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Effectiveness of the Felixer grooming trap for the control of feral cats: a field trial in arid South Australia

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Abstract

Context. Feral cats pose a significant threat to wildlife in Australia and internationally. Controlling feral cats can be problematic because of their tendency to hunt live prey rather than be attracted to food-based lures. The Felixer grooming trap was developed as a targeted and automated poisoning device that sprays poison onto the fur of a passing cat, relying on compulsive grooming for ingestion.

Aims. We conducted a field trial to test the effectiveness of Felixers in the control of feral cats in northern South Australia where feral cats were present within a 2600-ha predator-proof fenced paddock.

Methods. Twenty Felixers were set to fire across vehicle tracks and dune crossings for 6 weeks. Cat activity was recorded using track counts and grids of remote camera traps set within the Felixer Paddock and an adjacent 3700-ha Control Paddock where feral cats were not controlled. Radio-collars were placed on six cats and spatial mark–resight models were used to estimate population density before and after Felixer deployment.

Key results. None of the 1024 non-target objects (bettongs, bilbies, birds, lizards, humans, vehicles) that passed a Felixer during the trial was fired on, confirming high target specificity. Thirty-three Felixer firings were recorded over the 6-week trial, all being triggered by feral cats. The only two radio-collared cats that triggered Felixers during the trial, died. Two other radio-collared cats appeared to avoid Felixer traps possibly as a reaction to previous catching and handling rendering them neophobic. None of the 22 individually distinguishable cats targeted by Felixers was subsequently observed on cameras, suggesting death after firing. Felixer data, activity and density estimates consistently indicated that nearly two-thirds of the cat population was killed by the Felixers during the 6-week trial.

Conclusions. Results suggest that Felixers are an effective, target-specific method of controlling feral cats, at least in areas in which immigration is prevented. The firing rate of Felixers did not decline significantly over time, suggesting that a longer trial would have resulted in a higher number of kills.

Implications. Future studies should aim to determine the trade-off between Felixer density and the efficacy relative to reinvasion.

Additional keywords: conservation management, introduced species, invasive species, pest control, threatened species.

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Introduction

Domestic cats (*Felis catus*) are one of the most ubiquitous mammal species on Earth and they are present on every continent except Antarctica. They cause considerable impact to wildlife populations in Australia (Woinarski *et al.* 2012) and overseas (Medina *et al.* 2011; Loss *et al.* 2013; Nogales *et al.* 2013). Cats are responsible for the decline of many birds, mammals and reptiles and the failure of numerous reintroduction programs (Short *et al.* 1992; Fischer and Lindenmayer 2000; Shier and Owings 2006; Moseby *et al.* 2011*a*). Although many threatened species populations are now protected from cats through exclusion fencing (Moseby and Read 2006; Burns *et al.* 2011; Legge *et al.* 2018) or isolation on islands, many declining species in the wild still contend with a profound threat from feral cats and, therefore, feral cat control remains a priority management action for numerous conservation agencies (Commonwealth of Australia 2015).

Up to 6 million feral cats are present in Australia (Legge *et al.* 2017) and control methods include live trapping, poison baiting and shooting (Commonwealth of Australia 2015). Shooting and live trapping are time consuming and expensive, and their effectiveness depends on the skill of the operator, the terrain and the palatability of the bait to lure cats into traps (Short *et al.* 2002). Additional management options are required to supplement or provide an alternative to expensive shooting and trapping exercises to target small cat populations or individuals. Cats prefer to hunt live prey and scavenge less frequently than do other predators such as canids (Christensen *et al.* 2012; Read *et al.* 2015*a*). Although some baiting programs have been effective (Algar *et al.* 2007, 2013), results have been dependent on availability of alternative prey (Christensen *et al.* 2012), with poor uptake in areas where prey are abundant (Moseby and Hill 2011). Therefore, poison baiting alone is unlikely to be a sustainable method of controlling cats once prey densities recover.

Felixers (Thylacion, Adelaide, SA, Australia) are automated poisoning devices that spray a measured dose of poison onto the fur of cats when they pass within 4 m (Read *et al.* 2014). Cats then ingest the poison through compulsive behavioural grooming, without relying on their hunger as a pathway to poisoning as is the case with bait delivery by meat baits. A sensor array detects and distinguishes cats from other animals on the basis of their silhouette and movement pattern with a high target specificity (Read *et al.* 2019). An internal camera with infrared flash, photographs all firing and non-firing events that trigger the sensors. Felixers can be used with or without lures and are best placed on corridors along fence lines, watercourses and roads utilised by cats, or inbuilt audio lures can be activated to attract cats within range.

Feral animal control should be targeted, effective and sustainable (Commonwealth of Australia 2015). Although pen trials have demonstrated proof of concept poisoning (Read *et al.* 2014) and field trials have shown high target specificity (Read *et al.* 2019), here, for the first time, we assess the success of Felixers in satisfying the second and third criteria. Twenty Felixers were set for 6 weeks within a 26-km^2 predator-proof fenced 'Felixer Paddock' in northern South Australia, where ~50 feral cats were resident. Our three aims were to first determine whether Felixers could reduce the cat population over time, measured by comparing cat activity, density and abundance in the Felixer Paddock and an adjacent 37-km^2 fenced 'Control Paddock' where no Felixers were deployed. Second, we aimed to determine the target specificity of Felixers by recording the percentage of non-target firings, with a success criterion set at greater than 60% activation by targets and less than 5% non-target activations. This non-target criterion was selected on the basis of the aim of a very high target specificity, so as to provide assurance that Felixers could be used safely in peri-urban areas or where threatened species are present. Finally, we aimed to measure the sustainability of control by comparing the Felixer firing rate over time to test whether cats showed innate or learned trap shyness towards Felixers. Results were used to suggest improvements to field deployment so as to maximise the efficacy of grooming traps for feral cat control.

Materials and methods

Study area

The trial was conducted at Arid Recovery, an ecosystem restoration and research project supported by BHP, the South Australian Department for Environment, the University of Adelaide, Bush Heritage Australia and the local community. The Arid Recovery Reserve incorporates 123 km^2 of arid land surrounded by a predator-proof fence (Moseby and Read 2006; Moseby *et al.* 2011*a*). The Reserve was divided into six paddocks, with cats, foxes (*Vulpes vulpes*) and rabbits (*Oryctolagus cuniculus*) removed from four of these, totalling 60 km^2. The remaining two paddocks were used as experimental paddocks and included the 26-km^2 Felixer Paddock where the Felixer trial was conducted and an adjacent 37-km^2 Control Paddock. These experimental paddocks were separated by a 1.2-m-high netting fence with an overhang in the direction of the Control Paddock that prevented cats from entering the Felixer Paddock. The Felixer Paddock contained feral cats, rabbits, reintroduced bettongs (*Bettongia lesueur*) and bilbies (*Macrotis lagotis*), whereas the Control Paddock contained feral cats and rabbits. Both paddocks contained similar habitats, comprising longitudinal orange dunes separated by interdunal clay swales. Dunes supported *Acacia* and *Dodonaea* shrubland, whereas swales were vegetated with chenopod (*Maireana* spp. and *Atriplex* spp.) species. Sparse minor ephemeral creek lines occurred in both paddocks. Dunes were present throughout both paddocks, but with a higher density in the south-east of the Felixer Paddock and north-east of the Control Paddock (Fig. 1). The climate is arid with hot dry summers and mild winters. Rainfall is likely to fall in any month and the long-term average annual rainfall is 166 mm (Bureau of Meteorology, http//www.BOM.gov.au, accessed January 2020).

Felixer-trap configuration

Felixer design progressed from a prototype tested in 2015, to more advanced Version 2 units in 2017 (Read *et al.* 2019) and, finally, the Version 3 units that incorporated design features identified through earlier trials. Twenty Version-3 Felixers were deployed at widely spaced locations around the Felixer Paddock for 41 days from 5 February 2018 until 18 March 2018, with internal cameras for detecting wildlife (Fig. 1). The density of Felixers was 0.77 traps per square kilometre, and units were evenly spaced throughout the paddock. Felixers were set along unformed vehicle tracks, across creek lines and on dune crossings, areas where local studies indicated preferential use by cats (Moseby *et al.* 2009). Prior photo-only trials within the Arid Recovery Reserve had already demonstrated negligible non-target triggering at the site (Read *et al.* 2019), thus, the APVMA permit requirement to conduct 2 weeks of non-toxic confirmation before the experiment commenced (APVMA Permit 80926) had already been satisfied. Felixers contained up to 20 sealed cartridges, each containing 12 mg of 1080 held in a red-dyed gel.

The maximum spraying distance of each Felixer was set at 1.5–3.5 m (at 0.5-m intervals), depending on the extent of flat ground in front of each Felixer and the likely walking path of feral cats. Successful firing of each of the Felixers was confirmed after installation and at the conclusion of the study, through use of a plastic template in the shape of a cat pushed in front of the Felixer. Audiolures were disabled from all Felixers for the first 31 days, after which four randomised lure programs were enabled on all Felixers for the remaining 13 days of the trial. Each program alternated nights of playing one of eight different calls (cat on heat, contact call of button quail, distress calls of rat, starling, sparrow, thornbill, fairy wren and

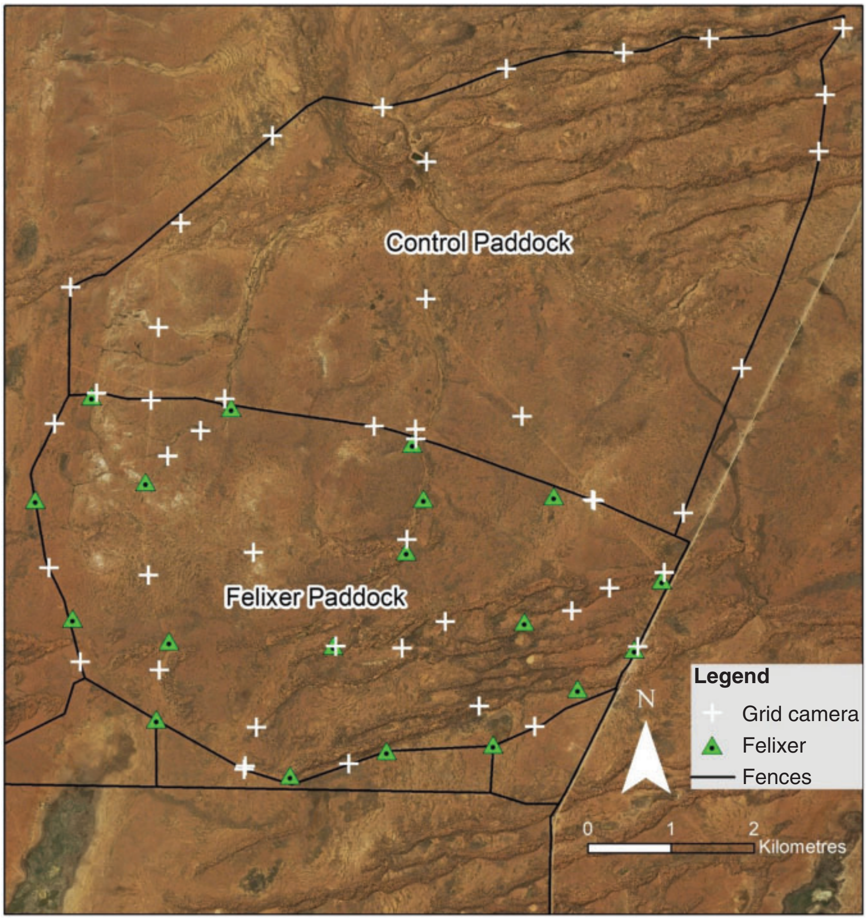

Fig. 1. Map of the study area, including the Felixer Paddock where the trial was conducted and the nearby Control Paddock used as the procedural control. Felixer locations are presented as green triangles and white crosses are extra remote cameras used in the analysis.

computer-generated bisbee call), with one night of no lure. On each active night, the lure type was played for 8–10 s every 15 min from dusk until dawn.

Target specificity and firing sustainability

Felixer data, including photos of all target firings and non-target passes and log files that detail the time, date and sensor triggering of each pass, were uploaded onto the Felixer Management System (www.thylation.com, accessed May 2018) for analysis. The number of firings and passes per unit was recorded for feral cats and all other species. We also assessed whether Felixer firing rate changed throughout the study, by comparing the count of firings over successive 3-day periods in a simple linear model with a Poisson distribution, compared with a null model that assumed no relationship.

Individual cat survival

Monitoring of individual cat survival included radio-collaring and camera traps.

Within the Felixer Paddock, six cats were captured in cage or leghold traps and fitted with 110-g GPS and VHF radio-collars (Quantum 4000 Enhanced, Telemetry Solutions, Concord, CA, USA) with mortality sensors being triggered after 10 h of inactivity. Collars were fitted at least 1 month before Felixer deployment and VHF signals were checked for mortality signals every 3–5 days, but were not approached unless a mortality signal was detected, in which case the carcass was retrieved and the cause of death determined. Radio-collared cats that were still alive at the conclusion of the study were euthanased by a professional shooter on an All-Terrain Vehicle. Any cats euthanased at the end of the study were photographed to enable cross-referencing with any images on camera traps and inbuilt Felixer cameras.

We also established a camera grid of 20 Bushnell (119776C; Bushnell, Overland Park, KS, USA, www.bushnell.com, accessed 20 February 2020) remote cameras placed at least 1 km apart along unformed vehicle tracks throughout the Felixer Paddock (hereafter called grid cameras, Fig. 1). Six extra Reconyx (Hyperfire 600, Reconyx, Holmen, WI, USA, www.reconyx.com, accessed 20 February 2020) cameras were added to the grid along sand dunes during the period that Felixers were set. A similar grid of 20 Bushnell cameras was established at the adjacent Control Paddock where cats were present but uncontrolled. The cameras were set at a height of 30 cm from the ground and left to record for 132 days from 20 November 2017 to 1 April 2018, including 77 days before Felixer deployment, 41 days during Felixer deployment and 15 days after Felixers were removed.

Cameras were checked every month and photos were downloaded. The detection rate of cats on cameras was calculated each fortnight and photos were also used to identify individual cats. We considered each detection as independent if not part of the same sequence of photos from a trigger. In addition, 20 Reconyx remote cameras (Hyperfire 600) were placed at Felixer traps at a height of 30 cm (hereafter called trap cameras) over the same period as grid cameras. Each camera was set facing a Felixer at a distance of ~3 m away and at ~68° to the perpendicular firing angle, so as to maximise detectability (Meek *et al.* 2012).

All images from the grid and trap cameras and inbuilt Felixer cameras were reviewed to identify individual cats. For each nominated individual, we drew a dossier of pelage markings with defining features. Because of the likely high relatedness of cats within the fenced paddocks, pelage markings were more similar than for other researched feral cat populations (McGregor *et al.* 2015). Therefore, some cats in photos could not be identified and other identifications were classed only as 'likely' to be a unique individual.

We used camera images to compare the fate of individual cats fired on by Felixers, compared with those that were not. In-built Felixer cameras and trap cameras set adjacent to Felixers were used to identify cats that were fired on by a Felixer (confirmed and likely). Once all images were assigned to individual cats, we created detection histories for each cat and assigned them to a 'fired on' or 'not fired on' group. To test whether being fired on by a Felixer reduced a cat's probability of a subsequent detection, we used the stats package 'nlme' (Pinheiro *et al.* 2019) in R (v3.5.1, www.r-project.org, accessed April 2019) to run mixed-effects linear models of the change in probability of a cat being detected on a remote camera after firing or not, with individual cat being the random effect. We ran three models, namely, a change due to Felixer firings, a change between the first and second half of the Felixer deployment period (suggesting a seasonal or natural change in detection rates), and a null model suggesting no change in detection over the deployment period. These models were compared within an information theory framework (Burnham and Anderson 1998), using Akaike information criteria corrected for small sample sizes (AICc) (Burnham and Anderson 1998), and best-supported models were those with ΔAICc of <4 from the top model, the highest Akaike weight (probability of being the best model), and the null model not within this candidate set.

Changes in the activity and density of the cat population

We measured the change in cat activity before and after Felixer deployment using track counts in the Felixer and control paddocks, essentially creating a before–after control impact study. We used an all-terrain vehicle to drag a steel bar along three 1-km-long transects on dunes in each paddock, and recorded counts of cat tracks the following morning (see Moseby *et al.* (2018) for detail of methods). This was conducted on the following four occasions: in October and December 2017 before the trial, once in February 2018 during the trial, and once in March 2018 after Felixers were removed.

We compared cat activity by using a mixed-effects linear model assuming a Gaussian distribution, with individual transects as random effects, and paddock and before or during or after Felixer deployment as 0, 1 and 2 respectively, as fixed effects. Each combination of paddock and before or during or after trial was added into the model comparison set, along with a null model.

Additionally, cat activity on cameras was compared before (77 days) and after (15 days) the trial using occupancy analysis on the 40 original grid cameras spread throughout the Felixer and Control Paddocks in the 'unmarked' library (v.0.12-3; Fiske and Chandler 2011). Cat activity detected on cameras during the 40 days of Felixer deployment was not included. Cats were classed as being detected or not on each camera during every 3-day period. We ran models considering whether detectability of cats changed before and after the trial and an interaction term between the treatment and control paddocks. We kept occupancy constant in the models because cats were detected on all cameras and roamed throughout each paddock. We also included two other variables that previous research suggested were likely to affect detectability, namely, daily maximum temperature as it relates to camera performance (Read *et al.* 2015*b*), and whether the camera was within 500 m of a dune system, cat's preferred habitat in the region (Moseby *et al.* 2009). These models were compared within the information-theory framework discussed above (Burnham and Anderson 1998).

We also compared the change in cat density within the Felixer Paddock, on the basis of the cats having been detected on the Reconyx grid and trap cameras. To measure cat density, we used spatial mark–resight models (Efford *et al.* 2009; Efford and Fewster 2013) in the 'secr' library (v.3.0.1.; Efford 2017). A 'before' session (77-day period before Felixer deployment) was compared with an 'after the trial' session (15-day period after removal of Felixers and before euthanasia of the remaining cats), and we assumed closed populations within each session. We did not consider the time during the trial itself, because high numbers of cats were likely being killed over that time period and violated assumptions of a closed population. Kittens (<2% of detections) were not considered in the analysis because of the potential correlation of their movements with their mothers and an unknown entry point into the population. Cats we could not identify were classed as the unmarked portion of the population, and we assumed that they had similar home-range sizes and detectability as did identified cats.

For the spatial mark–resight analysis, we tested different detection-function shapes for cats' home-ranges (half-normal, hazard-rate and exponential), and chose the shape with best support for further testing of secondary variables (Borchers and Efford 2008; McGregor *et al.* 2015). Non-spatial secondary variables included two classes within the population with different home-range sizes (a two-class mixture model possibly influenced by sex), a behavioural response from cats to cameras (whether detection probability changes after the first encounter with Felixer), and whether detection probabilities gradually changed through time. Spatial variables tested included whether density was higher in the south-eastern section of the paddock, which was dominated by dunes. The best-fitting model from the set of competing models was chosen on the basis of AICc, and this model was used to derive density estimates (Burnham and Anderson 1998).

Table 1. Non-target and target passes recorded on the 20 Felixer traps over the 6-week trial Numbers in parentheses denote firings

Felixer ID	Cat	Bettong	Bilby	Rabbit	Rodent	Bird	Goanna	Human	Unsure	Vehicle	Total
SP030013	0 (0)	5	1			1		1	9	6	23
SP030014	0 (0)	9				9		1	7	8	34
SP030017	6 (6)	22		1		140		1	28	28	226
SP030019	2 (1)	13				2			2	4	23
SP030021	4 (4)	31		1	3	27		1	14		81
SP030022	3 (1)					15		5	22	9	54
SP030023	1 (1)	13		5		2		2	2	10	35
SP030024	0 (0)	3				1			9	11	24
SP030026	1 (1)	1				2		1	6	6	17
SP030031	1 (0)					4	2	2	1	3	13
SP030034	2 (2)	5				3	1		2	7	20
SP030042	2 (1)	17				140			5		164
SP030043	0 (0)	2				3		2	3	8	18
SP030045/57	1 (1)	8				7			13	4	33
SP030046	7 (6)	6				1		2	13	43	72
SP030047	3 (3)			6				3	9	14	35
SP030048	1 (0)	6		2				1	3	1	14
SP030052	1 (1)	1				1		7	86	3	99
SP030053	5 (4)	6		1	1				10	36	59
SP030054	3 (1)	17						1	2		23
Total	43 (33)	165	1	16	4	358	3	30	246	201	1067

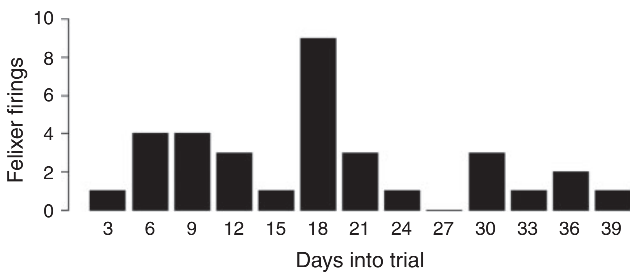

Fig. 2. Felixer rate of firings in 3-day blocks over the duration of the trial.

Results

Target specificity and firing sustainability

Throughout the 6-week study, 1067 images were taken by the 20 Felixers, 43 of which were cats. In total, 33 of the 43 cat detections (77%) were identified as targets by the Felixers and fired on. Cats not correctly identified as targets were either walking non-perpendicular to the firing direction or had crouched in front of the Felixer and, hence, had not satisfied the identification algorithm (Read *et al.* 2019); however, at least three of these same cats were, subsequently, correctly targeted by Felixers. Fifty-seven per cent of activations were from just four of the Felixers and 20% (4) of the Felixers did not record any cat passes.

No non-target firings were recorded from 1024 non-target passes. None of the 358 birds or 165 burrowing bettongs that passed the Felixers activated them, neither did smaller numbers of humans, cars, rabbits or bilbies (Table 1). Detections of birds were also highly clustered, with two Felixers accounting for 78% of the bird detections, being mainly willie wagtails (*Rhipidura leucophrys*), cinnamon quail thrush (*Cinclosoma cinnamomeum*) and Australian magpie larks (*Grallina cyanoleuca*), which repeatedly stood in front of the Felixers.

Over the trial, we did not detect a change in the firing rate of Felixers (Fig. 2), with the null model retaining AICc support similar to that of the model assuming a change over time (null model AICc weight $= 0.57$, time model delta $= 0.6$, $t = -0.99$, $P = 0.34$). The firing rate averaged 0.08 per day.

Individual-cat survival

Of the six radio-collared cats, one died of natural causes during the trial, one was likely to have been killed by a Felixer and one was confirmed killed by a Felixer. The confirmed kill was found a day after being sprayed with a Felixer and the fur of the animal was stained by dye (Fig. 3). The cat was in good body condition (i.e. there was fat and muscle around the hips). The likely kill was found in an advanced state of decay within 550 m of a Felixer that fired on a cat matching its broad description (image quality was marginal for this firing) 2 weeks earlier. This cat was found 3.6 km outside its regular home range, and the Felixer firing occurred 2 days after this cat was no longer regularly detected via VHF tracking in this region. The remaining three cats did not walk in front of a Felixer, although one was witnessed on a Reconyx camera walking near a Felixer, but seemingly avoiding it.

After the Felixers were removed, the remaining three collared and 16 uncollared cats were euthanised by a professional shooter. None of these 19 cats was identified by inbuilt Felixer cameras as being fired on by a Felixer during the trial.

Of the nine cats detected on Felixers when audiolures were activated, four were detected on nights with lures playing and five were detected on the alternate nights without lures. Only two cats were fired on by Felixers within 3 min of an audiolure playing, with one each of sparrow and plague rat calls coinciding with Felixer activation.

Although 44 cat detections were recorded by the inbuilt Felixer cameras, only 19 (43%) were also recorded on the

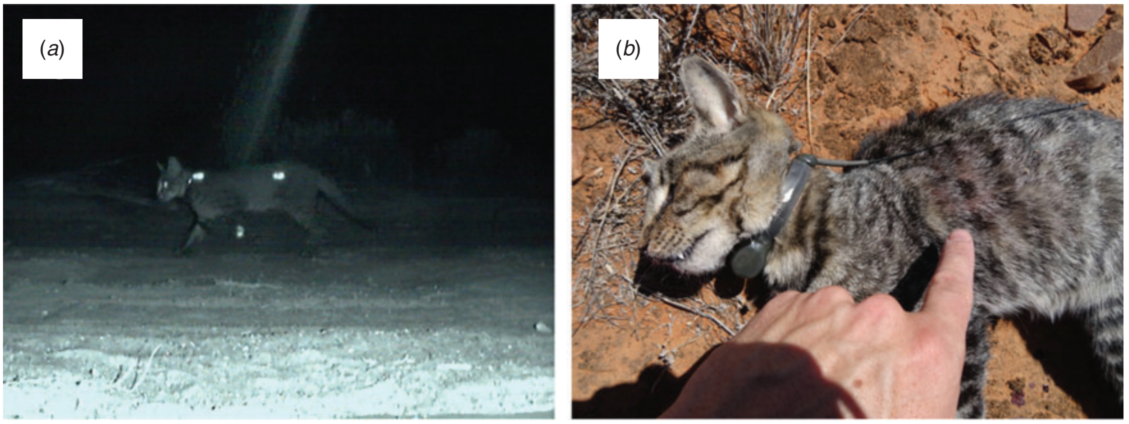

Fig. 3. Pictures taken of (*a*) a collared feral cat fired by on by a Felixer, and (*b*) found dead the next day with remnant gel stain on its flank.

Reconyx trap cameras set facing each Felixer during the study period. There were an additional 10 cat detections on the Reconyx cameras set facing the Felixers that were not detected on the inbuilt Felixer cameras, suggesting that these cats approached the Felixer but then avoided walking in front of it.

There were 272 independent detections of feral cats from 3432 trap-nights on the monitoring cameras in the Felixer Paddock. Eight of these were from kittens, which were removed from all further analysis. Seventy detections were from unidentifiable cats, and we could identify 31 individuals from 194 detections.

We compared detection rates over time for individual cats that were confirmed as fired on by a Felixer with those that were not. We considered only 22 of the 31 identified individual cats because we did not consider those detected on fewer than three occasions, or those where photos indicated that they may have been fired on, but the quality of the photo prohibited confirmation of identity (Table 2). For the 22 individual cats used in analysis, these had an average rate of detection of 0.3 per 100 trap-nights before either being fired on by a Felixer or, for cats not fired on, before the midpoint of the trial (s.e. = 0.05, min = 0.05, max = 1.25). No cat known to be fired on was detected on cameras after firing ($n = 16$). For those cats not fired on, their detection rate after the mid-point of the trial was 0.31 per 100 trap-nights ($n = 6$, s.e. = 0.04, min = 0.08, max = 1.06). Comparing three mixed-effects models of likely cause found most support for the model that considered Felixer firings (AICc weight = 0.88, conditional $r^2 = 0.4$, null-model delta = 4.02, $z = -3.4$, $P = 0.004$, Appendix 1).

Changes in the activity and density of cat population

Cat activity from track counts decreased from 14 to 4 tracks per kilometre in the Felixer Paddock after the Felixer trial, yet remained stable at about eight tracks per kilometre in the Control Paddock over the same timeframe (Fig. 4). Feral cat-track trajectories were best explained by the before–after impact control model (AICc weight = 0.783, conditional $r^2 = 0.4$, null model delta = 6.71, Appendix 1), which reported a significant decline in track activity of 73% only in the Felixer Paddock (Fig. 4, d.f. = 16, $t = -2.82$, $P = 0.047$). The cat-detectability survey on the 40 grid cameras was best explained by the before–after impact control model (Fig. 5, AICc weight = 0.91, null model delta = 35.59, $z = -3.04$, $P < 0.001$, Appendix 1), where detections dropped by ~40% in the Felixer Paddock, whereas no change was detected in the Control Paddock. The top model also included the extra variables of whether the camera was in a dune-dominated area ($z = 5.52$, $P < 0.001$) and the maximum temperature on the day of detection ($z = -2.43$, $P < 0.001$).

We measured cat density by using spatial mark–resight models before and after the Felixer trial, on the basis of cat detections on grid and trap cameras. Each identified cat (31) was considered marked, and cats from the 70 unidentifiable photos were considered unmarked. The most parsimonious model of cat detectability and density in the Felixer Paddock (with an AICc weight of 0.973, Appendix 1) considered cats with hazard-rate home-range use (functionally, cats have a core home range, yet are occasionally found far outside), and two latent classes of individuals (likely to be representing differences between sexes). It also considered cat density to change between sessions (before and after). Cat density in the paddock before the trial was estimated at 1.84 cats per km^2 (95% CI: 1.44, 2.25) and 0.64 cats km^2 after (95% CI: 0.41, 1.01). This equates to ~48 cats being inside the paddock before the trial (95% CI: 38, 61) and 17 afterwards (95% CI: 11, 26, Fig. 6). Note the 'after trial' estimate period started after the three collared cats were removed, so we added these to post-Felixer trial population estimates. These modelled estimates of 48 cats before and 17 after the trial correlate well with the summed total of 33 cats fired on by Felixers (and assumed dead), one radio-collared cat dying from natural causes and 19 cats shot at the conclusion of the trial (estimated 53 before the trial and 19 afterwards), with both figures suggesting a 64–65% decrease in cat density.

Discussion

Camera data, track counts, radio-collaring data and Felixer firings all suggested that Felixer grooming traps reduced the cat population size over the 6-week study period. Camera-based density estimates suggested a 52–63% (95% CI) decline, cat activity declined by 65% on track counts, camera detections dropped by 40% and Felixer firings, shooting and radio-collar data suggested a decline in cat abundance of 64%. Cats within

Table 2. Details of the camera detections for individual cats identified through radio-collaring or remote cameras and whether they were fired on by Felixers

The identity of cats classed as 'likely' fired on by Felixers could not be identified with certainty, owing to poorer-quality images. Uncollared cats detected less than three times are not presented. For cats not fired on, after-trial detection rate this is the detection rate after the midpoint of Felixer trial

Individual ID	Collared?	Fired by Felixer?	Detections on remote cameras			
			Before trial		After trial	
			N	Detections per100 trap-nights	*N*	Detections per 100 trap-nights
C33	Yes	Died natural causes	n.a.	n.a.	n.a.	n.a.
C34	Yes	No	0	0	0	0
C36	Yes	No	4	0.2	2	0.16
C37	Yes	No	4	0.2	3	0.25
C42	Yes	Yes, confirmed kill	25	1.25	0	0
C41	Yes	Likely	1	0.05	0	0
TA11		No	2	0.1	5	0.41
TA12		No	3	0.15	13	1.06
TA18		No	1	0.05	4	0.33
TA20		No	7	0.35	1	0.08
TA22		No	4	0.2	3	0.25
TA24		No	3	0.15	1	0.08
TA5		No	0	0	4	0.33
TA17		No	0	0	2	0.16
Black 1		Yes	2	0.1	0	0
Black 2		Yes	7	0.35	0	0
TA1		Yes	3	0.15	0	0
TA13		Yes	4	0.2	0	0
TA14		Yes	5	0.25	0	0
TA19		Yes	10	0.5	0	0
TA23		Yes	7	0.35	0	0
TA6		Yes	5	0.25	0	0
TA7		Yes	2	0.1	0	0
TA9		Yes	5	0.25	0	0
TA25		Yes	0	0	0	0
TA16		Likely	7	0.35	0	0
TA21		Likely	3	0.15	0	0
Tswirl		Likely	4	0.2	0	0

the Control Paddock did not decline over the same period. Results suggest that Felixers were effective at reducing the cat population in this pioneering study.

Felixers were completely target specific and only fired on feral cats, of which spatially explicit capture–recapture analysis and tracking of collared individuals suggested 100% kill rate by Felixers. Over 1000 animals passed the Felixer traps, but only cats were identified as targets and fired on with poison. Such a high rate of target specificity is unmatched by other cat-control methods aside from shooting and gives confidence that the devices can be used in a range of situations and land uses. In comparison, non-target uptake of poison baits can be high (Glen *et al.* 2007; Moseby *et al.* 2011*b*; Dundas *et al.* 2014) and cage and leghold traps are also known to injure and trap many species of non-target animals (Surtees *et al.* 2019).

Unfortunately, owing to logistical constraints, the trial duration was set at 6 weeks; however, the consistent rate of Felixer firings, even at the end of the study, suggests that cat density would have been reduced further had the trial continued. At the average rate of 0.8 cat firings per day, ~2 months may have been needed for eradication (estimated 17 cats being left at the end of 6-week trial and 0.8 cats killed per day this equates to an additional 21 days being required for population eradication). Although this estimate assumes no Felixer shyness or avoidance by cats, the consistent firing rate recorded despite the reduction in cat density suggests that uncollared cats were not avoiding Felixers. Some evidence of Felixer avoidance was recorded in radio-collared cats, being consistent with other studies that have found that feral cats that have been captured on multiple occasions or frequently approached, can be neophobic or learn to avoid human-related objects (Short *et al.* 2002; Fisher *et al.* 2015). Future trials should include both direct and indirect measures of cat survival to avoid this bias and any radio-collared cats should be collared well in advance. However, under normal conditions, cats present in an area would not have been subjected to capture and collaring events before Felixer deployment and so would be less neophobic. Neophobia is also likely to be an issue only during initial deployment and cats should lose their fear of new objects over time. Our Felixer trial started as soon as Felixers were deployed and we did not allow for an acclimatisation period in our trial. Despite this, a significant reduction in cat density was recorded. In future trials, Felixers could be deployed for several weeks in photo-only mode before activation, or left in the field for longer to offset or test for effects of neophobia.

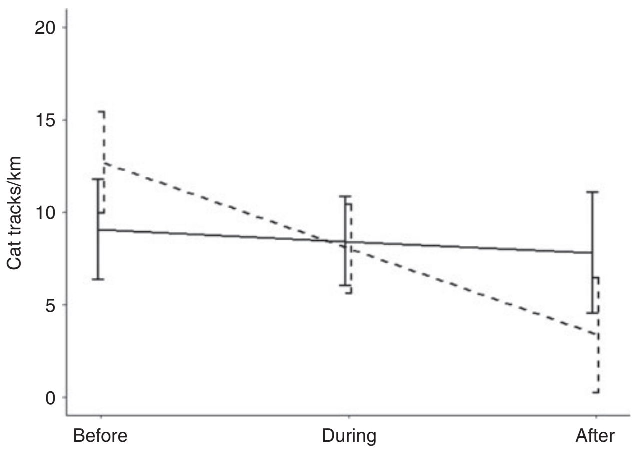

Fig. 4. Changes in track counts per kilometre of feral cats between the Felixer paddock (dashed line) and Control Paddock (solid line) before and after Felixer deployment, indicating a 73% decrease in the Felixer Paddock. Bars indicate standard errors.

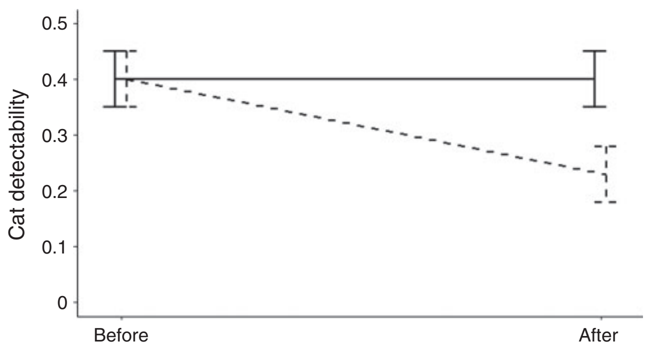

Fig. 5. Changes in detectability of feral cats from best occupancy model before and after the Felixer trial, derived from images from 40 remote cameras spaced widely across the Felixer Paddock (dashed line) and Control Paddock (solid line), indicating a 40% drop. Bars indicate standard errors.

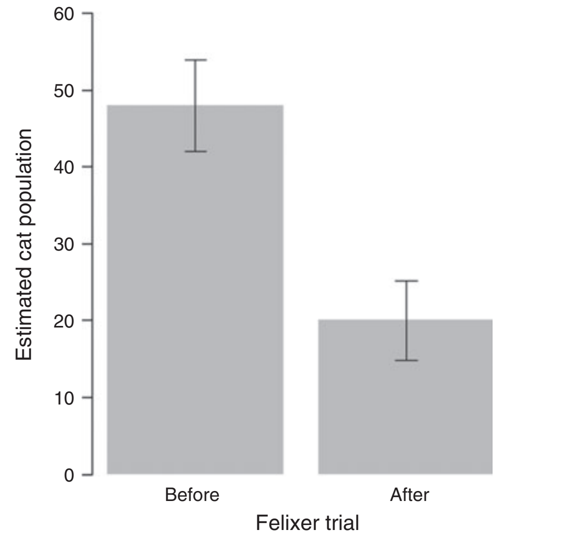

Fig. 6. Estimated cat population size within the Felixer Paddock before and after the Felixer trial, on the basis of spatial mark–resight (black bars indicate standard error).

The uncollared cats remaining at the end of the trial were not identified on camera as avoiding Felixers and it is likely that their survival was related to their home ranges having only a limited overlap with Felixers. Feral cat home ranges can vary dramatically (Edwards *et al.* 2001; Bengsen *et al.* 2016), with some individuals having ranges as small as 1 km^2 (Moseby *et al.* 2009) and, at a density of fewer than one Felixer per square kilometre, it could take significant time for a cat to passively pass a Felixer. Additionally, some Felixers recorded high firing rates, whereas 20% recorded no cat passes, suggesting that Felixer placement is an important aspect of successful deployment. Understanding space-use patterns of cats before deployment would be likely to significantly increase Felixer efficacy. Careful placement of baits and cage traps is also considered to be important for improving efficacy of other cat-control methods (Short *et al.* 2002; Moseby *et al.* 2011*b*).

Although some movement of cats from the Felixer Paddock to the Control Paddock was possible because of the floppy top facing the Felixer Paddock, none of the radio-collared cats moved paddocks during the trial and the cat activity in the Control Paddock did not change significantly over the trial period. This suggests that the decline in cat activity in the Felixer Paddock was related to cat mortality.

Thirty-three cats were estimated to have been killed by Felixers over the 6-week period. The amount of person hours to install the 20 Felixers was estimated at 18 h, equating to nearly two cats per hour of effort. This compares with 72 cats being removed just outside the site in 2018 using trapping and shooting comprising ~800 h of effort, or 0.09 cats per hour of effort (Arid Recovery Limited, unpubl. data). A cat-control program on St Helena Island reported 491 person days to trap 56 cats with live cage trapping, equating to 0.014 cats per hour of effort (Oppel *et al.* 2014). Live trapping is time consuming and logistically expensive because it involves daily checking and rebaiting of traps.

In all, 10 of the 44 cat passes in front of the Felixer traps did not result in firing. These cats were not identified as targets because of their slow movement or the angle that they walked in front of the trap. At least three of these cats were identified as later triggering the Felixer on a subsequent pass, suggesting that a failure to trigger the trap does not lead to persistent avoidance. A benefit of the Felixer is that animals are photographed and sensor information is recorded during all passes, allowing targeting algorithms to be continually refined to improve target specificity. By contrast, efficacy calculations and the ability to refine techniques of poison baiting or trapping are more restricted.

Unfortunately, the lure results were inconclusive because there was no significant increase or decrease in firing rates once lures were deployed. Audio lures can attract cats (Moseby *et al.* 2004) or increase their visitation time at trap sites (Read *et al.* 2015*b*), which can increase the efficacy of cat-trapping methods such as leghold trapping. However, some studies have not found an increase in mammal visitation rate from audio lures (Suárez-Tangil and Rodríguez 2017). The extensive range of Felixer audio lures available and the intermittent playback frequency suggest that testing the comparative effectiveness of each lure will require multiple field sites and long deployments.

This first field trial of Felixer efficacy was considered successful on the basis of the significant reduction in cat density recorded during the trial compared with the control area, and the fact that both of the target success criteria were met, namely, more than 60% of feral cat passes resulted in activation (actual 77%) and less than 5% of non-target passes triggered a firing (actual 0%). Our study was conducted over only a 6-week time period and future studies should be longer term and test the density of Felixers required to achieve a desired sustained reduction in cat density. This is likely to depend on cat density, and breeding and reinvasion rates and may vary according to habitat. Studies should measure these parameters during future trials, so that the efficacy of Felixers can be determined under a range of field conditions. Cat density varies considerably in Australia and is estimated to be between 0.2 and 0.7 per square km in natural environments (Legge *et al.* 2017), whereas the density in our study was considerably higher at $\sim$2 km^{-2}. Our trap density of 0.77 Felixers km^{-2} may be unrealistic in large areas unless the cost of the units can be reduced. However, the wide-ranging behaviour of cats reported in many areas (Edwards *et al.* 2001; Moseby *et al.* 2009) may mean that careful placement of traps in the preferred habitat could result in cats encountering Felixers even when in low density. GPS-tracking studies could assist with identifying optimum sites for Felixer placement. However, it is likely that Felixers will be most useful for removing cats from confined areas such as islands or inside or outside fenced reserves and reducing cat density in limited wild areas where threatened species are reintroduced or persisting at refuge sites. They may also be useful for reducing cat abundance over larger areas if they can be strategically placed at resource points or feral cat recolonisation routes, such as creek lines, fence lines, roadways and animal pads.

Conflicts of interest

The authors declare no conflicts of interest.

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Appendix 1. Results of Akaike information criterion adjusted for small sample sizes (AICc) model selection for linear mixed-effects models of feral cat tracks per kilometre, including marginal r^2 (Marg. r^2) and conditional r^2 (Cond. r^2)

Model description	Marg. r^2	Cond. r^2	Log-likelihood	AICc	Delta AICc	AICc weight
Before/after Felixer trial × Paddocks	0.18	0.4	−67.8	152.6	0	0.783
Before/after Felixer trial	0.12	0.28	−72.9	156.1	3.48	0.138
Paddocks	<0.01	0.2	−73.9	158	5.43	0.052
Null	0	0.13	−76	159.3	6.71	0.027

Appendix 2. Results of Akaike information criterion adjusted for small sample sizes (AICc) model selection for changes in individual cat-detection rates on remote cameras, including marginal r^2 (Marg. r^2) and conditional r^2 (Cond. r^2)

Model description	Marg. r^2	Cond. r^2	Log-likelihood	AICc	Delta AICc	AICc weight
Felixer firings alter detection rate	0.17	0.4	4.3	0.9	0	0.878
Change in detection rate through time	0.12	0.28	1	5	4.1	0.114
Null	0	0.19	−0.4	10.5	9.6	0.007

Appendix 3. Results of Akaike information criterion adjusted for small sample sizes (AICc) model selection for estimating density of feral cats on the basis of spatial mark–resight models from remote cameras

Unless specified, models assumed hazard rate detection function, and all variables not mentioned set as intercept only

Model description	Log-likelihood	AICc	Delta AICc	AICc weight
Two-class mixture model in home-range size	−894.7	1809.3	0	0.978
Cats change behaviour after first detection	−900.3	1816.8	7.5	0.023
No extra variables	−915.7	1844.3	35	0
Linear change in detectability through time	−914.4	1845.1	35.8	0
Exponential detection function	−918	1845.8	36.6	0
Half-normal detection function	−919	1847.7	38.4	0

Appendix 4. Results of Akaike information criterion adjusted for small sample sizes (AICc) model selection for occupancy models of feral cats

Occupancy part of the model was set as intercept for each model, and only variables affecting detectability were compared

Model description	Log-likelihood	AICc	Delta AICc	AICc weight
Before/after Felixer trial × paddocks + temperature + dune	−417.9	848.1	0	0.912
Paddocks + temperature + dune	−420.9	854.1	6	0.045
Temperature + dune	−421.6	855.5	7.4	0.023
Before/after Felixer trial + temperature + dune	−423.1	855.7	7.6	0.021
Before/after Felixer trial × paddocks	−436.6	880.1	32	0
Null	−439.6	883.7	35.6	0
Paddocks	−438.7	884.2	36.1	0
Before/after Felixer trial	−439.1	885	37	0