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Managing feral cats through an adaptive framework in an arid landscape

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HIGHLIGHTS

- We have suppressed feral cats (*Felis catus*) in remote arid zone of Western Australia for 16 years.
- Anthroposphere and biosphere interact through the distribution of sodium monofluoroacetate.
- We use sodium monofluoroacetate (1080) as our primary control technique.
- We provide management protocols for landscape-scale feral cat control.
- Threatened and endangered marsupials have been successfully reintroduced to Matuwa.

GRAPHICAL ABSTRACT

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ABSTRACT

Adaptive management is the systematic acquisition and application of reliable information to improve natural resource management over time. We have employed an adaptive management framework in the control and monitoring of feral cats (*Felis catus*) on the Matuwa Indigenous Protected Area over the past 16 years. We used 120 Reconyx PC900 camera-traps and a rapid survey technique called the cat track activity index (TAI) to determine if aerial baiting with *Eradicat*® was more efficient and/or cost-effective than track baiting plus leg-hold trapping. We found that aerial baiting at \$0.54 per percent decrease in cat detections is more cost-effective than track-baiting alone at \$0.56 per percent decrease in cat detections. Track baiting plus leg-hold trapping, however, is more cost-effective than aerial baiting alone at reducing the number of feral cats detections at \$0.39 per percent decrease in cat detections. Aerial baiting plus trapping was the most effective method of suppressing feral cats in an arid landscape with 97.7% reduction in cat detections. Trapping reduced the proportion of the population made up of adult cats from 51.5% to 38.7%, which may influence the efficacy of *Eradicat*®. Additionally, we found that cats were twice as likely to be detected on spinifex sandplain habitats than stony or hardpan habitats. We make several recommendations for refining feral cat management programs and future research.

1. Introduction

An adaptive management framework must be employed during the implementation of conservation programs on a landscape-scale (McCarthy and Possingham, 2007). Adaptive management is the systematic acquisition and application of reliable information to improve

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natural resource management over time (Wilhere, 2002). For adaptive management to be implemented the manager must be able to allocate management effort to discrete units, measure the outcome of a management action quantitatively, and have at least two possible management options to assess (McCarthy and Possingham, 2007). We have employed an adaptive management framework in the control and monitoring of feral cats (*Felis catus*) on the Matuwa Indigenous Protected Area over the past 16 years (Fig. 1).

The Rangelands Restoration program at the Matuwa Indigenous Protected Area (ex-Lorna Glen pastoral lease) in central Western Australia aims to achieve the successful reconstruction and conservation of Australian arid zone native species diversity. To date, five species have been successfully reintroduced to Matuwa; the bilby (*Macrotis lagortis*), brushtail possum (*Trichosurus vulpecula*), golden bandicoot (*Isoodon auratus*), burrowing bettong (*Bettongia leseuer*), and mala (*Lagorchestes hirsutus*), of which the final two are still confined to a predator-free fenced area; (Lohr, 2019). The successful reintroduction of native species to the arid zone can only be maintained if an effective, sustained feral cat control can be achieved (Algar et al., 2013a, 2013b; Denny and Dickman, 2010; Moseby et al., 2009a, 2009b; Moseby et al., 2011).

We define landscape-scale sustained feral cat control as the suppression of feral cat track activity index (TAI) to less than or equal to 10 cats/100 km of track-transect (Fig. 1; Algar et al., 2013a, 2013b). A benchmark of 'reducing and maintaining cat numbers to less than 10/100 km' had previously been proposed as the level at which successful reintroductions of native species could potentially occur (Morris et al., 2007). This definition of sustained feral cat control was based upon the level of cat suppression achieved at Matuwa between 2003 and 09 with an annual winter baiting program using the *Eradicat*® feral cat bait (Algar et al., 2013a, 2013b). Recent research from within the Arid Recovery fenced fauna reserve in South Australia validates this threshold of cat activity as suitable for native species recovery as bilby populations have been shown to be able to survive and increase in the presence of 0.46 cats/km^2 (Moseby et al., 2018). If we assume that track-transects detect all feral cats residing within 100 m of the track, then 10 cats/100 km of track-transect is approximately equivalent to 0.5 cats/km^2.

Following research at Matuwa between 2003 and 09, an annual winter baiting program using the aerial deployment of the *Eradicat*® feral cat bait was implemented across all of Matuwa as baseline feral cat control (Fig. 1; Algar et al., 2013a, 2013b). Initially, feral cat baiting alone successfully suppressed the feral cat population. Unfortunately, since 2012 there has been a gradual increase in the feral cat TAI back to levels first observed in 2003 despite on-going annual baiting (Burrows et al., 2018).

It is not known why there is an apparent reduction in the efficacy of the *Eradicat*® bait at Matuwa, but hypotheses include: 1) sustained feral cat suppression between 2003 and 2012 facilitated an increase in the abundance of small prey items (e.g., Dasyuromorphia and Rodentia), which decreased nutritional stress on all feral cats, decreasing the consumption of toxic baits (Christensen et al., 2013; Harper, 2005; Molsher et al., 1999); 2) annual baiting altered the feral cat population at Matuwa towards age and sex-based groups that are less inclined to consume baits; 3) annual baiting applied a selective pressure independent of sex and age against individual cats that scavenge food. In this study we collected data to compare with the second hypothesis.

The declining efficacy of the management program suggested that further adaptive management was required. Through consultation with the Western Australia Department of Biodiversity, Conservation and Attractions (DBCA) Western Shield Program (Algar and Burrows, 2004), the Matuwa Kurrara Kurrara Working Group and Tarlka Matuwa Piarku Aboriginal Corporation (TMPAC) we revised the annual winter baiting program such that Matuwa would be split into two discrete units or zones, which would receive different baiting applications plus the temporally discrete application of leg-hold trapping (Fig. 1).

We hypothesised that the application of baits along non-gazetted roads and tracks combined with landscape-scale leg-hold trapping of feral cats would be as cost-effective and efficient at suppressing cat abundance as aerial baiting alone. Western Shield aerial baiting typically drops clusters of 50 baits at one-kilometre intervals into intact

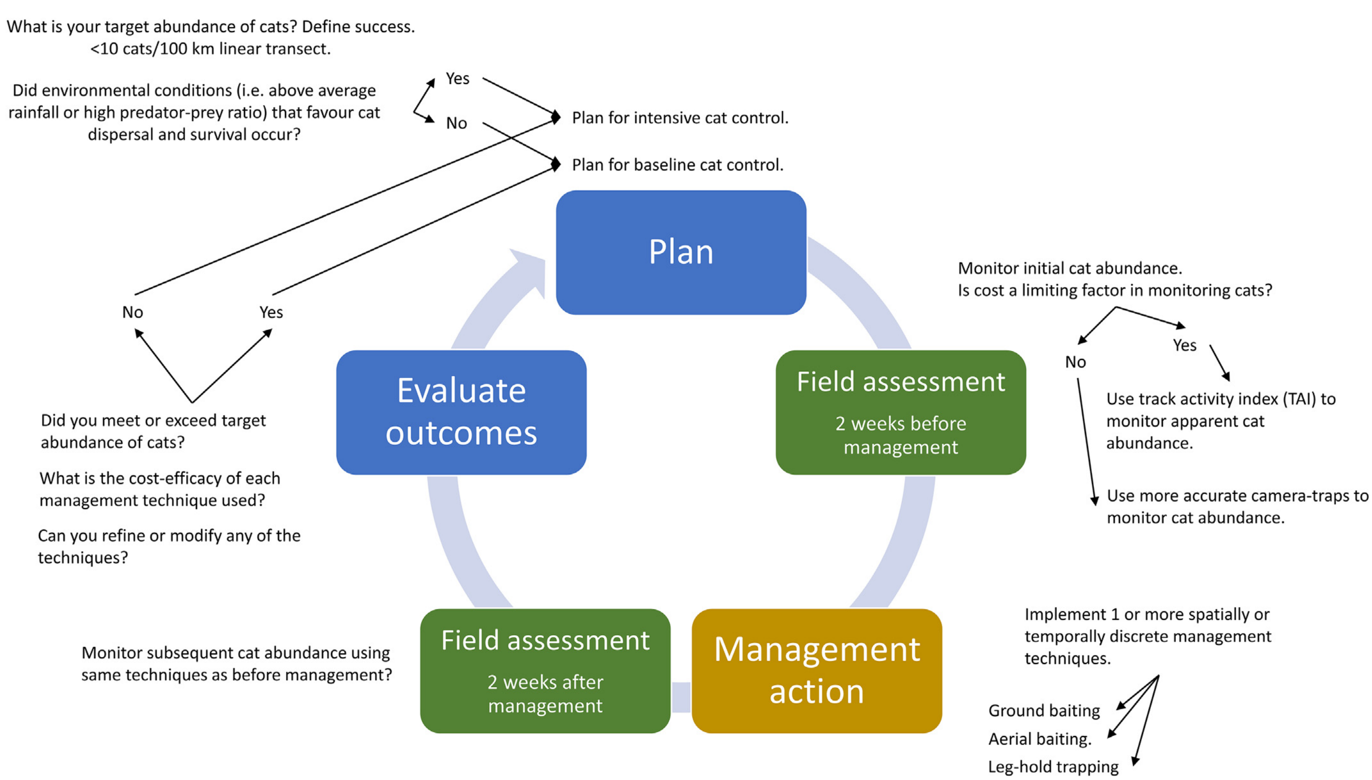

Fig. 1. Depiction of the annual adaptive management framework that should be employed in the control and monitoring of feral cats (*Felis catus*).

vegetation. Some research on the movement patterns of feral cats in open woodlands suggests that cats tend to travel along roads and tracks (Raiter et al., 2018) and hence may have a higher probability of encountering baits laid along tracks than baits deployed in intact vegetation. In South Australia, however, Moseby et al. (2009a, 2009b) noted that feral cats tracked via GPS data-logger radio-collars were found to use temporary focal points (relatively small areas used intensively over short periods of time before being vacated for other areas within the home range); a movement pattern that suggests that clusters of baits may be more effective for suppressing feral cat abundance in the arid zone. Contradictory research supports our need for more adaptive management research.

Additionally, we hypothesised that leg-hold trapping would reduce the proportion of older, experienced cats in the population and increase the reduction in feral cat detections. Captive trials have demonstrated that cats will preferentially hunt over consuming scavenged food (Adamec, 1976). It is rare that >1–2% of the feral cat's diet consists of scavenged food (Jones and Coman, 1981) though it is more commonly consumed during dry winters (Paltridge et al., 1997) when prey availability is low. Large male cats are proficient hunters capable of hunting both small, large and/or aggressive prey species (Moseby et al., 2015). Cats are also solitary animals (Genovesi et al., 1995), especially in the arid zone where prey is small and more dispersed, that use faeces as scent posts to mark and defend good hunting areas and other resources from subordinate cats (Corbett, 1979). By removing older, experienced hunters we hypothesise that younger less experienced and probably subordinate cats would migrate into our population (Liberg, 1980) where they may be more susceptible to taking bait.

Two methods of monitoring the cat population over time were employed to quantitatively assess the efficacy of our alternative management techniques. Additionally, data collected from captured cats were used to elucidate possible mechanisms behind the apparent reduction in the efficacy of *Eradicat*® baits over time.

2. Materials and methods

2.1. Study site

The Matuwa Indigenous Protected Area (IPA) is a 2440 km^2 ex-pastoral station purchased by the Western Australian Government in 2000 (Bode et al., 2012). The reclaimed pastoral lease was de-stocked over a period of three years and is situated approximately 137 km east-north-east of Wiluna at 26° 13′ S, 121° 33′ E (Fig. 2). The site has common boundaries with Wongawol, Yelma, Millrose and Granite Peak pastoral leases as well as a small area of Unallocated Crown Land that separates Matuwa from the Kurrara Kurrara Indigenous Protected Area (ex-Earaheedy pastoral lease). Matuwa straddles the boundary between the Murchison and the Gascoyne Bioregions (IBRA; Thackway and Cresswell, 1995). The study site comprises two main land systems: (1) Bullimore–sand plains and dunes dominated by spinifex (*Triodia* spp.); and (2) Sherwood–breakaways and stony plains dominated by mulga and other acacia shrublands. The vegetation unit most common across the station is the hummock grasslands, shrub steppe (Beard et al., 2013): *Acacia aneura* (mulga) and *Eucalyptus kingsmillii* over *Triodia basedowii* (hard spinifex). Smaller areas of low *A. aneura* woodland are also present. The geology and geomorphology of the area is

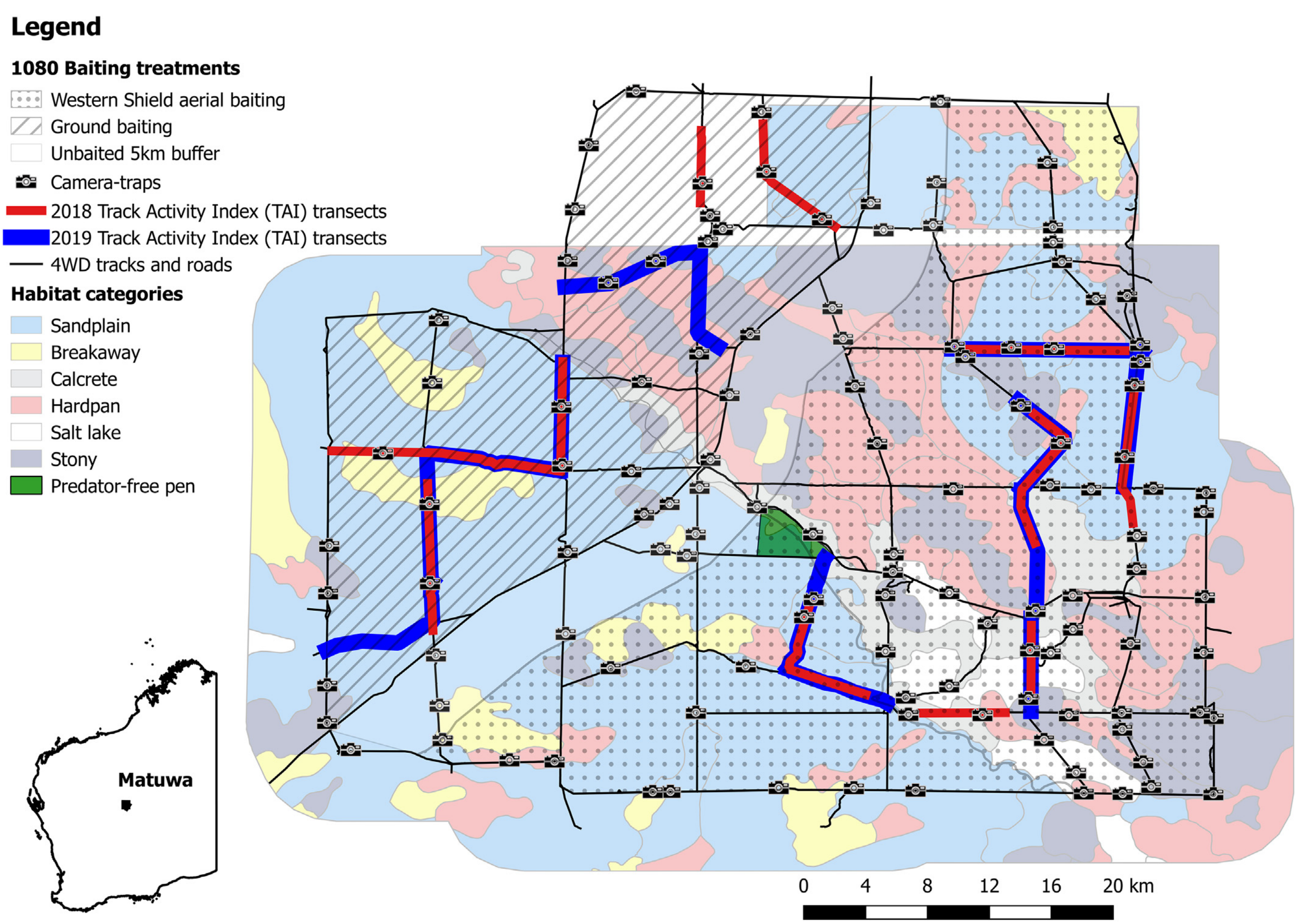

Fig. 2. Map depicting the *Eradicat*® baiting treatments used on the Matuwa Indigenous Protected Area in 2018 and 2019, plus the location of camera-traps and track-transects used to monitor the feral cat population, the presence of 4WD tracks, and habitat categories. Inset map depicts the location of the Matuwa Indigenous Protected Area in central Western Australia.

described by Mabbutt (1963). The climate of the area is characterized by low and erratic rainfall with the annual average of 261.7 mm (Bureau of Meteorology, records 1898–2018; weather station No. 13012 located in Wiluna, Western Australia 137 km WSW of Matuwa). Average maximum daily temperatures range from 19.5 °C in winter to 38 °C in summer and average minimum temperatures range from 5.4 °C in winter to 23.0 °C in summer.

Matuwa is the location of “Operation Rangelands Restoration”, the largest science-based arid zone wildlife reconstruction project ever undertaken in Australia with the aim to restore the property's natural ecosystem function and native species diversity, through the management of introduced predators and the subsequent reintroduction of 12 locally extinct arid zone mammal species (Morris et al., 2007; Sims et al., 2017). In 2014, Matuwa reverted to exclusive possession native title land held in trust by Tarlka Matuwa Piarku Aboriginal Corporation (TMPAC) on behalf of the Wiluna native title holders (Langford and Tran, 2015). Informal joint management between the DBCA and TMPAC has been ongoing since 2014.

2.2. Baits and baiting program

Toxic baiting is recognised as the most effective method for managing feral cats in Australia (Algar et al., 2007; Algar et al., 2013a, 2013b; Algar and Burrows, 2004; Environment Australia, 1999; Short et al., 1997). The poison bait used, known as *Eradicat*®, was developed and manufactured in Western Australia for the control of feral cats (Algar et al., 2007; Algar and Burrows, 2004). *Eradicat*® baits contain 4.5 mg of directly injected ‘1080’ (sodium monofluoroacetate, a metabolic poison). Prior to being laid, feral cat baits are thawed and placed in direct sunlight. This process, termed ‘sweating’, causes the oils and lipid-soluble digest material to exude from the surface of the bait increasing their palatability to cats. All feral cat baits are 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 reducing bait degradation by ant attack and maintaining the palatability of the bait to cats as the physical presence of ants on and around the bait medium may deter consumption.

Earlier research in the arid and semi-arid zones indicated that the effectiveness of baiting programs for feral cats is maximised by distributing baits during the cool, dry winter periods (Algar and Burrows, 2004). At this time, the abundance and activity of all prey types, particularly predator-vulnerable young mammals and reptiles, is at its lowest, and bait degradation risk due to adverse weather conditions, and ant activity is low compared to other seasons.

2.3. Aerial baiting versus track baiting

In an adaptive management framework, we compared the effectiveness of control and cost-efficacy of a broadscale non-habitat specific aerial bait delivery with ground-based track baiting. Matuwa was divided into two zones by a gazetted road, Granite Peak Rd (Fig. 2). On the 4 July 2018 and the 14 July 2019, DBCA's Western Shield aerial baiting program deployed *Eradicat*® baits to the eastern area of the property (1312 km^2). The Western Shield baiting prescription requires an aircraft, outfitted with purpose-designed bait delivery hardware, flying at a nominal speed of 160 kt and 500 ft. (Above Ground Level) to deploy the baits at defined points. Fifty baits are released at each drop point, along flight transects 1 km apart, to achieve an application rate of 50

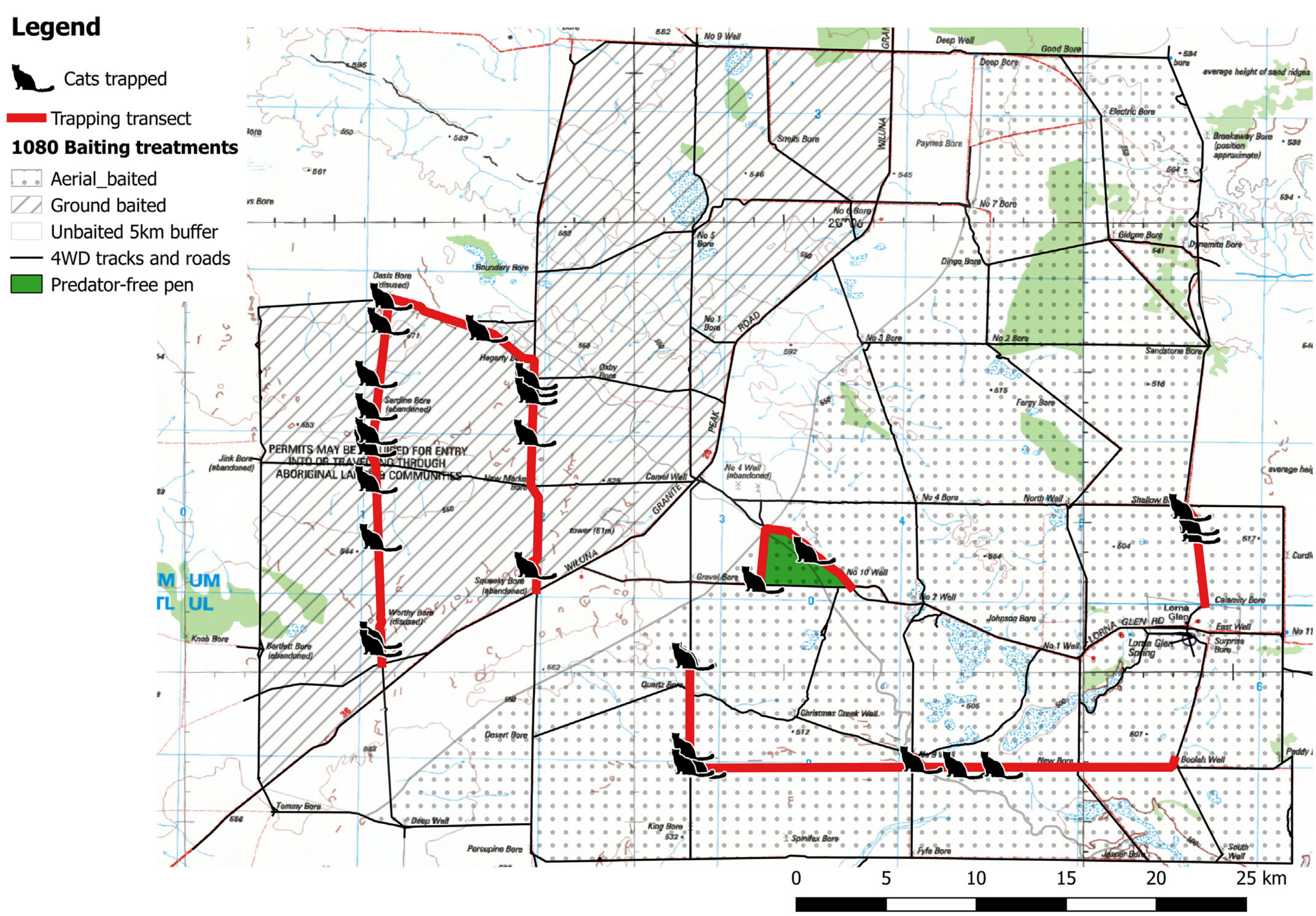

Fig. 3. Depiction of the 40 km trapping circuit used in August 2018 and the location of captured cats on the Matuwa Indigenous Protected Area.

baits/km^2. The resultant ground spread of 50 baits is approximately 200 × 40 m (Algar et al., 2013a, 2013b). In the same weeks track-based applications of one *Eradicat*® bait every 100 m was applied to the western half of the property's non-gazetted roads (220 km 4WD track within 785 km^2, approximately 2.8 baits/km^2). To ensure independence between the zones, a non-baited buffer of 5 km width following the Granite Peak Rd, separated the two baited zones; a distance that has been adopted at other sites in the arid zone (Burrows et al., 2003; Doherty and Algar, 2015; Edwards et al., 2000) and was considered to be larger than the average radius of a cat's home range (female = 2.93 km, male = 3.70 km) for the area (Wysong, 2016).

The efficacy of these two bait deployment techniques and trapping was monitored using a feral cat track activity index (TAI) and camera-traps (Fig. 2). Camera-traps provide a more reliable survey technique for cryptic species such as feral cats (Raiter et al., 2018), but are a considerably more expensive and time-consuming tool to implement with less cultural value within an Indigenous Protected Area. In contrast, the TAI provides a relatively cheap, rapid survey technique for feral cats, but is susceptible to error from inexperienced observers, and unfavourable weather conditions erasing tracks (Fig. 1). Using two survey methodologies will help elucidate true trends in the data.

2.4. Track activity index (TAI)

Approximately two weeks pre- and post-baiting, experienced observers ran 50 km of TAI transects (Fig. 1; Algar et al., 2013a, 2013b) on each half of the property for at least three days (Fig. 2). Track-transects and the associated measure of TAI consist of 3–5 repeated and sequential daily surveys over 100 km of sandy 4WD tracks, which are initially cleared of any animal tracks by towing a heavy iron drag behind a 4WD vehicle. Observers, driving all-terrain vehicles (ATVs) at a speed of 10–15 km/h then inspect the tracks for cat tracks, 1 h after sunrise, and clear new signs of animal activity by towing a light-weight chain iron drag. To minimise spatial autocorrelation cat tracks that occur within 1 km radius of one another on a daily survey are aggregated into one cat detection. Data are scaled against the total length of track-transects surveyed within a day and then averaged across sequential surveys. TAI data were analysed via generalised linear models and mixed-effects models in the package lme4 v1.1-21 (Bolker, 2019) with baiting treatment, time period, and the total rainfall that occurred one, two or three years prior to the survey included as fixed effects while year, month, and season were included as random effects. Models were compared via AICc in the package AICcmodavg 2.2-2 (Mazerolle, 2019).

2.5. Camera-trap monitoring

In March 2018, 120 camera-traps (Reconyx PC900 Hyperfire Professional Covert camera; Reconyx, Wisconsin, U.S.A.) were installed at Matuwa (Fig. 2) using a stratified-random design based on the 20 most common geological types in the Wiluna region (Farrell, 1999). The geological survey of Western Australia provided the most comprehensive and diverse spatial environmental dataset for Matuwa. The cameras were placed between 30 m and 200 m away from an ungazetted track, mounted on a 30 cm high plastic sand peg, facing south, with the aperture parallel to ground, in a space with at least 3 m of open ground in front of the camera. Herbaceous

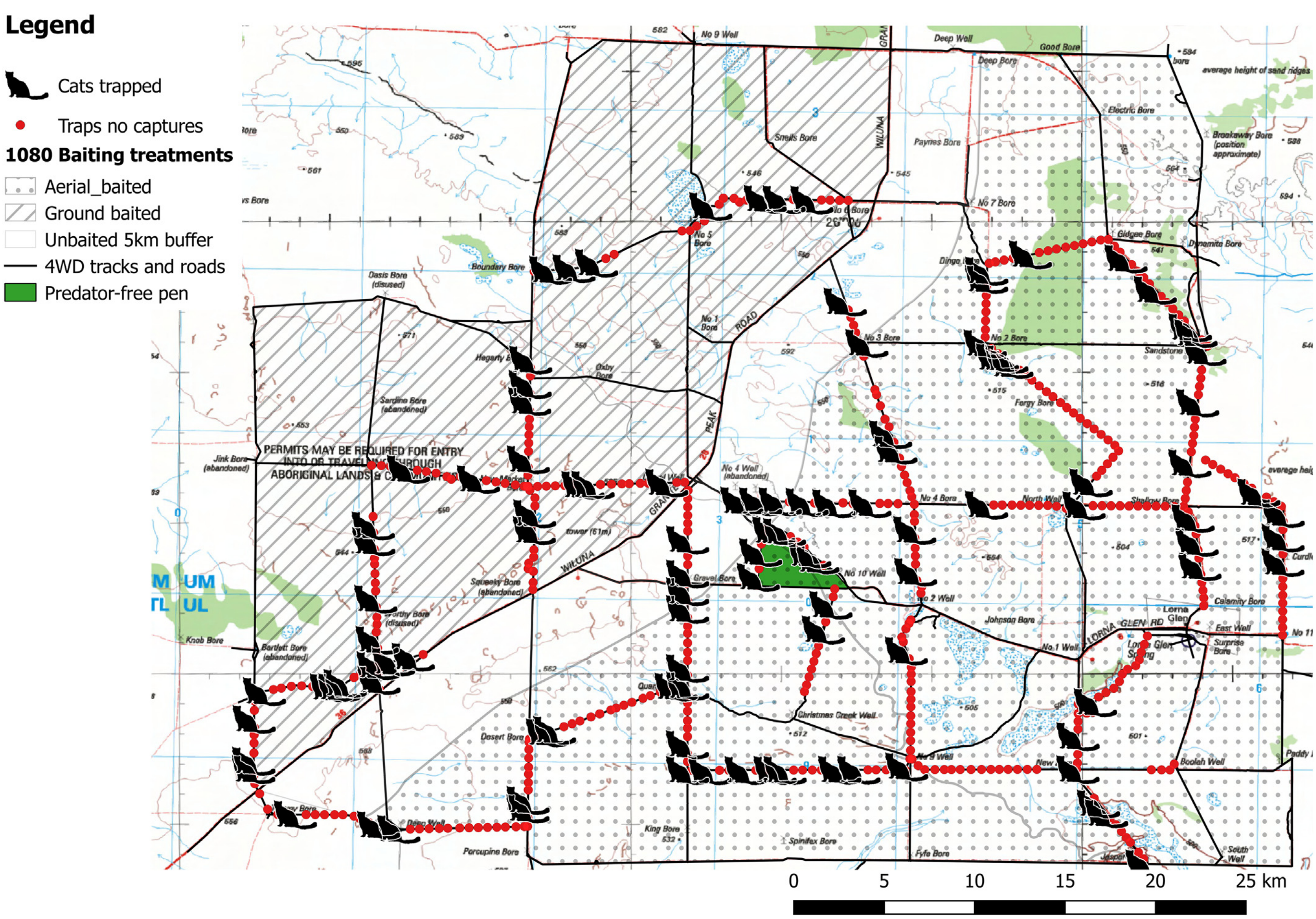

Fig. 4. Depiction of the 287 km trapping circuit used in March, April and May 2019 and the location of captured cats on the Matuwa Indigenous Protected Area.

Table 1
Percentage cover of each habitat category on the aerial and track-baited zones and adjacent 5 km wide buffers.

Habitat category	Western buffer track-baited zone	Track baited zone	Aerial baited zone	Eastern buffer aerial-baited zone
Breakaway	13.66	11.34	5.25	6.14
Calcrete	1.32	1.73	9.87	0
Hardpan	10.97	19.17	25.27	22.64
Salt lake	1.47	0	5.97	1.79
Sandplain	64.52	57.28	43.79	47.84
Stony	8.04	10.47	9.82	21.57

vegetation was removed if present immediately in front of the camera. Camera-traps were programmed to capture three photos per trigger, with no quiet period. Timed photos were also taken at 11:00 and 23:00 h to monitor the quality of photos and operation of the camera. Three cameras were moved in June 2018 by 100 m, 2 km, and 9 km to prevent environmental damage, increase the distance between camera-traps and allow easier access respectively. Camera-traps were, on average, 2.80 km from their nearest neighbour (min = 0.97 km, max = 5.92 km). Spatial autocorrelation is very unlikely at this scale (Kays et al., 2010) despite the potentially large home-ranges of feral cats (Wysong, 2016).

Cameras remained on-site from the 15 March 2018 until 17 October 2019. Cameras were installed two months before the initiation of the feral cat research to allow wildlife to acclimatise to the presence of a novel object in their habitat and photos taken between the 15 March and the 2 May 2018 were removed from the final dataset. As of the 2 May 2018, all camera-traps were set with two olfactory lures (Catastrophic and Canines-a-plenty from Outfoxed Pest Control, Victoria, Australia). Lures were placed on two natural sticks approximately 30 cm tall and 1 m apart, 3 m from the front of the camera and refreshed on seven occasions, before and after management actions.

Camera-traps used over long time-periods are liable to fail at some point during the study. Any cameras that malfunctioned were replaced and the number of malfunction-days was used to correct the total number of camera-days during analysis (Supplementary material Table 1).

Photos were stored in the Colorado Parks and Wildlife Photo Warehouse database (CPW) (Ivan and Newkirk, 2016). All photos of feral cats were viewed by at least two observers to confirm species identification. To minimise temporal autocorrelation, we grouped consecutive photos if they were <5 min apart and used these sequences as independent records for subsequent analysis of detection rate and daily activity patterns (Kays et al., 2015).

The duration of the camera-trap study was broken up into 17 discrete time periods (Supplementary material Table 1). The number of independent records of feral cats was analysed using a zero-inflated model with Poisson distribution in RStudio version 1.2.5019 (RStudio Team, 2016) running R version 3.6.1 (R Core Team, 2018) using the package pscl 1.5.2 (Jackman, 2017) and AICc in the package AICcmodavg 2.2-2 (Mazerolle, 2019). The dependent variable consisted of 80.7% zeros with null deviance close to residual deviance. Tukey *post-hoc* tests were calculated via the package emmeans 1.4.2 (Lenth et al., 2019). Explanatory variables were time period, baiting treatment, habitat category (Fig. 2), distance between camera-trap and property boundary (km), and number of days since the olfactory lure was replenished.

2.6. Leg-hold trapping

While supplementary leg-hold cat trapping campaigns can be used to augment effective cat control (Algar et al., 2013a, 2013b), there has been minimal application of leg-hold trapping at Matuwa between 2010 and 2018. As part of this revised adaptive management framework (Fig. 1), two trapping programs were conducted in 2018–2019. The first, a small-scale exercise, was conducted immediately following the 2018 baiting program to provide a snapshot of the population demographic of resident cats that had survived the bait period. The results of this first trapping program were used to inform whether and when a second more comprehensive trapping program across the site was required. Trapping was conducted using padded leg-hold traps, Victor 'Soft Catch'® traps No. 3 (Woodstream Corp., Lititz, Pa., U.S.A.) using a mixture of cat faeces and urine as the attractant. Several different trap sets were used; however, the main type of set employed open-ended trap sets, parallel to the track, with two traps positioned lengthwise (adjoining springs touching) and vegetation/sticks used as a barrier along the trap sides. Trapped cats were euthanased using a 0.22 calibre rifle shot to the head at point blank range.

All animals captured were sexed and weighed; a broad estimation of age (as either kitten, juvenile or adult) was recorded using weight as a proxy for age. The yearling weight/age classes reported by Jones and Coman (1982), was used to define the population age structure at that capture time. The only caveat to these age classes is that towards the end of a cat's life, it will lose condition and weight and therefore potentially move to a lower age class. Cats of both sexes <1.0 kg were considered to be kittens. Body weights for male cats 1.0 < 3.0 kg were considered to be juvenile animals, male cats between 3.0 and 4.0 kg, a weight that approximates that for sexual maturity and considered to be young adults of between 1 and 2 years of age and male cats >4.0 kg and were considered to be greater than two years of age. Body weights for female cats 1.0 < 2.5 kg were considered to be juvenile animals, female cats between 2.5 and 3.0 kg, a weight that approximates that for sexual maturity were considered to be young adults of between 1 and 2 years of age and female cats >3.0 kg and were considered to be greater than two years of age. The pregnancy status of females was determined by examining the uterine tissue for embryos.

The first trapping program was conducted in August 2018 over 10 consecutive days in the aerial then track-baited zones. Trapping circuits comprised a linear track length of 40 km, with traps spaced at approximately 0.5 km intervals and their locations recorded, using a Garmin GPS Rhino 650 (Garmin Ltd., Olathe, Kansas, U.S.A.) (Fig. 3). Data collected during this initial trapping program, namely adult male bias, suggested a further, more widespread trapping was warranted.

A second trapping program, using the same methodology, was conducted in March – May 2019 comprising 573 trap-sites across the entire study area (Fig. 4). Seventy-five kilometers of track access was trapped in the track baited zone and 212 km of track in the aerial baited zone. Chi-squared tests were performed on the trapping data to test whether there were significant differences in captures between the two baited zones.

Table 2
Weather conditions, temperature and rainfall, during baiting and in the 10 days post-baiting in 2018 and 2019.

Year	Min. temperature Average (min–max)	Max. temperature Average (min–max)	Total rainfall (mm)
2018	5.5 (1—10)	22 (16–26)	0.8
2019	3.5 (1.5–8.5)	21 (18–27.5)	0

Table 3
Models as ranked by AICc describing cat track activity index (TAI) collected between 2003 and 2019. Total number of models analysed was 13. No interactions between variables were included.

	Model	K	AICc	ΔAICc	Model likelihood	AICc weight	log likelihood
1	ST-Y	7	398.52	0	1	0.48	−191.29
10	ST2B-Y	8	399.29	0.77	0.68	0.33	−190.38
4	S-Y	6	401.71	3.19	0.2	0.1	−194.14
11	S2B-M	7	402.26	3.74	0.15	0.07	−193.17
3	ST-S	7	405.82	7.3	0.03	0.01	−194.95
2	ST-M	7	408.16	9.64	8.07^{-3}	3.89^{-3}	−196.11
9	T-S	4	413.95	15.43	4.47^{-4}	2.15^{-4}	−202.65
5	S-M	6	417.5	18.98	7.55^{-5}	3.64^{-5}	−202.04
6	S-S	6	417.98	19.46	5.95^{-5}	2.87^{-5}	−202.28
8	T-M	4	419.01	20.49	3.55^{-5}	1.71^{-5}	−205.18
7	T-Y	4	419.09	20.57	3.41^{-5}	1.64^{-5}	−205.22
12	T2B-S	5	419.68	21.16	2.54^{-5}	1.22^{-5}	−204.34
13	2B-Y	4	422.67	24.15	5.71^{-6}	2.75^{-6}	−207.01

S = time/survey period; 2B = annual rainfall as measured by Bureau of Meteorology at Wiluna weather station two years prior TAI survey; T = baiting treatment; Y = year, included as a random effect.

3. Results

3.1. Aerial baiting versus track baiting

In 2018, in the aerial baiting zone baits were deployed by an aircraft flying at an average speed of 157 kt and 741 m; and in 2019 the aircraft was flying at an average speed of 168 kt and 641 m. While deviating from the typical prescription, the aerial deployment of *Eradicat®* at Matuwa was relatively consistent across 2018 and 2019 ensuring results are comparable between years. However, it is unlikely that flying at this height would result in the intended on-ground bait distribution of 50 baits within an area of 200 × 40 m.

Weather conditions during baiting and in the 10 days post-baiting were relatively consistent across 2018 and 2019 (Table 1). The baiting period in 2018 was slightly warmer and wetter compared to 2019. There was no significant difference in the percentage of land assigned to each of six habitat categories (Fig. 2; Table 2) between the treatment zones and between 5 km wide west and east buffers ($P = 0.41$).

3.2. Track activity index (TAI)

Thirteen models that compare TAI data to three fixed effects variables were evaluated using AICc. The three best models identified year as the most significant random effect, while time/survey period, and treatment were the most significant fixed effects. Total annual rainfall that occurred two years prior to the survey appeared in models with delta AICc value less than one (Table 3).

On average (2003–2019), we recorded 5.96 more cat detections during pre-bait TAI surveys than post-bait TAI surveys, which is equal to a 39.7% decrease in the cat activity ($P = 7.42^{-3}$). In 2018, cat activity was similar in both areas before the implementation of the management treatments (difference = 0.91; $P = 0.99$; Fig. 5). At the end of the study, cat activity was significantly higher in the track baited zone, with 10.6 more cat detections per 100 km compared to the aerial baiting zone in the 2019 post-bait surveys ($P = 0.04$).

In 2018, aerial baiting resulted in a 12.5% decrease in cat detections whereas track baiting resulted in a 16% decrease (Fig. 5). Trapping in August 2018 further reduced the number of cat detections by 64.2% on the aerial baited zone and 28.4% on the track baited zone. Between the post-bait survey in 2018 and pre-bait survey in 2019, the number of cat detections on both aerial baiting and track baiting zones increased by 3 cat tracks/100 km of transect despite additional trapping, which removed 126 cats in March and April 2019. In 2019, aerial baiting reduced the cat activity on tracks by 32.4%, whereas the average number of cat

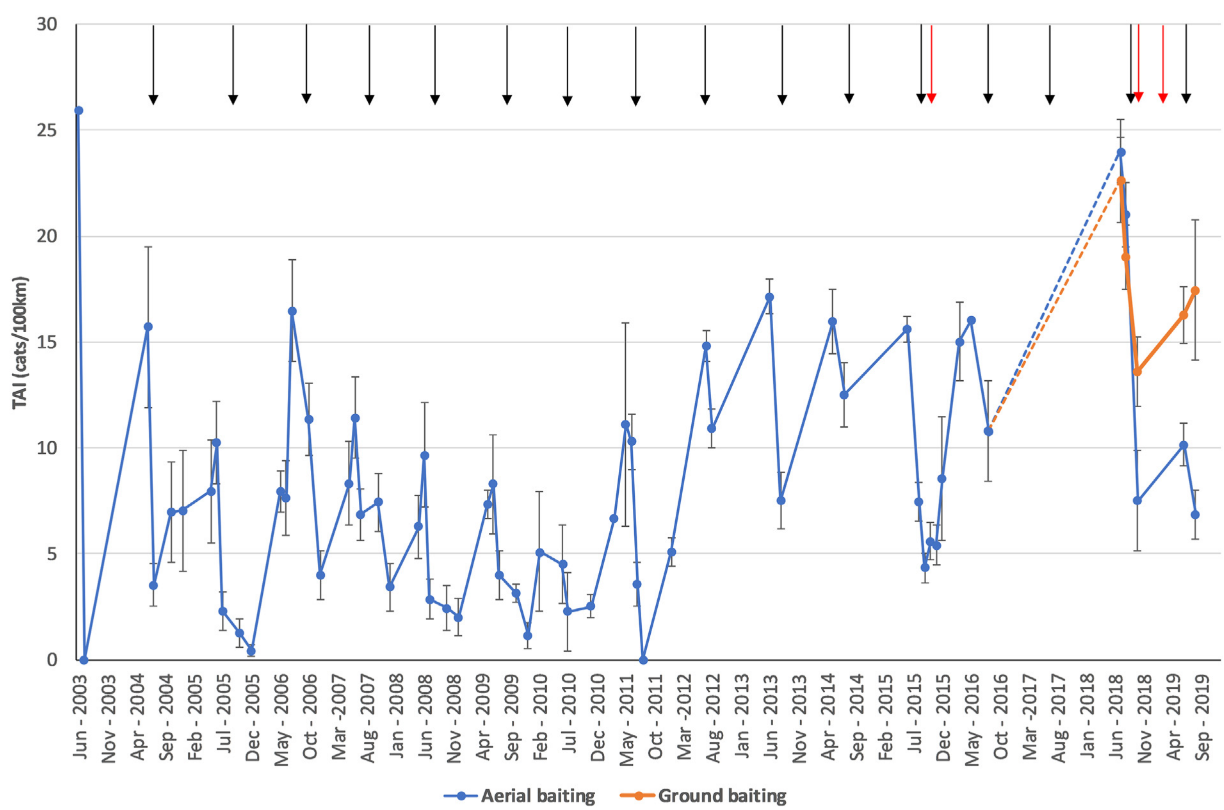

Fig. 5. Track activity index (TAI) ± standard error (SE) for each survey period from 2003 to 2019. Dashed lines represent large intervals (periods of 1+ years) where no cat TAI was conducted. Black arrows represent the timing of baiting sessions and red arrows represent the timing of trapping sessions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

detections in the track baiting zone increased by 1.2 cat tracks/100 km or 7.1% (Fig. 5).

There is evidence of a link between rainfall and the number of cats detected via TAI index but with an indistinct lag time. Generalised linear model comparisons suggest that the abundance of cats detected via TAI is most influenced by the total annual rainfall that occurred two years prior to the survey (Table 4). Rainfall that occurred in the same year as the survey had no relationship with the number of cats detected.

3.3. Camera-trap monitoring

Cameras were present at Matuwa for a sum of 61,800 camera-days: but 28 cameras malfunctioned at various times during the study resulting in a total of 1796 malfunction-days and 60,004 functional camera-days. A total of 336,447 photos was taken with 78,976 photos being removed from the dataset as they occurred prior to 2 May 2018 during the acclimatisation period. On average, the camera-traps took 4.3 photos per day, with two of those photos being timed photos used to monitor the quality of photos and operation of the camera. A total of 5836 photos was taken of feral cats and the final number of independent cat detections was 625.

The number of days since the olfactory lure was refreshed dominated the AICc model set, but had an insignificant effect size with the number of cats detections on the day a lure was applied being 0.27 with odds decreasing by 0.99 per day ($P = 0.85$), and hence the variable was removed from the final dataset. Similarly, distance between the camera-trap and the boundary of the property (km) had a negligible and insignificant effect on the number of cats detected with the number of cats being detected on the boundary being 0.31 and insignificantly increasing by 1.02/km ($P = 0.17$). Baiting treatment, time period and habitat were all significant explanatory variables and subject to further independent analysis.

Initially, there were more cats detected on the aerial baited zone than on the track baited zone (Fig. 6). This trend was reversed after the first application of the *Eradicat*® bait in July 2018, when cat activity was significantly higher in the track baiting than on the aerial baited zone ($P = 0.04$; Table 5). The reinvasion of cats onto Matuwa following control actions is an accepted phenomenon. Hence, the effect of *Eradicat*® baits is determined through the analysis of pre-bait cat detections against post-bait cat detections only (Fig. 1; Comer et al., 2018). Tukey *post-hoc* tests of the pre-bait and post-bait time periods only revealed that track baiting with *Eradicat*® baits did not significantly reduce cat activity in 2018 ($P = 1.00$) with seven independent cat detections in 420 camera-trap-nights in the pre-bait period and seven detections in 509 camera-trap-nights in the post-bait period (Fig. 6). In contrast, track baiting did significantly reduce the detection of cats in 2019 (16 cats down to 3; $P = 7.00^{-3}$). Aerial baiting significantly reduced the number of detections in both 2018 (26 detections to 5; $P = 0.02$) and 2019 (29 detections to 3; $P = 3.00^{-4}$).

Leg-hold trapping alone (i.e. post-bait/pre-trap vs post-trap) did not significantly change the number of cats detected on the track baited treatment in either 2018 ($P = 0.99$) or 2019 ($P = 0.76$). Similarly, trapping did not significantly reduce the number of cats detected on the aerial baited zone in 2018 ($P = 0.98$) or 2019 ($P = 0.86$). Trapping did, however, appear to compensate for the ineffectiveness of track baiting in 2018 with a total reduction in cat detections after baiting and trapping of 57.2% ($P = 0.81$). Whereas aerial baiting alone reduced cat detections by 68.8%, increasing to 77.8% after trapping ($P = 0.06$).

Cats were significantly more likely to be detected in sandplain habitat ($P < 2.00^{-16}$) than any other habitat, particularly salt-lake or hardpan habitats (Fig. 7). The baseline number of cats detected by camera-traps in the sandplain was 0.41, whereas only 0.08 ($P = 1.45^{-6}$) cats were detected in vegetation surrounding salt lakes and 0.22 cats were detected by camera-traps on hardpan habitats ($P = 0.04$).

Table 4
Four models comparing rainfall to the number of cats detected during track activity index (TAI) surveys at Matuwa.

	Model	K	AICc	Delta_AICc	ModelLik	AICcWt	LL	Coefficient	*P*-value
1	Two	3	428.48	0	1	0.51	−211.05	0.01	0.07
2	Prev	3	429.10	0.62	0.73	0.37	−211.36	9.80^{-3}	0.09
4	Three	3	431.15	2.67	0.26	0.12	−212.38	5.24^{-3}	0.37
3	Actual	3	431.36	2.88	0.24	0.12	−212.49	−0.03	0.44

Model 1 compares total annual rainfall from two years prior to TAI survey to the number of cat detections; model 2 compares rainfall from one year prior to TAI survey; model 3 compares rainfall and cat detections from within the same year; while model 4 compares rainfall from three years prior to the survey. Coefficient and *P*-value describes the modelled relationship between annual rainfall and number of cats detected.

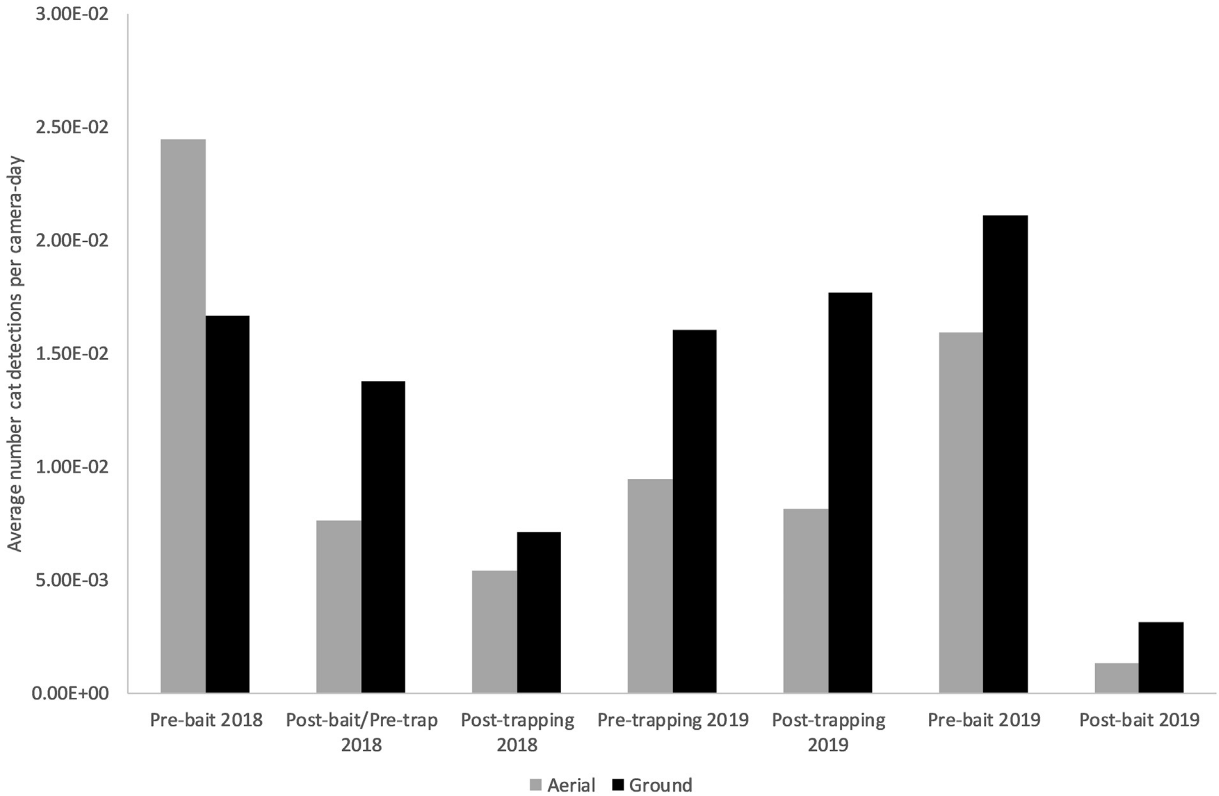

Fig. 6. Average number of cat detections per camera-trap-day in each baiting treatment and across time periods that occurred pre- and post-baiting or trapping.

3.4. Leg-hold trapping

The trapping program conducted in 2018, over 1600 trap-nights, resulted in the capture of 33 cats (% trap success = 2.1 cats/trap-night); capture locations are presented in Fig. 3. There was no significant difference in captures between bait zones ($Chi^2 = 0.3$, df = 1, $P > 0.5$) with 15 cats trapped in the aerial baited zone and 18 in the track baited zone. No kittens were captured. All juvenile cats (n = 4) were captured in the track-baited zone. There was a significant difference between adult male captures (n = 23) and adult female captures (n = 6). $Chi^2 = 9.97$, df = 1, $P < 0.01$. Twelve of the adult males were 2+ years of age (>4.0 kg, mean 4.1 (±S.E. 0.1) kg, range 4.1–5.2 kg). The population demographic of cats captured immediately post-baiting 2018 is presented in Fig. 8. Four of the six adult females were pregnant with 3.8 (±S.E. 0.5) kittens in utero.

The trapping program conducted in 2019, over 5398 trap-nights, resulted in the capture of 126 cats. Some of the 573 traps were decommissioned early when they captured non-target species such as dingo/wild dog hybrids (*Canis familiaris*) that destroyed the trap. Trap locations and capture sites are presented in Fig. 4. Ten of the cats (two 1–2 year and two 2+ year females; two 1–2 year and four 2+ year males) were trapped in the bait buffer zone and have been removed from bait zone analysis. Of the 116 cats trapped in the baited zones, 72 were captured in the aerially baited zone (% trap success = 1.6 cats/trap-night) and 44 cats were captured in the track baited zone (% trap success = 3.5 cats/trap-night). Assuming equal trappability between zones there was a greater number of cats/km in the track baited zone. If cat captures are standardised to length of track trapped, there was a difference in captures between bait zones with significantly more cats captured in the track baited zone ($Chi^2 = 10.9$, df = 1,

Table 5
Final ranking by AICc value set of zero-inflated models describing the impact of potential explanatory variables on the detection of feral cats at Matuwa by camera-traps with an olfactory lure.

No.	Model	K	AICc	ΔAICc	Model weight	AICc weight	LL
7	TCH	48	2801.33	0	1	0.99	−1351.51
5	TC	38	2833.43	32.1	1.07^{-7}	1.07^{-7}	−1377.99
3	C	34	2849.51	48.18	3.46^{-11}	3.46^{-11}	−1390.18
6	TH	16	2895.64	94.31	3.32^{-21}	3.32^{-21}	−1431.69
2	H	12	2898.48	97.15	8.03^{-22}	8.03^{-22}	−1437.17
1	T	6	2925.29	123.96	1.21^{-27}	1.21^{-27}	−1456.63
4	D	4	2936.67	135.34	4.09^{-30}	4.09^{-30}	−1464.33

Explanatory variables were T = aerial vs track baiting treatment; H = Habitat categories; C = discrete time periods; L = Days since olfactory lure was refreshed; D = Distance between camera-trap and boundary of Matuwa. L dominated the AICc ranking but had insignificant and negligible effect size, hence removed from this model set.

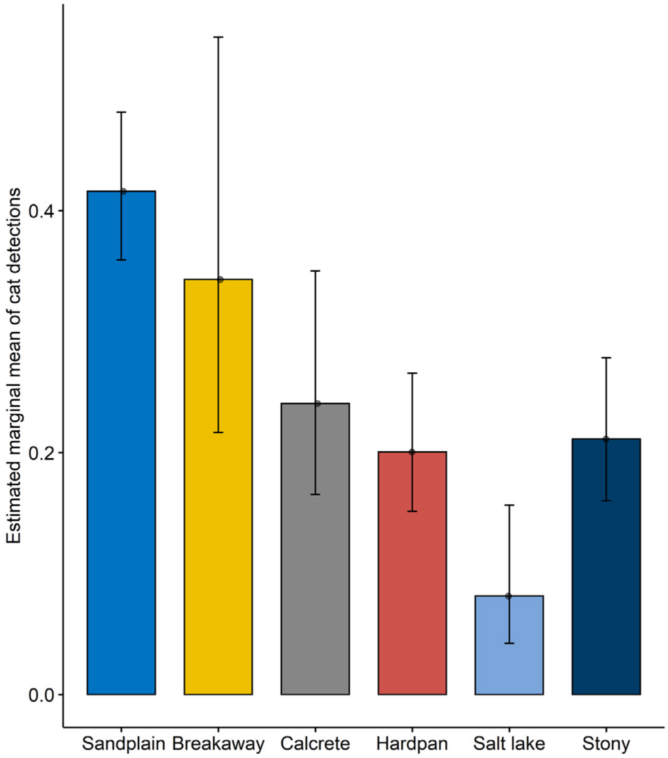

Fig. 7. Estimated marginal mean number of cats ± standard error (SE) detected at camera-traps placed in 6 habitat types on the Matuwa Indigenous Protected Area with error bars calculated from zero-inflated model with Poisson distribution.

$P < 0.001$) The population demographics of cats captured during the trapping program conducted in 2019 is presented in Fig. 9. Only the one kitten (female 0.9 kg) was captured in 2019. More juveniles were captured in 2019 compared to 2018, increasing from 12% to 23% of cats captured. Simultaneously, the proportion of cats captured that were 2+ years of age decreased from 52% to 37%. The proportion of captured cats 1–2 years of age remained relatively constant. Necropsies performed on all adult female cats caught in March–May 2019 indicated four were lactating and a further two had three kittens each in utero.

4. Discussion

Both TAI and camera-trap data suggest that track baiting is less effective than aerial baiting. Our results are similar to previous studies on the efficacy of aerial baiting and ground baiting, with aerial baiting reducing apparent cat abundance on average by 70% (Algar et al., 2007; Algar et al., 2013a, 2013b; Algar and Burrows, 2004; Comer et al., 2018; Moseby et al., 2009a, 2009b; Short et al., 1997), whereas ground baiting on the Charles Darwin Reserve in Western Australia has correlated with 4.9% increase in cat abundance in 2013 and an 85% decrease in cat abundance in 2014 (Doherty and Algar, 2015). This result is not unexpected given that 50 baits/km^2 were deployed using aerial baiting compared to only 2.8 baits/km^2 via track baiting. However, track baiting combined with 10 days of leg-hold trapping in 2018 resulted in a 65.6% reduction in cat detections as compared to 68.8% reduction for aerial baiting alone. Aerial baiting combined with 10 days of leghold trapping post baiting provided the best reduction in cat detections of 97.7%.

In 2018 and 2019, aerial baiting via the Western Shield program cost AU$37/km^2 ($0.54/% decline in cat detections on camera-traps) and was slightly more cost-effective than track baiting alone at AU$35/linear km (Burrows et al., 2018) or AU$9.80/km^2 ($0.56/% decline in cat detections on camera-traps). Matuwa has a relatively high density of 4WD tracks with the average distance between tracks being 4 km.

Track baiting plus trapping was more cost-efficient than aerial baiting alone costing AU$0.39/% decline in cat detections on camera-traps (compared to $0.54/% decline for aerial baiting alone). Aerial baiting plus 10 days of trapping was equally cost-effective ($0.54/% decline) as aerial baiting alone with additional cost further suppressing the abundance of cats with sum decline of 97.7%. The average cost of 10 days trapping/km^2 at Matuwa was calculated as AU$15.47/km^2.

Ultimately, we implemented 30 days of trapping on each zone between baiting events. Baiting efficacy in 2019 was higher than 2018 on both baiting zones possibly due to the removal of older experienced cats from the population. Considering the sum efficacy of August 2018, March and April 2019 trapping plus baiting in 2019, aerial baiting plus

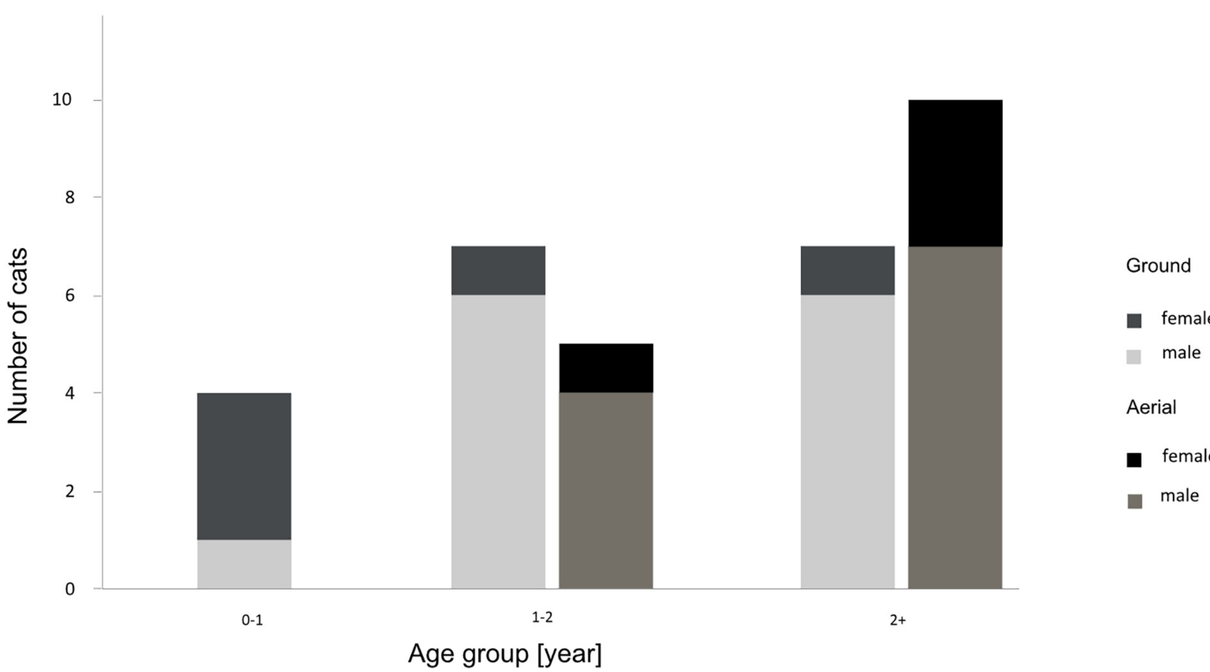

Fig. 8. Sexes and ages of the cats captured on the Matuwa Indigenous Protected Area using leghold traps immediately post-baiting in August 2018.

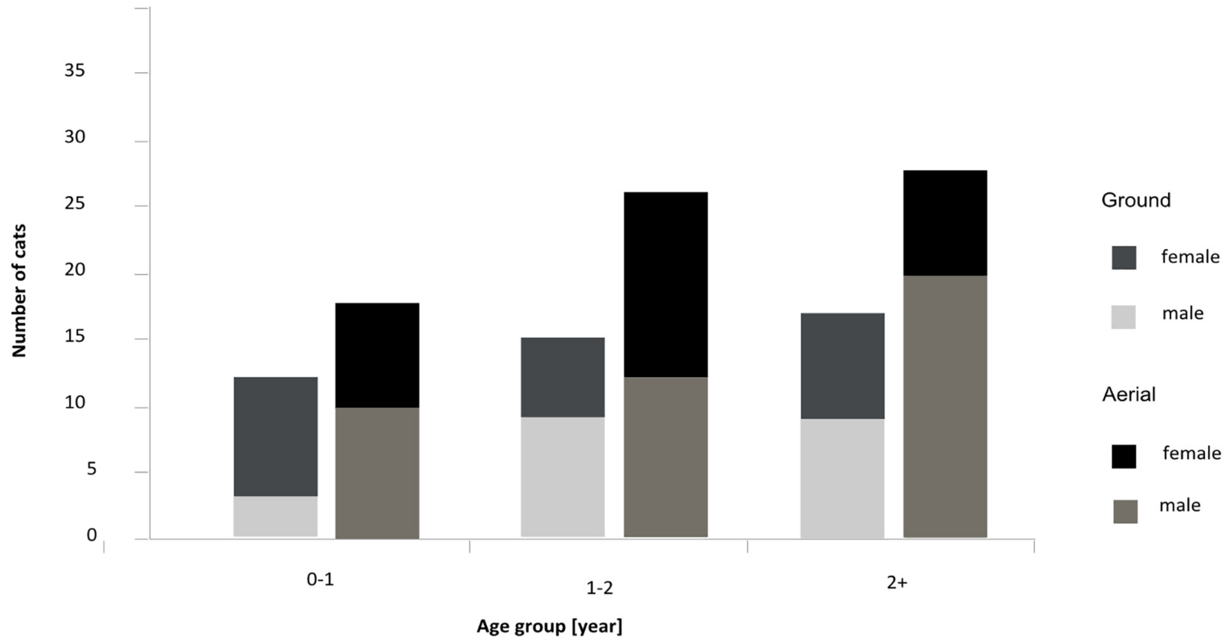

Fig. 9. Sexes and ages of the cats captured on the Matuwa Indigenous Protected Area using leghold traps in March, April and May 2019.

trapping cost $0.62/% decline in cat detections whereas track baiting plus trapping cost $0.46/% decline in cat detections.

We have used known costs for calculating the cost-efficacy of baiting and leg-hold trapping in this instance rather than modelling with a set of assumptions (McGregor et al., 2016). Our average trap success rate of 2.4 cats/trap-night was >10-fold higher than previous attempts to calculate the cost-efficacy of leg-hold trapping though this may be because previous researchers were attempting to catch cats on multiple occasions (McGregor et al., 2016). The limited number of landscape-scale treatment zones means that we only have one data point measuring the cost-efficacy of aerial baiting versus track baiting plus leg-hold trapping. Further studies, preferably at sites that have not been subject to past cat management, are required to verify that track baiting plus leg-hold trapping can effectively suppress cat abundance.

The use of leg-hold trapping to control cats is valuable beyond the basic decline in the abundance of cats. As hypothesised, in both the

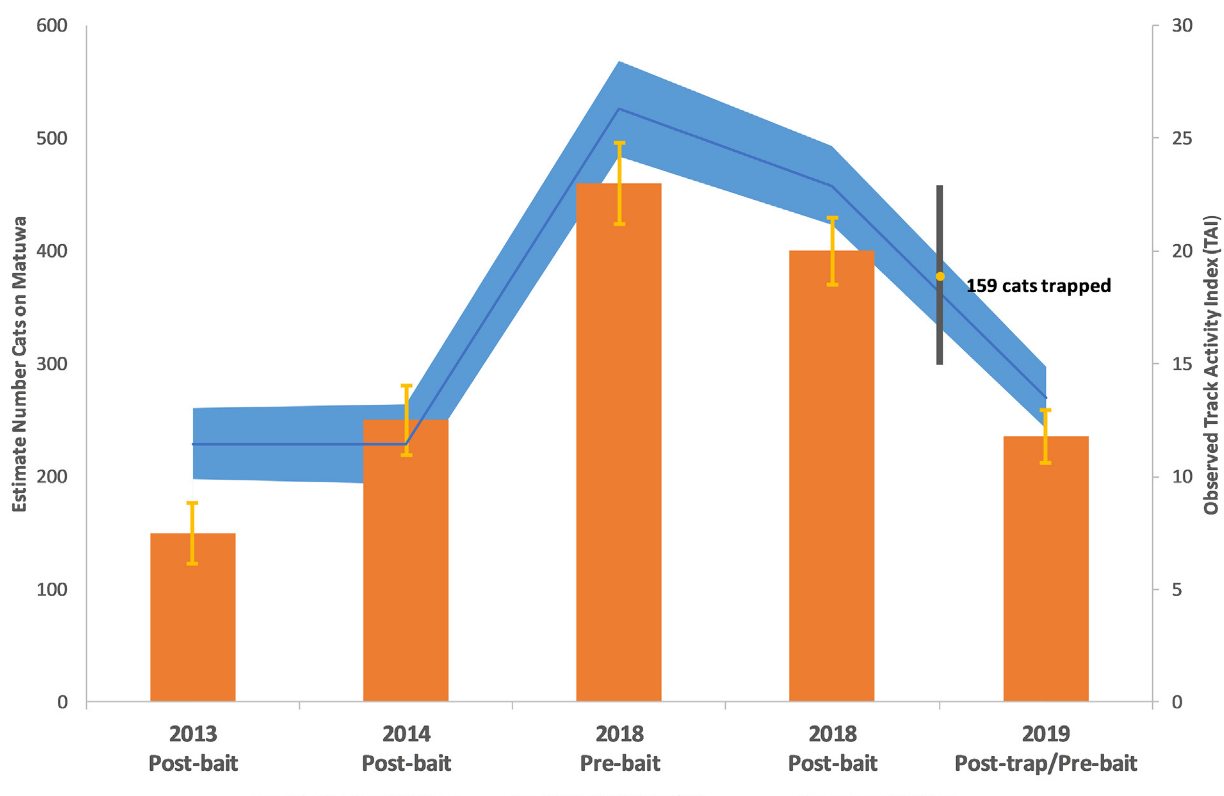

Fig. 10. Selected track activity index (TAI) data (columns) and the derived estimate and standard error for feral cat abundance on Matuwa (shaded line) in comparison to the known number of feral cats removed by trappers in the 2018 post-bait/2019 pre-bait period (vertical line). Post 2014 cat abundance on Matuwa estimated as $= 22.86 * \text{TAI} + 0.4758$.

aerial baited and track baited zones, trapping reduced the proportion of older, experienced cats in the population and increased the proportion of juvenile, inexperienced hunters. In 2007, during the last landscape-scale leg-hold trapping program at Matuwa we recorded a population that consisted of 26.7% adults (2+), 51.7% young adults (1–2 years) and 21% juveniles (Algar et al., 2013a, 2013b). In 2018, the cat population at Matuwa was dominated by adults (51.5%) rather than young adults. Other feral cat populations have been dominated by adults with 74% documented in central New South Wales (Molsher, 2001), 60% on Little Barrier Island, New Zealand (Veitch, 2001), 51.3% at Heirisson Prong, Western Australia (Short et al., 2002) and 69.5% on the Cocos Islands (Algar et al., 2003). By May 2019, we had altered the demographics of the Matuwa cat population such that is only consisted of 38.7% adults. Changes in the population demographics may have been responsible for the increase in baiting efficacy, which went from 68.8% to 91.5% and 17.5% to 85.2% in the aerial and track baited zones respectively.

These results suggest that our second hypothesis that annual baiting altered the demographics of the feral cat population at Matuwa towards age and sex-based groups that are less inclined to consume baits is supported. However, we cannot refute hypothesis one, as the abundance of small prey items has not been consistently measured at Matuwa with the most recent survey occurring in 2010. That research, however, did suggest that the abundance and species richness of Dasyurids did significantly increase between 2002 and 2010, while Muridae were variable (Chapman and Burrows, 2015). As with other documented predator-prey relationships, there is likely a complicated and dynamic link between rainfall, the productivity of vegetation, the abundance of prey species, and the abundance of predator species (Laundré et al., 2014). It is possible the Dasyurid abundance declined on Matuwa during our research in response to lower rainfall (Morton, 1990) and facilitated increases in bait efficacy.

We were able to detect a relationship between cat detections and rainfall with a two-year lag. That relationship, however, was weak, probably because the weather data were collected at a site 137 km WSW of Matuwa in an arid landscape known to experience patchy distributions of rainfall (Low, 1979; McAllister, 2012; Morton, 1990).

The dispersal of young cats is not clearly understood, especially in arid environments; however, dispersal cannot occur before the permanent canines have erupted, which commences three and a half months after birth (Hemmer, 1979). Females rarely venture as far afield as males, often establishing a home range close to that of their mother. Yearling/subordinate males tend to remain within their natal range until they are old and strong enough to establish their own home range (Liberg, 1981; Liberg and Sandell, 1988). As they grow, they come under increasing attack from older males and in their second year they usually disperse (Liberg, 1981). The positive relationship between biennial lagged rainfall and cat detections may be a result of minimal dispersal of cats less than two years of age and dispersing cats responding to higher prey abundance in wetter areas.

At Matuwa indices of cat activity suggest that cat dispersal occurs in the late summer through autumn and early winter with notably little movement in spring months (Algar et al., 2013a, 2013b). The increasing number of cat detections between post-trapping 2018 time period and pre-bait 2019 time period (Fig. 6) suggests that cats start exploring further and potentially expanding their home-range immediately after the removal of conspecifics. We hypothesise that more cats were detected after management actions had been implemented because cats were actively expanding their home-range in response to lower cat density (Bengsen et al., 2016; Turner, 2014). Cats expanding their home-range may be more curious about olfactory lures and hence more likely to be detected by camera-traps. Further research is required to determine if surviving cats do expand their home-range after the implementation of management and hence, due to the limitations of cat detection methodologies, may be masking the efficacy of those management techniques.

Detecting cats and measuring their abundance is difficult because they are a cryptic species and frequently lack unique markings (Rees et al., 2019). We used two methods of detecting cats, which did confirm that aerial baiting was more effective than track baiting, although the measured magnitude of management efficacy varied. In 2018, the average variation in percent decline detected by camera-traps versus TAI was 50%. In 2019, the average variation was larger at 75.9%. This variation suggests that while track based detection techniques may be useful for maximising the total number of cat detections (Nichols et al., 2019; Raiter et al., 2018), they may also be susceptible to bias caused by nuances in cat behavior and ultimately lead us to conclude that we are less successful at suppressing a cat population than in reality. Hence, we conclude that the track activity index (TAI) is the weaker survey method because it only detects cats that are using tracks, a potentially behaviourally biased subset of the population, and is susceptible to the weather, experience of observers, and spatial autocorrelation with limited means to verify data. The TAI is, however, a more cost-efficient method of surveying large open landscapes than camera-traps and a more accessible and culturally appropriate technique for use on Indigenous Protected Areas.

Despite suggested weakness of TAI when compared to camera-trap data, extrapolations from TAI data correspond remarkably closely with leg-hold trapping results (Fig. 10). Liberg et al. (2000) documented a strong relationship between cat density and home range size (Eqs. (1) and (2)); a relationship later refined by Turner (2014) and Bengsen et al. (2016). In winter of 2013 and 2014 estimated female (n = 4) and male (n = 21) cat home range (95% KDE ha) at Matuwa was 2689 ± SE 1085 ha (range 1528–4858 ha) and 4302 + SE 1436 ha (range 913–33,518 ha) (Wysong, 2016). Outliers were not dealt with in the analysis of the male home range data. Inputting estimates from Wysong (2016) into relationships described by Liberg et al. (2000) suggests that in 2013, Matuwa had a feral cat abundance of approximately 229 cats [SE = 72; with 72 (34.5–147) females and 156 (13.1–1017.9) males]. The average observed TAI in 2013 and 2014 winter post-bait periods was 10 cats/100 km (7.5 cats/100 km and 12.5 cats/100 km respectively). Assuming a linear relationship between TAI and estimated abundance (cats on Matuwa = 22.86 ∗ TAI + 0.4758) we can extrapolate change in cat abundance over time (Fig. 10). The validity of a linear relationship between cat abundance and TAI cannot be verified with currently available data, however, we know trappers removed 159 feral cats from Matuwa between the 2018 post-bait period and the 2019 pre-bait period. Using Eqs. (1) and (2), the estimated change in cat abundance from TAI equates to 188 (standard error range = 160–215). The correlation between TAI and trapping data may be because both techniques are applied on or very close to tracks.

$$\ln F = -0.7988x + 5.0875; r^2 = 0.9095 \tag{1}$$

$$\ln M = -0.8281x + 6.0928; r^2 = 0.8778 \tag{2}$$

F = female home range (ha); M = male home range (ha); x = ln density (cats/km^2).

5. Conclusions

As per an adaptive management framework the purpose of this research was to improve our ability to suppress a feral cat population in the arid zone. Our data lead us to make several management recommendations.

First, our study has provided additional evidence that annual aerial baiting with *Eradicat*® is more effective than track baiting when cats need to be controlled at a landscape-scale. Annual aerial baiting does, however, eventually result in adult male bias in a cat population, which may reduce the efficacy of baiting over time. As with many pest species, feral cats should be managed using an integrated pest management approach (Giles, 1980; Witmer, 2007). In periods of high food availability (Christensen et al., 2013), which may be indicated by periods of above average rainfall, managers should implement intensive cat control (Fig. 1) incorporating landscape-scale leg-hold trapping programs into their management plan. Annual aerial baiting should be considered baseline cat control. Given the increase in the adult bias in the population at Matuwa between 2007 and 2018 we suggest that the maximum interval between intensive trapping programs should be 10 years. Track-baiting should only be used to offset the costs of a trapping program or on sites too small to allow aerial baiting.

Second, cats are twice as likely to be detected on spinifex sandplains than other habitats (Fig. 7). If funding is limited, then sandplain habitat should be prioritised for cat management, especially if the native species diversity and abundance is higher on sandplain habitat (Chapman and Burrows, 2015). Cats also appear to be somewhat of an edge species (Nichols et al., 2019; Ries and Sisk, 2010). Hence, cat management should also be applied to any habitats, adjacent to sandplain, that may provide cats with shelter from climatic extremes common in the arid environment (Low, 1979), such as forested or wooded drainage lines, breakaways or calcrete ridges with caves.

Third, future research should focus on verifying our ability to infer cat abundance from indices such as camera-traps data and TAI. Rapid survey indices will allow feral cat research and management to be implemented at more sites, but that will mean the scientific community will need to be able to contend with more environmental variability that may confound results. Cat abundance may be measured through spatially explicit capture-recapture techniques applied to camera-trap data (Rees et al., 2019), though it is a laborious process. Future research on the home-range and habitat usage of cats should attempt to determine if there is any bias in cats that influences their willingness to use tracks and hence susceptibility to being detected or trapped.

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CRediT authorship contribution statement

Cheryl Anne Lohr: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization, Project administration.**Dave Algar:**Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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