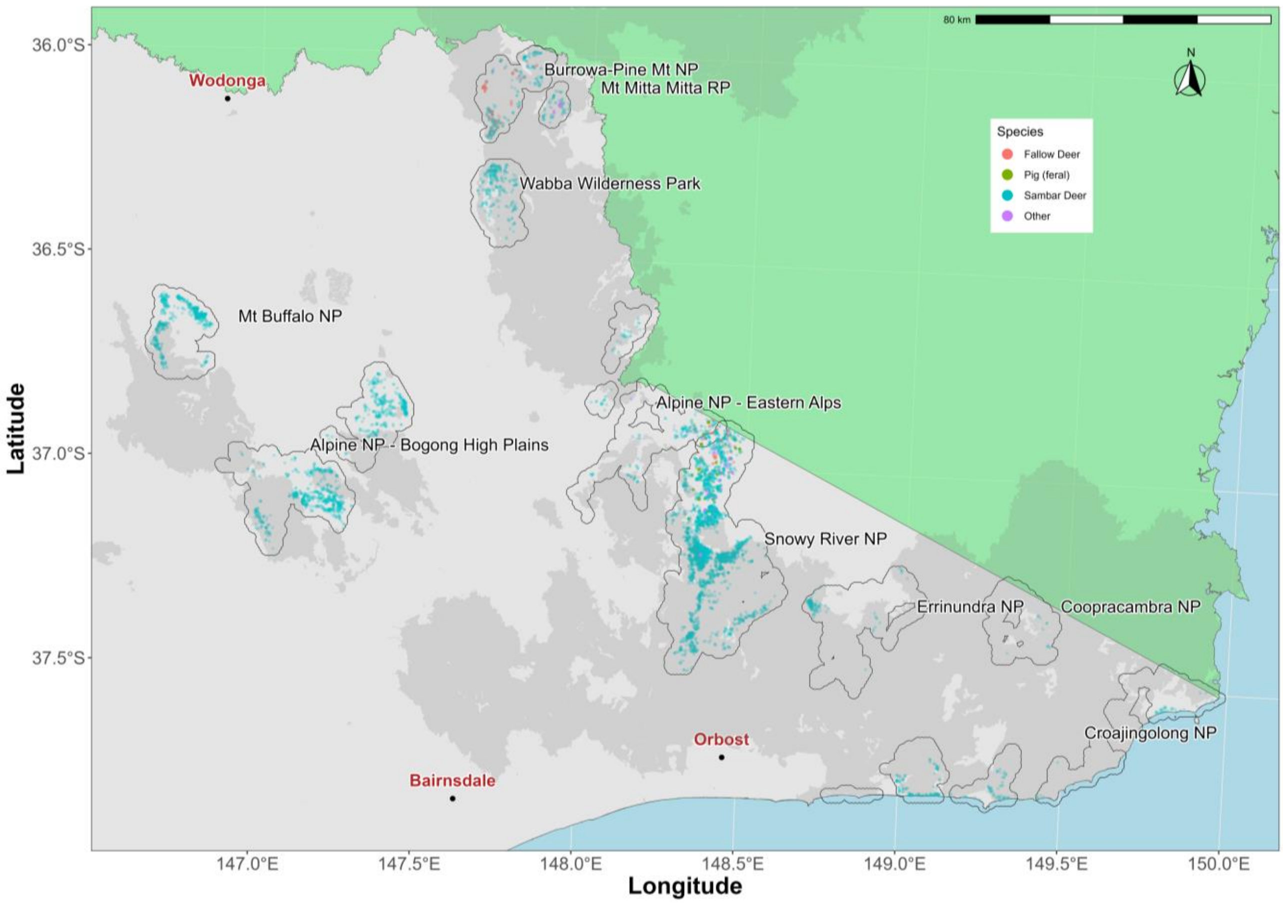

Figure 2. Locations of shot individuals for the main invasive species detected within each operational area (OA) between February 2020 and May 2022.

Grey polygons surrounding locations for each OA represent the total search area. Dark shaded area shows the extent of the 2019–20 bushfires.

2.1 Aerial operations

Aerial shooting operations were conducted in accordance with all relevant Victorian interagency aviation operating procedures, including SO 4.06 Aerial shooting operations (Victorian Government 2020) and the Parks Victoria Aerial Shooting Guideline (Parks Victoria 2020). Aerial shooting was conducted from a helicopter (AS350 B2 Squirrel) with the pilot in the front right seat, one shooter in the rear right seat and one spotter in the front left seat, whose primary role was acting as an air safety observer, but who also relayed sightings of deer to the shooter and recorded data. Aerial shooting procedures placed an emphasis on the humane destruction of animals in accordance with Victorian animal welfare legislation (Victorian Government 1986). The shooter used a semi-automatic centre fire rifle (.308 calibre), firing protected point ammunition ranging from 130–180 grains, suitable for use on large herbivores. Only shots to the thorax (heart-lung) or head were taken under favourable conditions. This was followed up with further heart-lung shots once the animal had collapsed to ensure a rapid death. The pilot was required to verbally confirm the death of the animal, with assistance of the observer and shooter, prior to continuing the search. Independent on-ground veterinarian audits were conducted over the course of the operation to ensure procedural compliance (e.g. verify shot placement and the use of multiple shots per animal). The destruction of wild deer as part of the operations were authorised under an Authority to Control Wildlife permit issued by the Victorian Office of the Conservation Regulator in consultation with the Game Management Authority.

2.2 Abundance estimation

The data on individuals removed from aerial shooting and the search effort expended per unit time ('catch and effort data') can be used to estimate the size of the initial population within each OA as well as the rate of detection (and removal) per unit of search effort (Gould and Pollock 1997; Chao and Chang 1999). To facilitate analysis, data from individual helicopter missions within each of the five periods of control (Table 1) were aggregated into five removal occasions. Hence, we adopted a robust design for the data with five primary periods, and each primary period consisting of five occasions (secondary periods). As the length of each period was roughly 4 months, each occasion corresponded to roughly 24 days and could consist of several missions. This was undertaken to ensure that search coverage was consistent between occasions. Since missions were staggered between OAs, some areas had no mission data for one or more occasions and some OAs had no mission data for a particular period. These missing data windows were treated as missing completely at random and accounted for in the analysis.

Analyses of the sequence of removals and search effort for each occasion within each period were used to estimate the initial abundance $\hat{N}$ (i.e. before the start of removal activities) for each OA and the detection rate per unit of search effort. Using the estimate of initial abundance at the start of the period, the residual abundance in each area following the final removal occasion ($\hat{R}$) could also be derived. As there were five distinct periods of control spanning 27 months, it would be unreasonable to assume that the population in each OA was demographically closed (i.e. there were no additions or losses to the population other than removals) over this entire period. For example, Sambar deer (*Cervus unicolor*) births occur all year round with a peak between April and July (Watter et al. 2020). Hence, the aerial shooting data encompasses at least two breeding seasons. Movements of deer in response to increasing snow depth at higher altitudes are also likely to have occurred during this period (Comte et al*.* 2022). To account for these potential demographic changes over the entire control period, it was assumed that populations in each OA were open to demographic changes between each of the five control periods and closed to demographic changes within each period.

To account for both removals due to aerial shooting and natural demographic changes to the population, a generalised N-mixture model was employed (Dail and Madsen 2011; Hostetler and Chandler 2015). The generalised N-mixture model explicitly models change in the population between sampling periods, allowing the closure assumption underpinning the standard N-mixture model to be relaxed. By modelling population change as a function of parameters governing 'additions' or 'losses' between sampling periods, as well as imperfect detection, unbiased estimates of population abundance are possible using counts from 'open' populations (Dail and Madsen 2011; Hostetler and Chandler 2015). The structure of the generalised N-mixture model used to analyse the removal and search effort data for each OA and period is described further below.

2.3 Generalised N-mixture model

The generalised N-mixture model used here assumed that removals followed a multinomial observation process over occasions within each period (Dorazio et al. 2005; Haines 2019). Separately for each of the five periods, the number of individuals that were removed from each OA were divided into five occasions, and individuals were assigned to an occasion based on the date it was shot.

The counts of individuals shot within a particular OA i, $(i = 1, \ldots, I)$ during a particular period t, $(t = 1, \ldots, 5)$ and occasion j, $(j = 1, \ldots, J)$ (y_{ijt}) therefore represented a multinomial sample $\mathbf{y} \sim \mathrm{Multinomial}(n, \boldsymbol{\pi})$ with cell probabilities for each occasion j (π_j) equal to:

$$\pi_j = \prod_{k=1}^{j-1} 1 - p_k \;\; p_j$$

where p_j was the probability of detection (and removal) during occasion j and n was the total number of individuals removed from the operational area, during that period.

It follows that the total number of individuals removed during the period was dependent on the total population size at the start of the period (i.e. $j = 0$) and the probability of removal over all occasions.

The latter was calculated as:

$$\pi = \sum_{j=1}^{J} \pi_j$$

and the complete model for the total abundance for each OA i and period t (N_{it}), allowing for demographic changes between periods, was given by:

$$y_{ijt} \sim \text{Multinomial}(n_{it}, \pi_{ijt}^{c}) \qquad \text{(Equation 1)}$$

$$n_{it} \sim \text{Binomial } N_{it}, \boldsymbol{\pi}_{it}$$

$$N_{i1} \sim \text{Poisson } \lambda_{i1}$$

$$\log \lambda_{i1} = \beta_{\text{i}} + \zeta_i$$

$$R_{it} = N_{it} - n_{it}$$

$$N_{it} \sim \text{Poisson } R_{it-1} e^{r_{it}}$$

$$\text{cloglog}(p_{ijt}) \sim \alpha_0 + \log(E_{ijt}) + \boldsymbol{\kappa}_i \log j$$

$$\kappa_i \sim N \ \mu_k, \sigma_k$$

$$r_{it} = \eta_1 + \eta_2 A_i + \eta_3 S_t + \eta_4 A_i S_t$$

where the conditional cell probabilities $\pi_{ijt}^{c} = \pi_{ijt}/\dot{\pi}_{it}$. The intercepts β_i represented the average (baseline) initial abundance in each OA i (i.e. before the start of control activities) and R_{it} was the residual abundance at the end of the period, which was given simply by subtracting the number removed during the period from the abundance at the start of the period.

The parameter ζ_i was fitted to the model as an offset representing the (log) search area (km^2) subject to aerial control. The parameter r_{it} represents the per-capita rate of increase in the population in OA i between periods $t-1$ and t, with $r > 0$ representing an increase and $r < 0$ representing a decrease. The r_{it} were modelled as a linear function of the average elevation (meters above sea level – m.a.s.l.) of OA i (A_i) and season (winter/summer) occurring between period $t-1$ and t (S_t), with $\eta_{1,\dots,4}$ being parameters to be estimated.

The detection (and removal) probability p_{ijt} was modelled as a linear function (on the complementary log-log scale) of the amount of helicopter search effort (km) E_{ijt} with α_0 representing the (log) removal rate for one unit of search effort (i.e. hazard rate). We also allowed the detection probability to vary over occasions by adopting a model for the baseline hazard rate (Allison 1982). This was achieved by allowing the detection probability to depend on occasion j according to parameter κ_i, which allowed the detection probability to also vary for each OA i. Values of κ less than zero indicated that the detection probability decreased with increasing occasions, while values > zero indicated a corresponding increase with occasion number. A hierarchical normal prior distribution was used to model κ_i, with mean μ_k and standard deviation σ_k.

To account for the differing sizes of each OA, E_{ijt} was also standardised by dividing by the size of the OA (in km^2). Hence, units of effort were effectively km of search effort per km^2 of total habitat searched. Finally, an estimate of the overall percentage decline in the population achieved over the five periods was given by:

$$D_i = 1 - \frac{R_{i5}}{N_{i1}} \times 100\%$$

which was calculated by taking the ratio of the residual abundance in the last period (Period 5) to the initial abundance in the first period (Period 1) for each OA i. Similar metrics were also calculated separately for each period in each OA (e.g. $1 - R_{i1}/N_{i1}$; $1 - R_{i2}/N_{i2}$ ..., etc.).

The model specified in Equation 1 was fitted to the joint removal data for Sambar deer from all 10 OAs in a Bayesian framework by Markov chain Monte Carlo (MCMC) using Nimble (NIMBLE Development Team 2020). Weakly informative normal or half-normal priors, specified as $N(0, 5)$, were specified for all unknown parameters. For Fallow deer (*Dama dama*) and feral pigs (*Sus scrofa*), which were detected at only three and two OAs, respectively, there was insufficient data to provide an adequate estimate of the removal rate (α_o). Hence, to assist estimation for these species, an informative prior distribution was used for α_0 by assuming the removal rate was normally distributed – with a mean equal to the mean value of the estimate of α_0 for Sambar deer, and standard deviation equal to three times the standard deviation of the Sambar deer estimate. We judged convergence of the posterior distribution of the parameters based on visual inspection of traceplots and estimates of the Brooks–Gelman–Rubin convergence criterion $\hat{R}$ from three independent chains (Brooks and Gelman 1998). Following convergence, the model was updated for 10,000 iterations leaving a total of 30,000 samples for each parameter, which were used for further inference. We assessed model fit by conducting posterior predictive checks (Gelman et al. 1996), which involved comparing the number of removals in each area during each period with the corresponding number predicted by the model.

2.4 Search effort recommendations

The parameter estimates from the fitted model in Equation 1 included an estimate of the removal probability per km of helicopter search effort (parameter α_0). This parameter can be used, in turn, to estimate the amount of search effort that would be required to achieve a certain level of population reduction. Accordingly, posterior estimates of α_0 and κ_i were used in a Monte Carlo simulation approach to examine the intensity of helicopter search effort required to reduce population abundances of Sambar deer by various proportional amounts. Simulated search effort was divided into five removal occasions to replicate operational conditions, where consecutive ‘missions’ are usually conducted in a particular site over several months. However, we limited this approach to occur within a single period, where the population was assumed to be closed to natural additions or losses.

Given an initial abundance within a notional OA i, simulated removal of individuals occurred over each removal occasion j, with the probability of removal calculated as:

$$P_j = 1 - \exp(-\exp\ \alpha_0 + \ \kappa_i \log(j)\ \ E_j) \qquad \text{(Equation 2)}$$

where P_j was the probability of removal during occasion j ($j = 1, \dots, J$), given search effort E_j (km per km^2 of habitat) and parameters α_0 and κ_i were estimated by Equation 1.

The predicted search effort required to achieve various levels of population reduction was compared with that achieved from each OA, in each of the five periods (Table A1 – Appendix), by overlaying the estimated population reductions and associated actual search effort onto the plots of predicted search effort.

2.5 Effects of recruitment

The effect of Sambar deer recruitment (recolonisation) on the effectiveness of aerial deer control was investigated by undertaking the simulation approach described above over several periods. However, unlike control within a single period, the deer population between periods was allowed to increase due to natural recruitment. Estimates of the average per capita rate of increase (r) derived from the model (Equation 1) were divided by the average length of the interval (in months) between periods of control (calculated from the start and end dates of each period from the 10 OAs) to provide an average monthly rate of increase r_m. Aerial deer control was then simulated over five successive periods with increasing intervals between each control period from 1 to 12 months. Hence, following simulated control in a particular period, the Sambar deer population at the start of the next period was estimated as:

$$N_{t+1} = \ R_t\ e^{\,r_m \cdot\, I} \qquad \text{(Equation 3)}$$

Where N_{t+1} was the population size at the start of period $t + 1$, R_t was the residual population at the end of period t (i.e. following control) and I was the length of the interval (in months) between period t and $t + 1$ when no aerial control was undertaken and hence, the population could increase through natural recruitment. Aerial control within a period was simulated using Equation 2 (above) with a similar level of average search effort to that used for the more intensively searched OAs (i.e. 0.8 km/km^2).

3 Results

The total number of invasive animals shot through aerial control operations in each operational area are given in Table 2. Over 93% of the individuals removed were Sambar deer, and most of those were from the Snowy River NP (58%). The next most numerous species removed were feral pigs, which were detected in two OAs (Snowy River NP, Alpine NP–Eastern Alps) followed by Fallow deer, most of which were detected in Burrowa–Pine Mountain NP and the Snowy River NP (Table 2). A total of 361 missions were undertaken over the emergency response, Phase 1 and Phase 2, with approximately 40% of these missions being undertaken in the Snowy River NP (Table 1). The average search effort per mission was 71 km with 80% of missions between 47 and 163 km.

3.1 Sambar deer

Following fitting of the generalised *N*-mixture model (Equation 1), the model predictions of the total number of Sambar deer removed was a good match for the actual number removed (Figure A1 – Appendix), suggesting that the model was a good fit to the data. Estimates of the detection (and removal) rate of individual Sambar deer suggested that the average probability of detecting individuals from the helicopter was 0.11 (95% CI: 0.09, 0.12) per km of search effort, per km^2 of habitat. However, the detection probability varied among OAs, being highest in the Alpine NP–Bogong High Plains at 0.15 per km of search effort per km^2 of habitat and lowest at Errinundra NP at 0.02 per km of search effort, per km^2 of habitat (Figure 3). Apart from removals, the rate of natural recruitment (r) of Sambar deer also varied with the elevation (m.a.s.l.) of each OA as well as season (winter or summer) (Figure 4). Populations of Sambar deer in operational areas at the highest elevations (e.g. Alpine NP) exhibited decreases over the winter period and large increases over the summer period (Figure 4). Conversely, populations in operational areas at the lowest elevations (e.g. Croajingolong NP) exhibited the highest increases during the winter period and the lowest during the summer period (Figure 4). The recruitment rate in other operational areas were intermediate between these two extremes (Figure 4).

Table 2. Summary of the total number of each invasive species removed in each operational area (OA) between February 2020 and May 2022.

NP = national park, RP = regional park, WP = wilderness park.

Operational area	Sambar deer	Fallow deer	Red deer	Feral pig	Fox	Feral goat	Feral cattle
Alpine NP–Bogong High Plains	1018	0	0	0	1	0	0
Alpine NP–Eastern Alps	191	27	2	24	0	0	0
Burrowa–Pine Mountain NP	106	117	0	0	3	0	0
Coopracambra NP	7	0	0	0	0	0	0
Croajingolong NP	149	0	0	0	0	0	0
Errinundra NP	77	0	0	0	0	0	0
Mt Buffalo NP	579	0	0	0	0	0	0
Mt Mitta Mitta RP	33	0	0	0	1	23	0
Snowy River NP	3313	77	0	206	24	6	9
Wabba WP	271	0	0	0	0	0	0
Total	**5744**	**221**	**2**	**230**	**29**	**29**	**9**

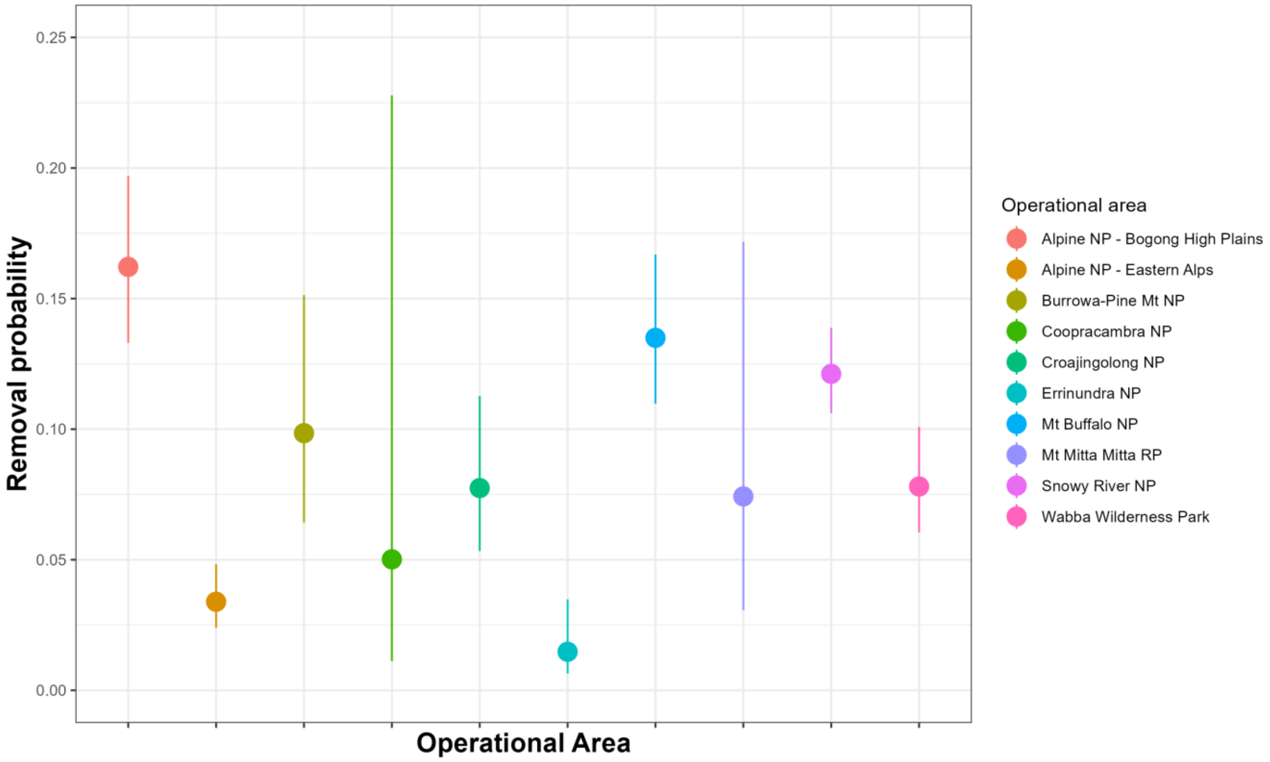

Figure 3. The probability of detection and removal of Sambar deer for each operational area during the final occasion for a helicopter search effort of 1 km searched per km^2 of habitat.

Error bars are 90% credible intervals. NP = national park, RP = regional park, WP = wilderness park.

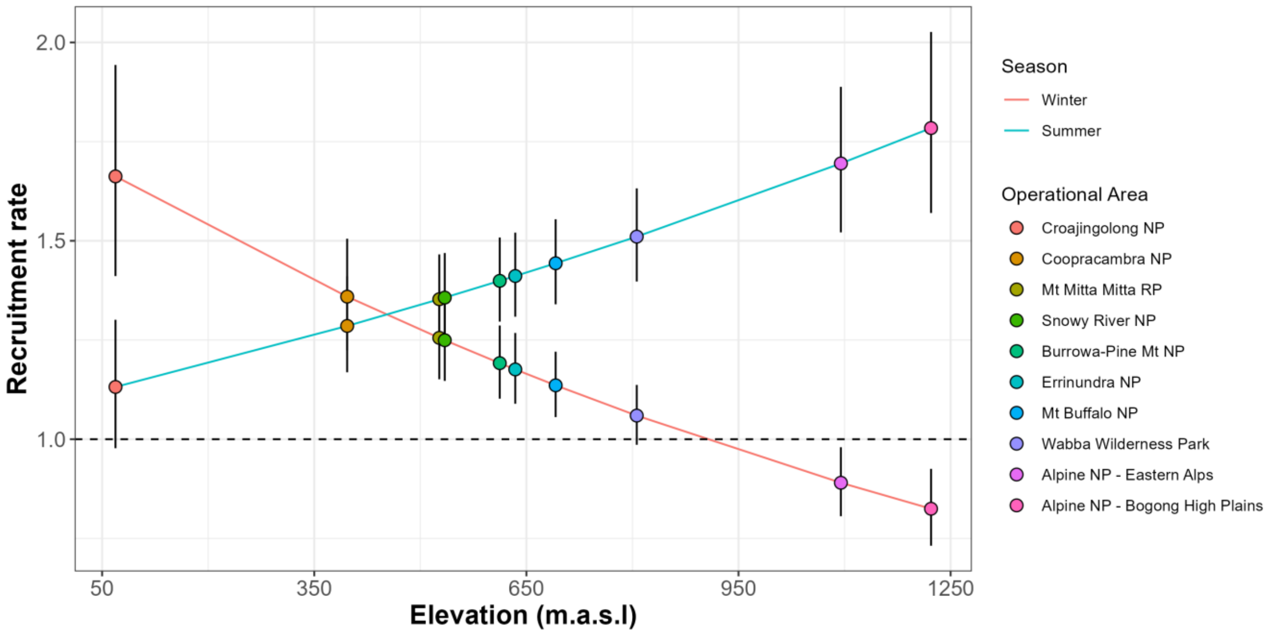

Figure 4. Relationship between the rate of natural recruitment (e^r) of Sambar deer due to natural additions and losses between periods and elevation (meters above sea level – m.a.s.l.) and season (summer/winter).

Values greater than 1.0 indicate net population increases; values less than 1.0 indicate net decreases. Points represent the estimates for each operational area (OA) with colours in ascending order of elevation. Error bars are 90% credible intervals. NP = national park, RP = regional park.

The estimated initial (N) and residual (R) densities of Sambar deer in each operational area over the five removal periods is given in Figure 5, and the estimated total percentage reduction in the populations due to removals is given in Table 3. Removals of Sambar deer over the five periods resulted in highest population reductions in the Snowy River NP and Mt Mitta Mitta RP, at 68% and 66%, respectively (Table 3). Population reductions of 62% and 53% were also obtained at the Mt Buffalo NP and Alpine NP–Bogong High Plains OAs. Reductions at Burrowa–Pine Mountain NP, Wabba WP and Coopracambra NP were uncertain, and populations increased at the remaining operational areas (Table 3). These results differed from the population reductions estimated following the emergency and Phase 1 removals between February 2020 and May 2021 (Ramsey 2021) as significant recruitment of Sambar deer during Phase 2, mainly due to deer movement, offset removals from helicopter shooting (Figure 5).

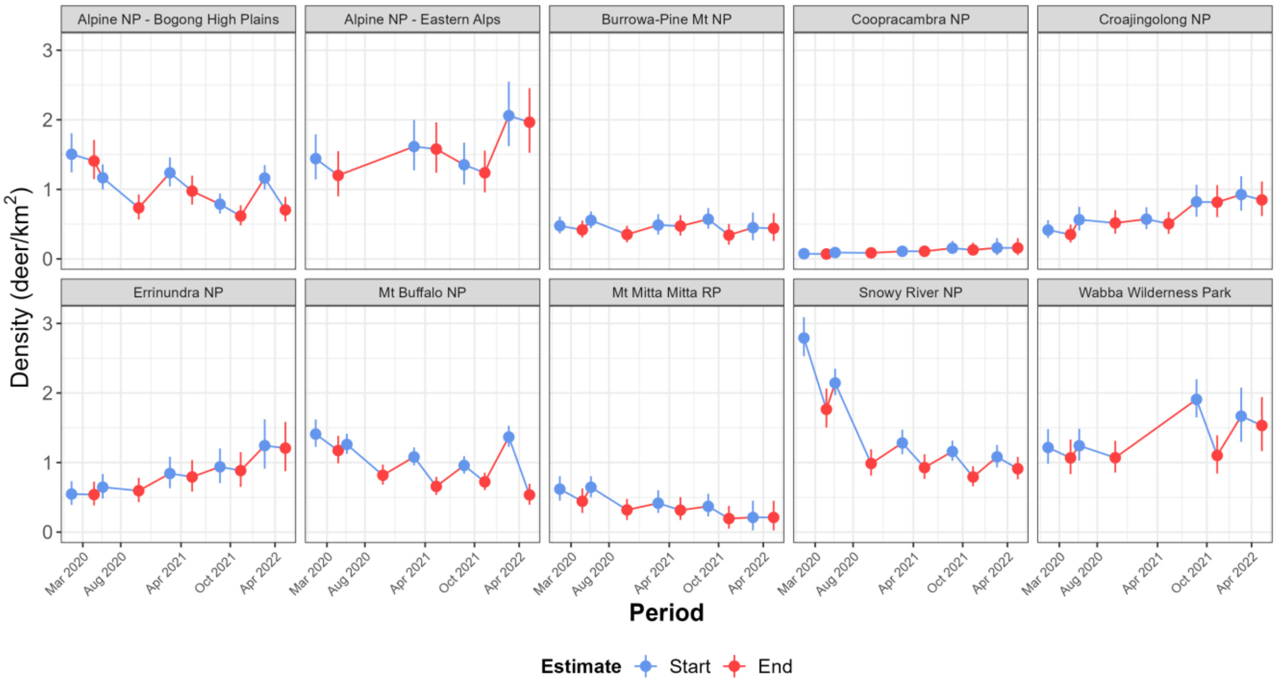

Figure 5. Estimates of the densities of Sambar deer at the start (blue points) and end (red points) of each period of aerial control in 10 operational areas (OAs) in Eastern Victoria.

Vertical lines indicate the 90% credible intervals for the estimates. NP = national park, RP = regional park.

Table 3. Estimates of the total change in Sambar deer abundance (%) achieved over the five periods of control for each operational area. LCI – lower 90% credible interval; UCI – upper 90% credible interval.

Positive values represent population declines and negative values represent population increases.
NP = national park, RP = regional park, W = wilderness park.

Operational area	Decline (%)	LCI	UCI
Snowy River NP	67.6	63.5	71.1
Mt Mitta Mitta RP	65.8	28.6	94.1
Mt Buffalo NP	62.0	51.9	71.2
Alpine NP–Bogong High Plains	53.1	44.7	60.9
Burrowa–Pine Mountain NP	7.7	-29.1	40.0
Wabba WP	-26.7	-57.2	0.4
Alpine NP–Eastern Alps	-37.2	-66.7	-11.3
Croajingolong NP	-107.7	-171.3	-53.6
Errinundra NP	-124.0	-187.2	-70.4
Coopracambra NP	-125.9	-312.5	4.6

3.1.1 Search effort required to achieve population reductions

The reductions achieved during each period of aerial control varied widely among OAs and was dependent on the amount of search effort conducted (Figure 6a). The highest reduction during a single period occurred at Mt Buffalo NP during period 5 (Mar – May 2022), which reduced the abundance of Sambar deer by 61% requiring 5 km of search effort per km^2 of habitat (Figure 6a, Table A1 – Appendix). Similarly high (>50%) reductions were achieved in the Snowy River NP and Mt Mitta Mitta RP during period 2 (Jun – Oct 2020), and again at Mt Mitta Mitta RP during period 4 (Sep – Dec 2021) (Table A1 – Appendix).

More generally, the amount of search effort predicted to be required to achieve various levels of proportional reductions in Sambar deer densities (Equation 2) over a single period suggested that a 50% reduction in density could be achieved with 7 km of search effort per km^2 of habitat (Figure 6b). This equates to 1.4 km/km^2 of effort in each of five removal occasions or alternatively, 1.75 km/km^2 of effort in each of four removal occasions. Simulated reductions in Sambar deer densities and associated 90% credible intervals encompassed the majority of the actual reductions achieved in each of the OAs over the five periods suggesting that the simulated relationship was a good match for the estimated reductions (Figure 6b).

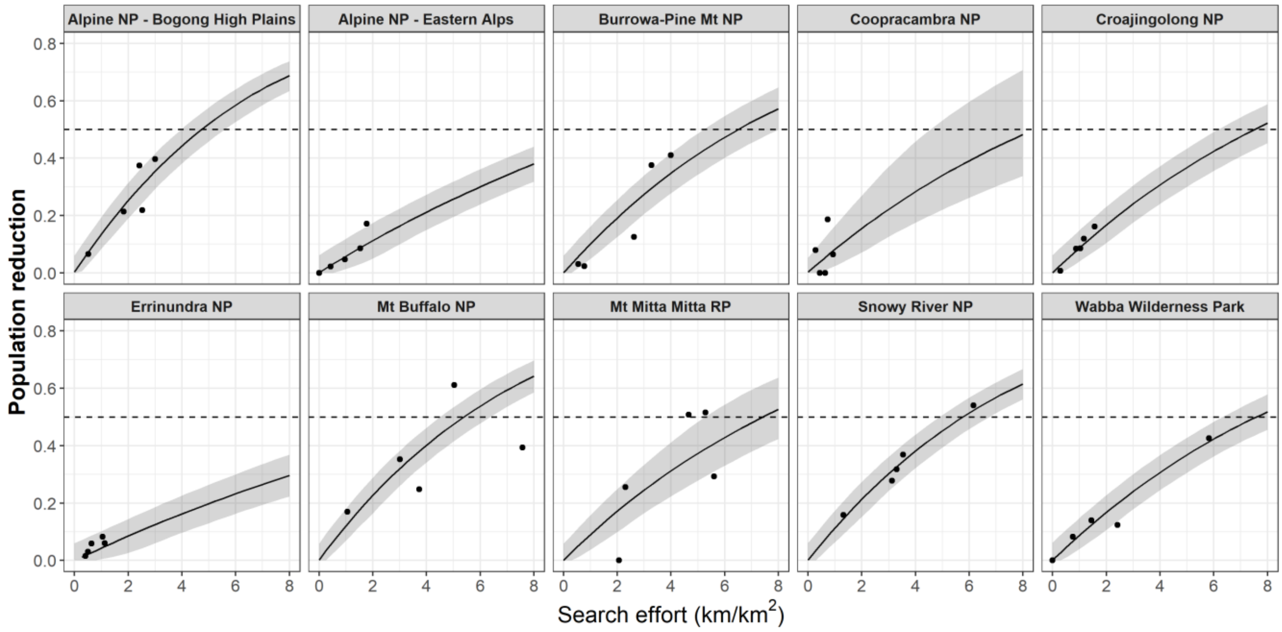

Figure 6a. The proportional reduction in population density of Sambar deer estimated for each of the five periods for each OA, plotted against the actual amount of search effort undertaken (solid points).

Solid line is the relationship between the proportional reduction and increasing search effort predicted for each OA (Equation 2). Shaded area is the 90% credible intervals. Horizontal dashed line indicates a 50% reduction. Search effort is total helicopter search effort expended during the period. NP = national park, RP = regional park.

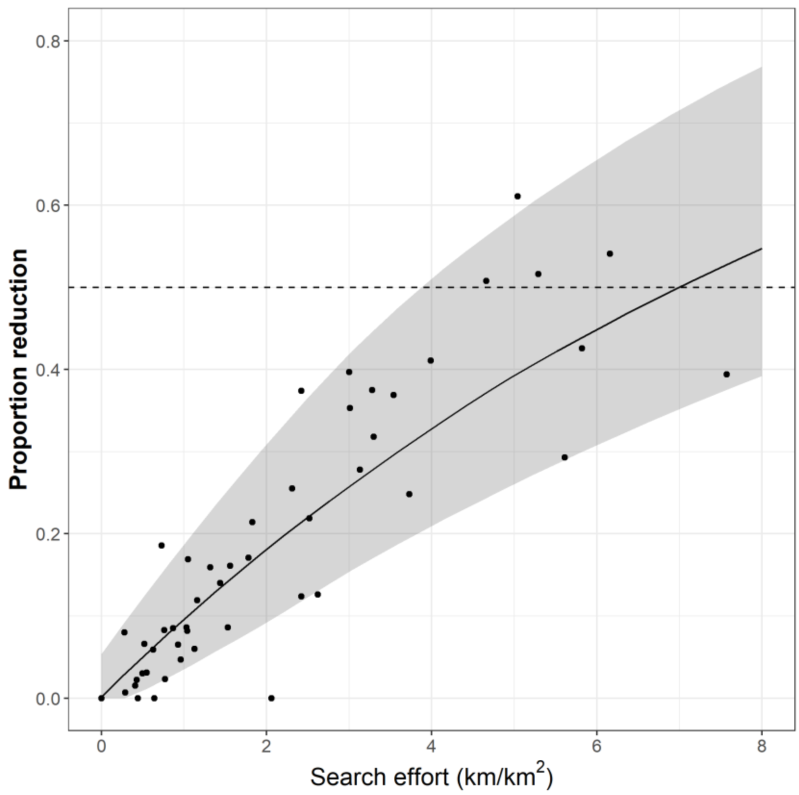

Figure 6b. Relationship between the proportional reduction in Sambar deer density and increasing search effort predicted from the combined data from each OA (Equation 2).

Shaded area is the 90% credible interval. Points are the estimated reductions achieved in each OA for each period against the actual amount of search effort undertaken in each period. Horizontal dashed line indicates a 50% reduction.

3.1.2 Effects of recruitment rate

The effect of increasing the time interval between periods of intensive control resulted in the erosion of Sambar deer population reductions due to aerial shooting (Figure 7). Assuming 0.8 km/km^2 of search effort in a single period, resulted in an approximate 35% reduction in Sambar deer density in period 1, on average (Figure 7). Assuming that each period of control was separated by a 1-month interval of no control resulted in an approximate 85% reduction in Sambar deer abundance by period 5. A similar level of overall reduction was also achieved if the interval between periods was 3 months. However, intervals longer than 3 months resulted in significant erosion of the gains achieved by aerial shooting such that, at intervals approaching 12 months, the Sambar deer population had increased (i.e. there were negative values for population reduction – Figure 7).

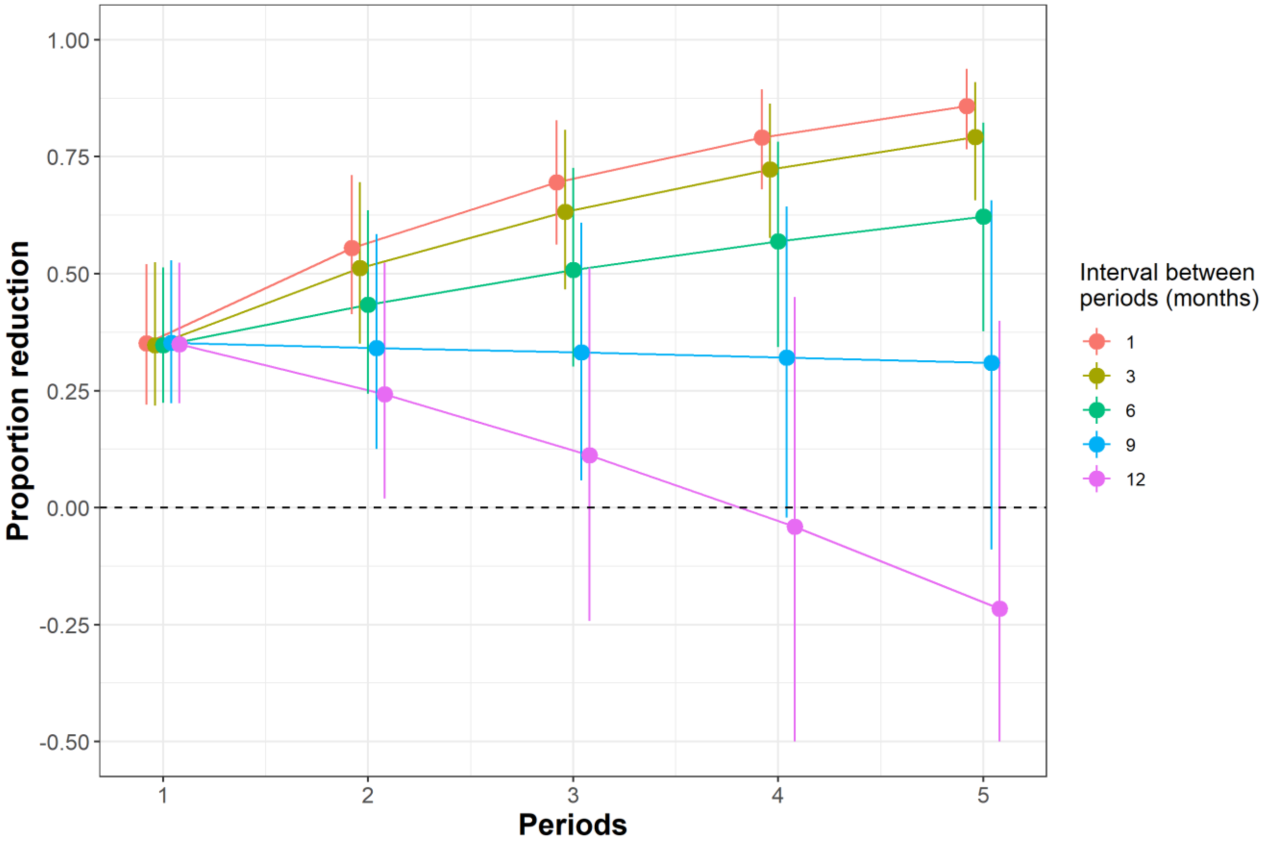

Figure 7. The cumulative proportional population reduction in Sambar deer achieved by aerial control over five periods, with increasing length of interval between periods.

Population reduction was simulated using Equation 2 assuming an average 0.8 km/km^2 of search effort. Population recruitment during each interval was simulated using Equation 3.

3.2 Fallow deer

Fallow deer were detected in three operational areas (Table 2). Estimates of Fallow deer densities were generally low in all three operational areas (< 0.4 deer/km^2) (Figure 8). A 54% reduction in abundance was estimated in Burrowa–Pine Mountain NP, but populations in both the Alpine NP–Eastern Alps and Snowy River NP appeared to have increased over the five periods of aerial control (Table 4). However, these estimated changes had high uncertainty (Table 4). Generally, Fallow deer populations appeared to have increased during winter (i.e. from period’s 1–2 and 3–4) and decreased during summer (i.e. from period's 2–3 and 4–5) while aerial control operations were not being undertaken (Figure 8).

Despite the low reductions in overall density achieved in two operational areas, the reductions achieved during periods of aerial control were similar to those obtained for Sambar deer, especially when search effort was high (Table A2 – Appendix).

Table 4. Estimates of the decline in Fallow deer abundance (%) achieved over the five periods for each operational area.

LCI – lower 90% credible interval; UCI – upper 90% credible interval. Negative values indicate population increases. NP = national park.

Operational area	Decline (%)	LCI	UCI
Burrowa–Pine Mountain NP	54.4	18.6	81.4
Snowy River NP	-24.3	-104.2	38.1
Alpine NP–Eastern Alps	-452.9	-1150	-83.3

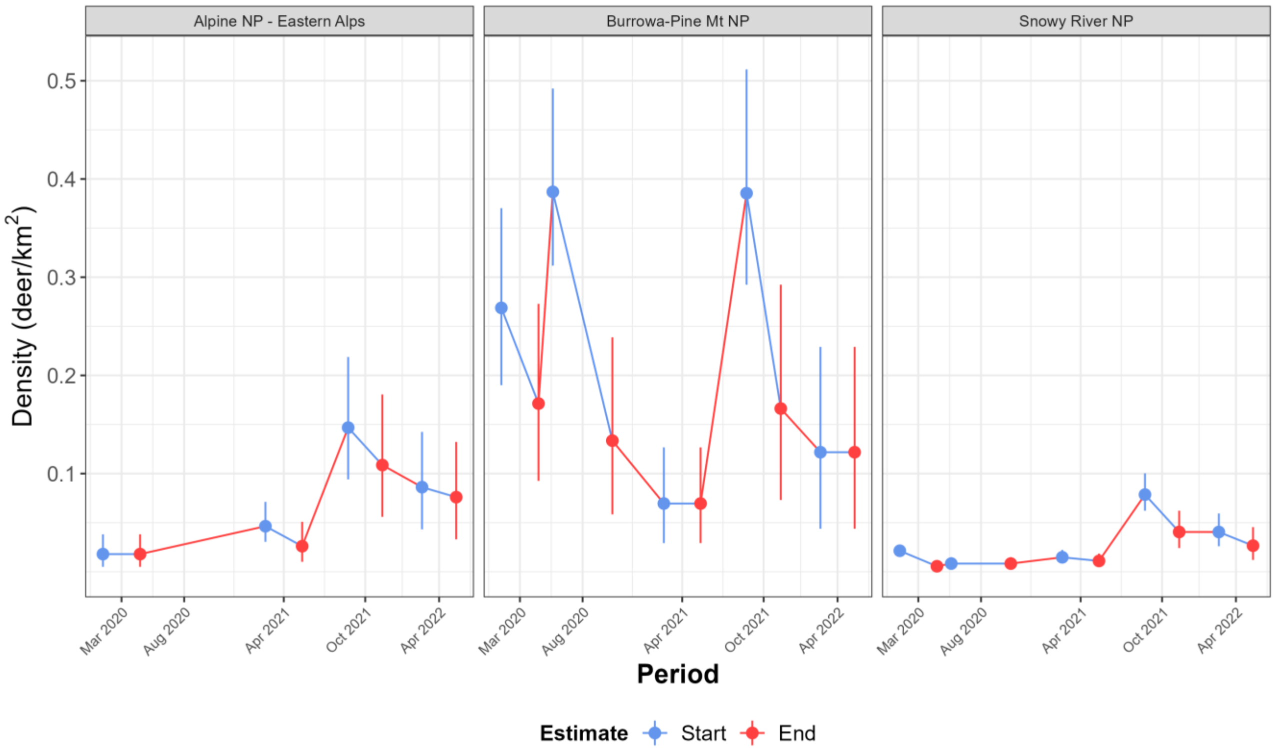

Figure 8. Summary of estimates of the initial and residual densities of Fallow deer at the start and end of each period, respectively, in three operational areas in Eastern Victoria.

Vertical lines indicate the 90% credible intervals for the estimates. NP = national park.

3.3 Feral pigs

Feral pigs were detected in two operational areas – the Alpine NP–Eastern Alps and the Snowy River NP. Estimates of feral pig densities were generally low in both OAs (< 0.3 pigs/km^2) (Figure 9). Populations of feral pigs appeared to have increased in both OAs between February 2020 and May 2022 due to natural recruitment, with increases of 68% estimated for the Snowy River NP and 270% for the Alpine NP–Eastern Alps (Table 5). Generally, feral pig populations appeared to have increased over summer (i.e. from period's 2–3 and 4–5) and decreased over winter (i.e. from period's 1–2 and 3–4) while aerial control operations were not being undertaken (Figure 9).

The reductions in feral pig densities achieved during periods of aerial control were generally lower than those achieved for deer with a maximum of 34% reduction in feral pig density achieved in the Snowy River NP during period 2 (Jun – Oct 2020). However, reductions during other periods generally ranged from 10–20% (Table A3 – Appendix).

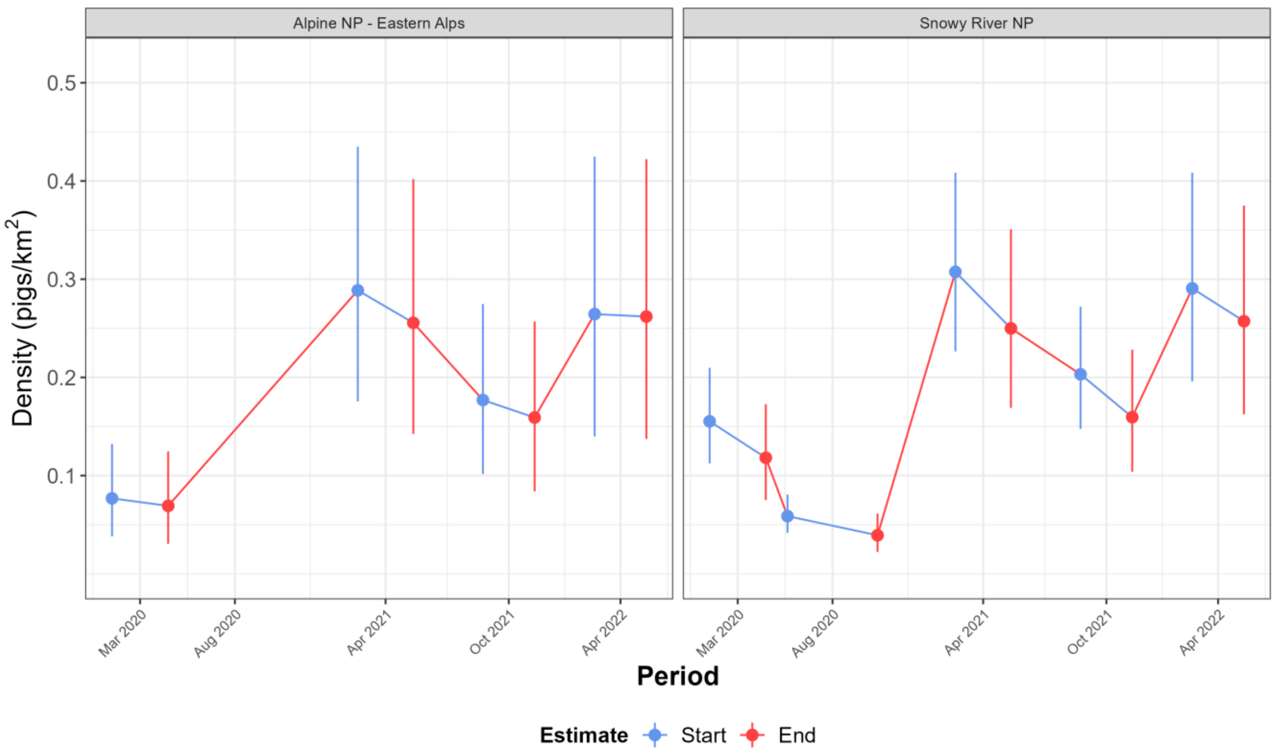

Figure 9. Summary of estimates of the initial and residual densities of feral pigs at the start and end of each period, respectively, in two operational areas in Eastern Victoria.

Vertical lines indicate the 90% credible intervals for the estimates. NP = national park.

Table 5. Estimates of the decline in feral pig abundance (%) achieved over the five periods for each operational area.

LCI – lower 90% credible interval; UCI – upper 90% credible interval. Negative values indicate population increases. NP = national park.

Operational area	Decline (%)	LCI	UCI
Snowy River NP	-67.7	-136.6	-11.1
Alpine NP–Eastern Alps	-270.1	-536.8	-88.7

4 Discussion

The analyses presented here used standard operational data collected during an extensive and intensive aerial shooting program to reduce introduced animal abundance in eastern Victoria. During this program, the collection of location data for all shot (and killed) deer and feral pigs as well as the recording of concurrent search effort data (helicopter search paths) allowed initial abundance, detectability (removal rate) and proportion of the population removed to be estimated using models based on ‘removal’ (or ‘catch–effort’) sampling (e.g. Gould and Pollock 1997; Dorazio et al. 2005; Haines 2019). Estimates of these parameters were obtained for Sambar deer from 10 operational areas (OAs), Fallow deer from three OAs, and feral pigs from two OAs over five periods of aerial shooting occurring between February 2020 and May 2022. An important aspect of the catch–effort model used here was the ability to relax the assumption of demographic closure, allowing an estimation of additions and losses between periods of intensive control. Population growth between periods of control was modelled using a simple exponential trend, with the growth rate dependent on the elevation of each OA as well as the season (summer/winter). The estimates of the removal rate also were allowed to vary among the OAs.

Over the entire period of aerial operations reported here, our results suggest that Sambar deer abundance was reduced by around 70% in two areas (Mt Mitta Mitta RP and Snowy River NP) and around 60% and 50% in two other areas (Mt Buffalo NP and Alpine NP–Bogong High Plains, respectively). However, results in the remaining OAs suggest that Sambar deer densities have either stayed static or increased over the five periods of aerial control. Population reductions estimated following the completion of the Phase 1 aerial shooting program (Ramsey 2021) appear to have been eroded or erased in some OAs following the addition of the Phase 2 aerial shooting data to the analysis. The longer time series of data has allowed a more sophisticated model to be fitted to the data compared with that used in Ramsey (2021), which has enabled deeper insights into the effects of the aerial shooting program among the different OAs. These are discussed in more detail below.

There were two main reasons for the variation in efficacy of the aerial shooting program among the different OAs. The first reason was that the level of population reduction achieved was strongly related to the amount of aerial search effort. Deer populations in OAs that exhibited no change or increases in deer densities inevitably were subject to relatively low helicopter search effort per km^2 of habitat (e.g. Coopracambra NP, Errinundra NP) compared with OAs that exhibited decreases in Sambar deer densities (e.g. Snowy River NP, Mt Mitta Mitta RP). The second reason was that there was variation in the recruitment rates of deer among different OAs, which was especially prominent during the Phase 2 aerial shooting program between November 2021 and March 2022. Analysis revealed that recruitment of Sambar deer, mainly due to deer movement, was dependent on both season and elevation, with areas at the highest elevations (Alpine NP–Bogong High Plains and Eastern Alps) exhibiting a net decrease in abundance during winter followed by net increases during summer. This pattern was reversed for areas at low elevation (e.g. Croajingolong NP), where recruitment was highest during winter and lowest during summer. Other studies have shown that Sambar deer move to lower elevations when snow cover increases at high elevations (Comte et al*.* 2022). Hence, the seasonal variation in recruitment among areas estimated here would appear to support this phenomenon.

Sambar deer recruitment in some operational areas (e.g. Errinundra NP, Croajingolong NP, Alpine NP–Eastern Alps) was sufficient to offset reductions due to aerial shooting, resulting in increases in Sambar deer densities over the 28 month duration of the program. Increased recruitment of deer may be related to the recovery of vegetation in these areas post-fire, especially in areas heavily burnt during 2019–20 (e.g. Errinundra NP, Croajingolong NP). Deer have been shown to re-occupy areas recovering from bushfires within 18–24 months post fire (Forsyth et al. 2013). Hence, the abundances of Sambar deer in areas heavily burnt during the 2019–20 bushfires may have been depleted initially when aerial control commenced, with populations now increasing as the understory vegetation recovers in these areas. These areas were also ones that received relatively lower aerial control effort, which was more concentrated in those OAs with higher initial densities of deer. As the deer population recovers in those areas heavily burnt by the 2019–20 bushfires, their priority for future aerial control effort should also increase to limit the potential recovery of deer populations in these areas.

The simulation of the effect of deer recruitment rates on the efficacy of aerial control suggested that successive periods of aerial shooting should be undertaken at intervals of no more than 3 months. Increasing the interval between control periods inevitably led to higher erosion of the gains achieved by aerial shooting due to effect of deer recruitment. This also suggests that a period of intensive aerial shooting should also be completed within about 3 months to limit the effect of deer recruitment.

For the other invasive species examined, analysis revealed that aerial shooting had reduced population densities of Fallow deer by around 54% at Burrowa–Pine Mountain NP. However, reductions from aerial shooting had been insufficient to reduce Fallow deer densities in the two other OAs, with populations increasing over the five control periods by 24% and 450% in the Snowy River NP and Alpine NP–Eastern Alps, respectively. However, it should be noted that the estimated population changes for this species had high uncertainty most likely due to the limited number of OAs with sufficient removal data, and the low densities of Fallow deer in these areas. Similarly, an analysis of feral pigs in two operational areas revealed that removals from aerial shooting were insufficient to reduce populations densities in both the Snowy River NP (68% increase) and Alpine NP–Eastern Alps (270% increase). As for Fallow deer, estimates of the changes in population densities had high uncertainty due to the limited number of OAs with removal data and the low densities of feral pigs. Despite this, aerial shooting was able to achieve population reductions of Fallow deer during a single period that were similar to those estimated for Sambar deer, indicating that with sufficient search effort, aerial shooting can effectively reduce Fallow deer densities. However, reductions achieved for feral pigs during a single period were somewhat lower than for deer.

Recruitment in populations of Fallow deer revealed that populations increased during winter and decreased during summer in the three OAs examined. For feral pigs, this pattern was reversed, with populations increasing during summer and decreasing during winter in the two OAs examined. Unlike Sambar deer, there were insufficient data to examine the effects of elevation on recruitment patterns for both these species.

Despite a long history of animal abundance estimation, especially in fisheries management (DeLury 1947; Schnute 1983; Mäntyniemi et al*.* 2005), there are few examples of the use of catch–effort models on data collected during aerial control operations (Ramsey et al. 2009; Davis et al*.* 2016a; Davis et al*.* 2018). Studies applying catch–effort models to feral pig removal in the USA found that aerial shooting removed between 47% and 67% of feral pigs following three removal occasions (Davis et al. 2016a; Davis et al. 2018). Similarly, an analysis of the removal of feral pigs from Santa Cruz Island, California showed that around 77% of the total population of pigs were removed by aerial shooting (Parkes et al. 2010). A recent study of the efficacy of aerial shooting for removing deer from agricultural areas in NSW and Queensland found that shooting from a helicopter achieved reductions in deer densities ranging from 5–75% for Fallow deer and 48–88% for Chital deer (*Cervus axis*) (Bengsen et al. 2022).

A key assumption of the catch–effort models used here is that successive removals should be representative of the total population. This could be violated if the effective search area gradually increases over time. For example, this could occur as a result of the aerial shooting team increasing the area controlled as population density decreases. As population density decreases, less time is expended in the process of shooting (and ensuring the death of individuals. Hence, this excess time could be used to expand the area of search so that more target individuals are engaged. The end result is that the effective search area gradually increases over time. Ideally, the area searched should consist of repeated searches of the same area. Some investigations of the current helicopter search data have revealed that some sequential search area 'creep' has occurred in most operational areas (unpublished data). This has the potential to cause some bias in the estimates of density and/or the detection rate. Hence, to ensure unbiased estimates from the catch–effort models used here, the search area for a particular operational area should remain consistent throughout the period of aerial control.

Aerial shooting recommendations

The analysis of aerial search effort required to achieve reductions in deer density has suggested the amount of search effort needed during a single period of operations to effect various proportional reductions in Sambar deer populations. These estimates can be used by management to plan future deer control operations and estimate likely costs to achieve target densities. Aerial control efficiencies differed by OA, and were relatively high in some areas such as the Alpine NP–Bogong High Plains, Mt Buffalo NP, Burrowa–Pine Mountain NP and the Snowy River NP, but relatively low in other areas such as the Alpine NP–Eastern Alps, Errinundra NP and Coopracambra NP.

In general, reductions in Sambar deer densities of 50% during a single period could be achieved in most areas using a total of 7 km/km^2 of aerial search effort. Lower amounts of search effort (e.g. 5 km/km^2) could be used in areas with relatively high control efficiencies (see above). In practice, the recommended search effort would need to be undertaken over several occasions, defined as the number of helicopter missions required to undertake at least one complete search of the OA. Hence, five occasions would be equivalent to at least five complete searches of the OA, with each occasion consisting of 1.4 km/km^2 of search effort (i.e. 7 km/km^2 total). If four occasions were undertaken, then each occasion would consist of 1.75 km/km^2 of search effort. Due to the likely effects of deer recruitment (i.e. recolonisation) on reductions achieved by aerial shooting, the length of time required to complete a period of intensive control should be no more than 3 months. If high reductions (e.g. > 75%) in deer densities are required, then several such periods of intensive control would need to be undertaken with the interval between periods (i.e. where no aerial shooting occurs) also limited to no more than 3 months. Care also needs to be undertaken to ensure the size of the operational area searched by the helicopter team does not increase substantially over time.

To maintain reductions in Sambar deer densities over time, aerial shooting would be more cost-effective if effort was concentrated at certain times of the year to counteract the effect of natural recruitment to the population, especially due to seasonal movements of deer. Hence, in high altitude areas, aerial shooting should be undertaken mainly during summer and autumn to reduce the likely recruitment of deer that occurs as deer move back into the alpine regions as the temperature warms (Comte et al. 2022). Conversely, in low altitude areas, aerial shooting should be undertaken mainly during the winter and spring to counteract the movement of deer to lower altitudes over winter. Areas at intermediate altitudes can be subject to aerial control in either or both periods.

No recommendations have been provided on the aerial control effort required to achieve target densities for other invasive species (e.g. Fallow deer, feral pigs and goats) due to the limited amount of data, which precluded a comprehensive analysis. To gain a better understanding of the effectiveness of aerial shooting on other invasive species to achieve target densities, aerial operations may need to specifically target these species to obtain sufficient data for analysis. Until then, these species can continue to be targeted opportunistically while conducting operations on Sambar deer.

Finally, how much reduction in deer densities is required to protect biodiversity assets remains a point of conjecture. Studies that have used exclosures to measure deer impacts have provided evidence that deer reduce vegetation cover and inhibit tree regeneration and sapling growth (Forsyth et al. 2015; Davis et al. 2016b). However, the relationships between deer densities and deer impacts have not been investigated, making the setting of management targets problematic. More robust targets for deer management in Victoria will need to await the outcomes of future studies into density–impact relationships for deer.

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6 Appendix

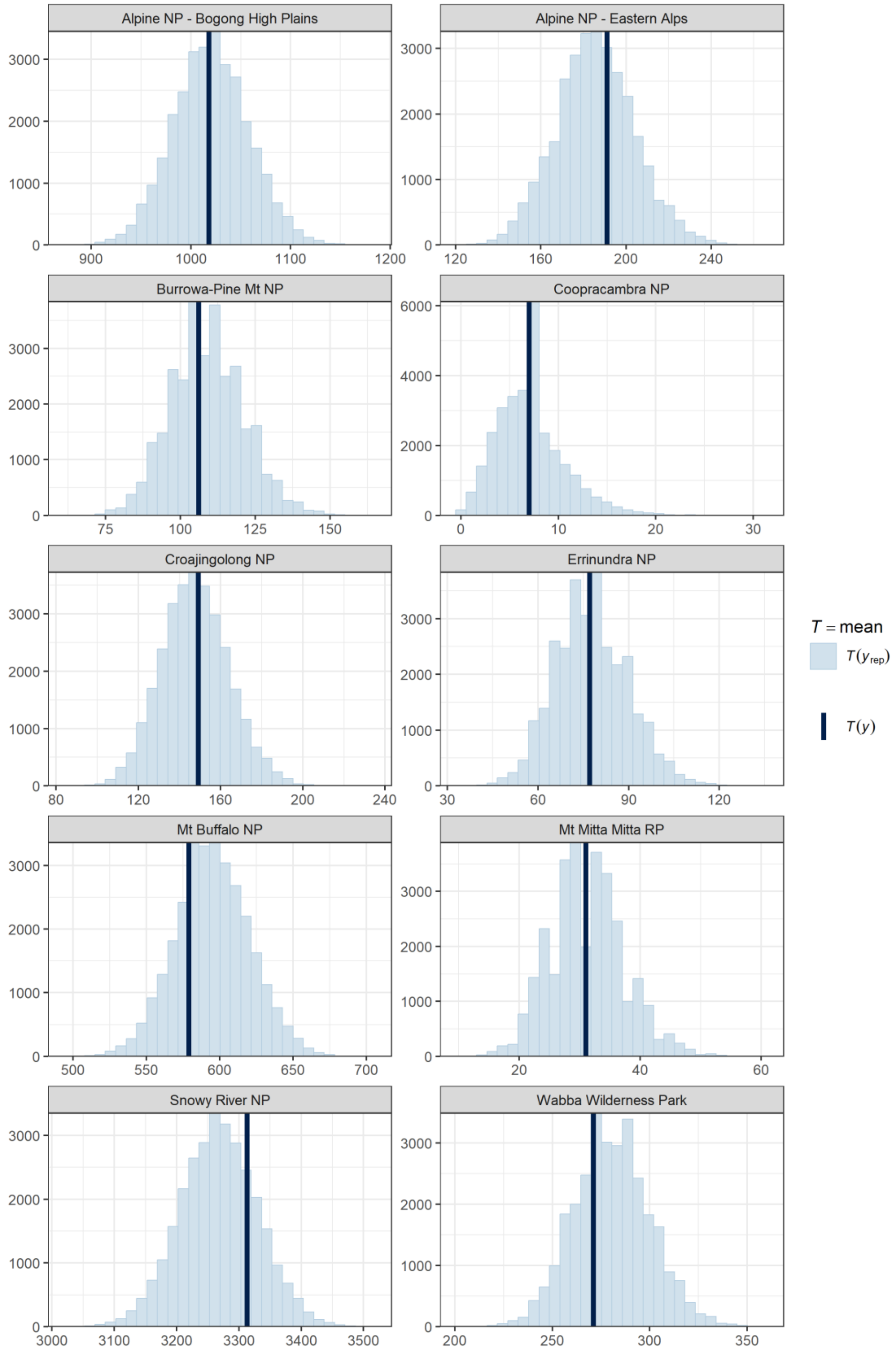

Figure A1. Posterior predictive checks of the number of Sambar deer removed from each operational area ($T(y)$ – solid vertical line) versus the distribution of the number of deer removed predicted by the model ($T(y_{rep})$ – light blue bars).

Table A1. Summary of estimates of the initial (*N*) and residual (*R*) densities (deer/km²), and percentage decline (*D*) of Sambar deer at the start and end of each period, respectively, in 10 operational areas in Eastern Victoria.

Area represents the effective search area (km²). NP = national park, RP = regional park, WP = wilderness park.

Operational area	Period	*N* (90% CI)	*R* (90% CI)	*D* (%) (90% CI)
Alpine NP–Bogong High Plains (717 km²)	1	1.5 (1.24–1.81)	1.41 (1.15–1.71)	6.6 (5.4–7.8)
	2	1.17 (1–1.36)	0.73 (0.57–0.93)	37.4 (31.8–43.2)
	3	1.24 (1.04–1.46)	0.98 (0.78–1.2)	21.4 (18–25.1)
	4	0.79 (0.65–0.94)	0.62 (0.48–0.77)	21.9 (18.1–26.1)
	5	1.16 (1–1.35)	0.7 (0.54–0.89)	39.7 (33.9–45.8)
Alpine NP–Eastern Alps (393 km²)	1	1.44 (1.14–1.79)	1.2 (0.9–1.55)	17.1 (13.5–21.2)
	2	1 (0.75–1.28)	1 (0.75–1.28)	0 (0–0)
	3	1.62 (1.27–2)	1.58 (1.24–1.96)	2.2 (1.8–2.8)
	4	1.35 (1.07–1.67)	1.24 (0.96–1.56)	8.6 (6.8–10.7)
	5	2.06 (1.62–2.55)	1.97 (1.53–2.45)	4.7 (3.7–5.8)
Burrowa–Pine Mountain NP (207 km²)	1	0.48 (0.37–0.61)	0.42 (0.31–0.55)	12.6 (9.6–16)
	2	0.56 (0.44–0.68)	0.35 (0.24–0.48)	37.5 (30–46.2)
	3	0.49 (0.35–0.64)	0.47 (0.34–0.63)	3.1 (2.3–4.2)
	4	0.57 (0.43–0.73)	0.34 (0.2–0.5)	41.1 (31.3–52.8)
	5	0.45 (0.27–0.67)	0.44 (0.26–0.66)	2.3 (1.5–3.6)
Coopracambra NP (200 km²)	1	0.08 (0.03–0.13)	0.07 (0.02–0.13)	8 (3.7–16.7)
	2	0.09 (0.04–0.16)	0.09 (0.03–0.15)	6.5 (3.1–12.5)
	3	0.11 (0.05–0.19)	0.11 (0.05–0.19)	0 (0–0)
	4	0.15 (0.07–0.26)	0.13 (0.05–0.23)	18.6 (9.6–33.3)
	5	0.16 (0.05–0.3)	0.16 (0.05–0.3)	0 (0–0)
Croajingolong NP (575 km²)	1	0.42 (0.3–0.56)	0.35 (0.24–0.49)	16.1 (11.6–21.5)
	2	0.56 (0.41–0.75)	0.52 (0.36–0.7)	8.6 (6.3–11.4)
	3	0.57 (0.43–0.74)	0.51 (0.36–0.68)	11.9 (8.9–15.5)
	4	0.82 (0.61–1.07)	0.82 (0.6–1.06)	0.7 (0.5–0.9)
	5	0.92 (0.69–1.19)	0.85 (0.62–1.11)	8.5 (6.4–11.1)
Errinundra NP (386 km²)	1	0.55 (0.39–0.73)	0.54 (0.38–0.72)	1.5 (1.1–2)
	2	0.65 (0.48–0.83)	0.6 (0.43–0.78)	8.2 (6.2–10.7)
	3	0.84 (0.63–1.08)	0.79 (0.58–1.04)	6 (4.5–7.8)
	4	0.94 (0.7–1.2)	0.88 (0.65–1.15)	5.9 (4.5–7.7)
	5	1.24 (0.91–1.62)	1.21 (0.88–1.58)	3 (2.2–4)

Operational area	Period	*N* (90% CI)	*R* (90% CI)	*D* (%) (90% CI)
Mt Buffalo NP (267 km^2)	1	1.41 (1.23–1.62)	1.17 (0.99–1.38)	16.9 (14.6–19.3)
	2	1.26 (1.12–1.41)	0.82 (0.68–0.97)	35.3 (31.3–39.3)
	3	1.08 (0.96–1.22)	0.66 (0.54–0.79)	39.4 (34.8–44.1)
	4	0.96 (0.84–1.09)	0.72 (0.6–0.85)	24.8 (21.6–28.1)
	5	1.37 (1.23–1.53)	0.54 (0.39–0.7)	61.1 (54.4–67.9)
Mount Mitta Mitta RP (39 km^2)	1	0.62 (0.45–0.8)	0.44 (0.28–0.63)	29.3 (21.9–38.9)
	2	0.65 (0.5–0.8)	0.32 (0.18–0.48)	51.6 (40.6–65)
	3	0.42 (0.28–0.6)	0.32 (0.18–0.5)	25.5 (16.7–36.4)
	4	0.37 (0.23–0.55)	0.19 (0.05–0.38)	50.8 (31.8–77.8)
	5	0.21 (0.03–0.45)	0.21 (0.03–0.45)	0 (0–0)
Snowy River NP (1077 km^2)	1	2.79 (2.53–3.09)	1.76 (1.5–2.06)	36.9 (33.2–40.6)
	2	2.14 (1.97–2.35)	0.99 (0.81–1.19)	54.1 (49.3–58.8)
	3	1.28 (1.12–1.47)	0.93 (0.76–1.12)	27.8 (24.1–31.7)
	4	1.16 (1.02–1.31)	0.79 (0.66–0.95)	31.8 (27.9–35.8)
	5	1.08 (0.93–1.25)	0.91 (0.76–1.08)	15.9 (13.6–18.4)
Wabba WP (214 km^2)	1	1.22 (0.98–1.48)	1.07 (0.83–1.33)	12.4 (10.1–15.2)
	2	1.24 (1.03–1.49)	1.07 (0.86–1.31)	14 (11.6–16.7)
	3	1.71 (1.42–2.03)	1.71 (1.42–2.03)	0 (0–0)
	4	1.91 (1.65–2.2)	1.1 (0.84–1.39)	42.6 (36.7–48.9)
	5	1.67 (1.3–2.08)	1.53 (1.16–1.94)	8.3 (6.5–10.4)

Table A2. Summary of estimates of the initial (*N*) and residual (*R*) densities (deer/km²), and percentage decline (*D*) of Fallow deer at the start and end of each period, respectively, in three operational areas in Eastern Victoria.

Area represents the effective search area (km²). NP = national park.

Operational area	Period	*N* (90% CI)	*R* (90% CI)	*D* (%) (90% CI)
Alpine NP–Eastern Alps (242 km²)	1	0.02 (0.01–0.04)	0.02 (0.01–0.04)	0 (0–0)
	2	0.05 (0.02–0.09)	0.05 (0.02–0.09)	0 (0–0)
	3	0.05 (0.03–0.07)	0.03 (0.01–0.05)	46.7 (28.6–66.7)
	4	0.15 (0.09–0.22)	0.11 (0.06–0.18)	27.7 (17.4–40.5)
	5	0.09 (0.04–0.14)	0.08 (0.03–0.13)	13.4 (7.1–23.5)
Burrowa–Pine Mountain NP (207 km²)	1	0.27 (0.19–0.37)	0.17 (0.09–0.27)	37.8 (26.3–51.3)
	2	0.39 (0.31–0.49)	0.13 (0.06–0.24)	66.8 (51.5–81.2)
	3	0.07 (0.03–0.13)	0.07 (0.03–0.13)	0 (0–0)
	4	0.39 (0.29–0.51)	0.17 (0.07–0.29)	58.5 (42.9–75)
	5	0.12 (0.04–0.23)	0.12 (0.04–0.23)	0 (0–0)
Snowy River NP (1077 km²)	1	0.02 (0.02–0.03)	0.01 (0–0.01)	75.1 (58.6–89.5)
	2	0.01 (0–0.01)	0.01 (0–0.01)	0 (0–0)
	3	0.01 (0.01–0.02)	0.01 (0.01–0.02)	27 (16.7–40)
	4	0.08 (0.06–0.1)	0.04 (0.02–0.06)	49.5 (38–61.2)
	5	0.04 (0.03–0.06)	0.03 (0.01–0.05)	36.5 (23.4–53.6)

Table A3. Summary of estimates of the initial (*N*) and residual (*R*) densities (deer/km²), and percentage decline (*D*) of feral pigs at the start and end of each period, respectively, in two operational areas in Eastern Victoria.

Area represents the effective search area (km²). NP = national park.

Operational area	Period	*N* (90% CI)	*R* (90% CI)	*D* (%) (90% CI)
Alpine NP–Eastern Alps (242 km²)	1	0.08 (0.04–0.13)	0.07 (0.03–0.12)	11.5 (5.8–20)
	2	0.04 (0.02–0.06)	0.04 (0.02–0.06)	0.0 (0–0)
	3	0.29 (0.18–0.43)	0.26 (0.14–0.4)	12.4 (7.6–18.8)
	4	0.18 (0.1–0.27)	0.16 (0.08–0.26)	11 (6.5–17.5)
	5	0.26 (0.14–0.42)	0.26 (0.14–0.42)	1.1 (0.6–1.8)
Snowy River NP (1077 km²)	1	0.16 (0.11–0.21)	0.12 (0.08–0.17)	24.8 (17.7–33.1)
	2	0.06 (0.04–0.08)	0.04 (0.02–0.06)	34.5 (24.1–46.7)
	3	0.31 (0.23–0.41)	0.25 (0.17–0.35)	19.3 (14.1–25.4)
	4	0.2 (0.15–0.27)	0.16 (0.1–0.23)	22.2 (16–29.6)
	5	0.29 (0.2–0.41)	0.26 (0.16–0.37)	12.1 (8.2–17.1)

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