Towards a feral Cat management strategy for Hattah–Kulkyne National Park: estimation of feral Cat density and bait uptake rates, and comparison of management strategies

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Summary

Feral Cats (*Felis catus*) are widespread across Australia and occupy most habitats. They are a significant predator of mammals, birds and reptiles and are identified as a major threat to endangered fauna. The impact of feral Cats on biodiversity is also recognised nationally in documents such as The Action Plan for Australian Mammals 2012. The Victorian Government has recognised predation by feral Cats as a threatening process under legislation related to threatened species.

The Arthur Rylah Institute for Environmental Research (ARI) was commissioned by the Mallee Catchment Management Authority (MCMA) to provide information that will inform future feral Cat management strategies at Hattah–Kulkyne National Park (HKNP). The aim of this project was to provide key information required for developing effective strategies for the management of feral Cats at a future date.

We assessed feral Cat density and consumption rates of non-toxic baits in autumn 2016 and in summer 2017. To obtain unbiased estimates of feral Cat density, we modelled spatially correlated detections of individual feral cats at multiple locations (based on images captured by digital cameras). We combined density estimates and consumption rates with movement models to assess various management scenarios proposed for reducing feral Cat populations. We assessed the body condition of feral Cats captured by the MCMA in 2016 and 2017 as a measure of the food stress they were experiencing during the period of the non-toxic bait trials.

In autumn 2016, the estimated abundance of cats within the 331 km^2 study area was 91 (range 57–128), with a corresponding density estimate of 0.27 cats/km^2. The estimated home range size was 7 km^2. In summer 2017, no feral Cat was recorded taking a bait, and overall, insufficient feral Cats were detected on cameras to allow estimation of density or home range size.

In autumn 2016, one male and five female feral Cats were captured from 1540 cage-trapping nights. All cats were in good or very good body condition, and none of the females showed signs of having been pregnant. In summer 2017, no feral Cats were captured, despite cage traps being operated in the same manner and with similar effort (1400 trap nights).

The ‘best’ strategy from the simulation modelling was aerial baiting with bait at 30 baits/ linear km and transects no more than 1 km apart. This was predicted to achieve high population reductions (>75%). For ground baiting, a high (>75%) population reduction was unlikely to be achieved, even at high bait densities (50 baits/km).

Based on the naïve occupancy (the proportion of sites at which the target species was detected) from this study and from previous surveys at HKNP, feral Cats appear to decline in abundance from spring to summer, and from summer to autumn. Previous research has linked changes in feral Cat abundance to changes in the abundance of their main prey (usually European rabbits, ‘rabbits; *Oryctolagus cuniculus*); changes in feral Cat bait uptake have been linked to changes in both feral Cat abundance and rabbit abundance. The link between rabbit abundance and feral Cats may, however, have been decoupled, due to the long-running and successful rabbit control program at HKNP.

While our results indicate that baiting would be most effective in autumn, we only conducted one trial and so have limited data from HKNP; we would urge caution in adopting this as *the* management strategy; rather, as intended, it provides a starting point for planning control actions in the future.

We assert that predicting when to undertake feral Cat control at HKNP is problematic because: (i) we have no information on the prey items of feral Cats at this site; (ii) there is considerable diversity of potential prey items present in the park; (iii) rainfall in the region is unpredictable; and (iv) irregular flooding events could affect the abundance of native species and feral Cats in an unpredictable manner.

There are a number of actions that could improve our capacity to prescribe a management strategy for feral Cats at HKNP:

Actions	Reasoning
1. Repeat the trial in autumn to confirm the results	While our recommended baiting strategy indicates that baiting would be effective in autumn it is based on a sample of one trial so we would urge caution in adopting this as *the* management strategy, rather, as intended, it provides a starting point for planning control actions in the future.
2. Undertaking surveys of potential prey items concurrently with bait take trails 3. Including environmental data into the analysis (e.g., rainfall, minimum and maximum temperature, habitat data) 4. Shooting feral cats to, a) collect body condition and b) diet information immediately following the bait trial	Due to the long-term and successful rabbit control program the link between feral Cat abundance and changes in rabbit numbers may have been decoupled. Information on feral cat diet and prey availability would also improve future management strategies.
5. Placing GPS tracking collars on feral Cats to improve our estimate of home range and movement patterns, increasing the precision of the model outcomes 6. Increase the number of camera/bait stations from 50 to at least 60	In order to optimise the sampling design more reliable/accurate information is required on home range size and shifts in habitat use between seasons. Also, reinvasion has been poorly studied and is a critical factor in the design of successful control programs. Knowledge of feral Cat movement will help determine when and how reinvasion occurs and assist in designing the optimal size of baited areas. Reinvasion pathways may also assist in identifying areas for additional control actions or opportunistic baiting. Placing two cameras within an area that was estimated be to the size of a feral Cat home range resulted in low detection probabilities in both 2016 (0.26) and 2017 (0.11). Increasing the number of camera sites would improve our confidence in detecting feral cats if they were present.
7. Implement a toxic baiting program to validate model predictions 8. To maximise the information gained from recommendation 7, attach GPS tracking collars to assess kill rates and movement patterns before, during and after a control operation	Validating our predictions on the rate of change in the feral Cat population is an important step as information gathered could be incorporated back into the model predictions and used to further refine the management strategy. This should be implemented once the current barriers to feral cat control are removed.

We have used the best available information to develop guidelines for undertaking poison baiting for feral Cats at HKNP, and established a possible framework for trialling plausible alternative strategies. Poison baiting alone may not be fully effective at reducing feral Cat populations to below critical threshold levels at which they no longer pose a significant threat to native species. However, it is the only tool that can be applied at a broad landscape scale.

1 Introduction

feral Cats (*Felis catus*) are widespread across Australia and occupy most habitats. They are a significant predator of mammals, birds and reptiles (Paton 1990, 1991; Trueman 1991) and are identified as a major threat to endangered fauna (Woinarski et al. 2014). Consequently, predation by feral Cats has been listed as a key threatening process in Australia under the *Environmental Protection and Biodiversity Conservation Act 1999*. The impact of feral Cats on biodiversity has also been recognised nationally in The Action Plan for Australian Mammals 2012 (Woinarski et al. 2014). The Victorian and New South Wales State Governments have recognised feral Cats as a threatening process in the *Flora and Fauna Guarantee Act 1988* and the *Threatened Species Conservation Act 1995*, respectively.

Currently, there is limited understanding of the effectiveness of available feral Cat control tools, or where, when and how to apply these in south-eastern Australia. Broad-scale baiting by deploying baits from the air is the most widely used method in those parts of Australia where it is permissible. However, baiting feral Cats has proved to be challenging, with inanimate baits seeming to be a less preferred food item relative to normal live prey (Fisher et al. 2014). Aerial baiting has been used effectively at a limited number of mainland arid sites, within times when feral Cats appeared to be food stressed (Algar and Burrows 2004, Algar et al. 2007, Moseby and Hill. 2011). It is unknown if a similar baiting window exists in mesic south-east Australian environments.

Increasing our understanding of effective feral Cat management approaches, and optimising management strategies, is limited by the current legislative framework in Victoria. Limitations on being able to destroy feral Cats on public land without first presenting them to a local council, not being able to deploy toxic baits from the air or to surface-lay baits, not being able to capture and destroy feral Cats in leg-hold traps, and not being able to capture and release feral Cats all restrict our capacity to develop best management practices in Victoria.

The Arthur Rylah Institute for Environmental Research (ARI) was commissioned by the Mallee Catchment Management Authority (MCMA) to provide information that will inform future feral Cat management strategies for Hattah–Kulkyne National Park (HKNP). The aim of this project was to provide key information required for developing effective strategies for the management of feral Cats at a future date. Basic information on: the rate at which feral Cats encounter and consume baits; non-target bait interference rates; when feral Cats may be food stressed; and methods for determining underlying feral Cat density will allow us to optimise future control strategies.

We used digital cameras to assess feral Cat density and home range, and non-toxic bait consumption rate by feral Cats and non-target species. We combined this information with movement models to assess various management scenarios for reducing feral Cat populations. We also utilised feral Cats captured during a limited control program implemented by the MCMA around the Hattah–Kulkyne Lakes system to assess body condition as a measure of food stress.

2 Methodology

2.1 Study area

The study was undertaken in the HKNP, Victoria (Figure 1) in March–May 2016 and in January–March 2017.

In 2016 and 2017, a camera-trapping array was established using 47 camera-trap sites set on an 800-m grid (Figure 1). This spacing was chosen to ensure that individual feral Cats could potentially be detected at multiple camera-trap locations within their estimated home range. Detections of individuals at multiple locations potentially produces spatially correlated detections, which is essential for obtaining unbiased estimates of population density when the population is totally or partially unmarked (Ramsey et al. 2015).

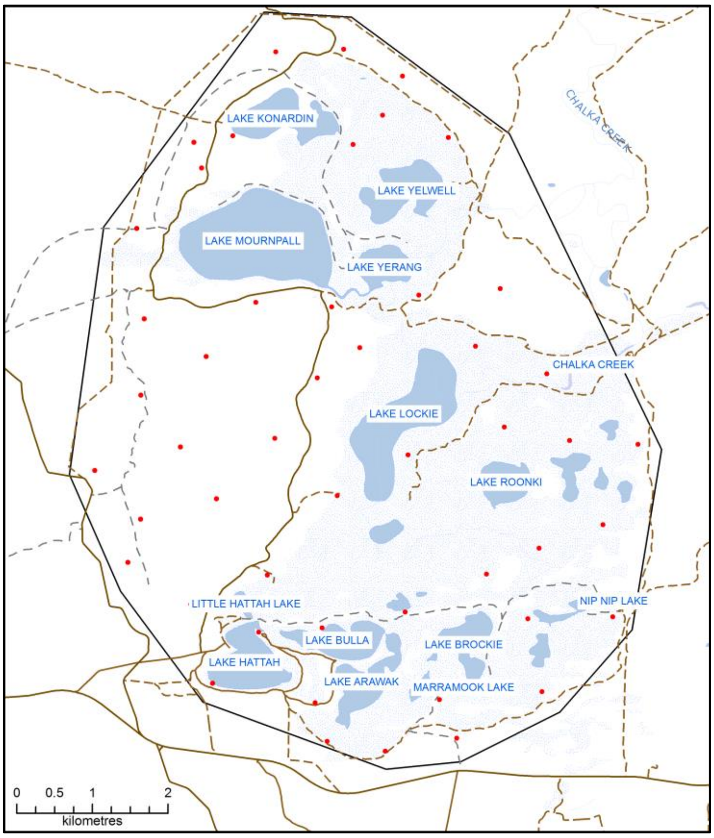

Figure 1. Hattah–Kulkyne National Park, showing the locations of the cameras used in the feral Cat monitoring study in 2016 and 2017 (red circles *n* = 47). Black polygon = study area.

Cameras were set for two periods of 35 days, from 30 March to 3 May 2016, and from 31 January to 2 March 2017. At each location, two Reconyx digital cameras (Reconyx, Holmen, WI, USA) were set at right angles 2 m from a lure. The lure consisted of a combination of (i) a non-toxic Eradicat® bait tethered to the ground by fishing line (attached to a peg buried in the ground), (ii) an audio lure (Felid-attracting Phonic, Westcare Electronics, WA) placed in a shrub or tree, and (iii) coloured feathers and tinsel tied above the audio lure.

The bait resembles a chipolata sausage in appearance, and is approximately 20 g wet weight, dried to 15 g, blanched and then frozen (Figure 2). It is composed of 70% kangaroo meat mince, 20% chicken fat and 10% digest and flavour enhancers (Patent No. AU 781829). Following the method described by Algar et al. (2014), prior to being laid, feral Cat baits were thawed and placed in direct sunlight. This process, termed ‘sweating’, causes the oils and lipid-soluble digest to exude from the surface of the bait. All feral Cat baits were sprayed, during the sweating process, with an ant-deterrent compound (Coopex®) at a concentration of 12.5 g/L, as per the manufacturer’s instructions. This process is aimed at preventing bait degradation by ant attack (the physical presence of ants on and around the bait medium may deter bait acceptance by feral Cats).

Figure 2. Non-toxic Eradicat bait used in the 2016 and 2017 trials.

Cameras were set to trigger on motion and to capture three images within 3 s, with no wait period between triggers.

Two cameras were used, set perpendicular to each other to increase the likelihood of detecting bait being taken and to get photos from different angles to help identify individual feral Cats. Photos of individual cats were inspected, and if distinctive natural markings could be used to identify the individual, a unique ID and corresponding detection history was recorded for that individual. Figure 3 provides an example of features used to identify individual feral Cats. For individuals that could not be identified, the number of detections of unmarked individuals per camera was recorded.

Figure 3. Features used to identify individual feral Cats. These included (i) number and position of bands on tail, (ii) number, shape and position of bands on forelegs and hind legs, and (iii) pattern of stripes and bands on body. Other unique identifiers included shape of ears, and colouring, e.g. white or tabby patterns.

2.3 Feral Cat trapping

As an initial step in understanding feral Cat body condition, we took advantage of the Mallee CMA feral Cat trapping program to collect samples of feral Cats. Thirty-five cage traps were set from 28 March to 10 June 2016 and from 15 March to 24 April 2017 at or near locations where feral Cats had been photographed at camera traps in the bait uptake trials and in previous investigations on the impact of Red Foxes (*Vulpes vulpes*; hereafter 'Foxes') on freshwater turtle (Eastern Long-necked Turtle *Chelodina longicollis*) nests (Robley et al. 2016a; Figure 4). Cage traps were baited with commercially available fresh chicken pieces, and were supplemented with an audio lure and a visual lure e.g., reflective tinsel. Cages were wrapped in plastic and covered with vegetation and placed at or near the base of a shrub. Cage traps were set on Monday mornings, then checked (and reset if necessary) each morning until the following Friday. Traps were wired open over the weekend and left baited to allow feral Cats to become accustomed to traps.

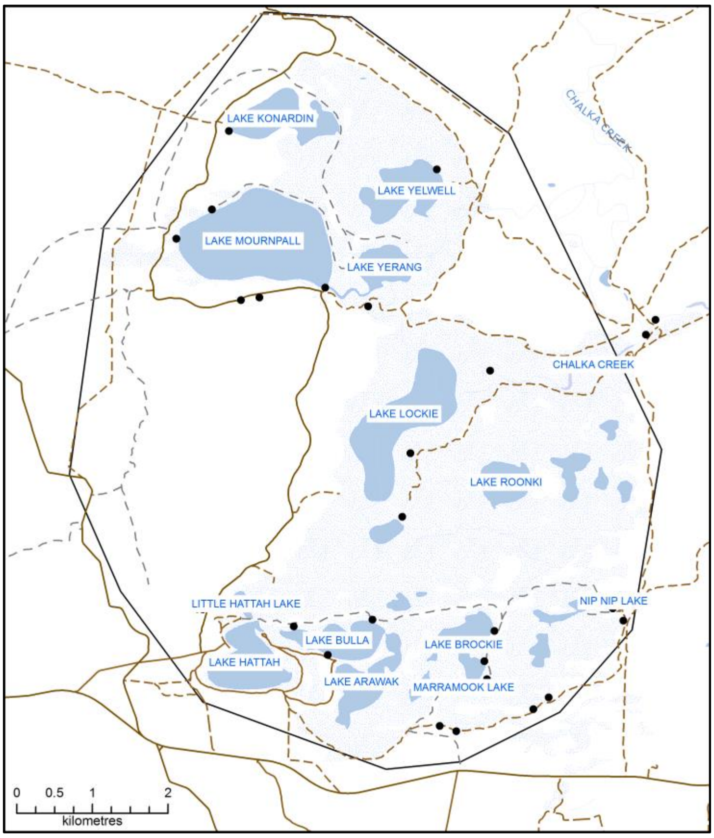

Figure 4. Location of cage traps set to capture feral Cats in 2016 and 2017 (black circles)**.** Black polygon = study area.

Trapped feral Cats were transported approximately 100 km in the cage trap to a veterinarian in Mildura, as per the legal requirements in Victoria. Each feral Cat was inspected by the veterinarian and then euthanased under anaesthetic. Feral Cat sex, weight, evidence of previous pregnancy and body condition were noted. Body condition was scored by examination of fat deposits along the lower spine and rump, as well as by inspection of visceral fat deposits around the kidneys. Body condition was scored 1 – 5, with 1 = very poor and 5 = very good.

2.4 Estimating feral Cat density

Few studies have estimated the density of feral Cats in Australia, due (in part) to the wide-ranging and generally cryptic nature of feral Cats. This cryptic nature means that monitoring designs that are usually suitable for density estimation may not be feasible, or may be too costly to implement (e.g. mark–recapture, involving physical capture and marking of individuals).

Recent advances in spatial capture–recapture (SCR) methods have enabled the development of spatially explicit alternatives for density estimation in unmarked or partially marked populations (Chandler and Royle 2013; Royle et al. 2013), and these techniques have been further modified for detection/non-detection data (Ramsey et al. 2015). SCR methods are ideally suited for estimating population density in wide-ranging, cryptic predator species. Unlike conventional (non-spatial) capture–recapture methods, SCR models explicitly incorporate a sampled area into the estimation process; hence, estimation of population density is straightforward. SCR methods also overcome other technical problems that cause bias in conventional capture–recapture methods, such as heterogeneity in detection, due to differential exposure of individuals with detection devices.

Here we provide estimates of the population density of feral Cats at HKNP. The feral Cat population included a number of individuals that could be identified from natural markings, and a number that could not be identified, and we used the data obtained from SCR methods (Royle et al. 2013) to obtain estimates of population density.

The assumptions of SCR models are that the marked individuals are a random sample from the population, and that marking occurs throughout the defined sampling area. For the HKNP feral Cat data, we can see no reason why feral Cats with distinctive marks were more likely to be detected than feral Cats without such markings, and feral Cats with distinctive markings could be detected on any of the cameras throughout the defined sampling area, so both these assumptions appear to have been reasonably well met. It was also assumed that all marked individuals were correctly identified and that no marked individuals were lost or emigrated from the area during the study. We used two observers to independently assess feral Cat identity, compared the results, and resolved any anomalies to reach a final consensus on the identity of individual feral Cats.

The SCR model was fitted to the 2016 data only using the JAGS software drawing 20,000 samples from the MCMC algorithm from each of three chains using diffuse initial values and discarding the first 10,000 leaving 10,000 samples from each chain to form the posterior distribution of the parameters. Convergence was assessed using the Brooks-Gelman-Rubin convergence statistic $\hat{R}$.

Appendix 1 provides a description of the modelling approach used.

2.5 Baiting strategies for feral Cats

We investigated the efficacy (percentage of population reduction) of different baiting strategies for the control of feral Cats in HKNP. We used a spatially explicit Monte Carlo simulation model of the baiting process to simulate the bait uptake by individual feral Cats, using the spatial algorithm given in Ramsey et al. (2005). The area used for simulations (331 km^2) covered much of the park (Figure 5). In this simulation, aerial transects went beyond the Park boundary; future simulation transects would be restricted to the public land estate.

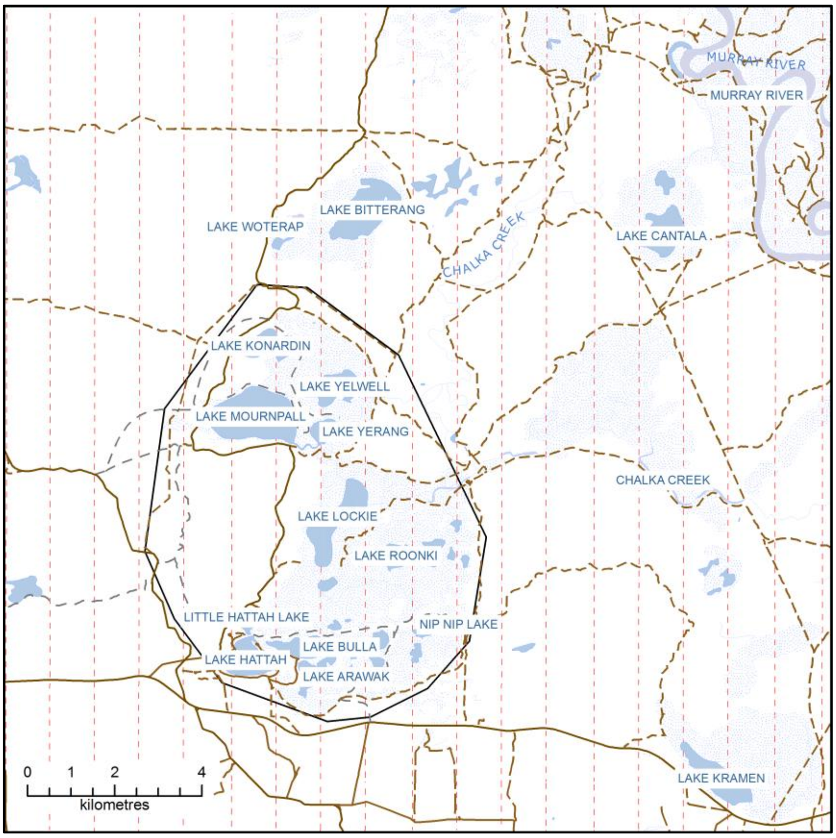

Figure 5. The area of Hattah–Kulkyne National Park used for simulations of the different baiting strategies for feral Cat control. Brown lines = roads/tracks; dashed red lines = simulated aerial baiting transects (1 km separation).

A brief description of the simulation algorithm is provided in Appendix 2.

2.6 Baiting strategies modelled

We modelled the effects of two different baiting strategies: aerial baiting from a helicopter or fixed-wing aircraft, and ground baiting. Aerial baiting involved dropping baits from the aircraft on defined transects running from north to south (Figure 5). Baits were then located on these transects according to a Poisson distribution with a given rate, the baiting density. We examined the effects of varying the baiting density from 5 baits per linear kilometre to 50 baits per linear kilometre. We also looked at the effects of different spacing between the transects (0.5, 1, 2 or 5 km between transects). For ground baiting, baits were only placed on the available road network (Figure 5), with the baiting density varied as per aerial baiting. Baits were assumed to be active for 10 days (D. Algar, Department of Parks and Wildlife, Western Australia pers. comm.). We compared these baiting strategies by calculating the proportional population reduction following the 10 days of bait exposure.

3 Results

3.1 Feral Cats at Hattah–Kulkyne National Park

In 2016, six feral Cats were captured from 1540 cage-trapping nights (approximately one feral Cat per 257 cage-trapping nights). One male and five females were captured, each weighing between 2.5 kg and 5.5 kg (Table 1). All feral Cats were generally in average to good body condition (mean = 3, SD = 0.5), and none of the females showed signs of placental scaring, indicating that they had not been pregnant. No feral Cats were captured in 2017, despite 1400 nights of cage-trapping.

Table 1. Details of feral Cats captured at Hattah–Kulkyne National Park

Feral Cat #	Date captured	Sex	Weight (kg)	Body condition score
1	06/03/2016	F	4.69	4.0
2	29/04/2016	F	3.56	3.0
3	03/05/2016	F	3.18	2.5
4	13/05/2016	F	4.10	3.0
5	08/06/2016	M	5.50	3.0
6	14/06/2016	F	2.62	2.5

3.2 Feral Cat abundance and density

In 2016, a total of 13 feral Cats could be identified through natural markings with five detections of unmarked feral Cats (Figure 6 and 7). In 2017, a total of three individual cats could be identified with five feral Cat detections at three sites recorded on cameras, an insufficient number to estimate meaningful density or home range size. In comparison, in 2016 there were 34 feral cat visitations at 22 different sites.

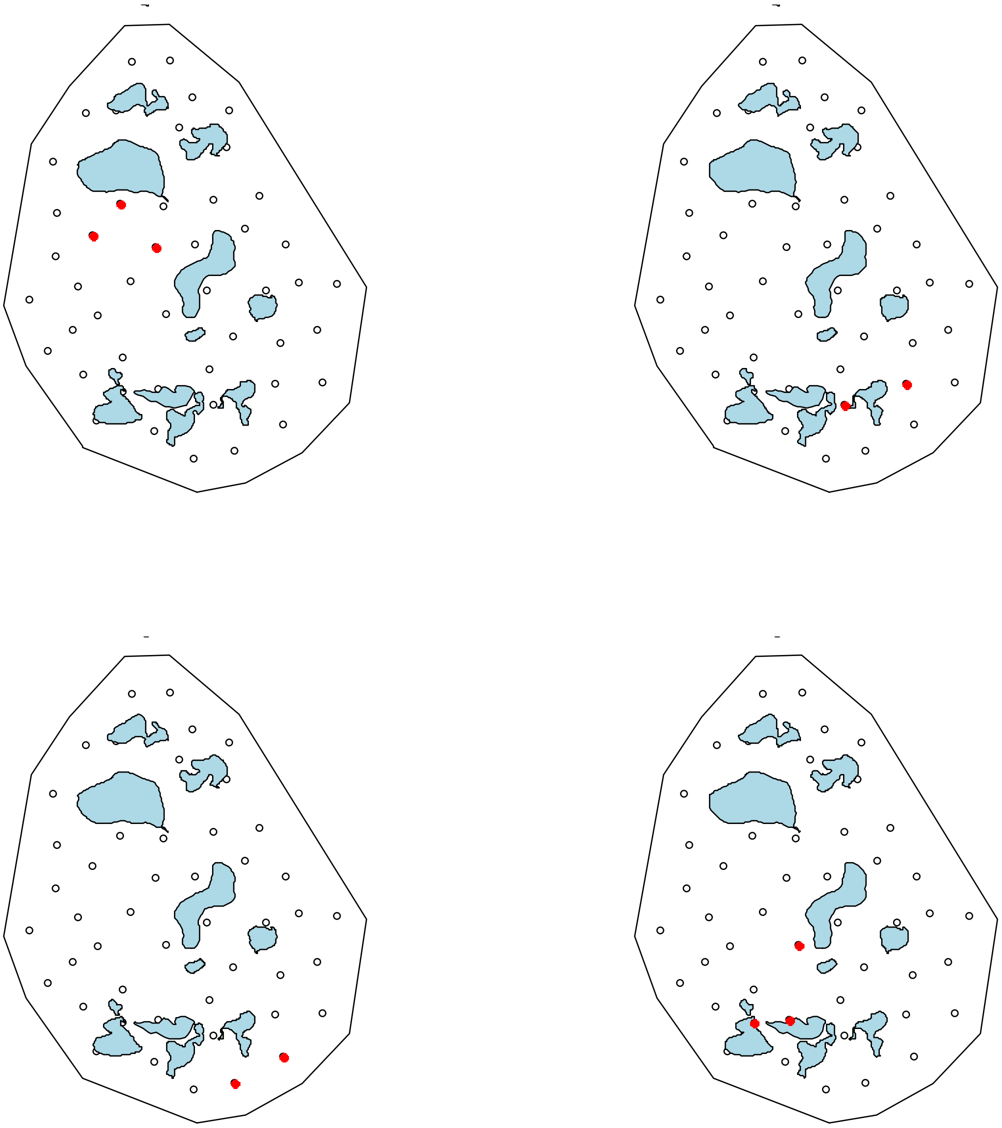

Figure 6. Detection histories for four of the 13 feral Cats that could be uniquely identified from natural markings, photographed on cameras at Hattah Lakes. Red circles indicate sites where detection occurred.

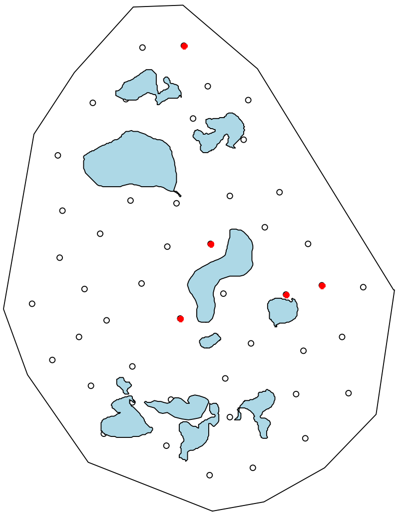

Figure 7. Detections of unmarked feral Cats on the camera array at Hattah Lakes. Red circles indicate sites where detection occurred.

In 2016, the estimated abundance ($\widehat{N}$) of feral Cats within the sampling area (331 km^2) was 91 (Figure 8a), with a corresponding density estimate of 0.27 feral Cats/km^2 [95% confidence interval (CI) 0.17–0.39] (Figure 8b). The precision of the estimates was considered high (Table 2). The estimated spatial scale parameter (σ) was 0.61 km, which corresponds to a 95% circular home-range size of 7 km^2. The daily probability of detection when a camera coincided with the centre of a feral Cat home range was 0.040 (Table 2).

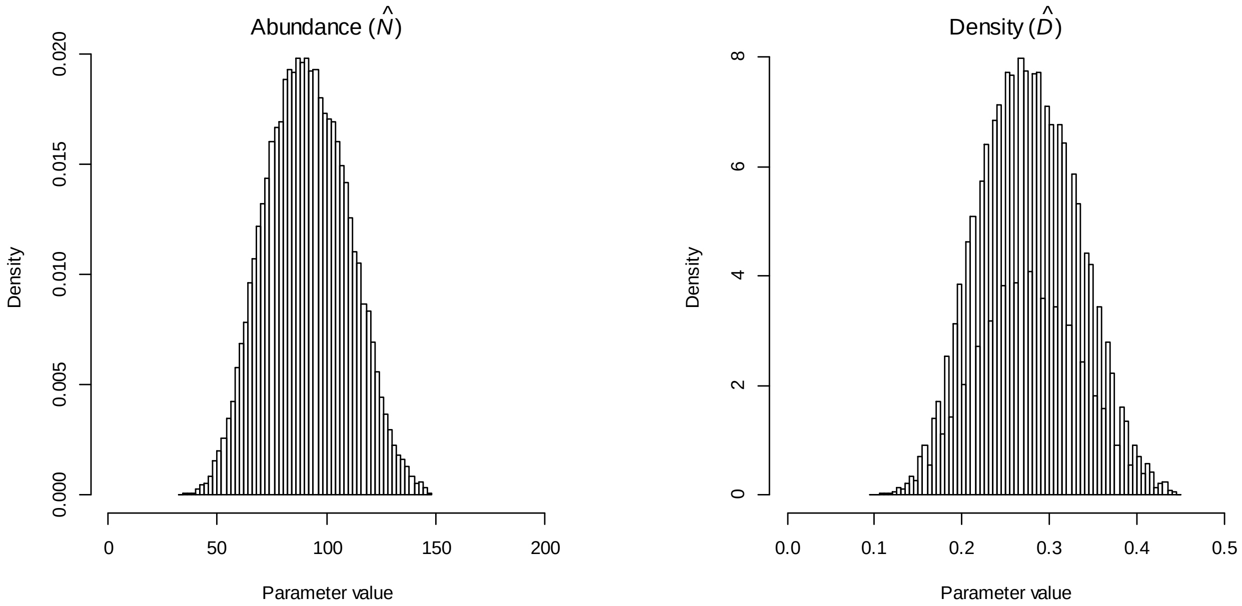

Figure 8. (a) Posterior densities of cat abundance ($\widehat{N}$) and (b) population density ($\widehat{D}$), following the fitting of the SCR model to the detection histories of marked and unmarked feral Cats at Hattah Lakes in 2016.

Table 2. Parameter estimates of feral Cat population size ($\widehat{N}$) and density, and the parameters of the detection function (g_0, σ) generated from the spatially explicit capture–recapture model applied to feral Cat detections at camera traps at Hattah Lakes National Park

Parameter	Mean	Median	SD	2.5% CL	97.5% CL
$\widehat{N}$	91.6	91	18.8	57	128
Density (cats/km^2)	0.27	0.27	0.06	0.17	0.39
g_0	0.040	0.038	0.013	0.020	0.072
σ (km)	0.613	0.606	0.08	0.469	0.803

CL = confidence limit.

In 2016, of the 34 bait encounters by feral Cats, only two feral Cats were recorded eating the bait (Figure 9). This corresponds to the probability of a bait being taken [(number of taken baits)/(number of encountered baits)] of 0.057. In 2017, there were only five bait encounters in total (at three different sites), and no feral Cats were recorded taking a bait.

Figure 9. Feral Cat at Hattah–Kulkyne National Park taking a non-toxic bait.

Non-target species accounted for the majority of bait uptake. In 2016, eight non-target species took a total of 25 baits. This included 12 baits taken by raven spp and 6 by Foxes. In 2017, non-target species accounted for 15 bait takes, 4 by raven spp, 4 by White-winged Choughs (*Corcorax melanorhamphos*), and only 1 by a Fox. Other species that took baits included goanna spp, Laughing Kookaburras (*Dacelo novaeguineae*), feral Pigs (*Sus scrofa*), Australian Magpies (*Cracticus tibicen*) and butcherbird spp.

3.3 Control strategies

For the simulated aerial-baiting strategies, high population reductions (>75%) were predicted for baits spaced at 30 baits/km when transects were no more than 1 km apart (Figure 10). Baits spaced at ≤10 baits/km always resulted in low to moderate population reductions (<60%), regardless of the distance between transects. Low population reductions also occurred when distance between transects was 2 km or more.

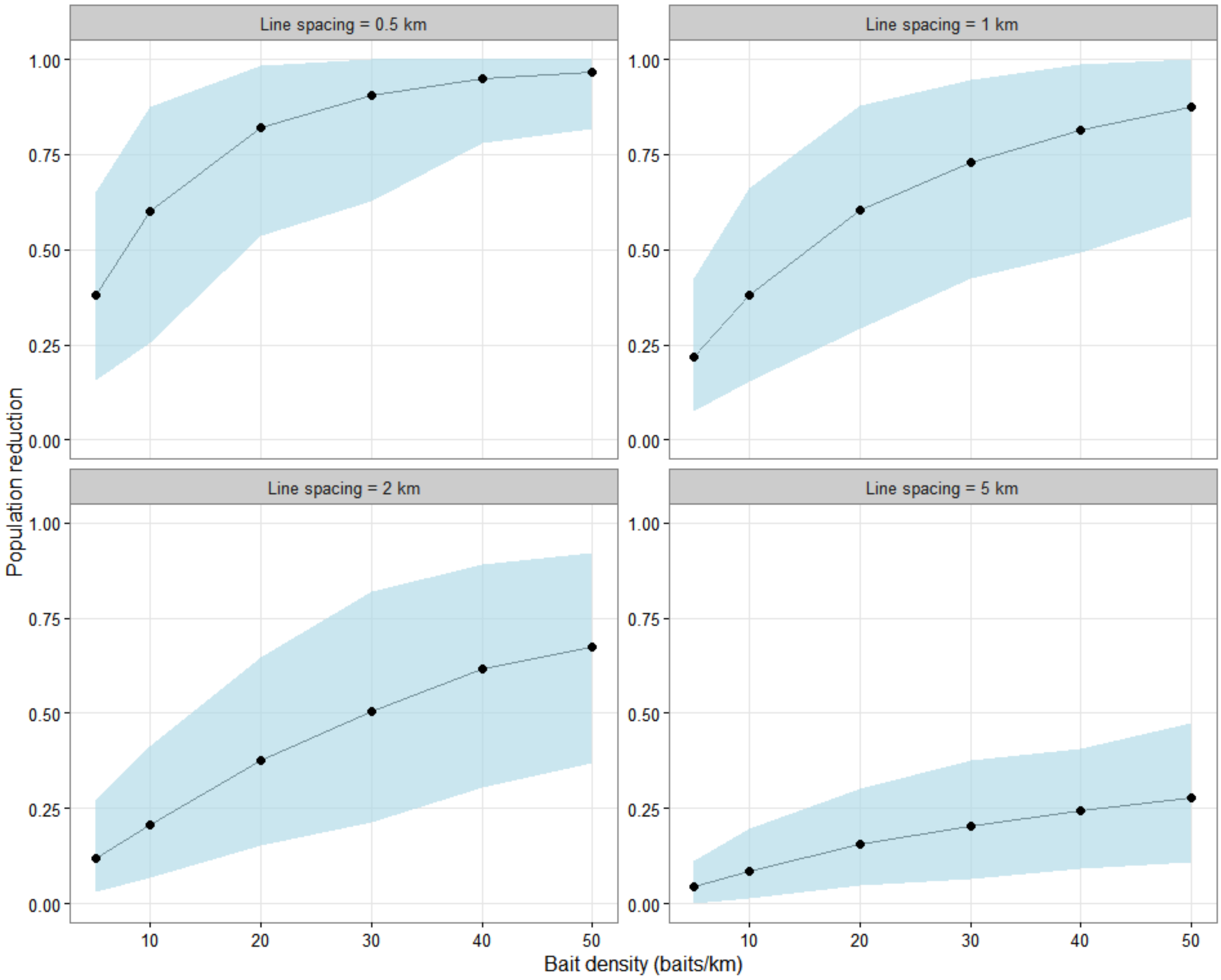

Figure 10. Modelled relationship between bait spacing on transects and proportional population reduction for aerial baiting of feral Cats, using varying spacing between transects.

For ground baiting, high (>75%) population reduction was predicted to be unlikely, even at high bait spacing (50 baits/km). At 50 baits/km placed on the accessible road network, a ≥75% population reduction was only likely to be achieved 13% of the time (i.e. 13 out of 100 attempts) (Figure 11).

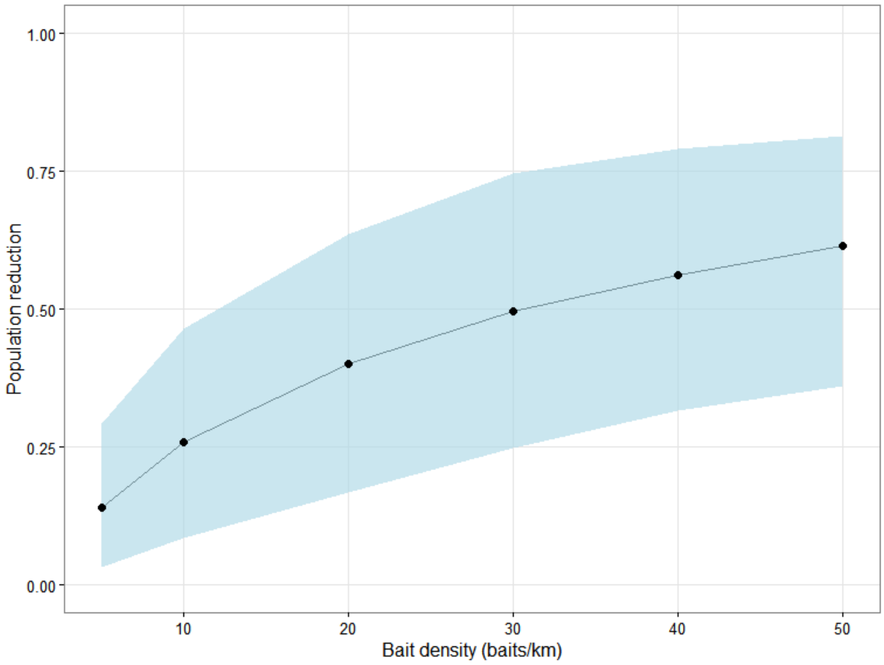

Figure 11. Modelled relationship between bait spacing and proportional population reduction for ground baiting of feral Cats on the accessible road network.

3.4 Temporal variation in feral Cat naïve occupancy

There is some evidence that feral Cat numbers vary spatially and temporally at HKNP, which may affect the possible timing of future control operations. From 2014 to 2017 broad-scale camera surveys were undertaken to assess changes in Fox activity pre– and post–Fox control at HKNP (Appendix 3). In 2014-2016 surveys consisted of broad-scale surveys while in 2017 camera surveys were focused on two spate areas, one around Lake Mornpall and surrounding lakes, and the second around Lake Kramen (Appendix 3). These showed that naïve estimates of feral Cat occupancy were generally higher in spring than in summer (Table 3), with the exception of summer 2017 around Lake Kramen. There was a peak in naïve occupancy in autumn 2016 at both the Mournpall block and around Lake Kramen, and a lesser peak in autumn 2017 in the Mournpall block but not around Lake Kramen, which at that time recorded the lowest naïve estimate of occupancy. Overall, the probability of detecting a feral Cat on a camera trap was low for all surveys.

Table 3. Feral Cat naïve estimates of occupancy and detection rates from several camera surveys at Hattah–Kulkyne National Park from 2014 to 2017. Naïve occupancy is the proportion of sites at which feral Cats were detected, without considering the probability that they went undetected at occupied sites. The number of camera sites is in parentheses. The cumulative detection probability is the chance of detecting a feral Cat at a site, if in fact it is present over the length of the survey period.

Year	Survey	Season	Naïve occupancy	Cumulative detection probability
Oct 2014[a]	Pre–Fox control	Spring	0.14 (*n* = 72)	0.24
Feb 2015[a]	Post–Fox control	Summer	0.09 (*n* = 68)	0.12
Oct 2015[b]	Pre–Fox control	Spring	0.12 (*n* = 103)	0.07
Feb 2016[b]	Post–Fox control	Summer	0.06 (*n* = 53)	0.11
Mar 2016[c]	feral Cat study	Autumn	0.47 (*n* = 47)	0.44
Jan 2017[d]	Pre–Fox control Lake Kramen	Summer	0.19 (*n* = 36)	0.20
Jan 2017[d]	Pre–Fox control Mournpall Block	Summer	0.07 (*n* = 41)	0.14
Feb 2017[c]	feral Cat study	Summer	0.06 (*n* = 47)	0.11
Mar 2017[d]	Post–Fox control Lake Kramen	Autumn	0.01 (*n* = 32)	0.03
Mar 2017[d]	Post–Fox control Mournpall Block	Autumn	0.27 (*n* = 41)	0.26

Sources: [a]Robley et al. 2016a; [b]Robley et al. 2016b; [c]this study; [d]Robley et al. 2017.

4 Discussion

This project has successfully applied field and analytical techniques to determine the density [0.27 feral Cats/km^2 (CI) 0.17–0.39] and abundance (91, CI 57–128) of feral Cats around the Hattah Lakes system, and provided the first quantitative assessment of (modelled) management strategies for controlling feral Cats in Victoria.

Our modelled estimate of feral Cat home-range size (7 km^2) was in close agreement with the estimate obtained using remotely sensed productivity data (Bengsen et al. 2015) for HKNP (6 km^2). These values are both within home-range estimates from arid and semi-arid sites (varying from 0.5–32/km^2, reviewed in Moseby and Hill 2011). Our density estimate (0.27 km^2) is comparable with that of other studies; for example, Jones and Coman (1982) estimated densities of 0.7 feral Cats/km^2 during winter and up to 2.4 feral Cats/km^2 in summer at HKNP. Other studies in arid environments report densities of between 0.03 and 2.8/km^2 (Ridpath 1990; Burrows and Christensen 1994; Mahon et al. 1998; Read and Bowen 2001; Short and Turner 2005), which reflects both the different types of analytical approaches used and the likely low productivity of the HKNP environment. Based on the naïve estimates of feral Cat occupancy obtained from previous survey results at HKNP (Robley et al. 2016a; 2016b), feral Cats appear to decline from spring to late summer, but increase in autumn, which appears to be a favourable time for feral Cat abundance.

It was estimated that aerial baiting at a spacing of 30 baits per linear kilometre (with transect lines spaced at 1 km intervals) would be required to achieve a meaningful level of population reduction (>75%) of feral Cats, which is similar to the recommendation of Moseby and Hill (2011), who similarly prescribed an aerial baiting rate of 30 baits/km^2.

Our results indicated that a similar level of population reduction could not be achieved using ground-based baiting, even at the relatively higher baiting spacing of 50 baits/km along the accessible track network. Ground-based baiting for feral Cats has achieved high levels of reduction elsewhere. Short et al. (1997) used poisoned laboratory mice, each impregnated with 1080, to achieve a 75% reduction in spotlight counts, and Doherty and Algar (2015) used track-based baiting to reduce feral Cat activity by 85%. The success of ground-based baiting is likely to be, in part, reliant on an extensive track network providing sufficient ground coverage to achieve the required bait density.

With either aerial- or track-based approaches, baits are placed on the surface because feral Cats will not dig up baits as do Foxes and wild dogs (Fisher et al. 2014). This increases the potential for non-target bait-take, which can both put native species at risk and reduce the efficacy of the feral Cat control operation by reducing the amount of bait available to feral Cats. A review of the native species present at HKNP that are likely to be impacted by ingesting toxic feral Cat bait should be undertaken prior to any surface-laid toxic baiting operation being undertaken.

In our study, a total 11 non-target species were recorded taking Eradicat bait over the two trials, the majority being taken by ravens and Foxes. Algar and Burrows (2004) reports Fox numbers being reduced following trials of feral Cat baits. Integrated feral Cat and Fox control would be possible by laying toxic bait attractive and palatable to feral Cats, with sufficient 1080 poison to kill Foxes (i.e. 4.5 mg).

Feral Cats captured as part of the MCMA trapping operation in autumn 2016 were in average to good body condition based on our basic methodology, suggesting they were not particularly food stressed at this time; also, naïve estimates of occupancy just prior to trapping were the highest recorded over 10 surveys. However, our method of estimating the degree of food stress and hence body condition was simple, relying on veterinarian judgement. In the context of understanding when to bait for feral Cats, a more direct measure of prey availability would be a better approach as a number of studies have found that prey availability can affect the success of trapping and baiting operations for feral Cats. Short et al. (2002) found that trapping success was largely explained by both the abundance of rabbits relative to that of feral Cats, and whether rabbits were increasing or decreasing, and the abundance of feral Cats, accounting for a 9-fold difference in feral Cat trap success. Feral Cats may have contracted to focal areas in the environment in search of favourable habitat. In arid northern Australia, feral Cats used temporary focal points (areas used intensively over short time periods and then vacated) for periods of up to 2 weeks (Moseby and Hill 2011). Hence, it may take many weeks before a feral Cat encounters a fixed trap location.

Short et al. (1997) found that the effectiveness of baiting feral Cats was maximised by baiting when prey abundance was low. Algar and Burrows (2004) suggest that in areas that experience a Mediterranean type climate, the optimum baiting period occurs in the drier autumn/early winter months, when young, predator-vulnerable prey are not present, but before the onset of winter rains. Christensen et al. (2013) suggests that bait uptake by feral Cats is more likely to occur when the ratio of feral Cats to their main prey item is low. They postulated three scenarios in which feral Cat baiting may be efficient: (i) when feral Cat abundance is high and competition for prey is high; (ii) when small mammals (main prey item) and feral Cat abundance is low; and (iii) when both small mammal and feral Cat abundance are high, resulting in a low predator-to-prey ratio. They used rainfall in the previous winter to predict the abundance of small mammals, and hence the timing of feral Cat control, up to six months in advance.

Parks Victoria have undertaken regular rabbit control (fumigation and ripping) across the park since the early 1990s, and rabbit haemorrhagic disease virus (RDHV) became established in 1996. Spotlight surveys undertaken by Parks Victoria in March and September each year indicate that rabbit numbers range from 0.2 to 1.2 per kilometre, and are generally less than 1 per kilometre across the Park (S. Southon pers. comm.). Hence, rabbits may not be a key component of the feral Cat's diet at HKNP. Due to the long-term and successful rabbit control program, the link between feral Cat abundance and changes in rabbit numbers may have been decoupled.

Information on feral Cat diet and prey availability would improve future management strategies. A survey aimed at assessing the response of native species to Fox control at HKNP in 2003 recorded four small mammals, three dragons, six geckos, four legless lizards, 12 skinks and three (small) snake species (Robley et al. 2008). In addition, the park is home to a range of small ground-nesting or low-nesting bird species. Thus, there is a wide variety of potential prey available to feral Cats at HKNP.

It is difficult to predict when to undertake feral Cat control at HKNP because:

(i) we have no information on the feral Cat's diet at this site and how it fluctuates through time;

(ii) there is a wide diversity of potential prey items present in the park, and we know little about the relative abundance of these species and how their abundance fluctuates through time;

(iii) rainfall is unpredictable in the region; and

(iv) irregular flooding events complicate the possible responses of native species and feral Cats.

While our research indicates that baiting would be most effective in autumn, we only conducted one trial; and so, we would urge caution in adopting this as *the* management strategy; rather, as intended, it provides a starting point for planning control actions in the future.

There are a number of actions that could improve our capacity to prescribe a management strategy for feral Cats at HKNP.

Actions	Reasoning
1. Repeat the trial in autumn to confirm the results	While our recommended baiting strategy indicates that baiting would be effective in autumn it is based on a sample of one trial so we would urge caution in adopting this as *the* management strategy, rather, as intended, it provides a starting point for planning control actions in the future.
2. Undertaking surveys of potential prey items concurrently with bait take trails 3. Including environmental data into the analysis (e.g., rainfall, minimum maximum temperature, habitat data)	Due to the long-term and successful rabbit control program the link between feral cat abundance and changes in rabbit numbers may have been decoupled. Information on feral cat diet and prey availability would also improve future management

4. Shooting feral Cats to, a) collect body condition and b) diet information immediately following the bait trial	strategies.
5. Placing GPS tracking collars on feral Cats to improve our estimate of home range and movement patterns, increasing the precision of the model outcomes 6. Increase the number of camera/bait stations from 50 to at least 60	In order to optimise the sampling design more reliable/accurate information is required on home range size and shifts in habitat use between seasons. Also, reinvasion has been poorly studied and is a critical factor in the design of successful control programs. Knowledge of feral Cat movement will help determine when and how reinvasion occurs and assist in designing the optimal size of baited areas. Reinvasion pathways may also assist in identifying areas for additional control actions or opportunistic baiting. Placing two cameras within an area that was estimated be to the size of a feral Cat home range resulted in low detection probabilities in both 2016 (0.26) and 2017 (0.11). Increasing the number of camera sites would improve our confidence in detecting feral cats if they were present.
7. Implement a toxic baiting program to validate model predictions 8. To maximise the information gained from recommendation 7, attach GPS tracking collars to assess kill rates and movement patterns before, during and after a control operation	Validating our predictions on the rate of change in the feral cat population is an important step as information gathered could be incorporated back into the model predictions and used to further refine the management strategy. This should be implemented once the current barriers to feral Cat control are removed.

This study provides clear guidelines for undertaking poison baiting for feral Cats at HKNP, and establishes a possible framework for trialling plausible alternative baiting strategies. Poison baiting alone may not be fully effective at reducing feral Cat populations (Moseby and Hill 2011) to below critical threshold levels at which they no longer pose a significant threat to native species However, it is the only tool that could be applied at a broad landscape scale.

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Appendices

Appendix 1. Description of the spatially explicit spatial–capture model (SCR model) used to estimate feral Cat density at Hattah Lakes, Victoria

The data consisted of an array of J sampling devices having locations at X = (x_{j1}, x_{j2}), (j = 1, 2, … J) and set for K occasions (k = 1, 2, … K) (here J = 47 and K = 35). The observations at each device, denoted h_{jk}, take binary values, indicating detection of at least one individual on Device j at Occasion k. Hence $h_{1\cdot}$ = (01001) indicates detections on Occasions 2 and 5 for Device 1. The resulting data are a $J \times K$ matrix of detections h.

The encounter histories for the SCR algorithm consist of two parts. The first part consists of the encounter histories h_{ij} for each marked individual i (i = 1 … m), detected by Camera j at Occasion k, while for the unmarked individuals, the full detection histories for each individual and device are latent (unknown) and must be estimated. We proceed with a general model for the unmarked population before detailing the model for the marked component.

The conceptual model underlying the detection process is a spatially explicit, individual-based model of detections on devices located in two-dimensional space. Consider a population of N individuals that are potentially at risk of being detected, with each individual $\mathbf{z}_i$ (i = 1, 2, …, N) defined by a centre of activity $\mathbf{s}_i$ = (s_x, s_y), its nominal home-range centre. The locations of home-range centres are unknown, but are fixed for the duration of sampling. Individuals move about their home-range centres according to some probability distribution (e.g. bivariate normal), and in the process they can potentially be exposed to detection. We also assume that home-range centres could be located anywhere within the area of interest A, with equal probability. This prior expectation is achieved by setting a random uniform distribution for the $\mathbf{s}_i$:

$$\mathbf{s}_i \sim \text{Uniform}(A). \qquad \text{Eqn 1}$$

Structurally, this is like assuming home-range centres are distributed according to an homogeneous spatial Poisson process, with constant intensity (density) over the area of interest A. However, it is important to note that Equation 1 implicitly allows for any realised spatial configuration for the locations of the home-range centres. Thus, inference is concerned primarily with estimating the locations of the unknown home-range centres, and hence, the abundance N (and density) of individuals within the region A (e.g. Royle et al. 2009).

Encounter process

Individuals can only encounter devices that occur within their home range. If we consider the situation with only one animal and one device, the probability of detecting the individual declines as a function of the distance d between the device and the home-range centre. Assuming movements around the home-range centre occur with bivariate normal probability, the probability of detection is given by the half-normal function:

$$p_{ij} = g_0 e^{-d_{ij}^2/2\sigma^2}$$
$$d_{ij} = \left\| \mathbf{x}_j - \mathbf{s}_i \right\| , \qquad \text{Eqn 2}$$

where g_0 is the per-occasion probability of detection when the home-range centre and device location coincide (i.e. d = 0), and σ is the spatial scale over which the detection probability declines with increasing distance between the home-range centre and the device (e.g. Efford 2004; Ramsey et al. 2005). Equation 2 states that each individual $\mathbf{z}_i$ with home-range centre located at $\mathbf{s}_i$ is detected at a device $\mathbf{x}_j$ per occasion k according to:

$$\mathbf{z}_{ijk} \sim \text{Bernoulli}\left(p_{ij}\right).$$

Unmarked component

For the unmarked individuals, the full detection histories for each individual and device $\mathbf{z}_{ijk}$ are latent (unknown) and must be estimated. Ramsey et al. (2015) avoided estimation of the full $\mathbf{z}_{ijk}$ array by conditioning on the trap-specific detections, which in this case have the same discrete Bernoulli distribution:

$$h_{jk} \sim \text{Bernoulli}\left(P_j\right), \qquad \text{Eqn 3}$$

where the probability that at least one individual is detected by device j (P_j) is given by:

$$P_j = 1 - \prod_{i=1}^{N}\left(1 - p_{ij}\right). \qquad \text{Eqn 4}$$

Furthermore, as detections on each occasion are assumed to be independent, we can aggregate the detections at each of the J devices by noting that:

$$n_j \sim \text{Binomial}\left(P_j, K\right), \qquad \text{Eqn 5.}$$

where:

$$n_j = \sum_{k=1}^{K} h_{jk} .$$

The estimation problem now reduces to one of estimating the latent $\mathbf{s}_i$ and hence N, the number of individuals in the population. We used parameter-expanded data augmentation (Chandler and Royle 2013) to fix the dimension of the estimation problem by considering the existence of U rather than N individuals in the population, with $U >> N$. Estimation then proceeds by introducing a set of U latent indicator variables w so that the model now becomes:

$$P_j = 1 - \prod_{i=1}^{U}\left(1 - p_{ij} w_i\right), \qquad \text{Eqn 6}$$

$$w_i \sim \text{Bernoulli}\left(\psi\right); i = 1, 2, \ldots, M .$$

This implies that when $w_i = 0$, the probability that individual i is detected in any trap ($p_{i.}$) is also 0. Conversely, when $w_i = 1$, then individual i contributes their individual detection probability p_{ij} to the marginal trap total P_j. Hence, the estimate of the population size of the unmarked component (the number of unmarked home-range centres residing within the area A is given by:

$$\hat{N}_u = \sum_{i=1}^{U} w_i . \qquad \text{Eqn 7}$$

Marked component

Since there could be more individuals with unique natural markings in the population than were detected, the size of the 'marked' population is essentially unknown. Hence, this part of the model can be implemented using the classic formulation for SCR models, where we use data augmentation to include several 'all–zero' detection histories (M–m) to accommodate these potential individuals. These detection histories h_{ij} (i.e. detected/not detected) were modelled using:

$$h_{ij} \sim Binomial\left(K, p_{ij} z_i\right), \qquad \text{Eqn 8}$$

where:

$$\begin{aligned} p_{ij} &= g_0 e^{-d_{ij}^2/2s^2} \\ d_{ij} &= \left\| \mathbf{x}_j - \mathbf{s}_i \right\| \qquad , \\ z_i &\sim Bernoulli\left(f_m\right) \end{aligned}$$

where p_{ij} is the per-occasion detection probability of Individual i in Trap j, K is the total number of occasions (camera nights) and z_i is a latent indicator variable for Individual i ($i = 1 \ldots M$). The parameters g_0, σ, $\mathbf{s}_i$ and d_{ij} are as defined in Equation 2. This model essentially estimates the size of the 'marked' population of cats. This model is then combined with the model for the unmarked component of the population, which uses the data augmentation algorithm given in Equations 2–7 above. However, the estimator for population abundance within the state–space now becomes:

$$\hat{N} = \sum_{i=1}^{U} w_i + \sum_{i}^{M} z_i \ , \qquad \text{Eqn 9}$$

where U and M are the size of the augmented data for the unmarked (U) and marked (M) datasets. The SCR model defined in Equations 8 and 9 above was fitted using MCMC sampling in JAGS (Plummer 2003). We defined the state–space by buffering the locations of the outermost cameras by 5 km in each direction, to give a total area A of 331 km^2. We drew 20,000 samples from the MCMC algorithm from each of three chains, using diffuse initial values, and discarded the first 10,000, leaving 10,000 samples from each chain to form the posterior distribution of the parameters. Convergence was again assessed using the Brooks–Gelman–Rubin convergence statistic $\hat{R}$.

Appendix 2. A brief description of the spatially explicit Monte Carlo simulation model of the baiting process, used to simulate the bait uptake of individual cats

feral Cats are assumed to occupy home ranges that are fixed for the duration of baiting. The density of feral Cats within the area followed a log-normal distribution, with the location and scale of the log-normal distribution estimated from the mean and standard deviation of the density estimates given in Table 1. The probability, p_{ij}, of an individual cat, *i*, encountering and eating a bait, *j*, declines with the distance, *d*, between its home-range centre and the bait location. This relationship was assumed be a half-normal function, like Equation 2.

$$\begin{aligned} p_{ij} &= g_0 e^{-d_{ij}^2/2\sigma^2} \\ d_{ij} &= \left\| \mathbf{x}_j - \mathbf{s}_i \right\| \end{aligned}, \qquad \text{Eqn 10}$$

where g_0 is now the probability of encountering and taking a bait, and σ is an index of home-range size. One difficulty in simulating bait uptake for feral Cats is that once a feral Cat takes a bait, it is unavailable for other feral Cats; hence, there is competition between feral Cats for baits (and vice versa). No simple expression is available for the p_{ij} over a time interval when feral Cats compete for baits, and baits simultaneously compete for feral Cats. Therefore, to handle these competing events, we simulated the sequence of bait uptake in continuous time by treating each combination of *X* feral Cats and *N* baits as a competing Poisson process (Keeling and Rohani 2008). Assuming the bait uptake rate doesn't change over time, the finite capture probability has an exponential distribution:

$$p_{ij} = 1 - e^{-\lambda_{ij} t},$$

where λ_{ij} is the instantaneous rate of bait uptake for feral Cat *i* and bait *j* over one time interval *t*. Since we are usually interested in the bait uptake over a single night, setting $t = 1$ gives:

$$\lambda_{ij} = -\ln\left(1 - p_{ij}\right). \qquad \text{Eqn 11}$$

The algorithm is then:

Calculate λ for each feral feral Cat+bait combination from Equations 2 and 10.

Simulate the time to first capture for each combination by drawing a pseudo-random number from an exponential distribution with rate λ.

Find the next bait-take (remaining feral Cat+bait with minimum time to first bait-take).

If time exceeds 1, then ignore this bait-take and exit.

Record bait-take and remove combinations involving this feral Cat or this bait.

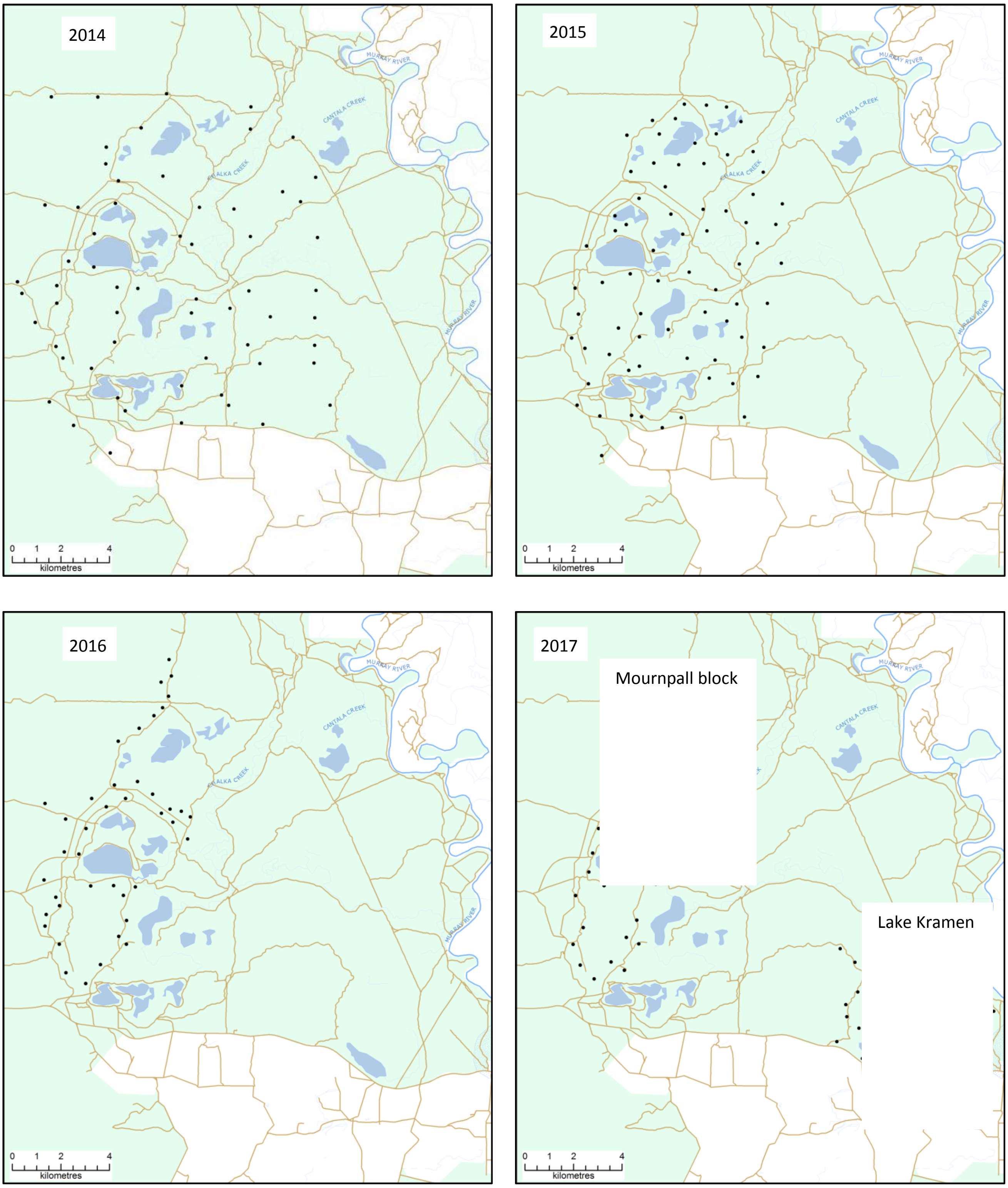
If at least one feral Cat and one bait remain, then go to 3; else exit.

Exponential pseudo-random numbers are obtained as $-\log(U)/\lambda$, where $0 \le U \le 1$ has a uniform distribution. Step 3 is expedited by sorting the list of combinations by ascending values of the simulated time to first bait-take (e.g. Ramsey et al. 2005).

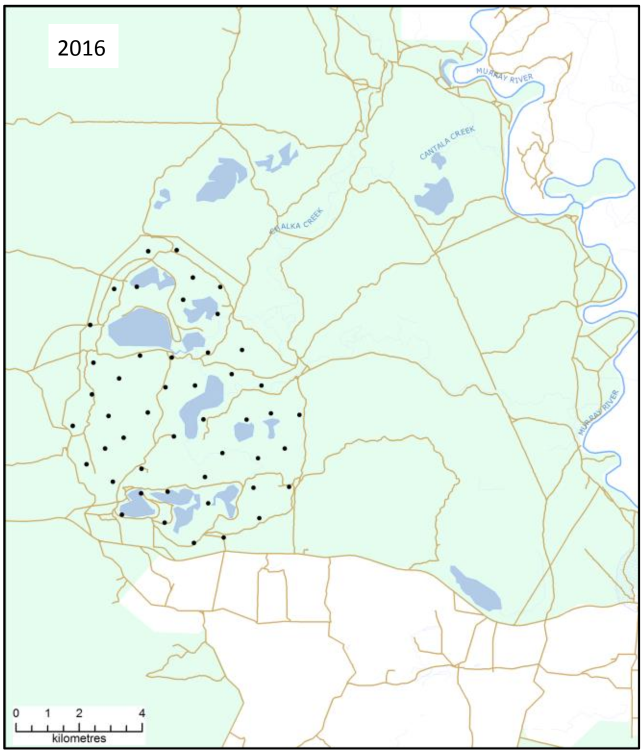
The parameters of the bait-take encounter function, g_0 and σ were taken from the estimates in Table 1. To account for variation in the bait-take rate, the parameter g_0 was simulated from a Beta distribution, and σ was simulated from a normal distribution, with means and standard deviations as given in Table 1.

Appendix 3. Locations of cameras used to survey foxes in 2014, 2015, 2016 and 2017, and feral Cats in 2016 and 2017 at Hattah-Kulkyne National Park.

Fox surveys



Feral Cat surveys 2016 and 2017



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