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An assessment of thermal detection in aerial culling of feral deer and pigs in northern Australia

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ABSTRACT

Context. Aerial culling can be a highly effective method for reducing populations of medium to large herbivores such as feral pigs (*Sus scrofa*) and deer (e.g. chital, *Axis axis*). In temperate Australia thermal cameras can improve the detection of animals and therefore the efficiency of aerial culling programs. In a warmer climate the thermal contrast between mammals and their surrounding environment will be less marked. The benefits of thermal detection in aerial culling under these conditions needs to be assessed. **Aims.** To quantify the efficiency (cost per animal removed) and effectiveness (culling rate) of thermal detection compared to conventional (unaided visual) approaches during aerial control of feral deer and pigs in a warm, tropical climate environment near Collinsville, Queensland, north-eastern Australia. **Methods.** Data from video recordings taken during a chital deer control program were analysed to compare culling rates and animal detections between thermal and conventional shooting runs. **Key results.** The thermal camera successfully detected animals under a variety of temperatures and in a range of canopy densities. The use of the thermal camera did not significantly increase the culling rate (number of animals removed h^{-1} or number of animals removed km^{-1}) compared to conventional detection. There were no consistent differences in the time taken to detect animals (search time) across thermal or conventional runs. **Conclusions.** Using thermal imagery is expected to provide significant gains in aerial culling rates over conventional detection when animal densities are lower and in dense canopy cover where animals are difficult to detect. **Implications.** Selective use of thermal imagery in northern Australia could yield benefits in future culling programs, but further assessments are recommended to optimise control practices.

Keywords: canopy cover, cost-effectiveness, culling rate, efficiency, helicopter, population control, shooting, visual detection.

Introduction

Aerial culling (i.e. aerial shooting from a helicopter) can be a highly effective method for reducing vertebrate pest abundance (e.g. 80% reduction in feral pigs, Saunders and Bryant 1988). It is used routinely in Australia by landholders, local authorities, and other pest managers in a range of environments to manage medium-large sized herbivores and is considered a suitable control technique for managing feral pigs (*Sus scrofa*) and deer (e.g. chital, *Axis axis*, and rusa, *Cervus timorensis*) (PestSmart 2021; Sharp *et al.* 2022; Terrestrial Vertebrate Working Group 2024). Recent approaches have further refined aerial culling practices for deer in Australia through examining shooting operations. The effectiveness and costs for culling chital and fallow (*Dama dama*) deer, and the likely proportional population reductions for given effort, have been extensively modelled (Bengsen *et al.* 2023) and support efficient planning and resourcing for conducting effective control programs. As demonstrated from sambar deer (*Rusa unicolor*) aerial culling, catch-effort data recorded during operations (with conditions) can be used to estimate the efficacy of control without additional pre (and post) monitoring, which can be expensive (Ramsey *et al.* 2023). Despite such advances, there remain fundamental issues requiring further study to achieve improved aerial culling programs

Aerial culling uses a helicopter as a platform to locate and then kill the target species in a pre-defined area. The effectiveness of aerial culling depends heavily on the ability to locate (i.e. visually detect) the target species in the environment. When populations are at high densities and habitats permit high detection probability (e.g. open habitats with sparse canopy cover), culling rates (i.e. animals shot h^{-1}) from aerial shooting are typically high. In habitats with dense canopy cover, tall forests (where the helicopter needs to operate at a higher altitude above ground level), or where there are fewer animals, detecting animal groups becomes more difficult, and culling rates are lower. Under these conditions, tools or technologies to improve the ability to detect animals may increase removal rates but require assessment to ensure that they remain cost effective.

In southern Australia, recent culling operations suggest that thermal-assisted aerial culling (TAC) can dramatically improve culling efficiency (Cox *et al.* 2023). TAC specifically uses a thermal camera operator, seated in the rear of the helicopter behind the shooter, to help locate groups of animals that can then be dispatched by a marksman, seated in the front next to the pilot (Cox *et al.* 2023). Other seating or equipment configurations, for example where the camera operator sits adjacent to the shooter, or a thermal scope is used, are considered a 'hybrid aerial culling approach' (Cox *et al.* 2023). Thermal imaging equipment relies on a contrast between the body temperature of the target pest animal and the environment. In southern Australia, under typical cool conditions, TAC has been highly effective for targeting feral deer and pig populations. In a study by Cox *et al.* (2023) in which thermal imaging equipment was used, the culling rate was doubled compared to conventional aerial shooting using unaided visual detection alone. Importantly, the TAC prevented wounded animals from escaping, reducing animal welfare concerns (Cox *et al.* 2023). The addition of a thermal camera operator can help remove more pigs per hour, and reduce the per unit area cost of aerial culling in selected habitats (Cox *et al.* 2025). The use of thermal cameras in aerial control programs in northern Queensland may help control deer and pigs that are difficult to locate in areas that have expansive vegetation canopies. These areas are not well-suited to conventional aerial culling (or ground control or trapping) given that visibility and ground access is limited. However, the use of thermal detection in aerial shooting programs remains largely untested in northern Australia. One example of its use in sub-tropical Australia was the detection and removal of the last rusa deer in an eradication campaign on Wild Duck Island, off the central Queensland coast (Amos *et al.*, In press). It is expected that thermal detection may not be as effective in warmer sub-tropical climates where there is a relatively short window of time with sufficient thermal contrast between the target pest and the surrounding environment. The technique also incurs an additional cost which must be justified, usually with a higher culling rate. Research is needed to clearly determine whether the addition of thermal detection is an improvement to the existing conventional aerial culling program in these areas of northern Australia.

The aim of this study was to determine the efficacy (culling rate) and efficiency (cost per animal removed) of conventional aerial culling, with and without thermal assistance, at Collinsville in northern Queensland. Data on time to detect feral deer and pigs and culling rates were collected and compared during aerial shooting flights conducted with or without thermal assistance under different vegetation and weather conditions. This information is used to quantify and compare the outcomes of aerial culling using thermal cameras with conventional aerial culling in north-eastern Australia.

Methods

Study area

Aerial culling of chital deer and rusa deer was undertaken by Whitsunday Regional Council (WRC) in July and August 2024 near Collinsville, Queensland, north-eastern Australia (Fig. 1). The program targeted deer but feral pigs and wild dogs (*Canis familiaris*) were also culled opportunistically. The study area (1996 km^2) comprises 12 cattle-grazing properties along the Bowen and Burdekin Rivers and tributaries ~100 km SW of Bowen. The large site contains contiguous chital deer and pig populations with spatial variation in densities. Preliminary aerial surveys undertaken in 2023 recorded areas of high deer and pig densities (up to 48.3 deer km^{-2} and 17.3 pigs km^{-2}, Gentle *et al.* 2024), although densities were not uniformly distributed across the site. The climate is sub-tropical and the summer-dominant rainfall averages 706 mm per annum (Collinsville Post Office 033013; www.bom.gov.au/climate/data, accessed 15 September 2025). Mean daily minimum and maximum temperatures range between 9.2 and 34.2°C year round, and between 9.2 and 25.1°C in the coolest month (July). Collinsville was considered an appropriate test site for thermal detection as deer and pigs are often difficult to find there, sheltering in heavy vegetation cover (e.g. rubber vine [*Cryptostegia madagascariensis*], tall grass, tree canopy) along water courses.

Aerial culling

Animals were culled from a Robinson R66 turbine helicopter. The shooter used a .308 Winchester semi-automatic rifle (Wedgetail WT25) fitted with an Eotech 518 holographic sight, and used 130-grain hollow-point or 150-grain soft-point ammunition. Culling forays ('runs') were conducted either with or without a thermal camera operator. Animal groups were detected either through visual detection only (hereafter 'conventional' culling) by the aircrew or through the additional assistance of a thermal camera operator. An experienced thermal camera operator detected animal groups and provided the helicopter-borne thermal imagery via a 12-inch HD output screen to the shooter. The conventional

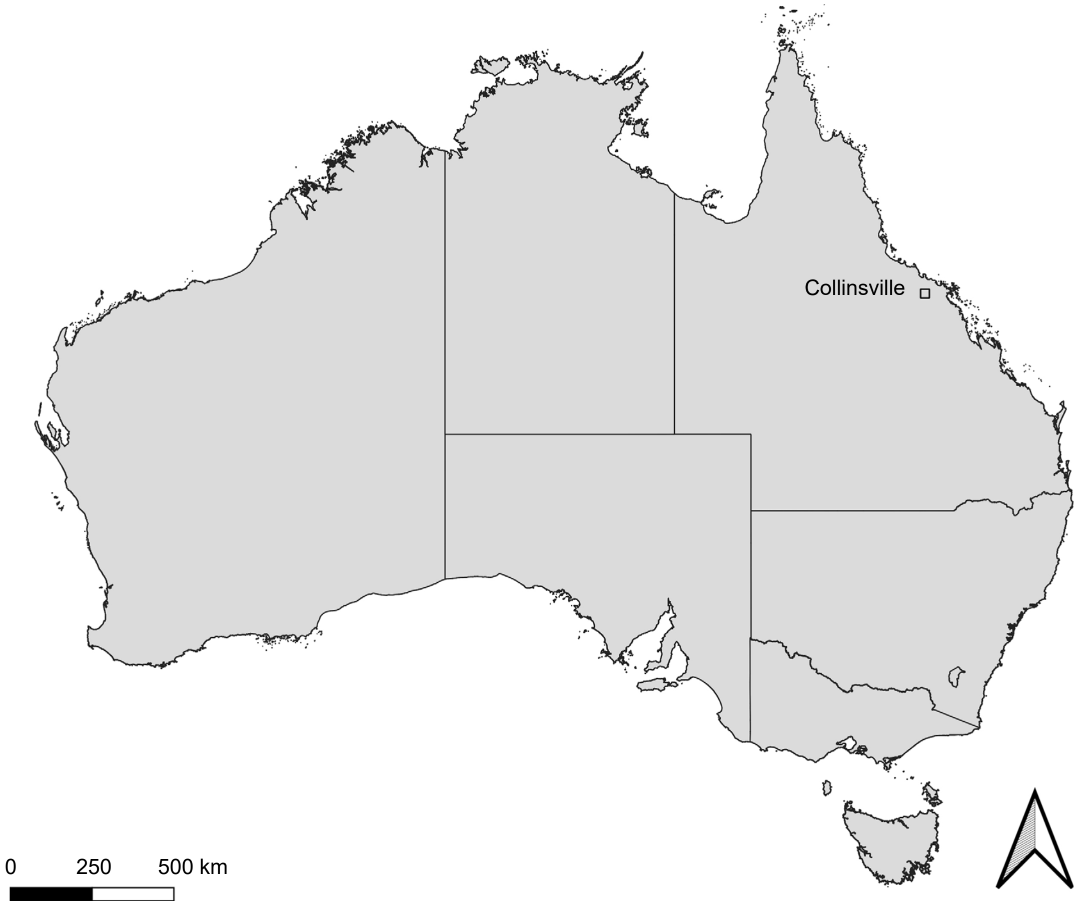

Fig. 1. Location of Collinsville study area in north-eastern Australia.

shooting runs consisted of a pilot (seated front right) and shooter (rear right). During the thermal shooting runs, the thermal camera operator was seated in the front next to the pilot. Shooting runs (~2–3 h duration) were mostly conducted in early morning and late evening to optimise conditions for thermal contrast. Additional runs were also occasionally undertaken during other periods of the day following flight delays and rescheduling (e.g. due to morning fog) to help meet operational requirements. To minimise potential for bias, paired runs (i.e. matched time of day periods for thermal and conventional runs) were also undertaken within two low-deer-density areas in the study site (TC and HH). Animals were shot in accordance with the 'Model Code of Practice for the Welfare of Animals: Feral Livestock Animals: Destruction or Capture, Handling and Marketing' (Standing Committee on Agriculture, Animal Health Committee 2002) and the 'National Standard Operating Procedure: Aerial Shooting for Feral Pigs' (Terrestrial Vertebrate Working Group 2024).

Thermal equipment and observation

We used an infrared thermal imaging camera (Jenoptic VarioCam980, 1084 × 760 HD, Infratec GmbH, Dresden) stabilised by a cinematic strong arm camera mount mounted via a harness to the camera operator. The infrared camera was aligned with a 2.5-W laser and a Sony ADX-55 4K video camera, and the video feed was transferred via HDMI to a 12-inch HD screen presented in front of the operator. The camera was fitted with a 30-mm-wide field-of-view lens which, in conjunction with the laser, directed the pilot and shooter to the location of the heat signature being viewed by the camera operator (Cox *et al.* 2023; J. Munn, pers. comm., August 2024).

In a typical TAC operation, the camera operator is seated beside the shooter; however, because the shooter preferred to sit behind the pilot, as per the conventional culling programs conducted by WRC, the operator was moved to sit beside the pilot, resulting in the 'hybrid aerial culling' configuration (Cox *et al.* 2023). When an animal group of interest was detected, the thermal operator verbally and visually indicated to the pilot and shooter the location of the group, which was subsequently detected and pursued for culling.

Data capture

A GoPro® video camera (Hero 12 Black), with time stamp, recorded shooting runs and events (from detection to culling, see 1–4 below). The camera was mounted to the seat support pillar behind the pilot and adjacent to the shooter, orientated to provide an unobstructed view of the culling. Following completion of the operation, video footage was examined visually by an observer to record: (1) species and group size detected; (2) time of detection; (3) scale of canopy cover where the group was detected (open, sparse, intermediate, dense); (4) time of first shot and last shot per group; and (5) number of animals culled.

The total time and distance of each shooting run, and the periods of time ferrying to and from shooting areas, were also calculated via video footage, GPS flight logs and flight records. Tallies (via hand-held tally counters) of each animal taxa culled were also recorded by the pilot to enable comparison with historical culling records.

Climatic conditions (air temperature, °C, and relative humidity, %) were recorded at 5-min intervals using data loggers (Hobo MX2301A) placed on board the aircraft and under shade at the landing zone.

On a sample of thermal shooting runs, the thermal camera operator used a digital voice recorder to note when animal groups were first detected and whether the detection was by thermal camera or visual observation (by any observer in the helicopter). Where no detection method was recorded for animal groups, either through recorder or operator failure, these were considered 'unknown'. Start and stop times were also recorded when using thermal detection within each run.

Following each thermal flight, the thermal camera operator provided a subjective rating on a scale from 1 (not usable) to 5 (excellent) for the application of thermal imagery (e.g. ability to detect animals, thermal contrast) and the need for thermal camera to detect groups on the run (e.g. reliance on thermal vs visual detection of groups).

Analysis

Culling rates

Descriptive statistics were initially used to identify differences in the number of animals (deer, pigs or wild dogs) removed per unit effort (hours or kilometres flown) during the thermal and conventional aerial shooting runs. Offtake of all species (primarily chital deer, but also feral pigs and wild dogs) was summed to determine the total cull. Culling rates were calculated for both the active shooting period (i.e. full time period − time on the ferry to and from shooting areas = active shooting period), and the shooting period including ferry time between the landing zone and shooting area.

Given that the data were not normally distributed, the non-parametric Wilcoxon rank-sum test was used to determine whether mean values in the animals removed h^{-1} or km^{-1} were significantly different (at the $P = 0.05$ level) between thermal and conventional detection. Statistical analysis was completed in R 4.0.5 (R Core Team 2021).

Time to detection

If the thermal camera increased the probability of detection, it would be expected that the average time taken to locate animal groups would be reduced compared to visual detection alone. The time to initial detection for the two methods was determined from recorded video footage and was the time (min:sec) taken to detect a group after initiating the search. The search time restarted immediately after the previous group was culled and the 'fly-back' procedures were completed. Survival analysis was used to compare the time to detection of animal groups on thermal runs with conventional shooting runs. The non-parametric Cox's proportional hazard regression model (Cox 1972) was used to determine whether the time to detection of an animal group during the aerial culling was influenced by the 'factors' detection method (thermal or conventional), time of day (early morning, midday, late afternoon), species (deer, pig or all species combined), relative animal species density (low, medium, high), canopy cover (open, sparse, intermediate, dense), and shooting foray (run) number (1–20; numbered in sequence), and the continuous covariate group size. Shooting run was considered as a continuous variable to allow for any potential changes in animal behaviour (e.g. increased concealment, evasiveness) across runs following increased exposure to aerial culling. The relative deer density in each culling area was ranked as either low, medium or high based on historical aerial culling and observations, current distribution and local knowledge (B. Fuller, WRC, pers. comm., 2024). Survival analysis was considered appropriate given that each animal group is effectively undiscovered or 'alive' until their detection. Survival rates over time can thus be a proxy for examining the speed of detection, with faster detection reducing survival time. All factors, covariates and plausible second-order interactions were modelled using *coxph* in R in an initial model and tested for significance using analysis of deviance, with non-significant factors sequentially removed from the model. Likelihood ratio test results indicated significant differences between the groups (Venables and Ripley 2002).

Pursuit time

Pursuit time (time between detection and first shot) for each animal group was also compared between the thermal and conventional detection methods. Survival analysis was used to determine whether the use of thermal detection (or other potential contributing factors and covariates described above) influenced pursuit time.

Initial detection of animal groups by thermal or conventional detection

The percentage of animal groups initially detected by either conventional or thermal means was examined within thermal shooting runs. This provides a measure of the relative ability of each detection method (thermal or conventional) to detect animal groups under the same environmental conditions.

Group size detected

During aerial culling operations, small groups with fewer individual animals can be more difficult to detect than large groups with many individuals. Thermal detection may offer advantages over conventional detection, especially when group size is small. To examine this, the average group size and distribution of group sizes detected were compared using a Wilcoxon rank-sum test and Kolmogorov–Smirnov test, respectively, between thermal and conventional shooting runs, and periods within thermal shooting runs with and without thermal assistance.

Comparative cost-effectiveness – culling with and without thermal assistance

The rates and costs of aerial culling, with and without a thermal camera, were compared using culling metrics from video footage. Costs were collated from WRC and represented the economic outlay associated with delivering the aerial culling program, including GST (where applicable), and were inclusive of helicopter hire, fuel, ferry and ammunition. Labour and travel expenses for the shooter were not included in the final values. The thermal camera operator was contracted at \$1000 AUD day^{-1} including travel time plus travel expenses. The number of animals h^{-1}, animals km^{-1} and cost (\$ AUD) animal^{-1} removed was calculated from the tally of animals culled per program and helicopter GPS track logs (hours and kilometres flown).

Ethics approval

This study was approved by the Queensland Department of Primary Industries Community Access Animal Ethics Committee (CA 2024/05/1860).

Results

Culling program

A total of 20 flights (10 per trial period) were completed during winter (Trial 1, 22–25 July; Trial 2, 19–22 August 2024). Collectively, 14 thermal runs (four in low, six in medium, and four in high animal density areas) and six conventional runs (two in low and four in high animal density areas) were flown across both trial periods. Culling removed 1881 animals (comprising 1365 deer, 508 pigs and 8 wild dogs) recorded in 41.6 h of video (Table S1). Most culling was conducted in high animal density areas (1075 animals in 20.7 h over 8 runs), with the remaining split between medium (501 animals in 10.7 h over 6 runs) and low density areas (305 animals in 10.3 h over 6 runs).

Conditions were cool to warm during Trial 1 (daily minimum–maximum temperatures, 2.2–28.1°C). Overnight minimum temperatures increased each consecutive day during Trial 1, reaching 12.6°C on 25 July. Daily temperatures were generally warmer in the second trial period, ranging from 10.9 to 31.9°C (Fig. 2).

The thermal camera was successfully used to detect animal groups across all 14 flights during the two trial periods, under a variety of temperatures. The thermal camera operator considered conditions to be sufficiently favourable for thermal camera use for the entire duration of eight thermal flights (~57%). However, there were at least some periods during six thermal flights (~43%) where the thermal camera was either turned off (not usable due to ambient conditions) or of limited use due to high animal densities allowing high rates of animal detections visually (Fig. 2).

Culling rates

Three groups of animals could not be identified to species level in the video footage and were excluded from offtake analysis. The number of animals culled in nine groups across five thermal shooting runs could not be visually confirmed via the video footage, due to either dense canopy cover, poor lighting or incorrect alignment of the video camera. To avoid a spurious culling tally from excluding these groups, the number culled (rounded down to the nearest integer) for these groups was conservatively estimated using the average number of shots (discernible in the video footage) to dispatch each species from the remaining (thermal culling) data (M. N. Gentle, unpubl. data).

Culling rates (animals h^{-1} and animals km^{-1}) of deer, feral pigs and wild dogs during each shooting run, including ferry time, are provided in Supplementary material Table S1. There was no significant difference in the animals removed h^{-1} between the detection methods (W = 38, P = 0.77). The mean number of animals (deer, pigs and dogs) removed h^{-1} during the entire thermal shooting runs (n = 14) was 46.5 (s.e. = 4.7) compared to 40.7 (s.e. = 10.4) during the entire conventional shooting runs (n = 6). After accounting for ferry times, the mean number of animals removed h^{-1} during thermal shooting runs was 55.3 (s.e. = 5.1) compared to 67.9 (s.e. = 12.4) during the conventional runs. Similarly, there was no significant difference between culling offtake after accounting for ferry time (W = 56, P = 0.27).

When culling rates were examined per kilometre, there was no significant difference (W = 36, P = 0.65) in the mean number of animals removed km^{-1} during entire thermal (0.9, s.e. = 0.1) and conventional (0.8, s.e. = 0.2) runs. There was also no significant difference between thermal and conventional runs following correction for ferry distance (W = 53, P = 0.39).

Lastly, culling rates were compared during paired runs conducted within low deer density areas in the study site (TC or HH), but with differing detection methods (visual or thermal). Runs 1 vs 4 (HH area) were conducted across consecutive afternoons, while runs 13 vs 14 were conducted consecutively in the same day (TC area). Offtake during thermal runs was greater than conventional runs in both area HH (27.9 vs 23.7 animals h^{-1}) and area TC (60.3 vs 13.8 animals h^{-1}).

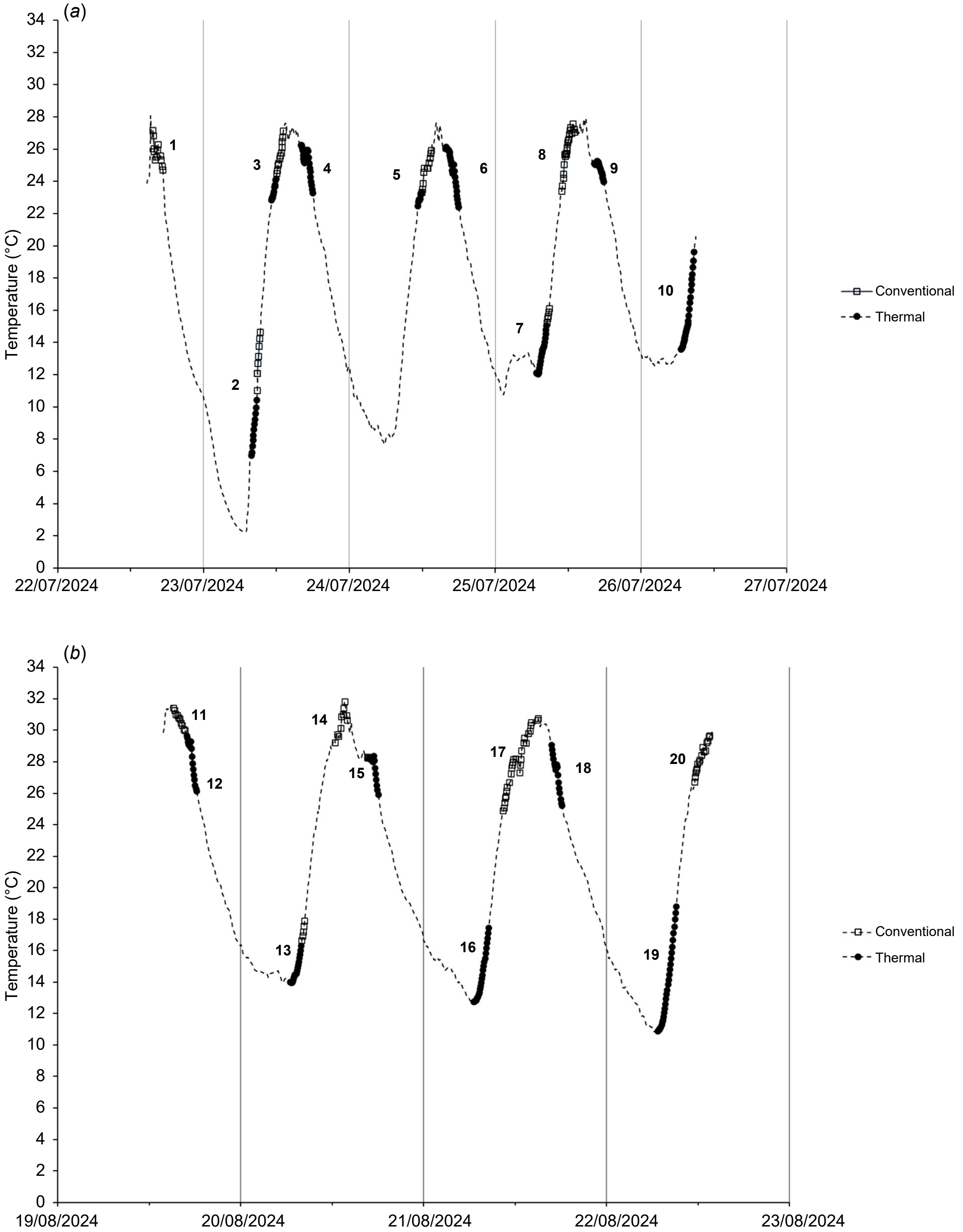

Fig. 2. (*a*, *b*) Ambient air temperature (°C) at the study area during each shooting run (as numbered) during Trial 1 (*a*, top) and Trial 2 (*b*, bottom). Time periods within runs 2, 3, 5, 7, 13 and 15 where thermal detection was considered 'usable' are highlighted by filled circles, remaining periods in these runs used conventional detection only (hollow squares). Thermal detection was considered useful for the entire duration of runs 4, 6, 9, 10, 12, 16, 18 and 19, while all other remaining runs used conventional detection only (runs 1, 8, 11, 14, 17 and 20).

Time to detection

Given a delay in video camera activation, the search time could not be accurately determined for the initial animal groups (n = 5) detected on five thermal runs (runs 2, 3, 4, 9 and 12) and were excluded from further analysis. The time to detection for the remaining 469 groups of animals (n = 329 during the thermal culling runs, n = 140 during conventional culling) were assessed. Across all thermal runs, the average time between dispatching one group and detecting the next group was 2:19 (min:sec, s.e. = 0:13, range 0:00–40:29). The mean search time on conventional runs was 1:58 (min:sec, s.e. = 0:20, range 0:00–29:50).

However, the time to detect a group was highly variable (range 0:00–40:29, see Table 1), and modelling the time to detection of animal groups as survival (= 1 – probability of detection, Fig. 3) indicated that the use of a thermal camera did not significantly influence detection time (χ^2 = 3.12, d.f. = 1, P = 0.08), nor did the factors species (χ^2 = 3.91, d.f. = 3, P = 0.27), time of day (χ^2 = 3.54, d.f. = 2, P = 0.17), shooting run (χ^2 = 1.95, d.f. = 1, P = 0.16) or the continuous covariate group size (χ^2 = 0.36, d.f. = 1, P = 0.27).

Table 1. Mean time to detection of animal groups and relative animal density

Run	Density[A]	Method of detection[B]	No. groups	Mean time to detection (min:sec)	s.e.	Min. time	Max. time
1	L	C	6	03:03	00:59	00:41	06:14
2	H	T	24[A]	01:15	00:16	00:09	05:17
3	H	T	39[A]	01:30	00:20	00:00	08:29
4	L	T	17[A]	03:29	00:33	00:00	08:14
5	M	T	30	02:02	00:24	00:00	08:59
6	M	T	26	02:29	00:31	00:00	09:34
7	H	T	39	01:38	00:15	00:00	06:44
8	H	C	60	01:01	00:10	00:00	05:12
9	M	T	26[C]	01:44	00:20	00:00	07:22
10	M	T	42	01:32	00:15	00:00	06:00
11	H	C	17	02:13	00:48	00:00	11:43
12	L	T	7[C]	04:34	01:35	00:36	11:24
13	L	T	21	02:22	00:26	00:00	06:40
14	L	C	7	08:43	04:04	00:22	29:50
15	M	T	22	02:08	00:23	00:00	07:16
16	L	T	11	09:41	03:58	00:00	40:29
17	H	C	25	01:42	00:23	00:00	08:18
18	M	T	8	07:46	03:51	00:01	26:02
19	H	T	17	00:59	00:16	00:00	04:14
20	H	C	25	02:10	01:02	00:00	25:47
Total C			*140*	*01:58*	*00:20*	*00:00*	*29:50*
Total T			*329*	*02:19*	*00:13*	*00:00*	*40:29*
Total all runs			*469*	*02:12*	*00:11*	*00:00*	*40:29*

[A] Summary statistics are provided for runs where a thermal camera was available (runs 2, 3, 4, 5, 7, 9, 10, 12, 13, 15, 16, 18 and 19), and where visual detection was used (runs 1, 8, 11, 14, 17 and 20). [A] Density of animals per shooting run: L, low; M, medium; H, high. [B] Method of detection: C, conventional; T, thermal. [C] Initial groups on these runs were excluded given that search time could not be determined due to camera failure.

Median detection time for conventional culling was 50 s (95% CI: 30–95 s, n = 140) compared to 65 s (95% CI: 46–103 s, n = 328) for thermal culling, but these were not significantly different (P = 0.08). However, there was a significant interaction between the detection method and canopy cover (χ^2 = 11.93, d.f. = 3, P = 0.008). Other interactions, including between density and detection method (χ^2 = 0.46, d.f. = 1, P = 0.49), did not significantly influence detection times. The detection times were thus examined for thermal and conventional detection separately within each canopy type.

Median detection times per canopy density during thermal culling are shown in Table 2. On the thermal shooting runs, the hazard rate for animal groups was greater in open (β = 1.69, z = 1.96, P = 0.05) and sparse (β = 1.49, z = 2.07, P = 0.04) canopy cover compared to dense canopy cover, indicating lower survival (i.e. faster detections). There was no difference in survivorship between intermediate and dense canopy cover (β = 0.65, z = −1.25, P = 0.21). On the conventional runs, detection probability was not different between canopy densities. Similarly, there was no difference in detection probability of animals detected in areas with higher levels of cover (dense, intermediate) between thermal and conventional detection (χ^2 = 1.19, d.f. = 1, P = 0.27).

Pursuit time

Pursuit (i.e. survival) times for animal groups were significantly increased by group size (χ^2 = 57.4, d.f. = 1, P < 0.001) and shooting run (χ^2 = 20.92, d.f. = 1, P < 0.001). Overall, the use of the thermal camera did not significantly influence the pursuit time (χ^2 = 2.65, d.f. = 1, P = 0.10), along with the factors density (χ^2 = 2.67, d.f. = 2, P = 0.26), species (χ^2 = 5.32, d.f. = 3, P = 0.15), and time of day (χ^2 = 1.69, d.f. = 2, P = 0.43). Canopy cover was not significant overall (χ^2 = 6.24, d.f. = 3, P = 0.10) but was retained into the final model given that it provided greater explanatory power over the reduced model (χ^2 = 10.37, d.f. = 3, P = 0.02). There were no significant interactions. The model hazard rates (β) for group size (0.93) and shooting run (0.96) indicated reduced risk (i.e. greater pursuit time) with increasing group size, and over the course of the culling program (i.e. greater pursuit time in later runs).

Initial detection of animal groups by thermal or conventional detection

The detection method for individual animal groups (i.e. thermal or conventional) was recorded during 11 shooting runs that utilised the thermal camera, specifically runs 5, 6, 7, 9 and 10 (Trial 1) and runs 12, 13, 15, 16, 18 and 19 (Trial 2). Detections

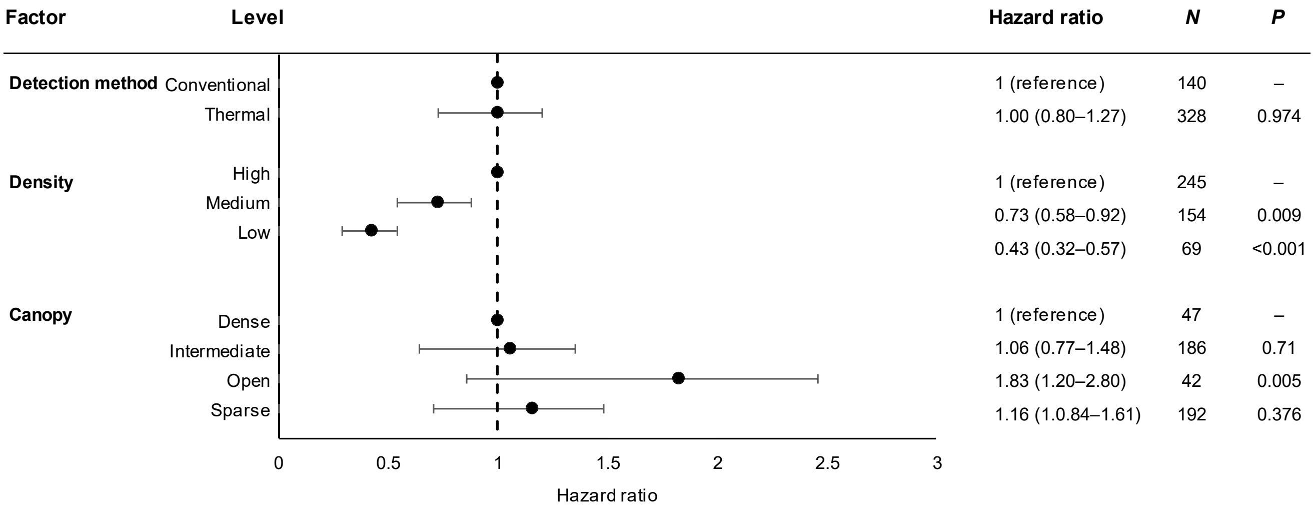

Fig. 3. Forest plot presenting the hazard ratios (relative to the reference group = 1), 95% confidence intervals and significance (*P*-values from likelihood ratio test results) for each level of the factors detection method, density and canopy cover (habitat) for the overall time to detection of animal groups.

Table 2. Median time to detection for animal groups per canopy density on thermal shooting runs

Canopy cover	*n* events	Median time to detection (s)	95% CI
Dense^{B}	35	126	72–181
Intermediate^{B}	120	73	55–100
Open^{A}	24	53	18–95
Sparse^{A}	148	42	32–55

^{A,B}Groups identified by different letters are significantly different ($P < 0.05$).

across the entirety of the 11 runs, including during periods where the thermal camera could not be used, were summed to determine the proportion of animal groups detected by either thermal or visual methods per shooting run (Table 3). More than half (51.8%) of all animal groups were detected using the thermal camera rather than by visual observation (27.9%) across all thermal runs (pooled). The method of detection for the remaining 20.2% of groups was not recorded. Excluding these unrecorded groups, thermal imagery detected almost 2/3 (65%, $n = 128$) of all taxa groups, with higher proportional detection of deer groups (67.4%, $n = 93$) than pig groups (59.3% $n = 32$). We cannot conclude that these groups would not have been eventually detected visually.

Table 3. Number and percentage of groups detected by each method (thermal or visual) for each taxon pooled across 11 aerial shooting runs utilising the thermal camera

Method of detection	Deer	Dog	Pig	All
Thermal	93 (52.8%)	3 (60%)	32 (48.5%)	128 (51.8%)
Visual	45 (25.6%)	2 (40%)	22 (33.3%)	69 (27.9%)
Unknown	38 (21.6%)		12 (18.2%)	50 (20.2%)
Total	176	5	66	247

Group size detected

The group sizes detected for deer and pigs were compared between the thermal and conventional shooting runs (Fig. 4). Groups of only 1 or 2 individuals comprised a greater proportion of deer (45%) and pig (41%) groups detected during the thermal runs compared to the conventional runs (26.3% and 21.1% respectively). The distribution of group sizes detected for deer was significantly different between

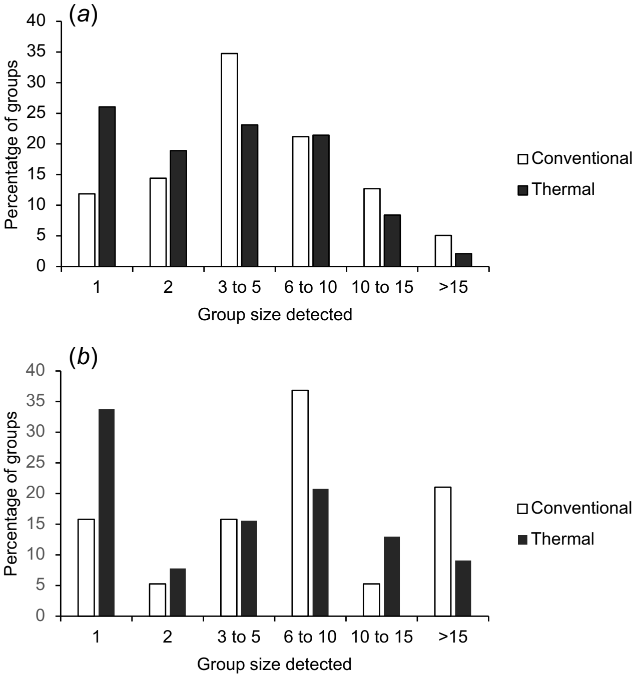

Fig. 4. Distribution of (*a*) deer and (*b*) pig group sizes detected during the thermal and conventional shooting runs.

thermal and conventional shooting runs (D = 0.189, P = 0.007). This was reflected in the mean group size. On the thermal runs, the average group size for deer (4.55, s.e. = 0.28, n = 238) was significantly less (W = 16770, P = 0.002) than that observed on the conventional runs (5.76, s.e. = 0.43, n = 118). However, the average group size for pigs on thermal runs (6.71, s.e. = 0.92, n = 77) was not significantly different (W = 906.5, P = 0.10) to that observed on the conventional runs (8.32, s.e. = 1.48, n = 19), nor was there a difference in the distribution of group sizes (D = 0.255, P = 0.15).

Group sizes were further compared within the thermal runs to minimise any differences due to variable environments between runs. The average group size of deer detected when the thermal camera was usable (4.22, s.e. = 0.29, n = 176) was not significantly different (W = 2655, P = 0.19) to when thermal camera use was unavailable (5.50, s.e. = 0.70, n = 62). Similarly, the average size of a pig group detected (6.51, s.e. = 1.04, n = 65) was not significantly different (W = 114, P = 0.81) to when the thermal camera was unavailable (7.83, s.e. = 1.67, n = 12). Lastly, there were no differences in the distribution of group sizes for deer (D = 0.161, P = 0.185) or pigs (D = 0.282, P = 0.23).

Comparative cost effectiveness – culling with and without thermal detection

The culling rate (animals h^{-1}) and cost animal^{-1} culled during the conventional and the thermal runs in the 2024 trial period are provided in Table S2. Inclusive of travel costs, the average cost day^{-1} for the thermal contractor was $1616.67 AUD ($1550 Trial 1; $1700 Trial 2). Using the actual costs of the thermal contractor (averaged per shooting run at $968.75–$1133.33 AUD for Trials 1 and 2, respectively), the average cost animal^{-1} culled during thermal runs ($60.68 AUD, s.e. = 8.5, range = $30.38–$127.23) was effectively identical to the cost animal^{-1} on conventional runs ($60.65 AUD, s.e. = 15.6, range = $23.70–$127.19).

After accounting for ferry times, the average cost animal^{-1} on thermal shooting runs ($51.93 AUD, s.e. = 6.3, range = $25.26–$93.80) was on average 50.3% greater than the cost animal^{-1} on conventional runs ($34.54 AUD, s.e. = 11.0, range = $15.34–$88.48).

Efficiency increase required to offset thermal contractor costs

Given the above average daily cost of $1616.67 AUD day^{-1}, and assuming two thermal runs of 2.25 h duration (i.e. total of 4.5 h of aerial culling) could be completed each day (from the 2024 program average), the actual cost of a thermal contractor was calculated as $360.62 AUD h^{-1}. Based on these costs and using the average cost of $1755 AUD h^{-1} for conventional culling from the 2024 program (WRC, pers. comm., December 2024), the addition of a thermal observer would increase the hourly cost of culling by ~20.5% ($2115.62 AUD h^{-1}). This suggests that the efficiency of aerial culling with thermal detection (i.e. number of animals h^{-1} removed) would also need to increase by >20.5% to offset the additional costs.

Discussion

This pilot trial tested a thermal camera to aid detection of feral animals in an aerial culling program in northern Australia. The thermal camera successfully detected animal groups (primarily deer, pigs and wild dogs) for at least some periods during all 14 flights conducted in late winter (late July–August 2024). Animals were detected at different times of the day (primarily early morning and late afternoon, but also at other times), under a variety of temperatures and where canopy cover ranged from dense to open. Observations from a sample of thermal shooting runs indicated that almost 2/3 (65%) of deer and pig groups were detected through thermal rather than visual observations. In two low density deer areas, culling rates were greater during the two thermal runs than during the matching conventional runs. Comments by both the shooter and pilot, both highly experienced in aerial culling programs on the study site, were also highly supportive of the technique, and observed that many deer and pig groups (particularly smaller groups in dense canopy cover, or groups that did not 'flush') would have remained undetected without the assistance of the thermal camera. Collectively, this is encouraging and supports the addition of a thermal camera in conventional aerial culling operations under (warmer) northern Queensland climatic conditions. However, examination of the time to detection, pursuit time, animal removal rates (animals removed^{-1}) and cost animal^{-1} indicate little overall benefit from the use of thermal detection across the pilot program. These results, and implications for future use of thermal cameras in aerial culling in northern Australia, are discussed below.

Video recording of the culling program provided useful data to investigate potential differences in search time, pursuit time and shooting offtake between thermal and conventional culling. Interestingly, there were no consistent differences in the time taken to detect animals (search time) across thermal and conventional runs, between thermal and visual detections within the same runs, or in paired runs (thermal and conventional) conducted in the same shooting area. Survival analysis also confirmed that search time was not significantly influenced by method of detection. There was also no difference in the search time for different species (deer or pigs), at different times of the day, or group size. However, on thermal runs, the search time was greater (i.e. a reduced probability of detection) in culling areas with low to medium deer density, compared with high deer density areas. This is likely due to a lower encounter rate when there are fewer animals available to detect (i.e. a greater search time between groups due to the reduced density). Detecting animal groups in areas with dense or intermediate levels of shelter (e.g. woodland or riverine woodland) was also more difficult, with longer search times than where canopy cover was open or sparse (e.g. open grassland).

Pursuit time increased with group size and increased over the course of the culling program (i.e. increasing run sequence number). The influence of group size is likely due to the increased handling time (i.e. mustering animals or positioning of the aircraft) required for larger groups of animals, to ensure suitable placement of the group prior to shooting commencing. An increase in pursuit time over the course of the culling program is possibly due to the remaining possibly more wary animals occurring in denser vegetation requiring greater handling time, or due to increasing evasive behaviour of surviving animals following exposure to culling. A range of temporary behavioural responses in deer and feral pigs may result from exposure to intensive aerial culling but are variable and inconsistent (Bengsen *et al.* 2024, 2025). Regardless of any behavioural changes occurring in the present study, there was no quantifiable reduction in pursuit times with thermal camera use following the initial detection of animal groups. The use of the TAC configuration, where the camera operator sits on the same side of the aircraft as the shooter, may better assist in tracking animals during pursuit compared with the hybrid configuration used here – reducing the reacquisition time – but requires testing under these conditions.

Following from a reduced time to detection or pursuit time, improvements to aerial shooting practices should ultimately increase the culling rate. Our results show that the use of thermal detection did not significantly increase the culling rate (number of animals removed h^{-1} or km^{-1}) compared with visual detection.

This contrasts with previous assessments using the TAC configuration which have found that thermal imagery can dramatically increase removal rates. The culling rate effectively doubled (12.1 deer h^{-1}) compared to conventional culling (6.8 deer h^{-1}) in a high-density population of fallow deer (>6 animals km^{-2}) on the Limestone Coast of South Australia (Cox *et al.* 2023). Feral pigs were also more efficiently removed with thermal detection (3.4 pigs h^{-1}) than with visual detection (1.2 pigs h^{-1}) on Kangaroo Island, at low pig densities (<0.2 animals km^{-2}) (Cox *et al.* 2023). Animal density and detectability are likely responsible for the lack of differences in the current study. Culling rates at Collinsville were considerably higher (conservatively an average of 45.2 animals h^{-1} from video observation, including ferry time) than those reported by Cox *et al.* (2023), probably due to very high densities of deer and pigs (e.g. up to 48.3 deer km^{-2} and 17.3 pigs km^{-2} in riverine habitats in 2023) (Gentle *et al.* 2024). In southern New South Wales, pigs were removed with thermal assistance at the average rate of 26.5 pigs h^{-1} at a pre-control density of 7.6 pigs km^{-2} (Cox *et al.* 2025). The high culling rate at Collinsville also suggests there was little difficulty in detecting animals to cull – at least in areas of high density – and is close to average maximum kill rates for deer (49.8 animals h^{-1}, Bengsen *et al.* 2023) and pigs (60.5 animals h^{-1}, Choquenot *et al.* 1999) and thus limited by 'handling' rather than search time. Thermal imagery could detect animals at Collinsville and has the potential to increase culling rates there and at other northern Australian sites, but significant gains over conventional detection are expected only where animals are difficult to detect such as at lower densities (as per Cox *et al.* 2023) or in dense canopy cover, or both. This was demonstrated during a deer eradication on Wild Duck Island, where the last remaining rusa deer was efficiently removed using thermal detection following increasing difficulty in detection during conventional aerial shooting (Amos *et al.* 2024). Limited data from the current study support this, with higher deer offtake on thermal runs than on conventional runs in two relatively low-density areas at Collinsville. In higher-density areas during the trial, offtake differed little between the two detection methods.

Comparisons between different detection techniques must also consider cost. The increased costs (~20.5%) associated with the thermal camera were not offset by an increased culling rate on thermal runs, resulting in a higher cost per animal removed. WRC records (B. Fuller, unpubl. data) show that the 2023 program (without the use of a thermal camera) removed more animals h^{-1} at a lower average cost $animal^{-1}$ than the 2024 trial. This further supports that the culling rate was more likely related to other factors (probably underlying deer and pig density) than detection method. This also suggests that, at the current animal density at this site, the addition of a thermal camera to the culling program *per se* is unlikely to lead to improvement in the cost effectiveness of operations. Selective use for low-density areas only, as indicated by differences in the low-density matched runs, could yield benefits, but more data are needed to guide optimal use.

Use of a thermal camera also offers potential benefits to control programs that may not be readily apparent through assessing detection or culling offtake statistics. Thermal cameras can be particularly useful at ensuring any wounded animals can be tracked and subsequently dispatched, improving animal welfare (Cox *et al.* 2023). Alternative control techniques are also likely needed to target residual animals from conventional aerial shooting programs (Saunders and Bryant 1988). Thermal imagery can also greatly assist at removing these elusive or evasive individuals, which may benefit control programs, particularly in the longer term (J. Munn, pers. comm., February 2025). The use of a thermal camera for detecting or tracking animals in aerial culling programs should ideally be considered for inclusion during review of the standard operating procedures and code of practice that guide aerial culling operations (e.g. Standing Committee on Agriculture, Animal Health Committee 2002; Terrestrial Vertebrate Working Group 2024). However, these potential benefits come at a cost and so must be considered case by case (e.g. eradication programs, contentious culling programs).

Given that the ability of thermal imagery to detect animals relies on a sufficient temperature differential between the animal and the environment, the 'usefulness' of thermal detection is heavily reliant on prevailing climatic conditions. This study was conducted in winter when temperatures are cooler, which is particularly important in the (warm to hot) northern Australian climate. Observations made by the thermal camera operator indicated that optimal conditions for thermal contrast were primarily in the early morning (usually before ~0800, or 1.5 h after sunrise) or late afternoon (after ~1700, or 1 h before sunset). It was also noted that on several morning runs, the 'prime' periods for thermal detection were missed (or not fully utilised) due to a delayed initial flight. Outside of optimal periods, the influence of heat (from direct sunlight exposure with limited cloud cover) on vegetation (e.g. tree trunks), rocks or bare ground can be problematic, limiting detections to more shaded or densely vegetated areas (J. Munn, pers comm. August 2024). These delays and physical limits restricted the use of the thermal camera during the trial, resulting in the thermal camera being applied to the entire duration of only 8/14 runs (57%). On the remaining runs, thermal camera use was either delayed (pm) or cut short (am). This indicates that environmental conditions, primarily temperature and solar exposure, will need to be considered in thermal shooting operations in northern Australia. Optimising the timing of thermal runs would also improve the thermal culling rates relative to conventional culling rates. In addition to ambient conditions, the camera operator and shooter also noted that the thermal camera was often not required at high deer densities given that sufficient animals were being readily detected visually. This also supports comparisons based on time to detection, pursuit time and offtake (as above).

Study limitations

This trial was undertaken during an aerial culling program which, like most control programs, aimed to maximise culling rates. As a result, culling runs were mostly conducted in high animal density areas (eight runs), with the remaining split between medium- and low-density areas (six runs in each). While thermal detection was tested across this range, greater benefits are only expected at lower densities, when the encounter rate is low and animals are more difficult to find. Most (4/6) conventional runs were conducted in high-density areas, potentially (positively) biasing these results. However, conventional runs were primarily undertaken during the late morning or early afternoon, when animals may have been seeking shelter or 'bedded down' (and less detectable), potentially reducing these culling rates (negative bias). In contrast, most thermal runs were conducted in the early morning and late evening when animal activity (and ability to detect) was relatively high, potentially increasing these culling rates. Where possible, paired runs (i.e. matched time of day periods and densities) for thermal vs conventional comparisons were undertaken to minimise potential bias. Additionally, outcomes were further compared within the thermal runs to minimise any variation between runs. While it was not possible to achieve balanced replication across all scenarios, our analysis approach and interpretation provide an appropriate and considered examination of the outcomes of thermal detection in an aerial control program.

Implications

Despite the lack of quantifiable differences between thermal and conventional detection, there is still value in using thermal imagery in culling operations in northern Australia. Thermal imagery was successfully used across a range of habitats to detect animal groups across the trial period. During thermal runs, detection was mostly (65% of animal groups) by thermal rather than conventional detection. There is also evidence that thermal imagery may be better than conventional detection at finding smaller groups, particularly for deer (see Fig. 4). However, animal density and habitat are likely to be important influences on the value of thermal detection in culling programs. Offtake on two thermal runs in low density deer areas was also greater than paired conventional runs, but such differences were not sustained across the trial. Results from this study show that at high densities or in open–sparse canopy cover at Collinsville, thermal detection of animals did not result in an increase in the culling rate (animals h^{-1}) or reduce the cost animal^{-1}. In these circumstances, at current densities at the study site, the detection of groups using visual detection alone appears more cost effective. Future applications of thermal imagery need to consider animal density and vegetation cover to ensure it can offer advantages over current conventional aerial culling methods.

Despite varying environmental conditions experienced during the trial periods (mid–late winter), thermal imagery could be used to detect animals in most conditions. However, optimal conditions for thermal contrast only persisted for short periods during the early morning or late afternoon, and preference should be given to using thermal culling during these times.

The above approach also demonstrates the importance of assessing new approaches or technologies against current best-practice programs. While qualitative assessments to examine potential uses and determine proof of concept are useful, quantitative approaches provide relevant metrics (e.g. cost, culling rate) to compare against current practices to aid decision -making. New approaches must offer improvements over current techniques before widespread adoption can be supported.

Conclusion

The thermal camera successfully detected animals under a variety of temperatures and in a range of canopy densities, which is promising for future applications of thermal imagery in culling programs in northern Australia. However, the use of the thermal camera at this location did not significantly increase the culling rate (number of animals removed h^{-1} or number of animals km^{-1}) compared to conventional detection. Thermal detection of animals at high densities or in easily detectable habitats is unlikely to improve the culling rate (animals h^{-1}) or cost animal^{-1} of culling over conventional detection alone.

Further assessment of using a thermal camera in northern Australia to detect animals during culling programs should be undertaken at low animal densities, particularly in dense or heavily vegetated habitats. Under these conditions, where detection of animal groups is difficult and culling rates are hard to maintain though conventional detection alone, thermal detection is likely to offer significant advantages. The use of the specific TAC configuration, where the camera operator sits on the same side of the aircraft to the shooter, may better assist in tracking animals following encounter than the hybrid configuration used here, but requires testing in northern Australia.

Supplementary material

Supplementary material can be accessed from the article page online.

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Data availability. The data from this study cannot be publicly shared due to ethical or privacy reasons but may be shared upon reasonable request to the corresponding author if appropriate.

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