CSIRO PUBLISHING

RESEARCH ARTICLE
https://doi.org/10.1071/WR25020

WILDLIFE RESEARCH

Investigations into aerial shooting approaches to achieve rapid removal of feral and pest animals

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Handling Editor:
Penny Fisher

Received: 10 February 2025
Accepted: 12 October 2025
Published: 6 November 2025

Cite this: Cox TE *et al.* (2025) Investigations into aerial shooting approaches to achieve rapid removal of feral and pest animals. *Wildlife Research* **52**, WR25020. doi:10.1071/WR25020

ABSTRACT

Context. Invasive animals continue to have a significant impact on the Australian landscape despite continual control efforts. Aerial shooting from helicopters is the most common tool used to control these animals at the landscape scale. However, most aerial shooting programs are generally applied *ad hoc*, prioritise effort based on assumed spatial distribution and are based primarily on visual sightings of the target species. **Aims.** To determine whether a systematic search approach using thermal technology could improve removal rates during invasive animal shooting campaigns to maximise management outcomes. **Methods.** We evaluated the impact of following-up two standard habitat-informed aerial shooting programs (one with thermal and one without) with a program that utilised a systematic search pattern utilising thermal equipment. We assessed the effectiveness of each program in reducing invasive animal populations and provide a cost comparison of each technique. **Key results.** Neither habitat-informed approach achieved management level reductions for any species targeted. The systematic approach reduced pig populations at both sites by >95%; a similar result was not achieved for goats or deer. Multi-species aerial shooting programs may decrease overall program effectiveness and non-participating landholders can provide areas of refuge to allow for rapid reinvasion. During both systematic search programs, 26% and 10% of animals were found outside of the effective search areas of the visual and thermal habitat-informed programs respectively. **Conclusions.** The systematic-with-thermal search approach can result in rapid local removal of pigs when it follows a habitat-informed approach. The systematic approach resulted in detections of target animals in areas the crew did not expect to find them. Targeting multiple species in a program appears to reduce program effectiveness. **Implications.** Our results demonstrated that following a habitat-informed aerial shooting program with a systematic-with-thermal program can result in a rapid removal of >95% of feral pigs. For habitat-informed programs the addition of a thermographer can improve program outcomes. Multi-species aerial shooting programs may result in decreased effectiveness overall, although further research on the functional response in multi-species programs is required before any conclusions can be drawn.

Keywords: African swine fever, deer, disease, effective control, effective management, exotic disease preparedness, feral pig, FMD, functional response, invasive, rapid removal, shooting, systematic search, thermal, ungulate.

Introduction

Feral and pest animals (hereafter invasive species) are of significant environmental and agricultural concern in Australia. Medium–large-bodied cloven-hoofed animals such as goats (*Capra hircus*), pigs (*Sus scrofa*) and deer (i.e. fallow *Dama dama* and sambar *Rusa unicolor*) are widespread, despite ongoing control by landholders and Government agencies. Current control methods can be costly, time consuming (Animal Health Australia 2023), and still not achieve the desired population reduction in a timely manner (Gentle *et al.* 2022).

For example, in 2019, the cost of managing feral pigs by landholders alone reached A$100 million (Hafi *et al.* 2023), whereas the average annual economic cost of feral deer is estimated at A$91 million (McLeod 2023). The cost of managing feral goats is complicated by their use as a supplementary income stream when rangeland conditions are poor (or the value of goats is high). However, where management does occur, costs can range from A$7 to A$25 million annually (Maas 1998; McLeod 2004). Despite the significant financial input into their management (rather than eradication), environmental and agricultural damage caused by feral animals is only reduced, but not eliminated. In addition, these cloven-hoofed animals would be significant contributing species to the maintenance and spread of exotic diseases such as foot-and-mouth disease (FMD) (Choquenot *et al.* 1996; Fleming 2004; Cripps *et al.* 2019), further costing the Australian economy up to $80 billion over 10 years, if it were to breach Australian borders (Buetre *et al.* 2013; Hone *et al.* 2022).

Aerial shooting is an effective landscape-scale method of controlling many large-bodied invasive species in Australia. The current standard method of searching for target animals in an aerial shoot is the habitat-informed approach. Habitat-informed searching is based on knowledge of the animal's habitat preferences, where the crew search pockets of land where they think target animals are likely to be in the landscape. Often, the same pilot and/or shooter repeatedly shoot the same areas over multiple programs. Consequently, they tend to have strong prior beliefs on where animals are expected to be encountered and subsequently shot, resulting in focused efforts at these localities. However, large swaths of the landscape are missed. Additionally, the crew may fly some of the area systematically, but this is usually performed in an *ad hoc* way (no predefined transects and only in areas considered to be suitable habitat for the target animal). Intensive effort using the habitat-informed approach can reduce invasive species populations to below those levels required for replacement within the year (i.e. where proportion removed (p) is equivalent to 1 minus the inverse of the intrinsic rate of increase (r_m) (Caughley 1980; Hone 1999); e.g. a 50–78% reduction in pigs (Gentle and Pople 2013), 40% reduction in goats (Parkes *et al.* 1996) and a 30–52% reduction in deer (Duncan *et al.* 2007; Forsyth *et al.* 2010; Hone *et al.* 2010)), with annual aerial shooting campaigns (or even more frequent) often required to effectively manage the pest population.

A 'searching transects' approach was used by Saunders and Bryant (1988) in a simulated FMD eradication exercise targeting pigs in western New South Wales (NSW), Australia. A systematic search approach of flying predefined transects and coming off those transects to shoot target animals (pigs) before resuming the transects, was also used by Hone (1983, 1990). Despite Hone (1990) stating that the entire study area was searched almost daily, it was also mentioned that flooded areas were not searched, indicating an incomplete search effort for the area. Although a more systematic search approach was employed, only an 80% (estimated range: 75–84% reduction) (Saunders and Bryant 1988) and 79% reduction (Hone 1990) in pigs was reported. No systematic approaches of any kind have been reported for any other invasive species. All these studies highlighted the issue of individuals being difficult to detect in dense habitat.

More recently, thermal imaging has been recommended to increase animal detection probabilities (McCann *et al.* 2004; Pulsford *et al.* 2022). Further, the use of high-quality thermal imaging in aerial shooting programs can double the shooting rate compared with visual aerial shooting (Cox *et al.* 2023), increasing the efficiency of aerial control programs. Pigs have been reported to alter their behaviour in response to aerial shooting programs, changing their movement patterns and bedding down when a helicopter approaches (Hone 1983; Saunders and Bryant 1988; Saunders 1993). Similarly, goats have also been reported to change their movement patters and hide from helicopters (Bayne *et al.* 2000). Anecdotally, sambar deer have also been reported to freeze under dense vegetation. This can make visual detection of these animals almost impossible, as detection in visual shooting programs relies heavily on movement of the animal, particularly in areas of dense ground cover. Thermal imaging can mitigate this adaptive advantage through detecting the animals radiating body heat rather than relying on their movement and has been shown to detect more animals in difficult or dense habitat environments than does visual detection (Lethbridge *et al.* 2019; Cox *et al.* 2023). However, limited studies to date have compared the effectiveness of thermal imaging technology in aerial control programs, and none has compared systematic and habitat-informed search approaches.

Here, we describe the outcomes of two habitat-informed aerial control programs (one with thermal equipment and one without) that were each followed up with an aerial systematic search program using thermal equipment. We assess the effectiveness of each program at reducing target species' populations to below levels required for replacement, provide cost estimate comparisons for the methods and discuss ways forward to improve aerial shooting program outcomes.

Methods

Location

The aerial control programs were undertaken in the following two areas of the Riverina region of southern NSW, Australia: the first, near Ellerslie in the tablelands of southern Riverina, and the second, near Maude in the semiarid region of western Riverina (Fig. 1). The Ellerslie site was mixed tenure, comprising private freehold lifestyle and farming blocks >5 ha, pine plantations and nature reserves. The Ellerslie site comprised 20,055 ha, but not all landholders participated in the program, with five blocks totalling 3226 ha non-consenting to aerial shooting, reducing the effective shooting block to 16,829 ha. The Maude site was a single mixed-enterprise private property on the Murrumbidgee floodplain. The study area was in the north-western corner of the property, comprising 4170 ha and was bounded by the

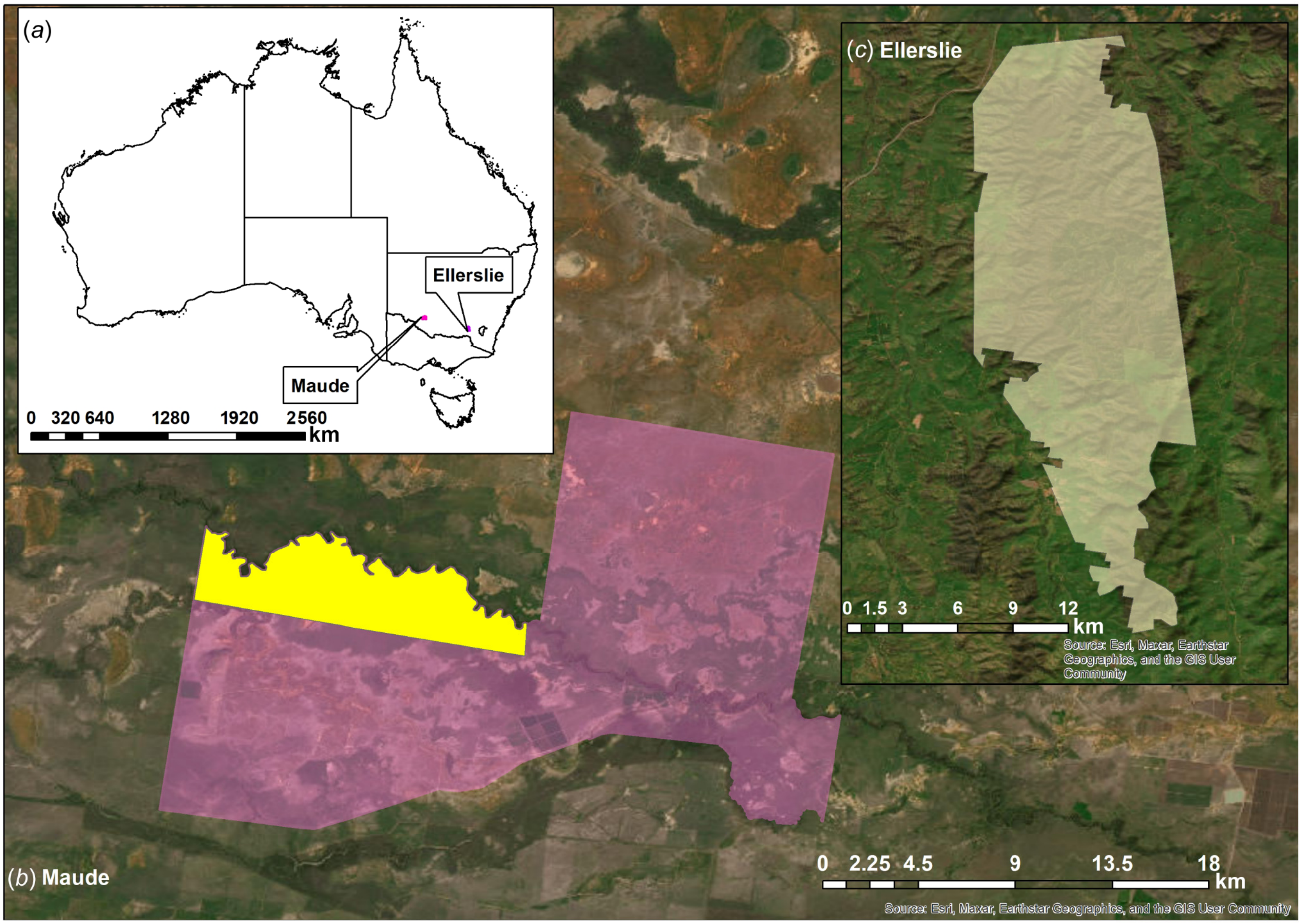

Fig. 1. (*a*) Location of the study sites near Maude and Ellerslie in southern New South Wales, Australia. (*b*) The Maude private property including our 4170 ha study area (yellow) located within the larger property (pink), and (*c*) the Ellerslie control site (cream) comprising private and public land.

Murrumbidgee River to the north and a property boundary of plain wire fencing to the west. Cattle pasture was to the south and east.

Aerial search approaches

Four aerial shooting programs were undertaken across the two sites. A visual habitat-informed aerial shoot was undertaken at the Ellerslie site from 20 to 21 January 2023 and was followed up with a systematic aerial shooting program that utilised thermal technology (the crew included a thermographer, a dedicated thermal imager operator in the rear left position) from 13 to 26 March 2023. A thermal habitat-informed aerial shoot was undertaken at the Maude site from 14 to 18 April 2024 and was followed up with a systematic-with-thermal aerial shoot from 18 to 25 June 2024.

Target animals at Ellerslie were expected to be predominantly sambar deer (*Rusa unicolor*) and goats (*Capra hircus*). Feral pigs (*Sus scrofa*) were expected to be at very low densities. Not all landholders participated in the aerial shooting program (Fig. 2*a*).

Target animals at Maude were pigs. The thermal habitat-informed control program was undertaken for a study on the welfare impacts of visual and thermal aerial shooting of pigs (TE Cox, K Watter, K Stone, J Sparkes, T Blumson, C Findlay, unpubl. data). The hours available for that study were spread across the entire property, not just in the study area, and the focus was shooting as many pigs as possible. The pilot was aware of the upcoming study on the systematic approach but was not aware of its location on the property. The systematic search program occurred only within the study area.

For both the habitat-informed searches, no pre-defined transects were created and crews had access to the entire property/shoot region and were free to determine how much time was spent in any location searching for target animals. The helicopter pilot flew to locations where target animals were thought to occur. Four flights were undertaken during the habitat-informed programs at both Ellerslie and Maude.

Crew configuration for the visual habitat-informed aerial cull comprised the pilot (front right), navigator (front left) and the shooter (rear right). The thermal habitat-informed search used two configurations. At both Ellerslie and Maude,

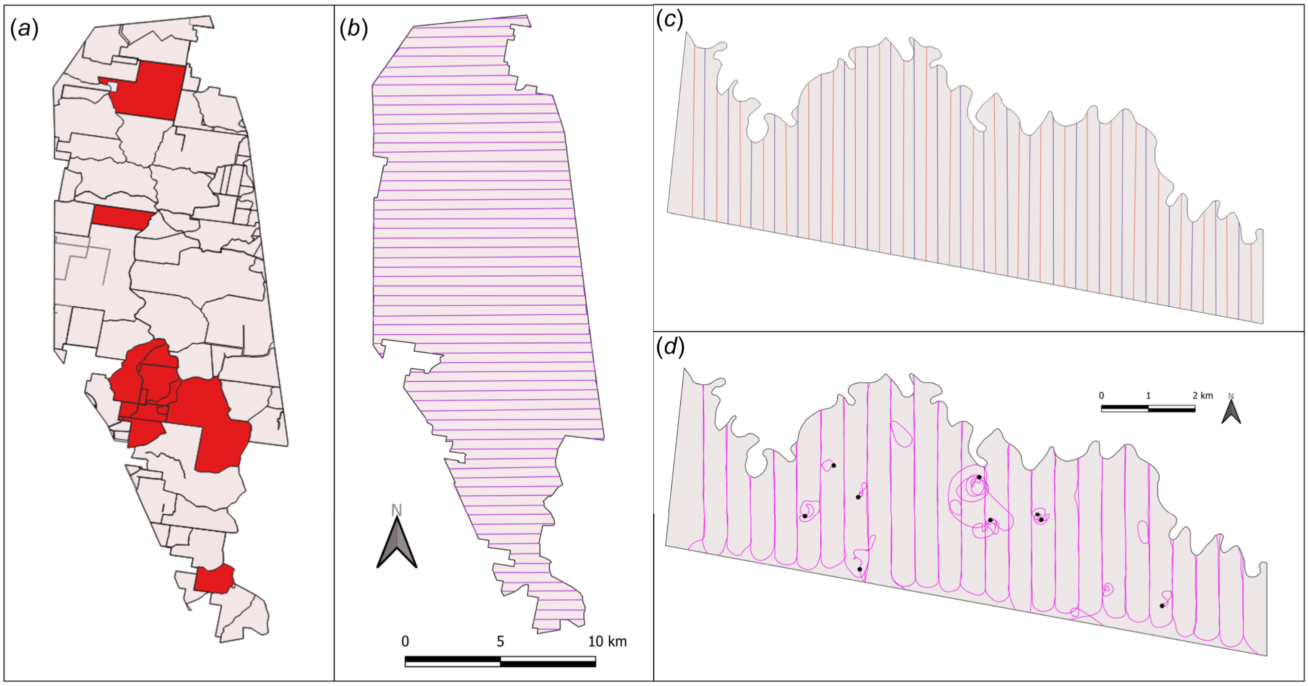

Fig. 2. The two study areas showing (*a*) the non-consenting landholder blocks (red) at the Ellerslie site, (*b*) the transects used for both runs in the Ellerslie systematic approach, (*c*) the offset transects used in the Maude systematic approach with Set 1 (purple) and Set 2 (orange) transect lines, and (*d*) an example of the systematic search pattern flown (pink lines). For (*b*) and (*c*), each set of transect lines were spaced 500 m apart. With a flying height of 91 m above ground level, this resulted in a thermal swath of 278 m, ensuring overlap of the previous and upcoming transect and therefore confidence that the entire study area was searched. For (*d*) the helicopter flew up and back along transects (in this example, the Set 1 transects at Maude) and when a possible target animal was detected, the helicopter came off the transect to engage. Once the target animal was removed (black circles), no further animals could be found, or it was deemed to not be a target, the helicopter resumed flying transects at the point it came off the transect.

a hybrid aerial shooting configuration which comprised the pilot (front right), shooter (rear right) and thermographer (rear left) was used for all flights at Ellerslie and three of the flights at Maude. A thermal aerial culling configuration (Cox *et al.* 2023), which comprised the pilot (front right), shooter (front left) and thermographer (rear left), was also used for one flight at Maude. The two thermal habitat-informed configurations were used at Maude as the flights were undertaken as part of another program assessing the animal welfare outcomes of the two shooting configurations (TE Cox, K Watter, K Stone, J Sparkes, T Blumson, C Findlay, unpubl. data). The hybrid aerial shooting configuration was used in the systematic search program, with the addition of a navigator in the front left. The thermal habitat-informed and systematic-with-thermal flights occurred in the 90–120 min after first light and before last light to maximise the heat differential between target animals and the environment, and to reduce the impact of solar on the thermal image. The visual habitat-informed program at Ellerslie occurred over 2 days, with three flights on the first day and one on the second. All visual flights occurred after sunrise and before sunset.

At Ellerslie, the systematic search approach consisted of parallel transect lines spaced 500 m apart in an east–west orientation (Fig. 2*b*). The helicopter flew up the transect line, turned around and flew back down the same transect line before moving onto the next transect. This allowed both sides of the transect line to be searched both visually and by the thermographer. When a possible target animal/s was detected, the helicopter came off the transect and engaged with the animal/s. When all animals were removed, no further animals could be found, or the detection was deemed not to be a target, the helicopter resumed flying at the point it came off the transect (Fig. 2*c*). The helicopter flew 91 m above ground level at an average speed of 32 knots, resulting in a maximum searchable swath of 278 m (assuming a camera angle of 30°, see 'Thermal equipment' in Supplementary material). This ensured a search area that overlapped the next and previous transect and resulted in full thermal coverage of the study area. After the transects were flown once over the entire study area, they were then flown a second time.

At Maude, the systematic search approach consisted of parallel transect lines spaced 500 m apart in a north–south orientation (Fig. 2*d*). Transect lines were flown in a manner consistent with those at Ellerslie. After the original transect lines were flown once, a second set of transects offset from the original transects by 250 m were flown at the same height and speed as were the original transects. After the offset transects were flown once, flights reverted to the original transects. This alternating pattern was repeated until all flight hours were used (21 h, including within-block ferry time), resulting in five full passes over the Maude site.

Data analysis

To determine search-area effectiveness for the visual habitat-informed programs, a swath of 150 m was assumed for each side of the aircraft, which is equivalent to a helicopter visual survey swath used in density estimation. For the thermal habitat-informed program we used the thermal swath of 278 m on the left and a visual swath of 150 m on the right. We created buffers using these distances for each of the helicopter tracklogs in QGIS (QGIS 2024) to visually represent search area effectiveness and to determine which animals culled during the systematic search would not have been detected using the habitat-informed approach. Only points >50% uncovered by the buffer were considered undetectable. For the systematic-with-thermal programs, the total search area swath was 428 m (the thermal swath plus a visual swath).

Pre-control thermal imaging surveys were undertaken at the Maude site prior to the implementation of the control programs (Todd and Cox 2024) to facilitate estimation of the pest animal population size. To estimate the population size for each species at Ellerslie, we used the non-spatial removal model in the Eradication Progress calculator of the Eradication Decision Support Tool (Gormley *et al.* 2021; landcare.shinyapps.io/EradicationDSS/, accessed 8 October 2024), which implements the catch-per-unit-effort (CPUE) model of Gould and Pollock (1997). CPUE models use successive removals and the relationship between harvest effort, probability of capture and the observed decline in catch over those successive removal events to estimate the abundance of closed populations. We assumed that these populations were closed because of the short period between shooting approaches at each site. We used the removal rate of animals per hour to compare between programs. We also estimated the proportion of animals removed from each population and shooting effort (h km^{-2}) to determine the effectiveness of the systematic methods to rapidly reduce the populations within the study area.

Program cost calculations

We followed guidelines similar to those in Bengsen *et al.* (2023) when calculating the cost of each program. The shooting programs were undertaken using a different type of turbine engine helicopter; the visual habitat-informed program was undertaken in a Bell 206 Jet Ranger helicopter (Bell Helicopters, Quebec), the thermal habitat-informed program was undertaken in an AS350 SD2 Ecureuil (Squirrel) helicopter (Aerospatiale, France) and the systematic-with-thermal programs were undertaken in an AS350 B3 Ecureuil (Squirrel) helicopter (Aerospatiale, France). Because the four programs took place using three helicopter types, we also provide a comparison of all programs using the same helicopter type (AS350 SD2) and adjusted helicopter costs for each program accordingly. This subsequently increased the costs for the visual habitat-informed program and decreased the costs for the systematic programs. We used an AS350 SD2 because it is considered the minimum turbine helicopter type with adequate power margin for a four-person crew, low-level operation. It is a requirement that an observer/navigator sit beside the pilot as a safety measure in NSW (Feral Animal Aerial Shooting Team 2023) and Victorian government run aerial shooting programs. Because this is not a requirement in most other jurisdictions, costs were also calculated without the additional crew member for comparison, again by using the AS 350 SD2, across all programs. The cost for the program is based on the effort inside the study area only and does not include the costs of ferry from the staging area to the study site or the cost of ferry from the helicopters home base to the staging area (but does include any ferry to transects that occurred within the study sites). Distance flown (km) was calculated on the helicopter flight paths that occurred within the study area. On the basis of the distance flown and the number of hours available for the programs, the average ground search speed for the habitat-informed approaches was 25 knots (45 km) h^{-1} and the systematic approach was an average ground speed of 32 knots (60 km) h^{-1}. We used these data to calculate the cost per hour within the study area. Ammunition costs were based on an average of four rounds per animal. The A$ values used in the calculations are provided in Table S1. No support crew, vehicle for the helicopter, crew travel, accommodation, meal or other subsidy costs were included in the calculations. Similarly, the costs of initial purchases of equipment (e.g. firearms, thermal imagers, PPE) were not included. Finally, any planning costs including project management, permitting and compliance (Holmes *et al.* 2015) were not included.

Animal ethics

This work was completed under the Animal Research Authority OAEC-0645 from the Orange Animal Research and Ethics Committee.

Results

The estimated population sizes for each of the targeted species at Ellerslie at the beginning of the visual habitat-informed program were 510 goats (lower confidence limit (lcl) = 271, upper confidence limit (ucl) = 750, s.e. = 114.3), 58 pigs (lcl = 56, ucl = 74, s.e. = 7.8) and 108 deer (lcl = 11, ucl = 227, s.e. = 56.6). In total, 16.9% (n = 114) of all target animals were removed during the habitat-informed program at Ellerslie (Table 1). Specifically, 21% (n = 108) of goats and 10% (n = 6)

Table 1. The overall effort-outcomes of each aerial search approach (visual and thermal habitat-informed and systematic-with-thermal); undertaken at the Ellerslie and Maude study sites.

Session	Shoot type	Species	Total animals removed	%Reduction	Distance flown (km)	Effort (km^2)	Time (h)	Animals removed (animals h^{-1})	Time spent searching (h km^{-2})
1	Visual habitat-informed (Ellerslie)	All	114	16.86	386	116	8.2	13.9	0.05
2	Systematic (Ellerslie)	All	123	21.89	1750.8	749	29.2	4.2	0.17
3	Thermal habitat-informed (Maude)	All	130	41.14	228.8	98	4.9	26.5	0.12
4	Systematic (Maude)	All	178	95.70	996.9	427	16.6	10.7	0.40

Data include the effective search area (Effort (km^2)), which is the effective search area (300 m for the visual habitat-informed and 428 m for the thermal habitat-informed and systematic approaches) by the distance flown; the proportion of the population removed (and cumulative proportions for each flight at each site); how many animals were removed for each flight hour in the study area for each program; and how many hours were spent searching per square kilometre of study site.

of pigs were removed. No deer were seen during the habitat-informed control program (Table 2). From the remaining population, the systematic-with-thermal program removed 21.9% (n = 121) of the remaining target animals (Table 1), including, specifically, 9% (n = 62) of goats, 8.5% (n = 11) of deer (sambar) and 96% (n = 50) of pigs (Table 2). The pre-control aerial survey at Maude estimated pig density to be 7.6 pigs km^{-2} (lcl = 4.7, ucl = 12.1, s.e. = 1.8), suggesting an abundance of 316 pigs (lcl = 198, ucl = 505) in the study area. The thermal habitat-informed program removed 41% (n = 130) of pigs, and the systematic-with-thermal program removed 95.7% (n = 178) of the remaining pig population (Tables 1, 2).

For pigs at Maude, there was a steeper decline in CPUE and cumulative kills by using the systematic-with-thermal approach than by using either of the habitat-informed approaches (Fig. 3). Additionally, there appeared to be a suggestion of an accelerating decline in kill rate (animals^{-h}) for the Maude program (Table 2). The thermal habitat-informed approach also had a steep decline for pigs. However, the visual habitat-informed program failed to result in a decline in CPUE and cumulative kills for any species. The thermal habitat-informed program at Maude had the highest average rate of removal at 26.5 pigs h^{-1} (lowest rate = 23.6 pigs h^{-1}, highest rate = 37.3 pigs h^{-1}), followed by the visual habitat-informed program at Ellerslie (2.8 goats h^{-1}; lowest rate = 2.7 goats h^{-1}, highest rate = 29.3 goat h^{-1}). The average rate of removal for the systematic-with-thermal program at Maude was 10.7 pigs h^{-1} (lowest rate = 0.4 pigs h^{-1}, highest rate = 22.9 pigs h^{-1}), with removals at Ellerslie averaging 3.5 animals h^{-1} (lowest rate = 0.2 deer h^{-1}, highest rate = 2.8 pigs h^{-1}) (Tables 1, 2). Shooting effort (h km^{-2}) was greatest in the systematic-with-thermal programs, with extensive effort applied in the Maude systematic-with-thermal program (0.4 h km^{-2}). The visual habitat-informed program had the lowest shooting effort at 0.05 h km^{-2} (Tables 1, 2).

The habitat-informed search approaches (both visual and thermal) were successful at finding animals; however, only 41.8% and 55% of the study site at Ellerslie and Maude respectively, were searched (Fig. 4). The systematic-with-thermal search approaches found animals both in areas where the habitat-informed searches occurred, but also in areas that were missed. At Ellerslie, 32 individuals (26% of animals removed during the systematic program) were detected outside of the effective visual habitat-informed searchable zones. For the thermal habitat-informed program at Maude, this was reduced to 18 individuals (10%) (Fig. 4). Extensive search effort was achieved for the systematic-with-thermal programs, ensuring that the entire study site was searched both visually and with thermal for each set of transects.

The most expensive part of the aerial shooting operations was helicopter hire. The visual habitat-informed program was the cheapest at A$140.34 per km^2 because of its use of a smaller helicopter type (Jet Ranger) (Table 3). Adding thermal to this approach and using a larger helicopter type (SD2) increased the cost by A$43.02–$183.36 km^{-2} for the thermal habitat-informed approach in NSW and Victoria (where an observer/navigator is required) (Table 3). However, the thermal habitat-informed program was far more effective, with 130 animals being removed in 4.9 h, compared with 114 animals being emoved in 8.2 h by using the visual habitat-informed approach. Within the systematic-with-thermal programs, and for pigs only, cost per square kilometre decreased for each flight/pass of the transects, whereas the cost per pig increased substantially (Table S2).

Discussion

We successfully reduced the pig populations by >95% in both study areas by using the systematic-with-thermal approach; suggesting that rapid localised mainland removal of pigs is achievable. The visual habitat-informed approach removed 11.5% of pigs at Ellerslie and the thermal habitat-informed approach removed 41.2% of pigs at Maude. Neither goats nor deer were effectively managed with either program at the Ellerslie site, with the last shooting runs in both the habitat-informed and systematic-with-thermal programs removing more animals than did the previous runs.

There was a wide range of animal removals per hour over the four programs. Both habitat-informed programs had higher removal rates than did their systematic counterpart, whereas the thermal habitat-informed program had the

Table 2. Detailed effort-outcomes per flight for the habitat-informed approaches, per pass of transects for the systematic-with-thermal approaches and per species targeted for the visual habitat-informed approach at Ellerslie, the thermal habitat-informed approach at Maude and the systematic-with-thermal approach at both sites.

Site	Shoot type	Species	Total animals removed	Cumulative %reduction	Distance flown (km)	Effort (km^2)	Time (h)	Animals removed (animals h^{-1})	Time spent searching (h km–2)
Ellerslie	Visual habitat-informed approach								
	Flight 1	All	8	1.18	141	42	3.0	2.7	0.02
	Flight 2	All	19	3.99	117	35	2.5	7.6	0.01
	Flight 3	All	6	4.88	23.5	7	0.5	12.0	0.00
	Flight 4	All	81	16.86	104.5	31	2.2	36.4	0.01
		Pig	6	10.34	23.5	7	0.5	12.0	0.00
		Goat	108	21.18	362.5	109	6.0	17.9	0.06
	Systematic								
	Set 1 (first pass)	All	62	11.03	702.72	301	11.7	5.3	0.07
	Set 1 (second pass)	All	61	21.89	1048.10	449	17.5	3.5	0.10
	Set 1 (first pass)	Pig	33	63.46	702.72	301	11.7	2.8	0.07
	Set 1 (second pass)	Pig	17	96.15	1048.10	449	17.5	1.0	0.10
	Set 1 (first pass)	Goat	27	6.72	702.72	301	11.7	2.3	0.07
	Set 1 (second pass)	Goat	35	9.33	1048.10	449	17.5	2.0	0.10
	Set 1 (first pass)	Deer	2	1.85	702.72	301	11.7	0.2	0.07
	Set 1 (second pass)	Deer	9	8.49	1048.10	449	17.5	0.5	0.10
Maude	Thermal habitat-informed approach								
	Flight 1[A]	Pig	20	6.33	25.18	11	0.5	37.3	0.01
	Flight 2[B]	Pig	40	18.99	70.53	30	1.5	26.7	0.04
	Flight 3[A]	Pig	27	27.53	53.69	23	1.1	23.6	0.03
	Flight 4[A]	Pig	43	41.14	79.41	34	1.7	25.5	0.04
	Systematic								
	Set 1 (first pass)	Pig	97	52.15	257.24	110	4.3	22.6	0.10
	Set 2 (first pass)	Pig	54	81.18	207.52	89	3.5	15.6	0.08
	Set 1 (second pass)	Pig	23	93.55	193.82	83	3.2	7.1	0.08
	Set 2 (second pass)	Pig	3	95.16	174.04	74	2.9	1.0	0.07
	Set 1 (third pass)	Pig	1	95.70	164.31	70	2.7	0.4	0.07

Data include the effective search area (Effort (km^2)), which is the effective search area (300 m for the visual habitat-informed and 428 m for the thermal habitat-informed and systematic approaches) by the distance flown; the cumulative proportions of the populations removed for each flight at each site; how many animals were removed for each flight hour in the study area for each program; and how many hours were spent searching per square kilometre of study site.
[A]Thermal habitat-informed program using the hybrid aerial culling configuration (Cox *et al.* 2023).
[B]Thermal habitat-informed program using the thermal aerial culling configuration (Cox *et al.* 2023).

highest removal rate of all programs. Part of this is likely to be due to the much higher starting densities at Maude than at Ellerslie. However, where pigs are the target animal, having a thermographer on board seemed to offer an advantage and increased the number of pigs removed. A similar situation is likely for cryptic deer such as sambar, who were only detected during the systematic-with-thermal program at Ellerslie. This may be due to the increased swath of the thermal imager, and the advantage thermal provides in detecting animals that can be difficult to see visually or that have a functional response to seek out refuge during control programs.

Choquenot *et al.* (1999) found that maximum kill rates were dependent on the availability of suitable refuge and the functional response of feral pigs to seek out this refuge during control programs. Data presented here provide a good indication of the functional response of feral pigs at starting densities of 0.5 and 7.6 pigs km^{-2}, and some indication of the functional response of goats and deer at low density, but it is potentially confounded by the use of thermal equipment in some of the programs, and the vastly different shooting efforts applied. A robust estimate of the functional response of animals to control programs requires data to be collected over a wide

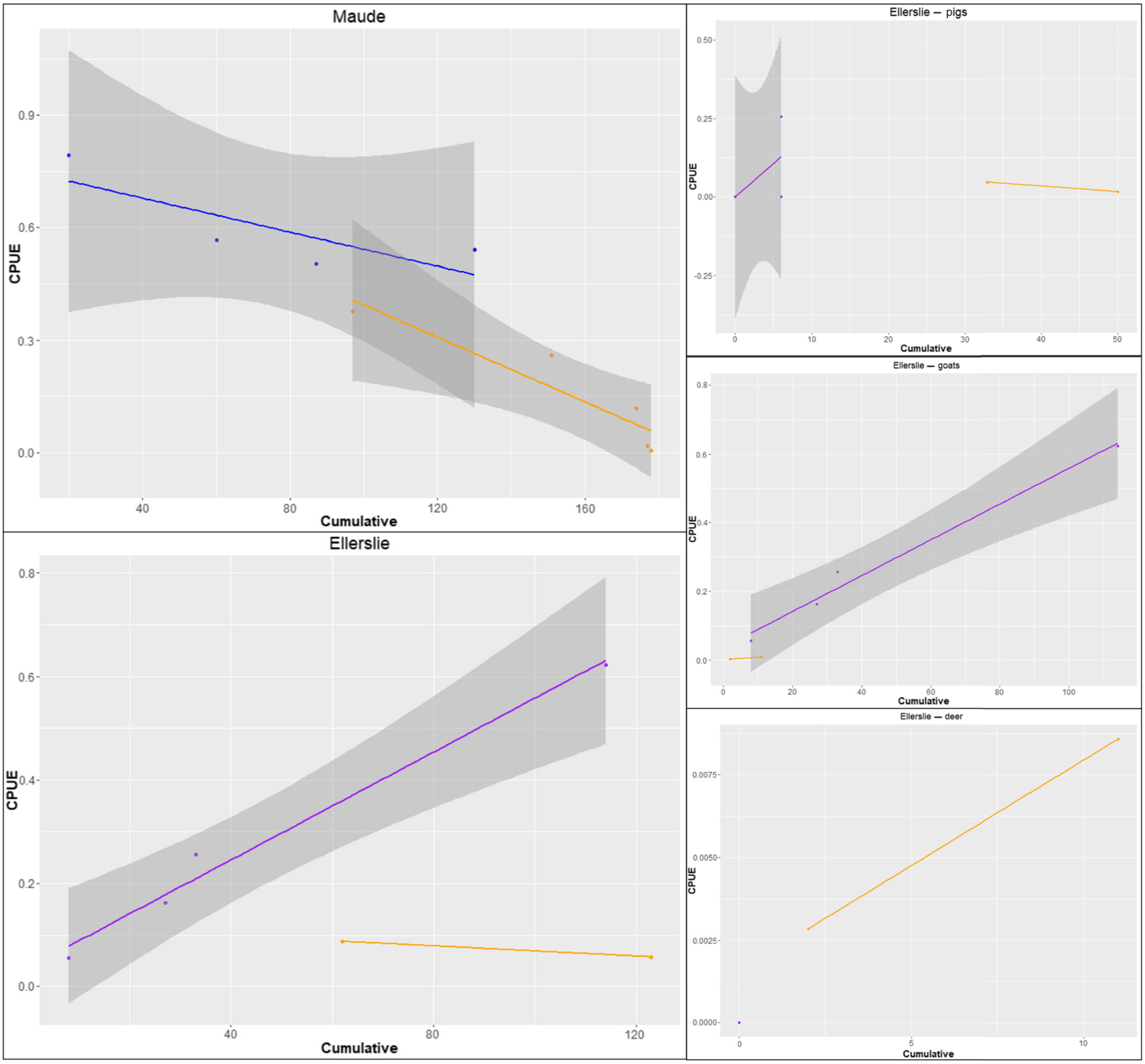

Fig. 3. Catch per unit rffort (CPUE) plots showing the overall cumulative removals at Maude and Ellerslie and for each target species at Ellerslie for each removal type (visual habitat-informed (purple), thermal habitat-informed (blue) and systematic-with-thermal (orange)).

range of starting densities (Bengsen *et al.* 2023), and we would argue, a range of approaches (with or without thermal, systematic or habitat-informed). The data collected within this study will be a valuable addition when included into larger datasets.

The functional response in multi-species programs also requires investigation. It is possible that multi-species control programs such as that at Ellerslie can result in ineffective reductions across all species. Any increase in the number of species (and therefore the number of individuals) targeted leads to a decrease in the chance that any one individual will be targeted. The same amount of effort (h km^{-2}) over a larger target population would result in reduced effectiveness (diminished top–down control) and that this 'switching' between target species could result in some type of prey population stability (Murdoch and Oaten 1975). Understanding the functional response of a multi-species control program may help in understanding why neither the habitat-informed nor the systematic multi-species programs at Ellerslie were effective across all species targeted. The functional response of aerial shooting programs has been investigated only for single species, namely, pigs (Hone 1990; Choquenot *et al.* 1999) and deer (Bengsen *et al.* 2023). Considerably more investigation into this area as it applies to aerial shooting is required.

We only observed a rapid decline in the number of pigs removed during the systematic-with-thermal programs,

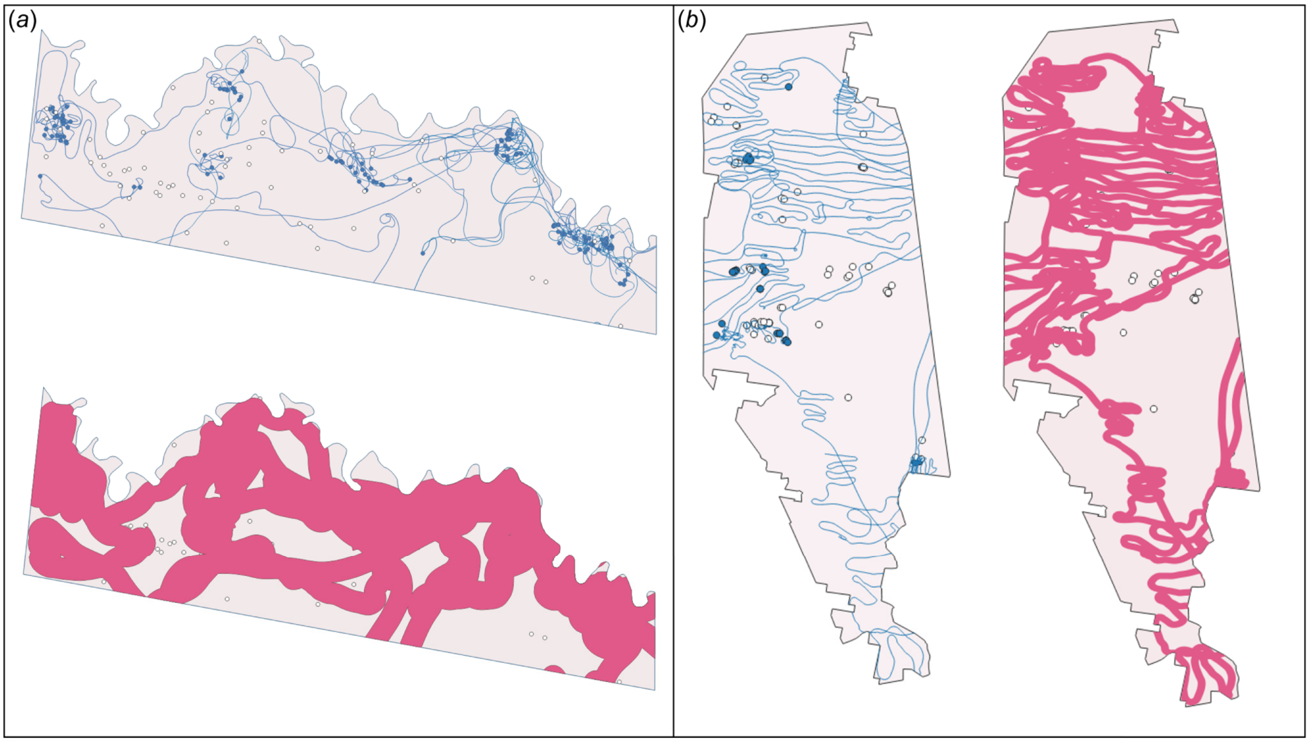

Fig. 4. (*a*) Maude and (*b*) Ellerslie. Animals removed (blue circles) during habitat-informed programs and the corresponding flight paths (blue lines) in comparison to where animals were removed with the systematic-with-thermal search pattern (white circles), which would have been missed using a habitat-informed search approach (Maude: $n = 18$, Ellerslie: $n = 32$). Only circles with >50% uncovered were considered undetectable. A buffer of 278 m on the left side and a 150 m on the right side of the tracklog was used to visually represent search area effectiveness for the thermal habitat-informed approach (*a*, Maude). A buffer of 150 m on each side of the helicopter tracklog was used to visually represent search area effectiveness for the visual habitat-informed search approach (*b*, Ellerslie).

Table 3. The costs (A$) of each aerial search approach undertaken at Ellerslie in January (visual habitat-informed) and March (systematic-with-thermal), and Maude in April (thermal habitat-informed) and June (systematic-with-thermal) 2024.

		Program costings			Alternate costings (SD2)	
Program	Shoot type	Cost	Cost per animal	Cost per square kilometre effort	Cost per square kilometre effort	Cost per square kilometre effort[A]
1[B]	Visual habitat-informed (Ellerslie)	A$16,251.62	A$142.56	A$140.34	A$142.71	A$133.25
2[B]	Systematic (Ellerslie)	A$116,254.84	A$945.16	A$155.14	A$155.14	A$130.48
3[C]	Thermal habitat-informed (Maude)	A$17,955.40	A$138.12	A$183.36	A$183.36	A$176.68
4[D]	Systematic (Maude)	A$67,067.49	A$376.78	A$157.19	A$157.19	A$132.52

Because three different helicopter types were used across the four programs, costs utilising the same helicopter type are also provided for comparison (alternative costings, SD2). Because of the requirement of an observer/navigator in New South Wales and Victorian government programs, costings without this additional crew member are also provided for other jurisdictions (alternative costings, SD2[A]). For detailed information on the cost per flight for the habitat-informed approaches and per pass of transects for the systematic-with-thermal approaches at both sites, see Table S2.
[A]Costing if the program occurred in an AS350 SD2 Squirrel without a dedicated observer.
[B]Costings based on using a Bell 206 Jet Ranger.
[C]Costing based on using an AS350 SD2 Squirrel.
[D]Costing based on using an AS350 B3 Squirrel.

with the systematic program at Maude showing an increasing decline in kill rate (animals^{-h}) with multiple passes of transects. This may be because pig density needs to fall below some critical value before shoot rates decline (Choquenot *et al.* 1999), and this was not achieved until the systematic program (the second shoot over the populations). The systematic-with-thermal approach needs to be evaluated as a first shooting approach to determine whether this result is an artefact of being the second shoot/perturbation event over the population. Substantial reductions (~80%) in pig populations via intensive visual shooting programs have been reported (Saunders and Bryant 1988; Hone 1990); however, these programs all used a systematic approach with almost complete coverage. This suggests that a consistent and systematic application of effort with complete coverage is key to rapidly reducing pig populations. The systematic approaches resulted in no areas being left unsearched. Likewise, most pigs and all deer removed during the Ellerslie systematic program were found in areas not searched by the visual habitat-informed crew. This highlights the importance of ensuring all areas, regardless of assumptions regarding suitability, are searched during a control program, particularly when high rates of reduction are required, and particularly in high-quality habitat areas. With the combination of the systematic search pattern and high-quality thermal imaging equipment, there should be greater confidence that an area has been thoroughly searched and that those pigs that have traditionally been difficult to find because of their avoidance behaviour, have in fact, been detected.

Previous research on aerial shooting for pigs has suggested 0.13–0.19 h km^{-2} search effort is the minimum required to reduce pig populations by 70% in high-density areas (Hone 1990; Saunders 1993). However, these were all systematic programs and likewise, only our systematic approaches achieved this level of search effort (Table 1). There is no recommended search effort for the habitat-informed approach, but based on the value for systematic search effort, there was insufficient effort applied during both habitat-informed programs. Crews in both habitat-informed approaches were free to distribute their effort as they saw fit. This is 'business as usual' for feral animal control where crews make the decision about where in an area the effort is spent. This could be driven by both the perceived number of animals in an area and the number of hours available to the crew during a program. It is possible that the habitat-informed crews simply had too few hours spread over too large an area. Care should be taken in planning habitat-informed programs to ensure sufficient hours are provided for the size of the area to be managed.

While the systematic programs were effective at rapidly reducing pig populations at both sites, it is less clear what is required for goats and deer. Bayne *et al.* (2000) reported on the functional response of goats familiar with aerial shooting to seek shelter and hide, with 50% of goats in that program not seen by the helicopter crews. It seems unlikely that this is what occurred at Ellerslie, with the visual habitat-informed program removing almost twice as many goats as did the follow-up systematic-with-thermal program. In this case, it appears the presence of non-consenting landholder blocks that provided areas of refuge contributed to the ineffectiveness of the program at Ellerslie. At least 278 goats were captured on the thermal footage within these no-shoot blocks during the systematic-with-thermal program. This suggests a capacity for rapid reinvasion of the area by goats and highlights the importance of getting all landholders on board during control programs, particularly those in the middle of the program area.

The systematic-with-thermal approach had benefits from a more general pig management objective. At least 50–78% of pigs need to be removed in a program to ensure removal outpaces replacement in the population (Gentle and Pople 2013). Whereas neither of the habitat-informed approaches achieved this, it was achieved using the systematic approach after the first pass of transects at both Ellerslie (63.5%) and Maude (53.0%). At an average cost of A\$129.21–\$136.27 km^{-2} of search effort (AS350 SD2 rates), this is a similar investment per square kilometre to the visual habitat-informed rate (A \$133.25 km^{-2}, AS350 SD2 rates), yet with a reduction in the pig population that could outpace replacement. A reduction of 82.2% at Maude and 96% at Ellerslie of the estimated pig population was achieved after the second pass of transects at a cost of A\$259.50 (Ellerslie) and A\$270.34 (Maude) km^{-2} (AS350 SD2 rates). These values give an indication of what a rapid-removal feral pig management program might cost in medium- and high-quality pig habitat areas.

Overall, systematic-with-thermal programs were more expensive than were habitat-informed programs. The cost of each pass of transects within the systematic-with-thermal program decreased as the transect runs became more efficient and less time was spent coming off-transect chasing pigs. This also meant that the cost per pig increased across the program as pig numbers declined, with more flight time spent not finding pigs. It is expected that this would occur during an eradication program, with more time spent searching for animals as the population decreases. This is true for all eradication efforts where the costs exponentially increase per animal as density declines.

Rapidly and reliably reducing pest animal numbers not only has important environmental and agricultural implications, but will also be critical in the event of an exotic disease outbreak. For example, it is acknowledged that feral animals, particularly feral pigs, could play a significant role in the maintenance and spread of FMD in Australia. Pech and Hone (1988) reported a 95.7% reduction in feral pig numbers in <21 days would be required to eliminate FMD at equilibrium prevalence from a population at threshold densities of 2.3–14 pigs km^{-2}. Our two systematic-with-thermal programs have shown that a 95.7% population reduction in <21 days is possible via aerial shooting alone at both the small and large scale and at very low and moderate pig densities. Neither habitat-informed approaches were able to achieve this. Further work on effective aerial control of other potential hosts of FMD such as goats and deer are clearly required.

Although neither of the habitat-informed approaches achieved the level of population reduction required to eliminate FMD at equilibrium prevalence, habitat-informed approaches may still play a vital role in exotic disease outbreaks. This approach could be used initially to target known hotspots of feral pigs within the outbreak area, as we have done here. Incorporating high-quality thermal imaging equipment into a habitat-informed approach would increase the likelihood of achieving the required knockdown. However, given that no habitat-informed approach has yet been reported to achieve the required 95.7% reduction, direct comparison of the approaches with sufficient effort is required to determine how effective the habitat-informed approach could be in such a scenario. The functional response of pigs to seek shelter during aerial shooting may be a factor, particularly for the visual habitat-informed program. However, the results from the thermal habitat-informed program hint at the effect thermal can have, particularly on any low-density refuge that can affect functional response.

Recommendations

The systematic approach to searching for animals produced the greatest reduction in feral pig numbers from the study areas, but had little effect on goat and deer numbers in a multi-species program. The implementation of a systematic shooting program can provide confidence that an area has been searched thoroughly, removing personal biases when deciding on areas to search. This can ensure that all animals in an area are likely to be targeted. The habitat-informed approach often misses or excludes large tracts of land because of perceived unsuitability for the target species. However, in high-value environmental or agricultural areas or in the event of a disease outbreak, no part of the region should be ignored, regardless of how unsuitable the habitat might be perceived to be. Furthermore, the addition of high-quality thermal imaging equipment and a dedicated thermographer are required to increase confidence in the likelihood of detecting individuals that exhibit avoidance behaviour in the presence of helicopters, particularly in areas where aerial shooting has been undertaken previously. This applies not only to the systematic search approach, but to the habitat-informed approach as well. The addition of a thermographer to a habitat-informed aerial shooting program can reduce costs per square kilometre by removing more pigs per hour and is strongly recommended. However, the selection of appropriate thermal equipment (Cox *et al.* 2021) needs to be considered. The implementation of a systematic-with-thermal search approach now needs to be conducted as a first-shoot program.

Further research on the functional response of deer and goats to aerial shooting is required. Neither of the programs implemented at Ellerslie achieved any management-level reductions in these populations, despite extensive effort in the systematic program. This may have been a function of this being a multi-species program, resulting in diminished effort across all species. Further investigation into the effectiveness of multi-species programs is urgently required.

Where habitat-informed programs are being implemented, it is necessary to ensure that sufficient effort (h km^{-2}) is being applied. Doing a little over a large area will not achieve appropriate levels of population reduction to outpace replacement. Programs that remove too few animals are doomed to be repeated year on year, and even though they may result in high body counts in the long term, they provide little actual benefit in reducing pest animal impacts (Warburton *et al.* 2012). Either appropriate funding needs to be applied for the area of control, or the area of control needs to be reduced to accommodate the level of funding.

Supplementary material

Supplementary material is available online.

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Data availability. Data are available from the corresponding author.

Conflicts of interest. The authors declare that they have no conflicts of interest.

Declaration of funding. This work was funded through the Riverina Local Land Services Pest Animal Levy.

Acknowledgements. We thank H. Cullenward for access to his property. We thank our pilot C. de Pagter and our two aerial shooters M. Davis and J. Christie-Johnston. We also thanks D. Forsyth and A. Bengsen for their feedback on earlier drafts.

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