CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/WR23115

WILDLIFE RESEARCH

Enhancing strategic deployment of baiting transects for invasive species control – a case study for feral pig baiting in north-eastern Australia

Cameron Wilson[A,B,*], Matthew Gentle[B,C] and Darren Marshall[D]

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

***Correspondence to:**
Cameron Wilson
Animal Biosecurity and Welfare, Biosecurity Queensland, Department of Agriculture and Fisheries, Bundaberg, Qld, 4670, Australia
Email: cameron.wilson@daf.qld.gov.au

Handling Editor:
Peter Caley

Received: 1 September 2023
Accepted: 27 March 2024
Published: 16 April 2024

Cite this: Wilson C *et al.* (2024) Enhancing strategic deployment of baiting transects for invasive species control – a case study for feral pig baiting in north-eastern Australia. *Wildlife Research* **51**, WR23115. doi:10.1071/WR23115

ABSTRACT

Context. Baits are used to deliver lethal or other substances in wildlife management programs across the globe. Successful baiting campaigns are contingent upon the availability of baits to target animals. Bait density is often increased in an attempt to improve bait encounter probabilities. However, this comes with a concomitant increase in cost and may result in significant bait wastage if deployed in areas of low target species activity. **Aims.** The aim of this study was to assess the effectiveness, efficiency and cost of different bait transect methods in intersecting home and core ranges of feral pigs as a case study to determine optimal spacing and placement of baiting transects. **Methods.** The authors simulated a variety of systematically spaced aerial transects, watercourse-aligned aerial transects and ground transects along property boundaries and farm tracks, and compared them with home and core ranges of feral pigs, at two study sites in Queensland, Australia. Transect effectiveness at intersecting pig ranges was determined through beta-regression and estimated marginal means (emmeans); efficiency was considered as emmeans per unit of transect length. **Key results.** The study found that systematically spaced aerial transects at 4 km intervals were the most efficient means of intersecting both home and core ranges of feral pigs. Additionally, no alternate transect method, either aerial or ground, provided significantly greater effectiveness at intersecting feral pig home and core ranges at these study sites. Ground transects along farm tracks and property boundaries were also between 113% and 192% more expensive than aerial transects at 4 km spaced intervals for either fixed-wing or rotary aircraft. **Conclusion.** Systematically spaced aerial transects at 4 km intervals are among the most effective and are the most efficient means of intersecting feral pig ranges at the study sites examined. **Implications.** Our methodology offers a blueprint for both vaccination and toxin baiting programs to assess and compare bait transect placements. More specifically for feral pig control, aerial transects with 4 km systematic spacing provide an effective and efficient means for intersecting feral pig ranges. Furthermore, additional data on bait encounter and interaction probabilities are required to determine transect effectiveness at bait uptake by the target species.

Keywords: aerial baiting, bait distribution, encounter rate, feral pig, interaction rate, meat baiting, poison baiting, transect placement, vaccination.

Introduction

Baiting is a strategic wildlife management method that delivers a substance to target individuals through deployment of food baits for consumption (Taggart *et al.* 2023). Wildlife managers use baiting in conservation or invasive species management across the globe. It can be utilised for the management of wildlife disease, involving the delivery of vaccines or parasitic treatments to susceptible species. For example, in Montenegro, management of sylvatic rabies in foxes (*Vulpes vulpes*) has relied upon the use of aerially distributed oral vaccinations (Henning *et al.* 2017). Similarly, bait-based oral vaccines have been deployed to counter transmission of classical swine fever (CSF) in wild boar (*Sus scrofa*) populations in Germany (Moennig 2015). Other, less common uses include delivering drugs to immobilise, inhibit reproduction or to induce conditioned taste aversion in wildlife (Taggart *et al.* 2023). However, the overwhelming majority of baits (89%) incorporate lethal toxins for invasive species control (Taggart *et al.* 2023). Globally, poison baiting has been used to control a wide number of species (Taggart *et al.* 2023), with successful applications ranging from wild dogs in Australia (Ballard *et al.* 2020), to possums in New Zealand (Morgan *et al.* 2000) and rodents in Pakistan (Shahwar *et al.* 2024). Regardless of the intended objective, whether it be to meet conservation or pest management goals, one fundamental principle underpinning baiting remains consistent: to deliver baits for consumption by the target taxa.

There are a number of critical factors in any baiting campaign that influence the outcome, including bait encounter, availability, attractiveness and palatability (Fancourt *et al.* 2021). Understanding and manipulating each of these factors can improve and optimise the program success. Bait encounter rates are dependent upon the availability of baits in the vicinity of a target species and can be improved by increasing bait density (Fancourt *et al.* 2022). An increase in bait density is also used in an attempt to account for uptake by non-target species. This ensures that sufficient bait remains available for the target species. Bait availability can be improved through the use of primary and secondary repellents to deter uptake by non-target species (Day 2003), or else by employing species-specific delivery systems (e.g. HOGHOPPER™). Presenting an attractive and palatable bait to an animal will likely improve the probability of bait consumption. This is achieved by adding attractants to the bait, such as specific flavours (Kelly *et al.* 2011), or by modifying the bait medium (Allen *et al.* 1989). The use of insecticides, such as Coopex® (Bayer Crop Science, Australia), can reduce insect attack, increasing or extending the period of bait attractiveness and palatability (Algar *et al.* 2007). Understanding these factors and the interactions between them provides opportunities to compare between competing deployment strategies and to refine the outcomes of baiting campaigns.

Australia accounts for almost 40% of all bait applications across the globe (Taggart *et al.* 2023), where a wide variety of introduced pests are targeted with the toxin sodium fluoroacetate. Depending on the target species, sodium fluoroacetate can be incorporated into meat, grain, fruit and/or manufactured baits. For feral pig control in north-eastern Australia (Queensland), meat is the most widely used bait medium, with 62% of local governments surveyed in 2022 ($n = 60$) indicating use (Wilson, unpubl. data). Due to vast and remote areas with limited ground vehicle access, western Queensland shires typically rely upon the aerial distribution of these meat baits without a free-feeding element. Where aerial applications are inappropriate or too expensive, ground distribution is utilised. Bait stations (i.e. clusters of 5–20 baits) are recommended where large numbers of pigs congregate; however, placement of baits along systematic aerial transects, watercourses or along vehicular tracks are the most common pattern for the dispersal of meat baits. Despite this, it remains unclear whether these patterns effectively target areas of high pig activity, raising questions about their efficacy and efficiency in bait campaigns. Ineffective bait distribution results in significant resource wastage and undermines encounter rates and subsequent bait interactions.

Utilising spatial ecology of feral pigs is critical in identifying optimal locations for bait placement aimed at increasing bait encounter rates. Previous research on feral pigs in Australia has shown that pigs demonstrate defined habitat use (Wilson *et al.* 2023*a*). However, there has been relatively little research on the placement of bait transects in relation to feral pig spatial habitat use, despite the importance of ensuring high bait encounters with feral pigs to improve control outcomes. Formal comparisons between competing strategies would also help to refine and optimise the distribution of baits in the landscape.

This study aims to compare the efficiency of competing feral pig 1080 meat baiting strategies (transect spacings, systematic vs targeted placement of both aerial and ground transects) to intersect with home or core activity ranges of feral pigs on two study sites in eastern Australia. This information is used to provide recommendations for pest managers for the optimal landscape-scale baiting of feral pigs and to offer a blueprint for conservation and poison baiting to assess and compare bait transect placements.

Methods

Data collection

Forty-two feral pigs (23 males, 19 females) were collared with Lotek Iridiumtrack Heavy Duty 3D (Lotek, Ontario, Canada) GPS collars across two locations, between May 2017 and January 2021 for an average of 378 days per pig. Details on how pigs were trapped and sedated along with collar tracking intervals is available in Wilson *et al.* (2023*b*). Animal ethics were approved by the University of New England (AEC 16-115 and AEC 20-023).

Study sites

Pigs were collared at two locations in eastern Australia: Arcadia Valley (Queensland) and Downfall Creek (Queensland). Both sites consist of a mix of open grassland and eucalyptus woodland, are in subtropical climates (Bureau of Meteorology 2022*a*) and experience similar annual rainfall (635–643 mm) (Bureau of Meteorology 2022*b*, 2022*c*). Cattle grazing is the predominant land use in both locations, although Downfall also supports natural gas extraction. Both sites are representative of grazing landscapes where feral pigs are actively managed, including through baiting.

To determine a study site for simulating control that encompassed the feral pig population, precise boundary limits were generated from the outer extent of the home ranges of pigs at each site. The 100% Minimum Convex Polygon (MCP100) of all pigs collared at each site were concatenated to form one polygon. MCP100's were generated using the adehabitatHR package (Calenge 2006) in R (v. 4.0.5) (R Core Team 2021). This area consists of the entire range of movements of all monitored pigs at each study site during the collaring period and represents a proxy area subjected to a bait campaign. For Queensland, Australia, areas not permitted to be baited with meat baits intended for feral pigs are specified in permit number PER89572 (Australian Pesticides and Veterinary Medicines Authority 2021). A summary of these sensitive areas, distance restrictions and a reference to access spatial data are displayed in Table 1. Areas not permitted to be baited and proposed bait transects were generated per study site.

Baiting strategies

In Queensland, meat baits can be placed individually or in clusters along transects or at bait stations, with options for ground or aerial distribution (fixed-wing or rotary). Hereafter, 'ground' refers to transect baiting by ground vehicle (e.g. car), 'fixed-wing' refers to transect baiting by aeroplane and 'rotary' refers to transect baiting by helicopter. All baiting transect strategies analysed in this study are displayed in Table 2.

Table 1. Meat baits intended for feral pig control are not permitted within certain distances of sensitive areas in Queensland, Australia.

Sensitive area	Distribution method	Distance restriction	Spatial data reference
Dwelling	Ground	150 m	Department of Resources (2021*a*)
	Fixed-wing aircraft	1000 m	
	Helicopter	500 m	
Permanent or flowing water	Ground	20 m	Department of Environment and Science (2022)
	Fixed-wing aircraft		
	Helicopter		
Boundary fence	Ground	5 m	Department of Resources (2021*b*)
	Fixed-wing aircraft	100 m	
	Helicopter	10 m	
Edge of public road	Ground	5 m	Department of Resources (2021*c*)
	Fixed-wing aircraft	10 m	
	Helicopter	10 m	
Stock route	Ground	Not permitted without local government approval	Department of Natural Resources Mines and Energy (2013)
	Fixed-wing aircraft		
	Helicopter		

These distance restrictions are dependent upon the distribution method: Australian Pesticides and Veterinary Medicines Authority (2021). Spatial data for the described sensitive areas were downloaded from the references provided.

Table 2. Meat baiting transect strategies as analysed in this study.

Distribution	Mechanism	Placement	Spacing interval
Aerial	Fixed-wing and rotary	Systematic-spaced	500 m
			1 km
			2 km
			3 km
			4 km
			5 km
			10 km
		Watercourse based	Not applicable
Ground	Ground vehicle	Farm tracks	Not applicable
		Property boundaries	Not applicable

Aerial transects

Systematic-spaced transects. A bounding box of the study site was created, and the southern edge was used to generate transects every x distance, so that all transects ran north–south. Transects were then cropped to the limitations of the study site. For the purposes of this study, we trialled seven different systematic transect spacings, namely: 500 m, 1 km, 2 km, 3 km, 4 km, 5 km and 10 km.

Watercourse transects. As a comparison with traditional transect spacing, we investigated placing aerial bait transects along watercourses, taking into account distance restrictions (Table 1). Water spatial layers were downloaded from the Department of Environment and Science (2022) and were used to generate proposed transects along watercourses. Due to the complex directional changes in a watercourse being not-conducive to aerial transects, we generated simplified transects (i.e. straightened watercourse), using the 'st_simplify' function of the sf package (Pebesma 2018) in R. To estimate a tolerance level for this function, we measured the average distance for each GPS location of Arcadia and Downfall pigs to the nearest watercourse feature. The 80th percentile (670 m) was deemed an appropriate choice that straightened watercourse features without oversimplification and misrepresentation. To improve efficiency, straightened watercourse features were then filtered to remove the smallest 10% of transects that would be inefficient to fly baiting transects along.

Ground transects

Farm tracks. To assess ground transects, we simulated baiting along private farm tracks. Baseline road and track datasets were downloaded through Department of Resources (2021c) and cropped to the study site limitations. Only road layers with a road type attribute of 'private' were retained in this part of the analysis. To avoid placing a bait directly on a farm track, we generated an offset polyline in ArcGIS Pro v 2.9.5 using the 'Copy Parallel' function with an offset of 11 m. This distance encompasses road width and non-permitted area buffers to ensure a bait transect only lies within permitted areas near roadways.

Property boundaries. In addition to farm tracks, we simulated baiting along property boundaries as commonly undertaken (Wilson, pers. comm. 2023). Spatial data on property boundaries were downloaded from Department of Resources (2021*b*) and cropped to display only those that intersected with the study sites. Property boundary polygons were first converted to polylines, then replacement polylines with a 6 m offset (to place transect within permitted areas) from the originals were generated using the 'Copy Parallel' function in ArcGIS. For properties that share a physical boundary (i.e. a fence), we generated a single transect. Where a road or creek provided a boundary between properties, multiple transect lines were permitted.

Transect correction for non-permitted areas

Spatial data on sensitive areas not permitted to be baited were downloaded from sources displayed in Table 1. Buffers with the distances described in Table 1 (Distance restriction column) were generated using the 'st_buffer' function from the 'sf' package in R. Because the permit specifies a distance from the edge of public roads, a distance of half the estimated road width (i.e. 5 m) was added as an initial buffer along polylines (placed on road centreline) before buffer zones of the widths described in Table 1 were added. For simplicity, we incorporated stock routes into our non-permitted areas. All non-permitted areas, per study site, were merged and boundaries dissolved in ArcGIS to create a single polygon. All transects and bait locations were then cropped using the 'Erase' tool in ArcGIS to exclude all sections within the polygon of non-permitted areas. Fig. 1 demonstrates an example map, displaying 4 km spaced fixed-wing transects and non-permitted baiting areas of our Arcadia study site.

Cost

Estimated costs of baiting incorporates the cost of the bait medium (500 g meat and 1080) and the distribution (vehicle and labour) of bait. Labour time to prepare baits and vehicle ferrying costs were not included in the total costs. The cost of bait was derived from Appendix table S1 in Wilson and Gentle (2022) and was estimated to be AUD\$3.89 bait^{-1}. Aircraft

Fig. 1. An example of a bait simulation at Arcadia, displaying 4 km spaced fixed-wing transects and non-permitted baiting areas.

expense was recorded as an hourly rate, including vehicle hire, fuel and pilot. Expenses for two different rotary aircraft (Bell Jet Ranger and Robinson R44) were drawn from two different providers used during feral pig surveys conducted in June 2022. Flying at an average speed of 80 km h^{-1}, the estimated cost of a turbine helicopter (Jet Ranger) was AUD$18.75 km^{-1} ($1600 h^{-1}), and the piston-engined (R44) was AUD$13.81 km^{-1} ($1105 h^{-1}). Costs for two different fixed-wing aircraft (Cessna 182 and 206) typically used in aerial baiting were provided by western Queensland councils (Quilpie and Longreach Shire Councils). Flying at an average speed of ~204 km h^{-1}, C182 expenses were estimated at AUD$3.41 km^{-1} ($696 h^{-1}), and at an average speed of ~213 km h^{-1}, C206 expense were estimated at AUD$3.48 km^{-1} ($742 h^{-1}). Ground vehicle expenses were estimated using a rate of AUD$0.78 km^{-1} (Australian Taxation Office 2023) at a speed of 15 km h^{-1}. Labour for bait distribution was estimated from the minimum wage of AUD$21.38 h^{-1} (Fair Work Ombudsman 2023) for the time taken to complete the baiting transect (transect length/speed).

Data analysis

Although we used combined MCP100s as a proxy for study site to simulate baiting transects, here we used individual nearest-neighbour local convex hulls (k-LoCoH) to provide accurate representations of home (90%) and core (50%) ranges of feral pigs. This allowed us to measure the length of bait transect for each baiting strategy (systematic, watercourse, farm tracks and property boundaries) that overlapped within the ranges of individual pigs. This measurement was compared with the total transect length of each baiting strategy to produce an estimated proportion of transect within the individual ranges of pigs. To determine whether this proportion is affected by transect spacing, we tested for significance through a beta-regression (see 'betareg' package (Cribari-Neto and Zeileis 2010) in R. We used the 'emmeans' package (Lenth *et al*. 2021) to calculate estimated marginal means and to conduct pairwise comparisons between transect spacing and placement to examine differences between individual baiting strategies. Estimated marginal means (hereafter emmeans) are extracted from the beta regression model and represent the average of the response variable (i.e. proportion of transects within feral pig ranges), while considering the influence of and potential correlations with other factors such as overall transect length, spacing and type (i.e. systematic, along watercourses, along vehicle tracks or boundaries). Transects with greater emmeans indicate a higher proportion of transect intersecting feral pig ranges and, consequently, more effective bait availability. Acknowledging that bait availability is influenced by factors beyond transect placement within pig ranges, we use the term 'proportional bait availability' as a more relatable term than 'emmeans.' Transect efficiency is assumed as emmeans per unit of transect length.

Results

Proportion of transects within ranges and percent of ranges crossed

Increasing spacing between systematic transects reduces the total transect length within ranges. Notably, 500 m spacing results in the highest total transect length (mean: 1459 km), with the longest mean lengths in home (24 km) and core (2.1 km) ranges. In contrast, 10 km spacing has the shortest total mean length (73 km) and corresponding shortest lengths within home (1 km) and core (0.1 km) ranges. See Supplementary Tables S1 and S2 for total length of each baiting strategy assessed, mean transect length and proportion within an individual pigs' home and core range, per study site.

Bait transects along farm tracks at Arcadia place a mean of 8.1 km of their total 395 km, within individual pig home ranges, significantly more than 2.2 km at Downfall. However, Downfall demonstrated a greater length of property boundary transects within home and core ranges than Arcadia. Watercourse transects show similar lengths within home ranges at our different sites, but Downfall has over twice the length intersecting core ranges compared with Arcadia.

Ground transects along farm tracks and property boundaries at Arcadia traverse ≥80% of home ranges, with even better coverage at Downfall. However, aerial transects, excluding 10 km spacing, cross over 90% of home ranges at both sites and aerial transects with ≤2 km spacing achieve 100% coverage of collared feral pig home ranges and ≥67% of core ranges at both sites. Rotary transects slightly outperform fixed-wing transects in intersecting feral pig ranges.

Influence of baiting strategy on proportion of transect within ranges

Home range

Decreasing the spacing between systematic aerial transects resulted in an increase in proportional bait availability (i.e. emmeans) when examining home ranges (Fig. 2). There were consecutive significant increases in proportional bait availability by reducing spacing from 10 km to 5 km intervals ($P \leq 0.001$), and from 5 km to 4 km intervals ($P = 0.042$). For aerial transect spacing narrower than 4 km, increases in proportional bait availability were insignificant ($P \geq 0.05$). Ground transects along property boundaries and farm tracks offered no significant ($P \geq 0.05$) gains in proportional bait availability over 10 km spaced aerial transects, despite having a >400% increase in total length of transect. Aerial transects with 3 km, 4 km and 5 km spacings, and those along watercourses, had significantly greater proportional bait availability ($P \leq 0.05$) over both ground transects, while simultaneously demonstrating transects up to half the total length. Proportional bait availability of watercourse transects differed little to transects with 5 km spacing ($P = 0.987$) but demonstrated an increase in the

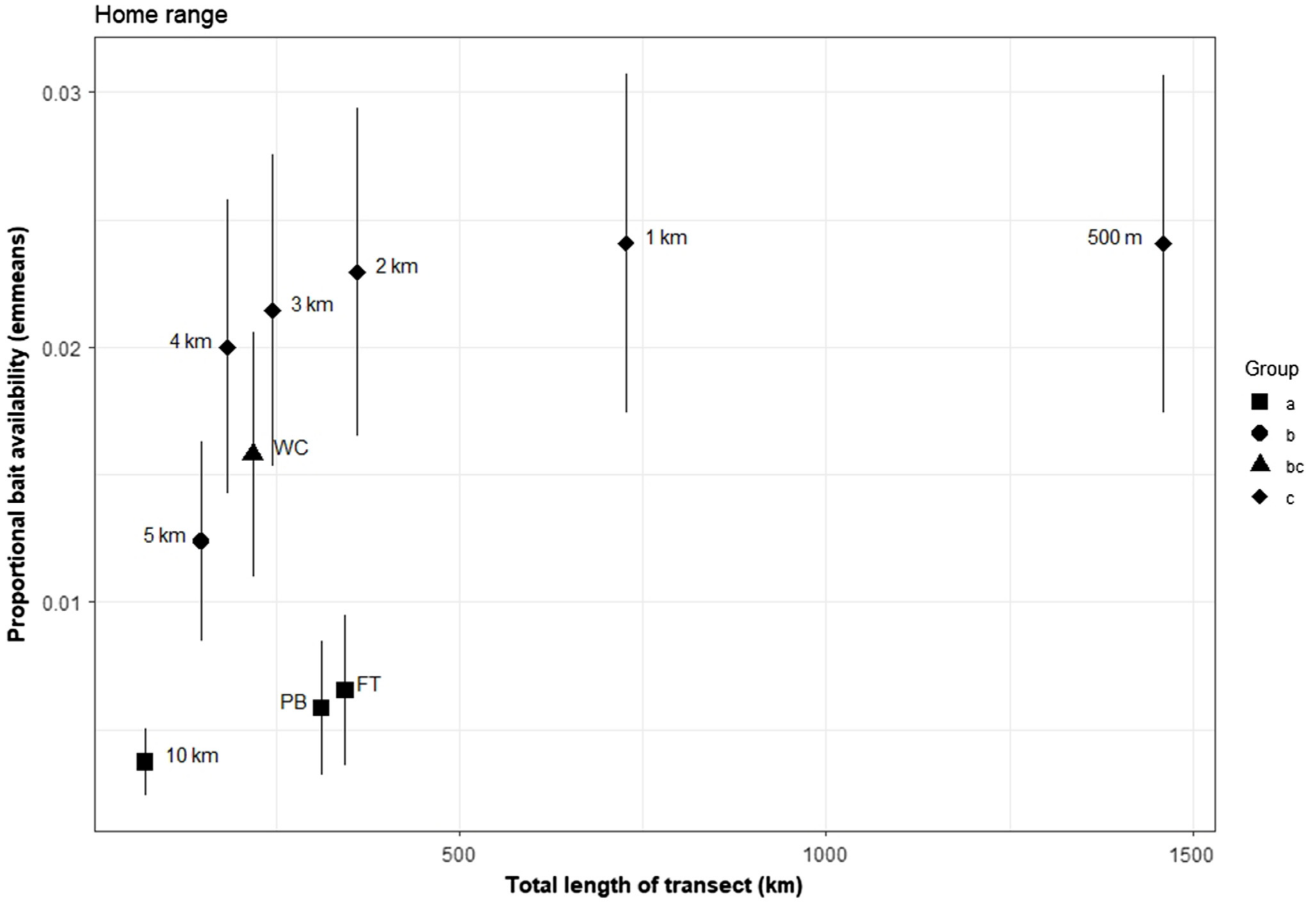

Fig. 2. Overall length of transect for various transect spacing and placements with corresponding emmeans for proportion of transect within home ranges. Group indicates significance grouping according to emmeans. WC, watercourse; FT, farm tracks; PB, property boundaries.

overall length of 146%. Only 4 km spaced aerial transects offered greater proportional bait availability and lower total transect length than watercourse transects.

Core range

Unlike home ranges, decreasing the spacing of systematic aerial transects did not consistently increase proportional bait availability within core ranges of feral pigs (Fig. 3). Transects with 5 km spacing indicated a slight increase ($P = 0.848$) in proportional bait availability over 10 km spacing, but 4 km spacings offered a significant increase ($P = 0.002$) over 5 km spacing. However, 3 km and 2 km spacings demonstrated decreases (albeit insignificant – $P \geq 0.05$) in proportional bait availability from 4 km spaced transects. Only 1 km and 500 m spaced aerial transects produced higher proportional bait availability than 4 km spacing, but at the expense of increasing overall transect length by 386–773%. There was a slight, but insignificant increase ($P \geq 0.05$) in proportional bait availability of 500 m spacing over 1 km. Ground transects along farm tracks and property boundaries did not demonstrate significant differences ($P \geq 0.05$) in proportional bait availability to aerial transects with 5 km or 10 km spacing yet demonstrated considerably larger total lengths of transect. Transects placed along watercourses indicated greater proportional bait availability over farm tracks ($P = 0.253$), property boundaries ($P = 0.045$) and 2 km spaced aerial transects ($P = 0.998$), while simultaneously demonstrating a shorter overall length. However, watercourse transects displayed slightly lower proportional bait availability ($P = 0.994$) and greater overall length (118%) than 4 km spaced transects.

Other variables

When pooling the proportions of transects that fall within respective home and core ranges into the same analysis, ground transects indicated a proportional bait availability of 0.0059, significantly ($P \leq 0.001$) lower than fixed-wing (0.0093) and rotary (0.0098) transects. There was no significant difference in proportional bait availability ($P = 0.626$) between rotary and fixed-wing transects. There was a significant difference ($P \leq 0.001$) in proportional bait availability between transects intersecting male ranges (0.0101) and

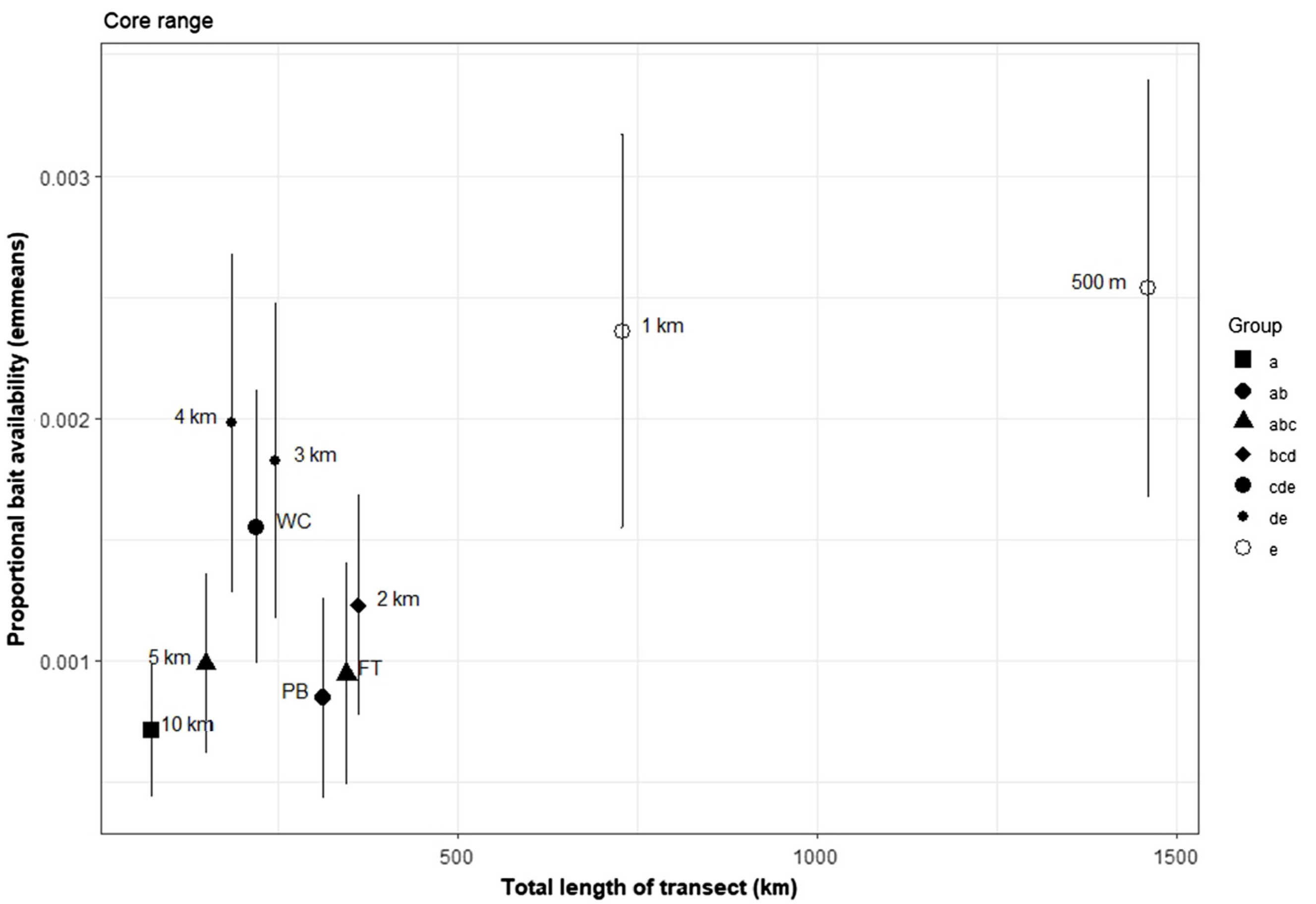

Fig. 3. Overall length of transect for various transect spacing and placements with corresponding emmeans for proportion of transect within core ranges. Group indicates significance grouping according to emmeans. WC, watercourse; FT, farm tracks; PB, property boundaries.

female ranges (0.0079). However, there was no demonstrated interaction between sex and transect spacing, with all paired transects exhibiting no significant difference ($P \geq 0.05$). There was no significant ($P \geq 0.05$) difference in proportional bait availability of paired transects between study sites, with the exception of 5 km spaced aerial transects, where Downfall (0.0149) demonstrated significantly ($P = 0.002$) greater proportional bait availability than Arcadia (0.0053).

Cost

The breakdown of total cost of bait (meat and 1080) and dispersal (vehicle and labour) for each baiting strategy are displayed in Fig. 4. For more detailed cost breakdown, see Table S3. Total cost was positively scaled with increased total transect length, coinciding with decreased spacing between transects. Systematic transects at 500 m spacing were over 20 times more expensive than 10 km spacing flown with equivalent aircraft. Watercourse transects were slightly cheaper (range: AUD$8468–13,742) than 3 km systematically spaced transects (range: AUD$9674–15,312) for equivalent aircraft. For fixed-wing aircraft, watercourse transects were between 34 and 40% cheaper than either ground transect. Distribution of meat baits via fixed-wing aircraft cost between 63 and 71% of rotary aircraft expense. Fixed-wing transects flown at 2 km spacing provided very similar expense to ground transects along farm tracks but slightly more than along property boundaries. Systematic transects with 4 km spacing demonstrated lower expense for both Jet Ranger and R44 aircraft than either ground transect.

Discussion

This study investigated the effectiveness, efficiency and cost of various baiting strategies and transect spacing (500 m, 1 km, 2 km, 3 km, 4 km 5 km and 10 km) at intersecting feral pig home and core ranges on two study sites in north-eastern Australia. Overall, our findings suggest that aerial transects systematically spaced at 500 m intervals have the greatest overall transect length intersecting home and core ranges of feral pigs and are thus considered to be the most effective at targeting feral pigs. However, the substantial increase in the overall length of 500 m spaced transects

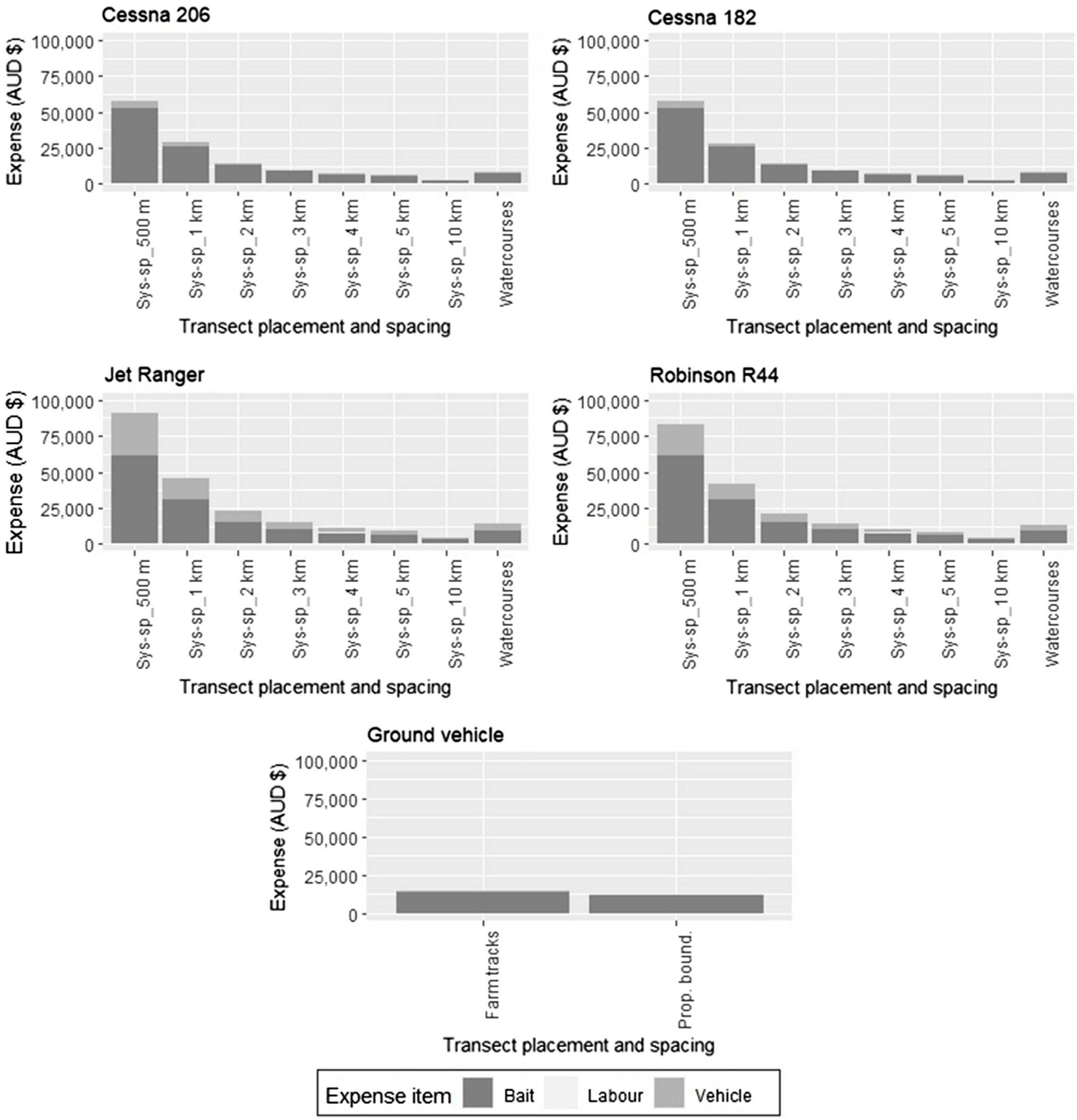

Fig. 4. Breakdown of baiting expense for different vehicle and transect placements/spacings examined in this study. Further information can be found in Table S3.

compared with 4 km spaced transects, without a significant gain in proportional bait availability, suggests that they are inefficient and wasteful. As such, considerable length of 500 m spaced transects fall outside pig ranges. We found that systematically spaced transects with 4 km intervals are the most efficient, while still being very effective at placing transects within the ranges of feral pigs. Although the selection of transect method or spacing is ultimately dependent upon the desired goal and resource constraints, our results suggest that 4 km systematically spaced transects are the most efficient method for placing bait transects within the home and core ranges of feral pigs at these study sites. However, without data on the rate of meat bait encounter and interaction by feral pigs, we cannot model mortality or definitively determine the most effective method for removing feral pigs.

Proportion of transects within ranges and percent of ranges crossed

As expected, increasing the total length of transect by reducing spacing between transects results in a larger quantity of transects falling within the home and core ranges of feral pigs. Systematically spaced transects at 500 m place a greater average length of transect within these ranges but at a considerably greater overall transect length. For efficiency, transects placed along watercourses demonstrate the greatest proportion of total length of transect within the activity ranges of pigs (Tables S1 and S2). This result is consistent with outcomes of previous ecological studies, which have demonstrated that pigs exhibit a preferential selection of habitat with proximity to water (Saunders and Kay 1991; Dexter 1996; Caley 1997; Mitchell *et al.* 2007; Wilson *et al.* 2023*a*). Watercourse-aligned transects may demonstrate a higher proportion of transect within pig ranges, but flying transects with such complex directional changes and orientation would be difficult, time-consuming and likely to add considerable cost. As such, practitioners are more likely to fly simpler, linear (i.e. larger) watercourses, which may influence the proportion that falls within pig ranges.

Although a greater length of transect within the ranges of pigs will result in higher bait availability and higher probability of bait encounters, if the proportion of transect length within their home range to total transect length is low, the overall efficiency will also be low.

Influence of baiting strategy on proportion of transect within ranges

The choice of baiting strategy significantly influenced the proportion of transects falling within both the home and core ranges of feral pigs. Aerial transects with 10 km spacing (the largest examined here) and ground transects along farm tracks and property boundaries had similar effectiveness at placing transects within both ranges of feral pigs, despite both ground transects having a considerably larger overall length and concomitant cost (Table S3). This suggests that there is little to gain by undertaking ground baiting over more effective and more efficient aerial baiting. No baiting strategy examined here demonstrated a significantly greater proportional bait availability than 4 km spaced aerial transects for either home or core ranges, nor higher efficiency (emmeans km^{-1}). Aerial transects placed at less than or equal to 3 km intervals offer greater effectiveness at intersecting pig home ranges but are increasingly inefficient and wasteful. A balance between effectiveness, efficiency and cost is ideal – therefore, systematically spaced transects at 4 km intervals are recommended.

It was observed that systematically spaced transects at 5 km intervals were more variable than all other transects when compared between study sites. The higher proportional bait availability of these transects at Downfall suggest that transects with this spacing would have a significantly greater proportion falling within the ranges of pigs at this site than at Arcadia. The reason for this is unclear, but because Arcadia demonstrated a marked decrease in proportional bait availability from 4 km to 5 km spaced transects, it is possible that ranges at Arcadia are geographically narrower than 5 km and conform to the shape of the valley and other landscape features (e.g. watercourses). Nevertheless, transect spacing less than 5 km apart, or those along watercourses, demonstrated greater consistency at intersecting feral pig ranges across multiple sites.

The slightly higher proportional bait availability of rotary transects to fixed-wing transects is likely due to the shorter distance restrictions imposed by PER89572 (i.e. resulting in longer transects; Table 1). But the higher proportional bait availability suggests that rotary transects may be marginally more effective than fixed-wing transects at placing baits within the ranges of feral pigs. The comparison of proportional bait availability between male and female pigs suggests that males have a higher average proportion of any baiting strategy transect within their home or core range, suggesting greater access to baits or control tools. However, it is important to note that a longer transect length falling within pig home ranges may not equate to greater control effectiveness, because the latter depends upon bait encounter and interaction rates. Additional research is needed to quantify the probability of bait encounter and subsequent interaction rates by feral pigs to assess the number of baits and length of baiting transect required for pigs to be susceptible to baiting. The true impact of the observed difference in baiting strategy transect proportions between male and female pigs also needs further examination. The higher proportional bait availability demonstrated here may be a consequence of larger ranges of males compared with females (Wilson *et al.* 2023*b*), which could result in greater access to baits or other control tools (Dexter 1996).

Caveats

There are, however, important caveats to consider in this study. Firstly, data available on meat bait encounter and interaction rates for feral pigs are currently limited. Although the analysis here suggests that transects spaced at 4 km intervals are an effective and efficient means for placing bait transects within feral pigs' ranges, we cannot determine their effectiveness in controlling feral pigs. We need additional information on the number of baits or transect length necessary to achieve a high probability of bait encounter within a pig's range. It is possible that smaller transect lengths, such as ground transects along farm tracks, may be sufficient for desired control levels. Measuring encounter and interaction rates with baits is possible through tracking individuals in field trials and monitoring baits with cameras (e.g. Kreplins *et al.* 2018; Fancourt *et al.* 2021, 2022).

Secondly, this research has focused on meat baits distributed by air and ground to target feral pigs – the findings may not be applicable to fruit or grain baiting. PIGOUT® baits can also be distributed by air, and reduced distance restrictions (compared with PER89572 (Australian Pesticides and Veterinary Medicines Authority 2021)) may allow for longer transects and more PIGOUT® baits distributed within a pig's range. Despite this, simply distributing more baits may not necessarily lead to more effective pig management where PIGOUT® encounter and interaction rates are lower than meat. To counter low interaction rates, cluster baiting and free-feeding of non-toxic PIGOUT® baits is recommended, although further research is needed to determine the effectiveness. Additionally, there may be differences in baiting strategies around water points (e.g. dams) vs transects, which also require further research.

Thirdly, the starting point and orientation of the systematic transects will influence the proportion of transect that falls within a target animal's range. Narrow transect spacing (e.g. 500 m) increases the probability of crossing a range but changes in the starting point or orientation (i.e. north–south, east–west) of the transect may affect the proportion that actually falls within the animal's range. Moreover, environmental factors, including landscape type, exert an influence on the size and shape of home ranges (feral pigs; Clontz *et al.* (2022)), which may have affected the results of this study. Despite this limitation, systematic transects can identify when transects are too wide and may miss animal ranges, as well as indicate if transects are unnecessarily narrow and therefore negatively impacting efficiency. An increase in property size and/or decreased accessibility to ground vehicles will negatively influence the effectiveness of ground transects at intersecting home and core ranges of feral pigs. As such, the applicability of the ground delivery of baits in more extensive areas of Australia to achieve broadscale control is questioned. It is important to note that the pig ranges discussed in this research only include those pigs that were collared; there may be additional uncollared pigs whose ranges were crossed by the transects. Therefore, the data presented here serve as a comparison of competing strategies for targeting a representative sample of pigs on these study sites.

Our findings have solely focused on the actual distance covered during transects where bait is distributed, without taking into account additional factors such as the time taken to ferry to the starting point, the transit time of vehicles between transects or the transit time across non-permitted areas. Systematically spaced transects may have less transit time between them than watercourse transects, which are randomly orientated and more complex, and will differ greatly depending on site topography. This complexity is likely to substantially increase transit time between bait transects, which would further increase the cost of bait dispersal. Additionally, our study only modelled targeting watercourse transects from the air, but in areas with high accessibility, baits could be distributed from ground vehicles along watercourses. The labour cost of bait dispersal could also be improved through higher vehicle speed (i.e. less time spent dispersing baits) or through the use of motorised bait distribution devices (hoppers).

Implications and applications

The findings of this study have implications for the management of wildlife or vertebrate pests with poison baits or non-lethal substances. In the context of Australian feral pig management, employing more effective and efficient methods can lead to more targeted and resource-efficient baiting efforts, maximising the impact on feral pig populations while lowering overall expense and reducing impacts on non-target species populations. Implementing 4 km spaced aerial transects could improve the overall success of control programs by concentrating efforts in areas of higher pig activity – or else ensuring an appropriate transect spacing to intersect a high proportion of pig ranges. Moreover, these findings have broader applications for wildlife management globally. The methods used in this study may be applied to other species or other regions facing similar challenges, such as wild dog control in Australia (Ballard *et al.* 2020), rat control (Samaniego-Herrera *et al.* 2013) or possum control (Morgan *et al.* 2000) in New Zealand, or more unusual scenarios like brown tree-snake control in Guam (Siers *et al.* 2019). Alternatively, our approaches could be applied to refine other baiting applications, such as the aerial distribution of vaccines for foxes (Henning *et al.* 2017), raccoons or skunks (Rosatte *et al.* 2009), or to deliver oral antiparasitic drugs to treat lice on wolves (Gardner *et al.* 2013). The relevance lies in the adaptability of our methodology, offering a blueprint for comparing and refining competing baiting transect strategies.

Summary

This study found that aerial transects systematically spaced at 4 km intervals on two sites in north-eastern Australia were effective and efficient at intersecting home and core ranges of feral pigs. This indicates that this strategy is the most appropriate distribution spacing for baiting transects within feral pig ranges at these study sites. Additionally, no ground transect method produced a proportional bait availability significantly higher than any aerial method, which suggests that aerial transects are more effective at intersecting feral pig ranges than ground transects. This supports Fancourt *et al.* (2021)'s suggestion that landscape baiting increases probabilities of bait encounters over track-based baiting, though for a different species. This study utilised feral pigs as a case study, but the methodology can be applied to other baiting applications (e.g. invasive species control or disease prevention). Further research in this field should examine bait encounter and interaction rates by the targeted species.

This understanding will help to quantify the necessary number of baits and the length of transects required within an animal's range to have a desired probability of bait uptake.

Supplementary material

Supplementary material is available online.

References

Algar D, Angus GJ, Williams MR, Mellican AE (2007) Influence of bait type, weather and prey abundance on bait uptake by feral cats (*Felis catus*) on Peron Peninsula, Western Australia. *Conservation Science Western Australia* **6**, 109–149.

Allen LR, Fleming PJS, Thompson JA, Strong K (1989) Effect of presentation on the attractiveness and palatability to wild dogs and other wildlife of 2 unpoisoned wild-dog bait types. *Wildlife Research* **16**, 593–598. doi:10.1071/WR9890593

Australian Pesticides and Veterinary Medicines Authority (2021) Permit to allow minor use of a registered agvet chemical product for the control of feral pigs. Permit Number – PER89572. Available at https://permits.apvma.gov.au/PER89572.PDF

Australian Taxation Office (2023) Expenses for a car you own or lease. Available at https://www.ato.gov.au/individuals/income-deductions-offsets-and-records/deductions-you-can-claim/cars-transport-and-travel/motor-vehicle-and-car-expenses/expenses-for-a-car-you-own-or-lease/#:~:text=Use%20the%20rate%20for%20the,use%2072%20cents%20per%20kilometre [accessed 6 June 2023]

Ballard G, Fleming PJS, Meek PD, Doak S (2020) Aerial baiting and wild dog mortality in south-eastern Australia. *Wildlife Research* **47**, 99–105. doi:10.1071/WR18188

Bureau of Meteorology (2022*a*) Climate classification maps. Available at http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp?maptype=kpngrp#maps [accessed 8 April 2022]

Bureau of Meteorology (2022*b*) Summary statistics Miles Post Office. Available at http://www.bom.gov.au/climate/averages/tables/cw_042023.shtml [accessed 8 April 2022]

Bureau of Meteorology (2022*c*) Summary statistics Rolleston. Available at http://www.bom.gov.au/climate/averages/tables/cw_035059.shtml [accessed 8 April 2022]

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

Caley P (1997) Movements, activity patterns and habitat use of feral pigs (*Sus scrofa*) in a tropical habitat. *Wildlife Research* **24**, 77–87. doi:10.1071/WR94075

Clontz LM, Pepin KM, VerCauteren KC, Beasley JC (2022) Influence of biotic and abiotic factors on home range size and shape of invasive wild pigs (*Sus scrofa*). *Pest Management Science* **78**, 914–928. doi:10.1002/ps.6701

Cribari-Neto F, Zeileis A (2010) Beta regression in R. *Journal of Statistical Software* **34**, 1–24. doi:10.18637/jss.v034.i02

Day TD (2003) Bird repellents for pest control baits. Doctoral Thesis, The University of Waikato, Hamilton, New Zealand.

Department of Environment and Science (2022) WetlandInfo. Available at https://wetlandinfo.des.qld.gov.au/wetlands/ [accessed 9 June 2021]

Department of Natural Resources Mines and Energy (2013) Stock routes – Queensland. Available at https://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={A97FBCB0-2EA8-4768-9398-D6192879F6FD} [accessed 20 July 2021]

Department of Resources (2021*a*) Land use mapping – 1999 to Current – Queensland. Available at https://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={273F1E50-DD95-4772-BD6C-5C1963CAA594} [accessed 20 July 2021]

Department of Resources (2021*b*) Property boundaries Queensland. Available at https://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={3F217A59-1FDB-412A-813D-A1E7843FB618} [accessed 20 July 2021]

Department of Resources (2021*c*) Baseline roads and tracks – Queensland. Available at https://qldspatial.information.qld.gov.au/catalogue/custom/detail.page?fid={BEF06A7B-0F0B-4DE0-B7A6-D4B4C2651993} [accessed 20 July 2021]

Dexter N (1996) The effect of an intensive shooting exercise from a helicopter on the behaviour of surviving feral pigs. *Wildlife Research* **23**, 435–441. doi:10.1071/WR9960435

Fair Work Ombudsman (2023) Minimum wages. Available at https://www.fairwork.gov.au/tools-and-resources/fact-sheets/minimum-workplace-entitlements/minimum-wages [accessed 6 June 2022]

Fancourt BA, Augusteyn J, Cremasco P, Nolan B, Richards S, Speed J, Wilson C, Gentle MN (2021) Measuring, evaluating and improving the effectiveness of invasive predator control programs: feral cat baiting as a case study. *Journal of Environmental Management* **280**, 111691. doi:10.1016/j.jenvman.2020.111691

Fancourt BA, Harry G, Speed J, Gentle MN (2022) Efficacy and safety of Eradicat® feral cat baits in eastern Australia: population impacts of baiting programmes on feral cats and non-target mammals and birds. *Journal of Pest Science* **95**, 505–522. doi:10.1007/s10340-021-01433-9

Gardner CL, Beckmen KB, Pamperin NJ, Del Vecchio P (2013) Experimental treatment of dog lice infestation in interior Alaska wolf packs. *The Journal of Wildlife Management* **77**, 626–632. doi:10.1002/jwmg.495

Henning J, Giorgi E, Soares Magalhães RJ, Tizzani P, Viviani P, Pejovic N, Hrapović M, Potzsch C (2017) Factors influencing the success of aerial rabies vaccination of foxes. *Scientific Reports* **7**, 14376. doi:10.1038/s41598-017-14615-2

Kelly DJ, Corner LAL, Gormley E, Murphy D, Costello E, Aldwell FE, Marples NM (2011) Evaluation of attractant flavours for use in oral vaccine baits for badgers (*Meles meles*). *European Journal of Wildlife Research* **57**, 767–774. doi:10.1007/s10344-010-0485-7

Kreplins TL, Kennedy MS, Adams PJ, Bateman PW, Dundas SD, Fleming PA (2018) Fate of dried meat baits aimed at wild dog (*Canis familiaris*) control. *Wildlife Research* **45**, 528–538. doi:10.1071/WR17182

Lenth R, Buerkner P, Herve M, Love J, Riebl H, Singmann H (2021) emmeans: estimated marginal means, aka Least-Squares Means. R package version 1.7.0. Available at https://CRAN.R-project.org/package=emmeans

Mitchell J, Dorney W, Mayer R, McIlroy J (2007) Spatial and temporal patterns of feral pig diggings in rainforests of north Queensland. *Wildlife Research* **34**, 597–602. doi:10.1071/WR06064

Moennig V (2015) The control of classical swine fever in wild boar. *Frontiers in Microbiology* **6**, 1211. doi:10.3389/fmicb.2015.01211

Morgan D, Coleman JD, Sweetapple PJ (2000) 'Effectiveness of aerial baiting of possums in different seasons and different forest types.' (Department of Conservation: New Zealand)

Pebesma E (2018) Simple features for R: standardized support for spatial vector data. *The R Journal* **10**, 439–446. doi:10.32614/RJ-2018-009

R Core Team (2021) 'R: a language and environment for statistical computing.' (R Foundation for Statistical Computing: Vienna, Austria). Available at https://www.R-project.org/

Rosatte RC, Donovan D, Davies JC, Allan M, Bachmann P, Stevenson B, Sobey K, Brown L, Silver A, Bennett K, Buchanan T, Bruce L, Gibson M, Beresford A, Beath A, Fehlner-Gardiner C, Lawson K (2009) Aerial distribution of ONRAB® baits as a tactic to control rabies in raccoons and striped skunks in Ontario, Canada. *Journal of Wildlife Diseases* **45**, 363–374. doi:10.7589/0090-3558-45.2.363

Samaniego-Herrera A, Anderson DP, Parkes JP, Aguirre-Muñoz A (2013) Rapid assessment of rat eradication after aerial baiting. *Journal of Applied Ecology* **50**, 1415–1421. doi:10.1111/1365-2664.12147

Saunders G, Kay B (1991) Movements of feral pigs (*Sus scrofa*) at Sunny Corner, New South Wales. *Wildlife Research* **18**, 49–61. doi:10.1071/WR9910049

Shahwar De, Azeem SA, Kawan A, Mukhtar H, Sajawal A, Noureen S, Khalil S (2024) Significance of additives to enhance the acceptance of poison bait in poultry rodents of Haripur, Khyber Pakhtunkhwa, Pakistan. *PLoS ONE* **19**, e0272397. doi:10.1371/journal.pone.0272397

Siers S, Pitt W, Eisemann J, Clark L, Shiels AB, Clark C, Gosnell R, Messaros M (2019) In situ evaluation of an automated aerial bait delivery system for landscape-scale control of invasive brown treesnakes on Guam. USDA National Wildlife Research Center - Staff Publications. Available at https://digitalcommons.unl.edu/icwdm_usdanwrc/2252

Taggart PL, Taylor P, Patel KK, Noble DWA (2023) Baiting in conservation and pest management: a systematic review of its global applications in a changing world. *Biological Conservation* **284**, 110214. doi:10.1016/j.biocon.2023.110214

Wilson C, Gentle M (2022) Feral pig population control techniques: a review and discussion of efficacy and efficiency for application in Queensland. Department of Agriculture and Fisheries, Brisbane, Qld, Australia. Available at https://www.publications.qld.gov.au/ckan-publications-attachments-prod/resources/65da2abf-25e6-4464-a8ee-748dc579ff2d/feral-pig-control-techniques-a-review-and-discussion-of-efficacy-and-efficiency-for-application-.pdf?ETag=5ce4232aa26ec7bcac68d828f28bc129

Wilson C, Gentle M, Marshall D (2023*a*) Feral pig (*Sus scrofa*) activity and landscape feature revisitation across four sites in eastern Australia. *Australian Mammalogy* **45**, 305–316. doi:10.1071/AM22034

Wilson C, Gentle M, Marshall D (2023*b*) Factors influencing the activity ranges of feral pigs (*Sus scrofa*) across four sites in eastern Australia. *Wildlife Research* **50**, 876–889. doi:10.1071/WR22095

Data availability. The data that support this study were obtained from Southern Queensland Landscapes by permission. Data will be shared upon reasonable request to the corresponding author with permission from Southern Queensland Landscapes.

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

Declaration of funding. Fieldwork was supported by funding provided by the Queensland Murray Darling Committee (QMDC), Santos GNLG, Arrow Energy, Southern Queensland Landscapes, South East Local Land Services and the NSW Environmental Trust. Spatial modelling analysis was undertaken as part of the Queensland state government-funded African swine fever prevention and preparedness project.

Acknowledgements. All field work and data collected were completed by DM; CW analysed the data and led the writing of the manuscript; MG assisted in data analysis, project design and manuscript writing. Thanks to Damien McNair (Quilpie Shire Council) and Jeff Newton (Longreach Shire Council) for data on costs associated with aerial baiting. Thanks to Catherine Kelly for comments that improved the manuscript.

Author affiliations

[A]Animal Biosecurity and Welfare, Biosecurity Queensland, Department of Agriculture and Fisheries, Bundaberg, Qld 4670, Australia.

[B]Pest Animal Research Centre, Biosecurity Queensland, Department of Agriculture and Fisheries, Toowoomba, Qld 4350, Australia.

[C]School of Sciences, University of Southern Queensland, Toowoomba, Qld 4350, Australia.

[D]Southern Queensland Landscapes, Toowoomba, Qld 4350, Australia.