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ORIGINAL PAPER

Rapid eradication of invasive rusa deer (*Cervus timorensis*) from Wild Duck Island, Australia, using thermally assisted aerial culling and a camera trapping grid

Matt Amos · Michael Brennan · Anthony R. Pople · Steve Burke · Andrew J. Bengsen · Jordan R. Munn · David M. Forsyth

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Abstract Non-native rusa deer (*Cervus timorensis*) were introduced to the 380-ha Wild Duck Island, an important flatback turtle nesting site in Broad Sound Islands National Park, Queensland, Australia, in the mid-2000s. Initial attempts to remove the population through ground and aerial culling (2007–2017) were unsuccessful. A more comprehensive eradication program commenced in 2018, employing aerial culling. In late 2019, a grid of 44 motion-sensitive cameras was established to estimate deer population size and map its distribution. During 2018–2023, 168 rusa deer were culled. As the population declined, the hours flown per deer culled increased. To efficiently remove the remaining deer, a thermal imager was used in 2022, helping to remove 10 of the last 11 deer. In January 2023, the camera grid detected one remaining adult female, which was detected by the thermal imager and culled in August 2023 after only 28 min of flying. Subsequent monitoring over 4,094 trap days revealed no deer presence. Modelling of camera grid data indicated a 99.3% probability of eradication (95% C.I. 0.973–0.999), and no further signs of rusa deer have been observed during opportunistic searches. To the best of our knowledge, this is the first documented eradication of a non-native rusa deer population. Key factors enabling success included transitioning from ground-based to helicopter-based shooting and integrating thermal imaging to locate and remove the last 11 individuals. A robust monitoring program tracked progress towards eradication and enabled the probability of eradication to be estimated. The approach used in this project could be applied to other programs aiming to eradicate cryptic large mammals.

Keywords Aerial shooting · Camera trap · Great Barrier Reef · Ground-based shooting · Introduced · Non-native · Proof of freedom · Spatial mark-resight models · Ungulates

Associate Editor - Noelia Barrios-Garcia

M. Amos (✉)
Queensland Department of Primary Industries,
Toowoomba, QLD, Australia
e-mail: matt.amos@dpi.qld.gov.au

M. Brennan · A. R. Pople
Queensland Department of Primary Industries,
Dutton Park, QLD, Australia

S. Burke
Queensland Parks and Wildlife Service, Yeppoon,
QLD 4703, Australia

A. J. Bengsen
Department of Primary Industries and Regional
Development, Calala, NSW, Australia

J. R. Munn
Trap and Trigger Ltd., Wellington, New Zealand

D. M. Forsyth
Department of Primary Industries and Regional
Development, Orange, NSW, Australia

Introduction

Islands are critical for global conservation because their unique biodiversity is disproportionally more at risk of extinction (Tershy et al. 2015; Matthews and Triantis 2021). Invasive non-native mammals are a key threat to island biodiversity (Clavero and García-Berthou 2005; Jones et al. 2016; Spatz et al. 2022). The undesirable impacts of non-native ungulates on native ecosystems include modification of plant communities and an increase in bare ground (e.g. Davis et al. 2016; Wardle et al. 2011). These impacts can be more severe on islands where an introduced herbivore population is not regulated through emigration or predation and reaches very high densities (e.g. Klein 1968; Coblentz 1978; Vuren and Coblentz 1987). Additionally, island ecosystems may be more vulnerable to modification by ungulates than mainland ecosystems because the former have evolved in the absence of ungulates (Hess et al. 2015).

Eradication is the complete and permanent removal of the target species from a defined area, and within a defined time period (Bomford and O'Brien 1995). For eradication to be successful, Bomford and O'Brien (1995) outlined three criteria that must be met: (1) the rate of removal must exceed the rate of increase at all population densities; (2) immigration must be zero (i.e., no chance of re-invasion); and (3), all reproductive animals must be at risk to the eradication method. A fourth criterion, that animals can be detected at low densities, was listed as desirable (Bomford and O'Brien 1995). For islands that are a long way from the nearest source population of ungulates, or that are otherwise difficult to reach (e.g., due to strong currents or steep cliffs), then Criterion 2 is likely to be met. Meeting criteria 3 and 4 (which determine and assess criterion 1) can be difficult in thick vegetation and over large areas. There is a long history of eradicating some non-native ungulates (e.g. feral goats *Capra hircus*) from islands (Parkes 1984, 1990; Carrion et al. 2011). Eradications, however, can be expensive (Martins et al. 2006) and attempts often fail (DIISE 2018).

Whereas there is a long history of eradicating feral goats from islands, there are few successful examples of non-native deer (Family Cervidae) populations being eradicated (DIISE 2018). Globally, 19 or 20 species of deer have extant non-native populations, with fallow (*Dama dama*), sika (*Cervus nippon*), axis (*Axis axis*), rusa (*Rusa timorensis*), and red deer (*Cervus elaphus*) the most common and most widely distributed non-native deer species (Nugent et al. 2025). According to the Database of Island Invasive Species Eradications (DIISE 2018; Macdonald et al. 2019), of 408 island eradication attempts made for ungulates worldwide, only 27 (6.6%) were for deer species. Of these, thirteen attempts were successful, one was listed as successful but re-invaded, and the rest were recorded as "incomplete", "in progress" or "unknown".

Successful island deer eradications include red deer (*Cervus elaphus*) from Secretary Island, New Zealand (Macdonald et al. 2019), and fallow deer (*Dama dama*) from Kangaroo Island, Australia (Masters et al. 2018). These successful eradications highlighted the importance of a rapid population knockdown, ability to detect deer at low densities, and ability to change tactics (Masters et al. 2018; Macdonald et al. 2019). An attempt at eradication of Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) on Haida Gwaii, Canada, was unsuccessful, with likely reasons identified including lack of a robust population estimate, no assessment of removal methods and insufficient budget for contingencies (Irvine and Thorley 2024).

Here, we report the successful eradication of rusa deer (*Cervus timorensis*) from Wild Duck Island (WDI), a small island off the Central Queensland coast that supports vegetation of high conservation value and serves as an important rookery for the flatback sea turtle (*Natator depressus*), a species that nests only in Australia (FitzSimmons et al. 2020). Flatback turtles are listed as vulnerable by the Australian Government (Department of the Environment and Energy 2017) and globally as data deficient (IUCN 2024). In documenting this eradication, we identify the reasons for success which should help with the planning of attempts at eradicating non-native ungulates (particularly deer) elsewhere. Mammal eradication is difficult even when the above essential criteria appear easily met. New control and monitoring tools were required and can be applied elsewhere. Time taken to eradication is also important as it affects both the funding required for an attempt and continued socio-political support.

Methods

Study area

Our study was conducted on Wild Duck Island (22.00° S, 149.87° E; Fig. 1), Broad Sound Islands National Park, Central Queensland, Australia. This 380-ha island is one of 48 in the Broad Sound group. The Broad Sound area is characterised by shallow bays with macro-tides (> 4 m) that are the largest in Queensland resulting in fast-flowing tidal currents (Kingsford and Wolanski 2008; Hamann et al. 2011).

The terrain is undulating from low sand dunes to rocky outcrops and cliffs (maximum elevation: ~ 108 m above sea level). The vegetation is predominantly open forest consisting of bloodwoods (*Corymbia* sp.) and wattle (*Acacia julifera* subs *julifera*), but there are also areas of semi-evergreen vine forest, tussock grassland (*Heteropogon contortus*), and she-oak (*Casuarina* sp.) low woodland/open shrubland complex along the beach dunes (Queensland Department of Environment and Science 2021). Of the four vegetation communities ('regional ecosystems'; Sattler and Williams 1999) on Wild Duck Island, three are of conservation concern, and one is endangered (Queensland Herbarium 2024). The climate is subtropical with a hot humid summer (Bureau of Meteorology 2024a). The annual rainfall of 1,010 mm mostly falls during November–April (Bureau of Meteorology 2024b).

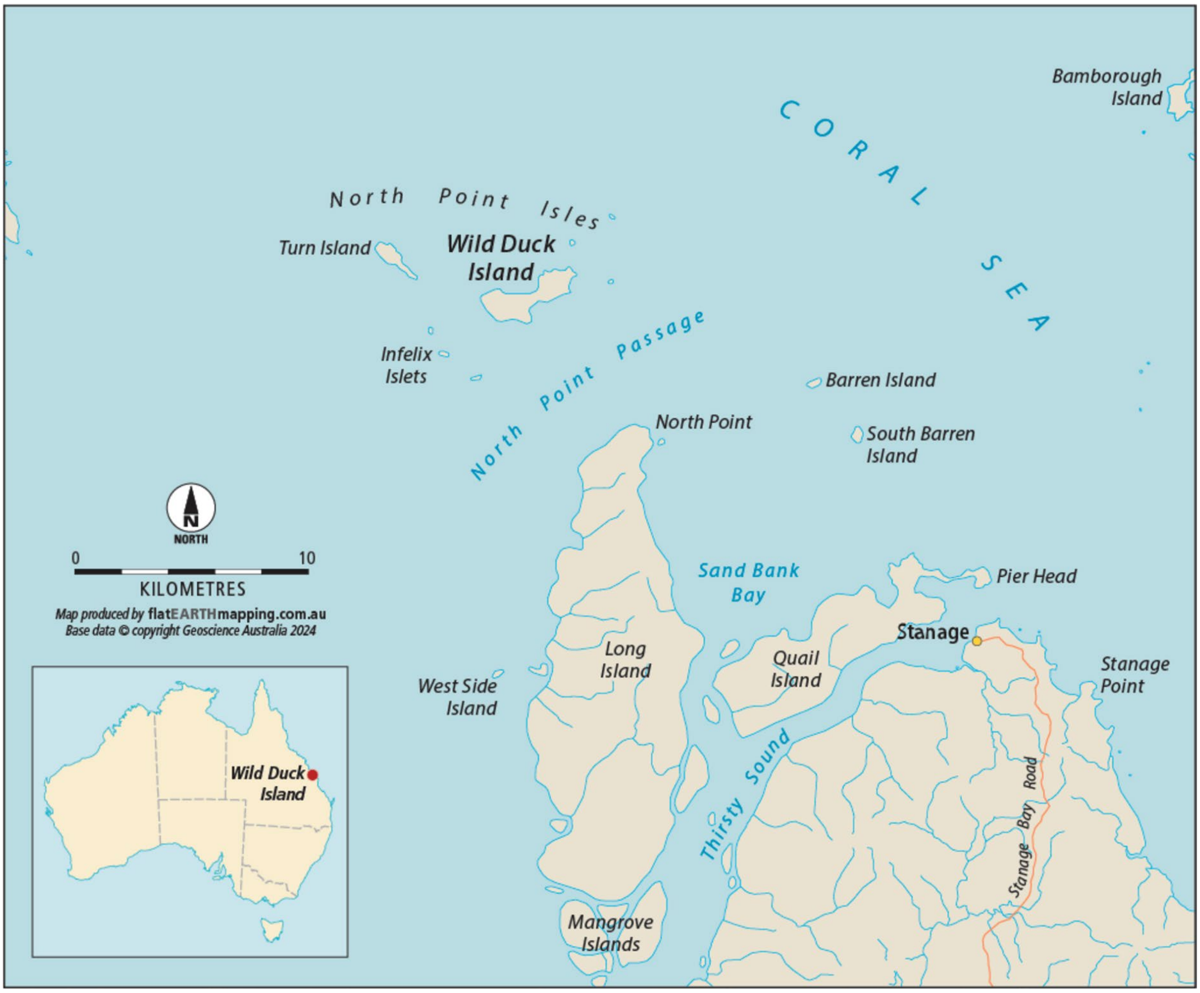

Fig. 1 Location of the 380-ha Wild Duck Island, Queensland, Australia. Rusa deer are also present on Long Island

Mean minimum and maximum temperatures are 22.5 °C and 31.7 °C in summer, and 10.9 °C and 23.8 °C in winter (Bureau of Meteorology 2024b).

Wild Duck Island is uninhabited and has no roads or tracks. During summer there is a temporary camp of four people who monitor flatback turtles as they come ashore to nest on the eastern and western beaches in the middle of the island (Limpus et al. 2013).

Study species

Rusa deer, which are native to Indonesia, have been introduced to many tropical islands in the Indo-Pacific region, as well as to mainland Australia and New Zealand (Moriarty 2004; Leslie 2011; Chalmers 2018; Martins et al. 2018). Adult males and females weigh up to 140 kg and 70 kg, respectively (Moriarty 2004). Coat colour changes seasonally but is typically reddish- or grey-brown (Moriarty 2004; Ingleby 2022). Breeding can occur throughout the year but mating peaks in August–September with a single fawn born 249 days later that is weaned at ~ four months (Woodford and Dunning 1992; Dryden 2000; Moriarty 2004; Hedges et al. 2015). Rusa deer can live up to 20 years (Forsyth et al. 2004; Ingleby 2022). The preferred habitat of rusa deer is woodland and forest (Hall and Gill 2005), and their generalist diet includes leaves, bark, shrubs and, when available, seaweed (Hedges et al. 2015; Ali et al. 2021).

On the west coast of New Caledonia, where the climate and vegetation are similar to those on WDI, seven (four female and three male) rusa deer fitted with VHF-transmitters had home ranges of 501 ± 33 ha and preferentially used the sclerophyll forest and flood plain habitats (Spaggiari and De Garine-Wichatitsky 2006). Two studies of rusa deer in Australia have shown them to have strong site fidelity with only small seasonal home range shifts (Moriarty 2004; Amos et al. 2023).

Rusa deer were illegally introduced to the island in 2005. Evidence of undesirable grazing, browsing and trampling impacts became increasingly obvious. Large groups of deer were observed grazing and trampling in the dune nesting habitat of flatback turtles, further highlighting the conservation concern.

History of control, 2007–2017

The rusa deer population on Wild Duck Island has been managed by the Queensland Parks and Wildlife Service (QPWS) since at least 2007 as part of the pest management strategy for the wider Broad Sound Islands National Park. Control of the population may have commenced earlier, but records prior to 2012 are limited. Aerial shooting (conducted via helicopter) was implemented between 2007 and 2015 in conjunction with and largely driven by pest control activities on neighbouring islands. In 2007, 29 rusa deer were culled, followed by the removal of 40 rusa deer and three feral pigs (*Sus scrofa*) between 2008 and 2011. Additionally, ad hoc ground shooting was conducted prior to 2012, although detailed records are unavailable. From 2012 to 2015, 33 rusa deer were culled during 22 h of aerial shooting operations. In 2016 and 2017, funding limited deer control to ground-based shooting using thermal vision equipment, which resulted in the removal of 12 rusa deer over three nights.

Eradication, 2018–2023

An eradication program with an increased budget began in 2018. Although deer are present on neighbouring Long Island (~ 7 km south of WDI; Fig. 1) and are known to be capable swimmers, eradication was considered feasible because the risk of re-invasion was considered very low due to two key factors: (1) deer were introduced to the island by people rather than arriving naturally, and (2) the large tides and swift-moving waters around WDI act as a significant natural barrier to recolonisation (Ariefiandy et al. 2016). The program used only aerial culling.

The aerial culling team consisted of a pilot and shooter for conventional shooting and also included a thermal-imager operator (Trap and Trigger Ltd., New Zealand) for thermally assisted aerial culling (TAAC; Pulsford et al. 2022; Cox et al. 2023). The shooter was positioned in the back right (behind pilot) for conventional shooting and back left (behind thermal operator) for TAAC. A Robinson R44 helicopter was used for all conventional culls. A Bell 206 Jetranger was used in August 2022 and 2023 for TAAC to provide increased power to counteract the weight of the extra crew member. The shooter used a Ruger Model SR762 (Sturm, Ruger

& Co. Inc., Southport, CT, USA) Semi-Automatic 0.308 calibre rifle with a Leupold Carbine Optic (Leupold and Stevens, Inc., Beaverton, Oregon, USA) red dot sight attached for conventional culling. The sight was changed to an iAiming 612 (Uniwin Smart Pty Ltd, Springvale, VIC, Australia) thermal imaging scope for TAAC. The thermal operator used an InfraTec VarioCAM HD® 980 (Infratec GmbH Infrarotsensorik und Messtechnik, Dresden, Germany) with a 1024 × 768-pixel detector, temperature resolution of ≥ 30 mK and a full frame rate of 30 Hz. The infrared camera was stabilised on a vest mounted handheld camera stabiliser arm and aligned with a 2.5w laser and a Sony ADX-55 4 K (Sony Group Corporation, Tokyo, Japan) video camera. The thermal operator viewed the thermal output via a separate detachable Aputure VS-5X V-screen (Aputure Imaging Industries Co. Ltd, Shenzhen, China) camera monitor with sun hood. The laser was used as a guide to pinpoint deer locations from a distance, which allows the pilot to plan an approach, and the shooter to anticipate the deer's specific location, and track its movements by following the laser.

Monitoring deer abundance using a grid of motion-sensitive cameras

Steep terrain and thick vegetation on WDI, and the need for accurate and repeatable estimates of abundance, precluded the use of some potential monitoring methods (Gardner et al. 2019; Forsyth et al. 2022). Given the relatively small size of the island and its remoteness, motion-sensitive cameras were considered the most suitable monitoring method independent of helicopter effort and kill data. They could be set and left for many weeks, with no need for staff to visit the island except to set and retrieve them. A grid of cameras was expected to provide unbiased and appropriately precise estimates of deer abundance with a detection probability sufficient to detect deer at very low density (Bengsen et al. 2022; Forsyth et al. 2022).

Four camera trap surveys were conducted on WDI: 2019, 2020–21, 2021–22 and 2022–23. The deployment time ranged from 62 to 182 days. The same hexagonal grid was used in all four surveys (Fig. 2). The design and analysis of data are described fully (along with data and code for the 2019 survey) in Bengsen

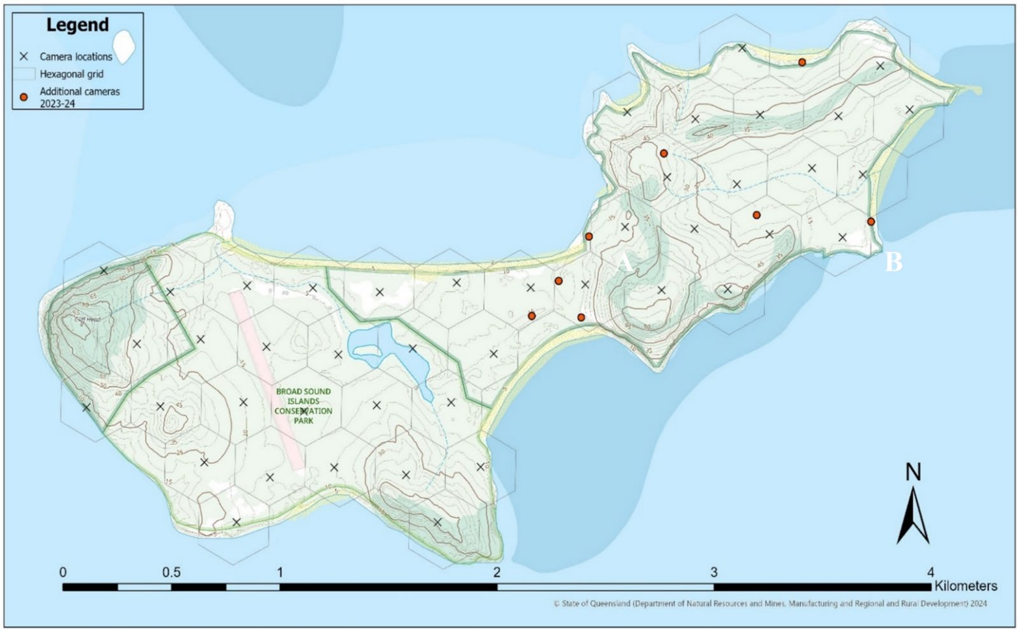

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Fig. 2 Map of Wild Duck Island showing the location of the 44 camera traps that formed the survey grid along with the 300 m hexagonal grid used for camera placement. An additional eight cameras were deployed for the proof of absence survey in 2023–24 where there was a high probability deer might be sighted et al. (2022). Briefly, a hexagonal camera trap grid with a spacing of 300 m between centroids was selected based on a likely rusa deer home range size, maximising detections of individual deer on multiple cameras and obtaining a comprehensive coverage of the island. The cameras were deployed within a 50-m radius around the centroid of each grid cell. This provided an approximately even spacing among neighbouring cameras, while allowing us to position cameras on game trails and other features that would enhance the probability of detecting deer that were using the area around the grid cell centroid. We used 44 Swift 3C cameras (Outdoor Cameras Australia, Toowoomba, Queensland, Australia) in the trapping grid with lithium batteries for extended battery life. Cameras were mounted ~ 60 cm above the ground and orientated so that the focal point was ~ 40 cm above the ground at a distance of 6 m. Cameras were set to low sensitivity, 5 MP photo size, a burst of five photos per trigger and no delay between triggers. To avoid the risk of modifying deer behaviour and introducing an uncontrolled source of bias to our estimates, no baits or lures were used to attract animals to the camera.

Consecutive photos of deer separated by < 10 min were grouped into detection events and the total number of deer for each event recorded. We attempted to identify individual deer on camera images using antler morphology (for males) and other distinctive natural markings (Fig. 3). We used this information to construct detection histories of marked and unmarked animals. We fitted Bayesian spatial mark-resight (SMR)(Royle et al. 2014) models to those detection histories to estimate population density and abundance in R 4.3.2 (R Core Team 2023). We specified vague priors for the σ and λ_0 parameters (U(0,5) and β(1,1), respectively). Models were run for between 1.65×10^6 and 8×10^6 Markov chain Monte Carlo (MCMC) iterations after discarding 5,000 burn in draws. The state space was defined by the perimeter of the island at high tide. See Bengsen et al. (2022) for further details of the approach to data processing and analysis.

Probability of eradication

We used the Proof of Absence (PoA) calculator at https://landcare.shinyapps.io/proofofabsence/ (Gormley et al. 2021; Ramsey et al. 2022) to estimate the probability that rusa deer had been eradicated on WDI following TAAC conducted in August 2023. On 24–25 October 2023, we deployed cameras at the same 44 sites as described above for 2019–2023. An additional eight Swift 3C cameras (wide angle model) were added to the grid (Fig. 2) to improve detection probability because one deer had been detected once

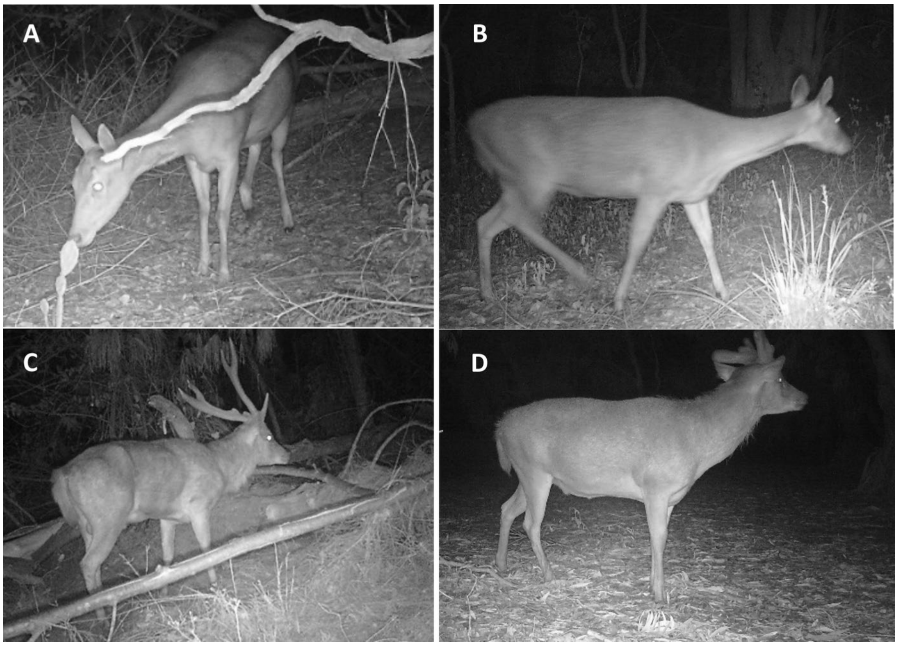

Fig. 3 Rusa deer images from four camera traps on Wild Duck Island. An identified female rusa deer due to unique hair whorls on forehead, photographed at Camera 38 (**A**) and Camera 41 (**B**) during the 2022–23 camera monitoring period. This deer is thought to be the last survivor and to have been shot in August 2023. An individually identified stag in hard antler (**C**) in 2019 and an individually identified stag in velvet (**D**) in 2020–21. This is possibly the same stag due to the unique antler formation

at only two camera locations in the 2022–23 monitoring. We located the additional cameras in areas with a high probability of detection based on previous detections on grid cameras and incidental observations of deer and deer signs (i.e., faecal pellets, footprints, antler rubbing and wallows). This boosted detection probability for the final survey above that required to estimate population size previously.

The maximum probability of detection g_0 was determined as $g_0 = 1 - \exp(-\lambda_0)$ (D. Ramsey, Arthur Rylah Institute, pers. comm.), where λ_0 (the expected encounter rate; Bengsen et al. 2022) was estimated from our SMR modelling. There is little difference between λ_0 and g_0 when λ_0 is low, as was the case with our estimates. We used the most conservative parameters obtained from our SMR modelling for PoA calculations; $\lambda_0 = 0.032$ and $\sigma = 222$ m (σ is the home range size scale parameter; Gormley et al. 2021).

The probability of detecting a deer, given that it is present, will depend on the number of cameras and the length of the survey period. We therefore examined the relationship between probability of eradication and five possible survey periods using the PoA calculator with conservative parameters and three prior probabilities (0.1, 0.5 and 0.95) to determine the minimum survey period to generate a high probability of eradication ($\geq 98\%$).

Ethics approval

The camera trap monitoring was approved by the Queensland Department of Agriculture and Fisheries Ethics Committee approvals CA 2019/04/1281 and CA 2022/08/1634. No approvals were needed for culling as rusa deer are classified as a restricted invasive animal under the Queensland *Biosecurity Act 2014*.

Results

Aerial culling for eradication

A total of 168 rusa deer were aerially culled in 94.1 h between 2018 and 2023 (Table 1). Culling efficiency (catch-per-unit-effort) was highest in the first three years of the aerial culling (Fig. 4) and thereafter declined approximately linearly as estimated deer abundance declined. Thermally assisted aerial culling was used for the final shoot of 2022, in which 10 of the 11 remaining deer were culled in 9.5 h. TAAC was also utilised to cull the last deer in 2023, which took approximately 28 min after 7.6 h of conventional aerial shooting had failed to locate that deer (Fig. 5). Aircraft hire for the program cost approximately AUD $175,000, with an additional AUD $10,000 for the thermal operator; however, costs for the shooter and ammunition were not included (S. Burke, pers. comm.).

Table 1 Aerial culling effort (without and with thermal imaging to detect deer) and numbers of rusa deer culled during the rusa deer eradication program on Wild Duck Island, Queensland, Australia, 2018–2023

Year	Aerial culling without thermal		Aerial culling with thermal[a]	
	Effort (hours)	Deer culled	Effort (hours)	Deer culled
2018	5.0	34		
2019	4.6	13		
2020	32.0	72		
2021	21.9	23		
2022	12.2	15	9.5	10
2023	7.6	0	1.3	1
Totals	83.3	157	10.8	11

[a] Aerial culling with thermal was utilised only in 2022 and 2023

Monitoring rusa deer abundance using a grid of motion-sensitive cameras

There were five camera trap surveys during the project. Four surveys occurred during the removal phase with the objective of estimating the abundance of deer on WDI. The fifth and final survey occurred after the removal phase with the objective of confirming that rusa deer had been eradicated (i.e., abundance was zero). The timing of deployment and retrieval of cameras along with the number of trap days and raw deer detections are summarised in Table 2.

Rusa deer abundance declined from an estimated 39 (95% CI: 31–51) in 2019 to 28 (18–47) in 2020–21 and 18 (14–24) in 2021–22 (Table 3). There were only two detections of one individual deer in the 2022–23 survey, precluding the estimation of population size using SMR. This adult

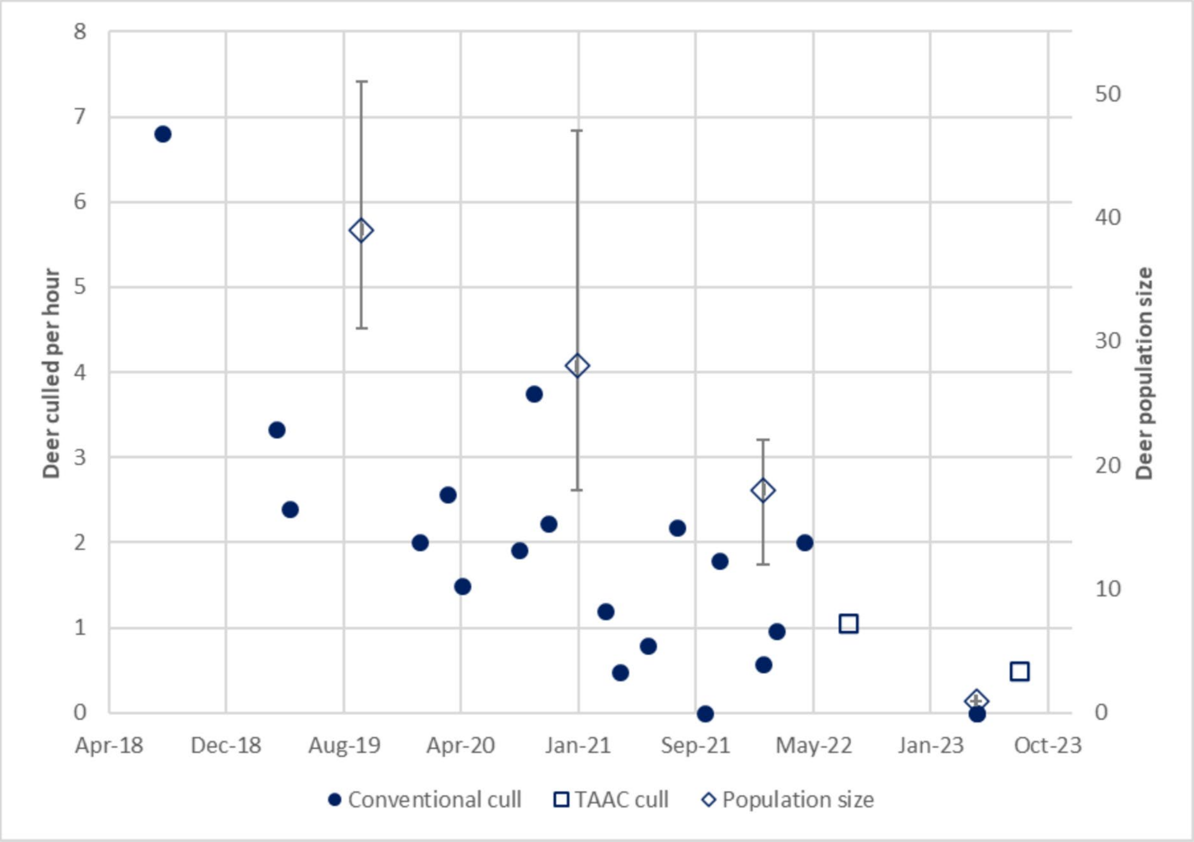

Fig. 4 Aerial shooting efficiency (deer culled per hour) for both conventional and thermally assisted aerial culling (TAAC) from 2018 to 2023 with estimates of population size (right axis)

female was identified by unique hair whorls on its temple (Fig. 3A, B). As the deer population declined, the spatial pattern of deer detections on the camera trap grid was used by the aerial culling team to focus their culling in particular areas (Fig. 6).

Each camera trap survey required an average of approximately 6 person-days for camera deployment, 4 person-days for retrieval, 10 person days for travel, 6 person-days for image tagging, and 3 person-days for data analysis. With staff costs estimated at AUD $525 per day, the total labour cost per survey was approximately AUD $15,225. Following Bengsen et al. (2023), travel costs (i.e., accommodation, food, incidentals, and vehicle use) were estimated at AUD $7,234 per survey based on the applicable rates provided by the Australian Taxation Office (2026) and accounted for a trip each for camera deployment and retrieval by two people. Additional expenses, including equipment (e.g., cameras, SD cards, and batteries) and boat charter were not included in this estimate.

Probability of eradication

The average duration of camera trap deployment needed to detect at least one of the individually identified deer in 2019, 2020–21 and 2021–22 was 377.5, 730.2 and 289.2 trap days, respectively. In 2022–23, one adult female deer was detected only twice in 5,400 trap days (Table 2). Using the PoA calculator, all three prior probabilities gave eradication probabilities > 95% at 42 days (2,184 trap days) and > 98% at 83 days (4,316 trap days) (Fig. 7). An 83-day deployment was therefore used in 2023–24 and provided 4,094 trap days from 51 working cameras without any deer detections. Using the data from the 2023–24 camera trap survey, the median (0.5) probability that

Fig. 5 Helicopter GPS tracklogs from (**A**) conventional aerial shooting in May 2023 and (**B**) thermally assisted aerial culling in August 2023

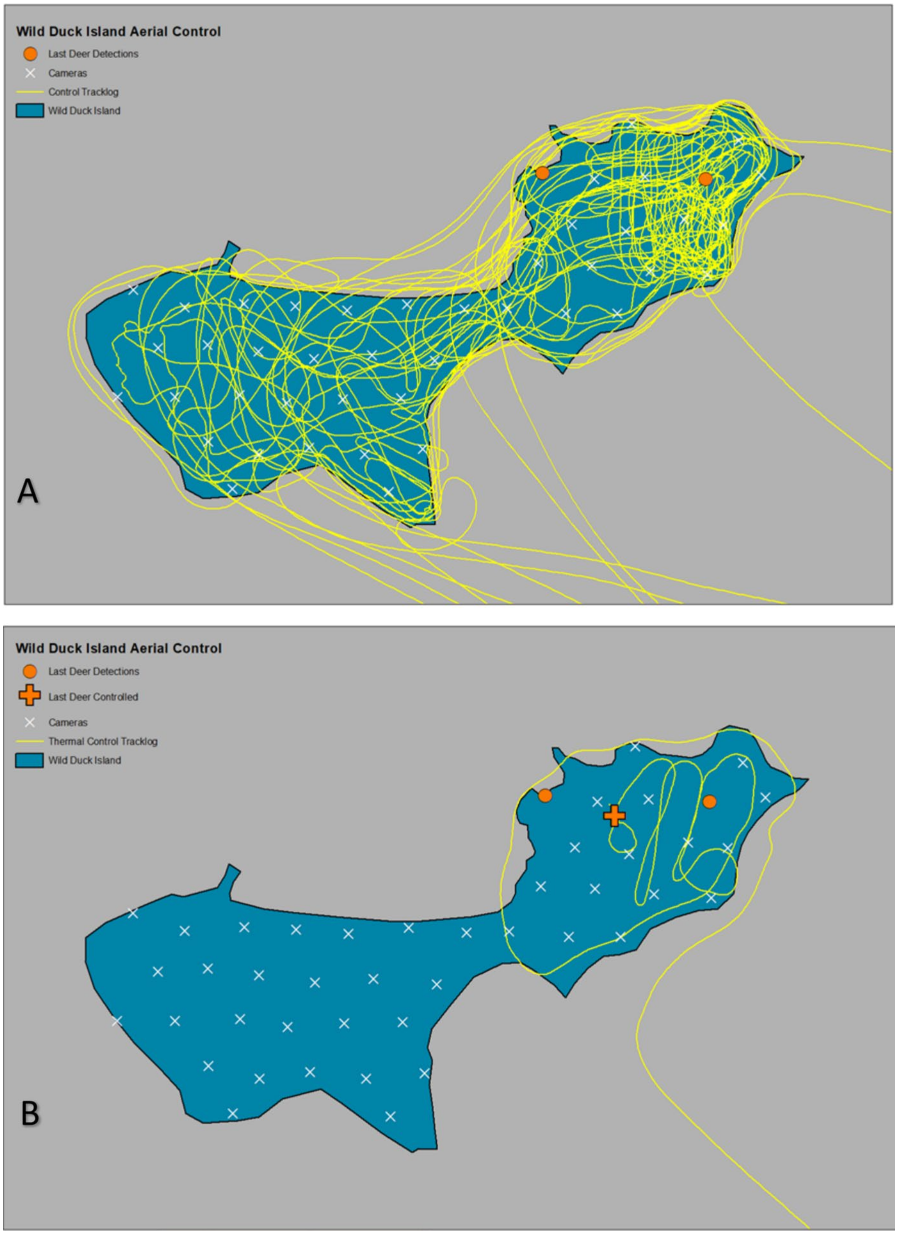

Table 2 Summary of camera surveys on Wild Duck Island, Queensland, Australia, 2019–2024

Year	Deployed	Retrieved	Camera days	Detection events	Recognizable individuals
2019	27/08/2019	29/10/2019	2,567	414	5
2020–21	20/11/2020	28/01/2021	2,434	128	3
2021–22	24/11/2021	15/02/2022	2,820	179	4
2022–23	23/11/2022	24/5/2023	5,400	2	1
2023–24	24/10/2023	17/01/2024	4,094	0	0

Table 3 Key parameters and rusa deer population size (*N*), lower (2.5%) and upper (97.5%) confidence limits and coefficient of variation (CV) from SMR modelling of the camera trap data from Wild Duck Island, Queensland, Australia, during 2019–2021. λ_0 is the expected encounter rate and σ is the home range size scale parameter

Year	Days	MCMC chains × 1,000 draws	λ_0 (SD)	σ (SD) (m)	Estimated number of deer			
					N	2.5%	97.5%	CV
2019	31	16 × 500	0.026 (0.004)	395 (23)	39	31	51	12.6%
2020–21	70	3 × 1,000	0.032 (0.011)	222 (42)	28	18	47	25.5%
2021–22	85	3 × 550	0.007 (0.001)	1,017 (136)	18	14	24	13.6%

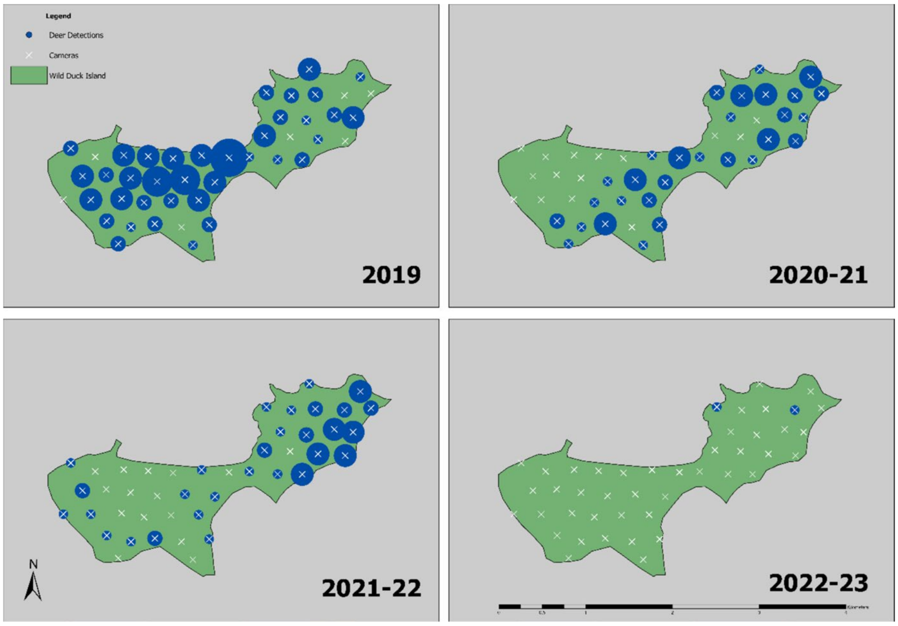

Fig. 6 Rusa deer detections at the 44 camera traps used to estimate rusa deer abundance on Wild Duck Island during (**a**) 2019, (**b**) 2020–21, (**c**) 2021–22, and (**d**) 2022–23. The area of the blue circles is proportional to the number of deer detections

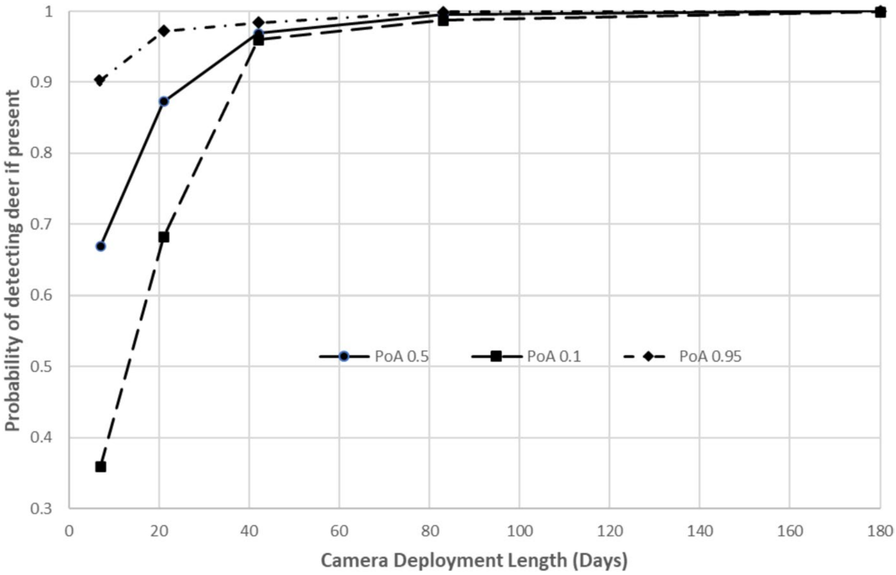

Fig. 7 Probability of eradication calculations for rusa deer on Wild Duck Island using a grid of 52 cameras deployed for 7, 21, 42, 83, 180 days and three prior probabilities (0.1, 0.5 and 0.95)

deer had been eradicated from WDI was estimated to be 0.993 (95% CI: 0.973–0.999).

We also did not observe any fresh signs of deer (i.e., sightings, tracks, faecal pellets, cast antlers, etc.) during the 2023–2024 camera trap survey. The team of four turtle researchers, who were on the island for two months during December 2023-January 2024, also did not observe any sign of deer, providing additional qualitative support for the last rusa deer being removed in August 2023.

Discussion

To our knowledge, this is the first documented successful eradication of an established rusa deer population globally. Of the 27 eradication attempts for cervids recorded in the Database of Island Invasive Species Eradications (DIISE 2018) only two attempts for rusa deer are listed, both on Le Predour Island, New Caledonia, with one listed as “Successful (Reinvaded)”, and the other as “In Progress”. Less than half of the eradication attempts for cervids on islands have been successful (DIISE 2018), demonstrating how difficult deer populations can be to eradicate.

Important steps in the strategic approach to invasive species control (Braysher 2017) are monitoring and evaluation, followed by modifying the program if needed. Masters et al. (2018) and Macdonald et al. (2019) also mentioned the importance of being able to change tactics in an eradication program. Two modifications to the existing control program that facilitated eradication on Wild Duck Island were: (1) switching from ground-based shooting to helicopter-based shooting, and then (2) using thermal imaging equipment to locate the last few deer so that they could be shot from the helicopter. Relative to ground-based shooting, helicopter-based shooting is, in real time, much quicker at detecting and shooting ungulates, and this advantage increases as topography becomes steeper and more complex, especially for isolated sites (Forsyth et al. 2023). With increased effort and the use of indicator dogs and team hunting tactics (Crouchley et al. 2007, 2011) it might have been possible to eradicate rusa deer using ground-based shooting, but WDI’s remoteness and tropical climate would have made this control method logistically difficult and potentially expensive. Helicopter-based shooting was relatively economical in person hours and was able to drive the population down quicker than recruitment. The duration of the knock-down phase of the eradication effort was similar to that reported for fallow deer on Kangaroo Island (Masters et al. 2018) and for red deer on Secretary Island (Macdonald et al. 2019), but the addition of TAAC to helicopter based shooting during the mop-up phase contributed to a shorter overall eradication time on Wild Duck Island.

Rusa deer distribution on the island appeared to shift from the more open vegetation of the island’s centre in 2019 to the steeper and more heavily vegetated eastern end in 2021 and 2022 (Fig. 6) as the population was culled. This could be due to surviving deer utilising small core home ranges in this area, individuals shifting their core home range to this area, or a mixture of these two. Theoretically, a rusa deer’s home range could include the entire island (380 ha) based on annual home range studies (Spaggiari and De Garine-Wichatitsky 2006; Amos et al. 2023) and thus be potentially captured at any camera station. However, if the WDI rusa utilised only small core home ranges (≤ 100 ha) (Moriarty 2004; Amos et al. 2023) during camera trap surveys, then they would realistically only be captured on cameras in one section of the island. It is likely that the majority of deer occupying the more open areas were culled first, and the others inhabiting the more densely vegetated eastern half of the island were harder to detect and thus culled in the latter stages. It is also possible that survivors may have been seeking cover to evade the helicopter. Survivor avoidance has been observed in previous ungulate eradication projects on islands (feral pigs *Sus scrofa* on Hawaii Volcanoes National Park; Katahira et al. 1993; feral goats *Capra hircus* on Raoul Island; Parkes 1984; red deer on Secretary Island; Crouchley et al. 2011) where the last survivors occupied steep or heavily vegetated areas and even caves. Given the small size of Wild Duck Island (380 ha) and the absence of natural barriers, it is likely that both small core home range areas and shifts in individual core home range areas contributed to the apparent deer distribution shift over the course of the eradication.

Thermal imaging equipment is a useful addition to helicopter-based shooting to increase detections when numbers are low and thick vegetation is encountered (Pulsford et al. 2022; Cox et al. 2023; Gentle et al. in press). The efficiency gains of changing tactics to include TAAC on WDI in 2022 are inconclusive as catch per unit effort was similar for the two methods (0.6–2.0 deer/hr (average 1.3) conventional versus 1.1 deer/hr TAAC) (Fig. 4). The two types of shooting were not conducted concurrently, so other factors such as weather, vegetation and particularly deer density may have affected the removal rate (e.g. Parkes 1984; Crouchley et al. 2011; Masters et al. 2018; Macdonald et al. 2019). However, the last surviving deer on WDI in 2023 successfully evaded removal during 7.6 h of conventional helicopter shooting but was finally detected and dispatched with the assistance of thermal imaging equipment in 28 min. Although TAAC was more expensive than conventional aerial culling, requiring a thermal imager operator and a turbine-powered (*cf* piston-powered) helicopter, its use enabled eradication to be achieved. Our findings align with those of Pulsford et al. (2022), Cox et al. (2023), and Gentle et al. (in press), indicating that the primary advantage of TAAC in our program was not an increase in overall removal efficiency, but rather an improvement in detection probability, particularly at very low population densities.

During the attempt to eradicate red deer from Secretary Island, New Zealand, "informed guesses" of the population size were commonplace (Macdonald et al. 2019). In contrast, we were able to estimate deer abundance as the population declined and to detect rusa deer when numbers were very low (i.e., Criterion 4 [see Introduction] was met). The camera trapping grid enabled us to robustly estimate the population size at the start of the eradication attempt, identify the number and location of survivors as the deer population was reduced, and finally to quantify the probability that the population was eradicated. Individual rusa deer were identified, which improved the SMR modelling. Individual identification of the final deer shot provided further evidence that the population had been eradicated.

A longer deployment in 2022–23 and a relatively close spacing of cameras (~300 m) were both beneficial when deer density was low and it was unclear how many deer remained. The suggested 90-day camera deployment of Bengsen et al. (2022) would have worked well for all our surveys but would have missed the second sighting of a lone cryptic deer in 2022–23, which was important to confirm the deer's identity. The relatively close camera trap grid spacing used was less than the suggested 1.5–2σ (Table 3; Efford and Boulanger 2019; Bengsen et al. 2022) but yielded both good detectability when numbers were low and provided a robust basis for quantifying the probability of rusa deer being eradicated from Wild Duck Island.

Bomford and O'Brien (1995) identified two other criteria that were desirable if eradication was to be successful. Criterion 5, that discounted benefit–cost analysis favour eradication over on-going control (e.g. Panzacchi et al. 2007); and Criterion 6, that there is a favourable socio-political environment. A formal benefit–cost analysis was not undertaken before embarking on the eradication of non-native rusa deer from WDI. Assigning an economic value to conservation or natural assets in a benefit–cost analysis to determine appropriate management is difficult (Panetta 2009; Braysher 2017; Fowler et al. 2023) and would be needed for QPWS to determine where investment should be prioritised across Queensland among conservation needs. The local question for deer on WDI was whether eradication was more cost effective than on-going control. The small size of the island and previous experience of QPWS with successful eradications of feral goats on offshore islands gave the project team confidence that eradication of rusa deer was achievable. The decision to eradicate was vindicated, with eradication achieved in six years. While formally uncosted, this avoided future deer control and environmental impacts. For criterion 6, there was no public opposition to the eradication program.

In summary, the rusa deer population on Wild Duck Island was reduced to a level at which no deer were detected despite intensive monitoring effort. An efficient knockdown using conventional aerial culling, followed by the incorporation of thermally assisted aerial culling, enabled rapid removal of the last 11 deer, while a dense camera trap grid provided high sensitivity for detecting survivors. The camera data from the final survey provided a proof-of-absence estimate indicating $a > 99\%$ probability that rusa deer had been eradicated, and no independent signs of deer were observed in the field. Together, these lines of evidence provide strong confidence that eradication has been achieved.

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Author contribution SB, AP, MB, DF, AB and MA conceived the ideas and designed the original methodology for this research project. All authors were involved in collecting the field data. Analysis of the data were performed by AB and MA. The first draft of the manuscript was written by DF, AP and MA. All authors contributed to subsequent drafts and gave final approval for publication.

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

Declarations

Conflict of interest The authors of this article declare no competing interests exist in regard to the research presented in this article.

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