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RESEARCH

Feral cats on Rakiura Stewart Island: population attributes and potential eradication tools

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Abstract: As a major threat to New Zealand's biodiversity, feral cats (*Felis catus*) are the subject of planned eradications on a number of offshore islands, including Rakiura Stewart Island. We used camera traps to estimate population density of feral cats on the north-east coast of Rakiura, and to investigate their movement behaviour and detection probability. We also used camera footage to compare the consumption of two types of non-toxic sausage baits (chicken and rabbit) with a view to future use of toxic baits. Population density of feral cats was likely between 1 and 2 cats per km^2. Non-target species (rats and possums) removed more than half the baits, greatly reducing bait availability for feral cats. Deer and birds (including kiwi) encountered baits but did not eat them. Cats had an apparent preference for chicken over rabbit baits, although small sample sizes prevent firm conclusions. Both bait types appeared to decline rapidly in palatability, and no baits were consumed by cats more than 5 days after deployment. Future trials and baiting regimes should consider ways to improve bait availability. Increased bait density, exclusion of rats and possums and/or more frequent replacement of baits will likely increase encounter rates by feral cats.

Keywords: bait, camera trapping, eradication, *Felis catus*, spatial detection parameters

Introduction

Feral cats (*Felis catus*) are one of the most damaging invasive predators in New Zealand and many other parts of the globe (Doherty et al. 2016; Murphy et al. 2019; Gillies & van Heezik 2021). In addition to preying on native species, feral cats are also vectors of diseases affecting humans, livestock and wildlife (Doherty et al. 2017; Taggart et al. 2019; Roberts et al. 2021). Island ecosystems globally account for more than 20% of terrestrial plant and vertebrate species. Given the high level of endemism and fragilities, invasive species such as feral cats cause significant impact to species and ecosystem function (Courchamp et al. 2003; McGlone 2006). As part of the Predator Free 2050 initiative, the Department of Conservation (DOC) plans to eradicate mammalian predators from several offshore islands, including Rakiura Stewart Island (hereafter Rakiura) (Beaven 2008; Russell et al. 2015; Roselli et al. 2021).

Rakiura supports a number of species of conservation concern, including Rakiura tokoeka / Stewart Island kiwi (*Apteryx australis australis*), tūturiwhatu / southern New Zealand dotterel (*Charadrius obscurus obscurus*), pītoitoi / Stewart Island robin (*Petroica australis rakiura*), tīeke / saddleback (*Philesturnus carunculatus*), and mōhua / yellowhead (*Mohoua ochrocephala*). Some of these species are now only found on adjacent cat- and rat-free islands (Harper 2009). Eradication of feral cats (as well as three rat species; *Rattus rattus*, *R. norvegicus*, *R. exulans*, and brushtail possums *Trichosurus vulpecula*) is proposed to allow recovery of these threatened biota (Beaven 2008). An eradication of feral cats from Rakiura would be extremely challenging given the size of the island (1746 km^2), that dense vegetation covers much of the island, and that there are limited tools available for removing feral cats. Domestic cats are also present in settled areas of Rakiura, which will limit removal methods in these areas.

Planning an eradication requires detailed knowledge of the target population. Required knowledge includes abundance, distribution, and patterns of movement, which inform the placement of control and monitoring devices such as traps, baits, and cameras (Fisher et al. 2015). In addition, confirming eradication success requires knowledge of detection probability of monitoring devices (Samaniego-Herrera et al. 2013; Kim et al. 2020).

Eradication also requires effective tools to remove all individuals of the target species. The majority of successful cat eradications have used more than one removal method (Nogales et al. 2004). The only effective method currently available for targeting feral cats in eradication and/or sustained control programmes over large areas is the use of toxic baits. All successful eradications on islands larger than 25 km² (n = 9) have utilised primary poisoning, except for Santa Catalina

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(30.2 km^2) (Campbell et al. 2011). Globally, baits targeting feral cats have either been distributed by aircraft (e.g. Algar et al. 2020), applied by hand at ground level (e.g. Doherty et al. 2022), or presented in bait stations (e.g. de Burgh et al. 2021). In order to achieve landscape-scale control of feral cats, DOC aims to develop a ready-made cat bait suitable for ground and aerial deployment in New Zealand (Roselli et al. 2021).

We used camera traps to investigate the population density, movement behaviour and detection probability of feral cats in a coastal area in the north-east of Rakiura. We also compared consumption by feral cats of non-toxic baits containing either rabbit meat or chicken. This trial aimed to compare the palatability of the two bait types, identify any potential risk to native species, and to quantify any effect of bait interference by non-target species on bait availability to feral cats.

Methods

Study site

Rakiura (47°S, 168°E) is an island of 1746 km² situated 30 km south of New Zealand's South Island (Fig. 1). The island has a cool, windy, temperate climate with an average annual rainfall of 1580 mm. The island is largely covered in untracked forest, shrubland and subalpine vegetation.

Approximately 85% of the island is public conservation land administered by DOC with most of the remainder managed by the Rakiura Māori Land Trust (8%). Around 2% of the island is freehold land, including the small town of Oban, which has a population of around 400 people (Beaven 2008).

Our study took place in an area of around 80 km^2 on the north-east coast of Rakiura, between the Murray River

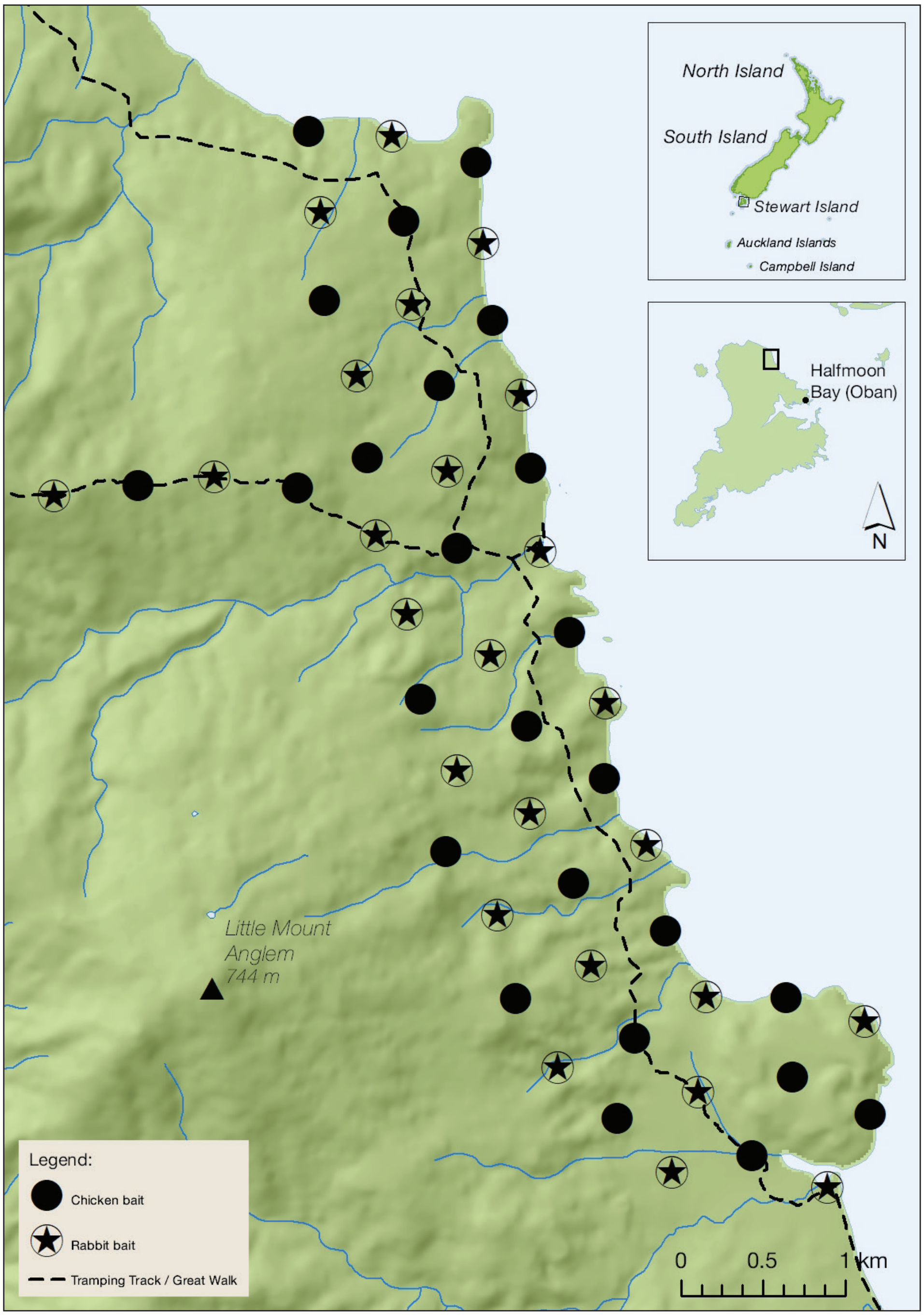

Figure 1. Fifty camera traps were deployed near the north-east coast of Rakiura Stewart Island. Camera sites were baited with sausage baits containing either chicken (solid circles) or rabbit meat (star circles).

and Saddle Point (Fig. 1). Most of the study site extended from the coast up to c. 300 m above sea level (a.s.l.) with the exception of a camera trap line on the Mt Anglem/Hananui walking track up to 520 m a.s.l.. This site was chosen as it was known to support high numbers of cats and kiwi, allowing us to investigate interactions of target and non-target animals with the bait. The study area was covered in predominantly mature mixed podocarp broad-leaf forest, though dense mānuka (*Leptospermum scoparium*) and umbrella fern (*Gleichenia cunninghamii*) stands were found at higher altitudes.

Camera trapping and bait trials

Fifty camera traps (Bushnell Aggressor, Bushnell Corporation, Overland Park, Kansas, and Browning Dark Ops, Prometheus Group, Birmingham, Alabama) were set approximately 500 m apart, and were left in place for 28 days. Cameras were placed in a 'soft grid' formation, which allowed field staff to choose a suitable location within a 100-m radius of the nominal grid point. This approach allowed cameras to be placed in locations where they were likely to be encountered by the target species, e.g. animal trails, walking tracks, and habitat boundaries (Nichols et al. 2019). Each camera was affixed to a tree close to ground level, and a single non-toxic bait was placed 2–3 m away in the centre of the field of view. Cameras were set to record video rather than still images, as video gives better resolution for interpreting behaviours such as interactions with bait (Glen et al. 2013).

Individual identification of cats was undertaken based on morphological traits, e.g. patterns of stripes or spots on the legs, flanks and tail. Some black cats could be identified by white patches, eye colour, ear colour and shape, tail length, or body size. Identification of cats was undertaken by a single observer (PMJ) for consistency. To evaluate potential risk to non-target species, we also recorded all occasions on which cameras detected other animal species, and whether those animals interacted with or removed bait.

Baits were sausages with a sheep gut casing, 19–21 mm in diameter, and weighing 18 g. The sausages contained either 100% rabbit meat or 90% chicken with 10% rice flour. These were alternated in the grid (Fig. 1). After 14 days the sites were revisited, and bait condition was recorded. Any bait still present was removed and all sites received a fresh bait of the same type. Memory cards were changed, batteries were changed if necessary, and camera settings were checked. Cameras were deployed on 17–18 March 2021, serviced on 31 March or 1 April, and retrieved on 14–15 April.

Data analysis

Spatial capture histories were compiled for each individually identified cat, and were analysed using spatially explicit capture recapture (SECR) modelling in Programme DENSITY 5.0 (Efford et al. 2004; Efford 2012). Multiple videos of an individual cat recorded by the same camera on the same day were treated as a single detection, unless the cat was recorded on another camera before returning to the first one. A habitat mask was applied defining ocean as non-habitat, and a spatial buffer was set based on the root pooled spatial variance (RPSV) using the rule of thumb 'buffer = RPSV × 4'. We used the 'Evaluate SECR log likelihood' function in DENSITY 5.0 to evaluate whether this buffer was appropriate (Efford 2012). For further explanation see Glen et al. (2022).

Initially, we pooled data for all cameras, regardless of bait type. To investigate whether there was temporal variability in the detection probability of cats, we then analysed the data from Round 1 (first 14 days) and Round 2 (last 14 days) separately. Finally, we conducted separate analyses for cat detections that occurred when bait was present, vs bait absent.

We used binomial generalised linear models (GLMs) to explore whether bait type (chicken or rabbit) and number of days since deployment influenced the probability of a bait being consumed by a cat. Few cats (6/17) were observed taking the same bait type on more than one occasion. Bait consumption was collapsed to a binomial response indicating whether an individual cat ever consumed the bait type during the study. Where individual cats were observed on multiple occasions, the mean number of days since deployment was used, and was calculated separately for observations where baits were consumed and not consumed. We first ran a GLM in which probability of bait ever being consumed was a function of bait type and days since deployment. We then ran reduced models that did not include either bait type, or time since deployment, and compared the full and reduced models using Akaike's information criterion with correction for small sample size (AIC_c) (Sugiura 1978). GLMs were run in R Studio version 4.1.1 (R Core Team 2015).

Results

The cameras recorded 113 cat detections: 31 when bait was present and 82 when no bait was present. At least 32 individual cats were identified. On seven occasions cats were unable to be identified to individual level. Therefore, the total number of individuals detected was between 32 and 36. The number of detections recorded on each camera ranged from 0–6 (Fig. 2).

Pooling data across the full 28 days, there were 93 captures of 32 individual cats. From these data, Program DENSITY 5.0 estimated a population of 33 cats (95% CI 32–37), with RPSV = 719 m. A buffer width of 2900 m (c. 4 × RPSV; see Methods) was therefore chosen for the SECR analyses. This buffer was confirmed to be suitable as doubling to 5800 m had minimal effect on the estimated log likelihood. Table 1 summarises the results of the SECR analyses for each of the modelled scenarios.

The cameras recorded 31 occasions on which a cat encountered a bait (Table 2). Cats that consumed bait appeared to eat all the bait available within 5–60 seconds. In terms of individuals, 17 cats encountered baits, and 8 of these consumed at least one bait.

On seven occasions cats were recorded sniffing rabbit baits without eating them; two of these individuals also mouthed the bait before rejecting it. One cat sniffed a chicken bait but did not eat it. Eight cats were recorded ignoring rabbit baits, whereas no cats were recorded ignoring chicken bait.

The full model that included bait type and days since deployment showed that consumption of baits appeared to decrease with time (Fig. 3). No baits were consumed by cats more than 5 days after deployment, despite 11 encounters being recorded on days 6–11. The reduced model in which days since deployment was not included as a predictor performed less well than the full model ($\Delta AIC_c = 6.71$), suggesting that there was a strong effect of days since deployment.

When baits were encountered by a cat on the day they were deployed, the full model estimated the probability of consumption for chicken bait was 99% (95% CI 50–100%). The corresponding estimate for rabbit bait was 90% (28–100%). The reduced model in which bait type was not included as a

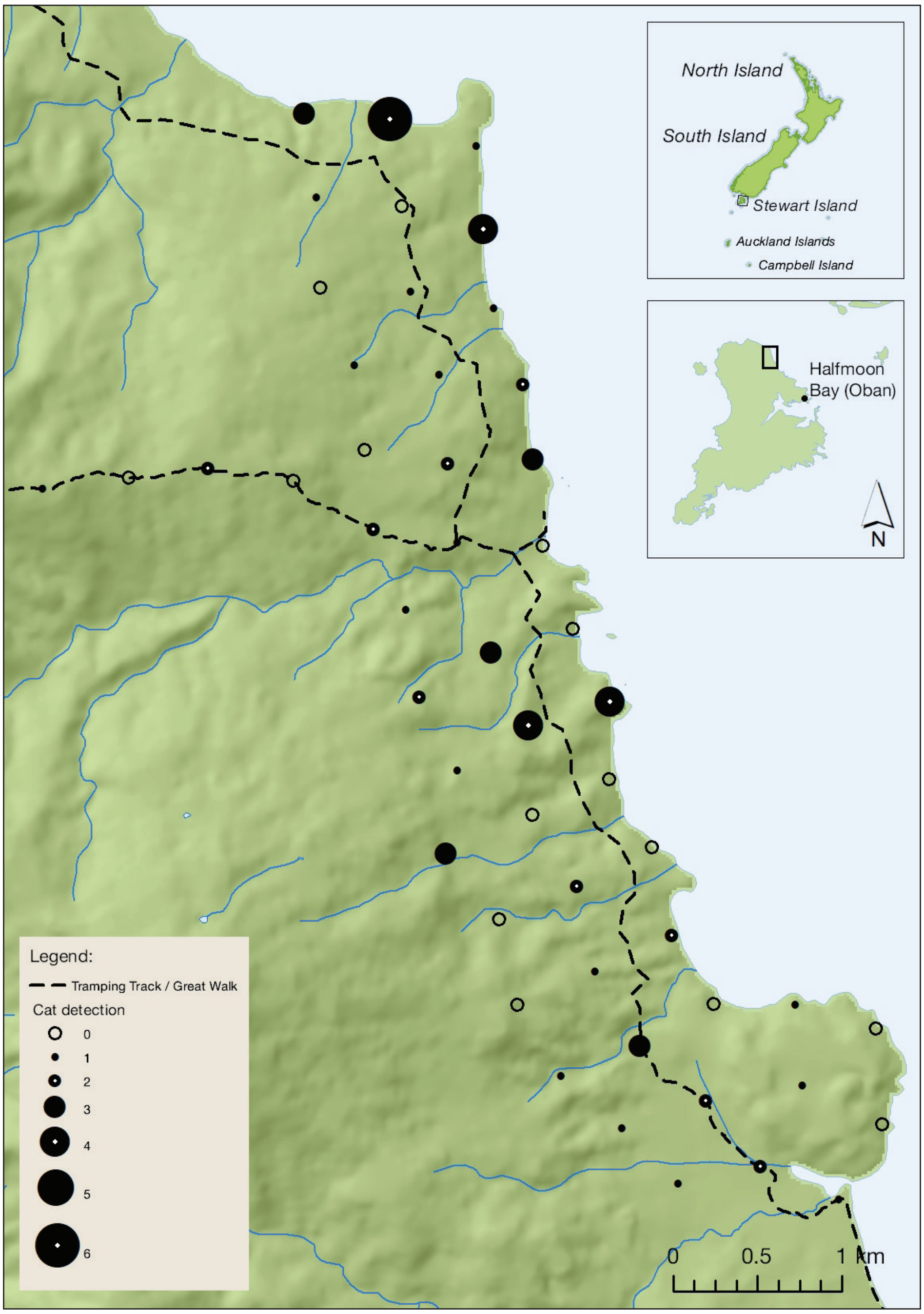

Figure 2. Numbers of feral cat detections recorded by each of 50 cameras on Rakiura Stewart Island.

Table 1. Number of independent cat detections*, number of individuals identified, estimated population density, and spatial detection parameters (g_0 and σ) for each of five modelled scenarios on Rakiura Stewart Island.

Model scenario	Detections	Individuals	Cats per km^2 (95% CI)	g_0 (95% CI)	σ (95% CI)
All detections, all cameras	113	32	1.0 (0.7–1.5)	0.05 (0.04–0.08)	643 (540–767)
Round 1, first 14 days	45	23	1.8 (1.1–2.8)	0.03 (0.02–0.05)	494 (373–656)
Round 2, last 14 days	57	25	1.5 (0.95–2.4)	0.02 (0.015–0.04)	899 (356–2271)
Bait present	13	10	1.1 (0.3–3.7)	0.01 (0.005–0.02)	899 (356–2271)
Bait absent	32	19	1.9 (1.1–3.3)	0.03 (0.01–0.06)	367 (261–518)

* Repeat detections of the same cat on a single camera on the same day were discarded, unless the cat was recorded on another camera before returning to the first one.

Table 2. Numbers of occasions on which feral cats encountered and consumed chicken or rabbit baits on Rakiura Stewart Island.

Bait type	Encounters (individual cats)	Bait consumed (individual cats)	Encounters resulting in consumption	Cats that consumed bait on encounter
Chicken	8 (8)	7 (7)	88%	88%
Rabbit	23 (13)	5 (3)	22%	23%
Total	31 (17)	11 (8)	35%	47%

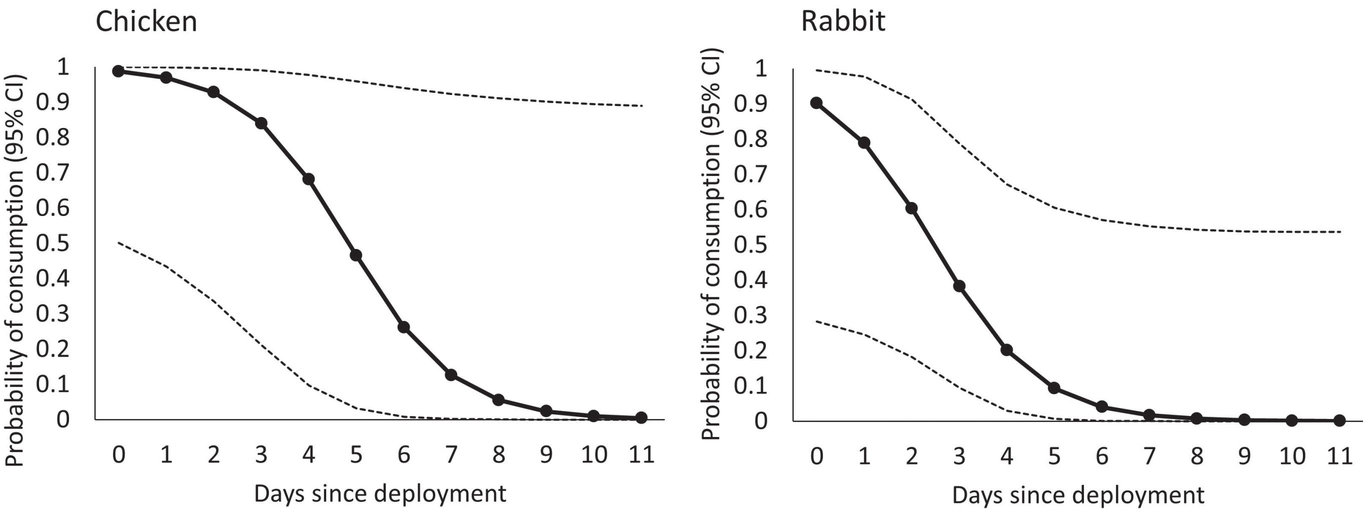

Figure 3. Estimated probability of consumption by cats declined sharply over time for both chicken (left) and rabbit baits (right). Probability of consumption for rabbit baits appeared to be lower, and declined more quickly than that of chicken baits. However, the wide 95% confidence intervals (dashed lines) indicate some uncertainty.

Table 3. Number of detections of all non-target species on camera, numbers of encounters with bait, and number of occasions on which the animal interacted with or consumed the bait.

Species	Detections	Encounters	Interactions	Consumptions
Invertebrates (moth, bee, isopod)	22	10	1	1
Song thrush (*Turdus philomelos clarkei*)	5	2	0	0
Hoiho (*Megadyptes antipodes*)	21	0	0	0
Dunnock (*Prunella modularis*)	25	13	0	0
Tūī (*Prosthemadera novaeseelandiae*)	1	0	0	0
White-faced heron (*Egretta novaehollandiae*)	8	3	0	0
Red-billed gull (*Chroicocephalus novaehollandiae scopulinus*)	5	0	0	0
Variable oystercatcher (*Haematopus unicolor*)	1	0	0	0
Bellbird (*Anthornis melanura*)	7	4	0	0
Sacred kingfisher (*Todiramphus sanctus vagans*)	1	0	0	0
Grey warbler (*Gerygone igata*)	1	0	0	0
Blackbird (*Turdus merula*)	10	6	1	0
Fantail (*Rhipidura fuliginosa*)	9	5	0	0
Tomtit (*Petroica macrocephala*)	40	19	1	0
Stewart Island kiwi (*Apteryx australis australis*)	126	67	17	0
White-tailed deer (*Odocoileus virginianus*)	68	22	8	0
Possum (*Trichosurus vulpecula*)	946	269	132	21
Rat (*Rattus* sp.)	300	74	53	30

factor performed only marginally better than the full model (ΔAIC_c = 1.08), suggesting that there was insufficient data to select between the full and reduced models.

The cameras showed that a large range of native and non-native species encountered bait. At least 51% of baits were removed by non-target animals, primarily possums and rats. These are thought to have been ship rats (*Rattus rattus*), as they are the dominant species in podocarp-broadleaf forest (Harper et al. 2005). In one case a possum consumed half a bait, the remainder of which was eaten by a cat. On 22 occasions a cat was detected at a site where the bait had previously been removed by rats (n = 10) or possums (n = 12), representing missed opportunities for cats to encounter bait. White-tailed deer (*Odocoileus virginianus*) encountered bait on 22 occasions, sniffed the bait on eight of these occasions, but consumed no bait (Table 3).

Fourteen species of native (n = 11) and non-native (n = 3) birds encountered bait 122 times, with most completely ignoring the bait (Table 3). One bait was partially consumed by intertidal isopods (species unknown), the only native species to consume baits. Stewart Island kiwi / tokoeka encountered bait 67 times. Kiwi sniffed the bait closely 11 times, and probed or picked it up but then dropped the bait six times; no kiwi, nor any avian species, consumed bait.

Discussion

This paper represents one of the few studies of feral cat population density on offshore islands of New Zealand (see also Harper 2007; Glen et al. 2022). Our camera trapping results suggest that population density of feral cats on the north-east coast of Rakiura was likely between 1 and 2 cats per km^2. However, due to imperfect identification of individual cats on camera, the true density could be as high as c. 3 per km^2. These estimates are higher than those obtained using similar methods on Auckland Island in the New Zealand subantarctic region (Glen et al. 2022), but well within the range of density estimates from other large islands (e.g. Legge et al. 2017; Hohnen et al. 2020a).

In the inland Rakeahua Valley, Rakiura, Harper (2007) estimated a population density of between 0.19 and 0.27 cats per km^2 over a 2 year study. These estimates were calculated from home range methods using collared cats, and likely an underestimate of true population density. However, this study was conducted in a single summer when a cohort of juveniles were likely present, which may have temporarily increased the population density, as most juveniles and some adults would succumb during the following winter as prey became scarce (Harper 2005). Additionally, Harper's (2007) study site extended from the valley floor to 716 m a.s.l., encompassing wetland and shrubland in the valley floor, as well as subalpine shrubland, although cats preferentially selected podocarp-broadleaf forest and avoided these latter habitats. On cool temperate Auckland Island, cats are more likely to use coastal areas than inland locations (Rodriguez-Recio et al. 2022), which may also explain differences between these Rakiura sites. In habitats where resource availability is patchy, marine-derived food might provide additional resources that sustain higher populations compared to inland sites (Rodriguez-Recio et al. 2022).

Our estimates of the spatial detection parameter g_0 were comparable to those from Auckland Island (Glen et al. 2022), and will help inform monitoring effort in an eradication. Estimates of g_0 ranged from 0.01–0.05, which suggests that a camera placed at the centre of a cat's home range would have a probability of between 1% and 5% of detecting the cat on any given day. This knowledge will guide management decisions on how much monitoring effort is needed to declare eradication success; the lower the detection probability, the more monitoring effort required (Anderson et al. 2013; Samaniego-Herrera et al. 2013; Russell et al. 2017). Future studies should explore variation in camera detection probability, both spatially across Rakiura, and in response to reduced population density.

Estimates of the spatial detection parameter Sigma were more variable than those from Auckland Island (Glen et al. 2022). As a rule of thumb, baits, traps and monitoring devices should be deployed at a spacing less than the value of Sigma to ensure a high probability that every individual will encounter at least one device. The lowest estimate of Sigma from our modelled scenarios was 367 m, suggesting that the 500-m spacing between cameras may have been too large. However, the small sample sizes of cats detected meant that our estimates had a high degree of uncertainty. We recommend an adaptive management approach in which estimates of g_0 and Sigma are refined using data from repeated camera deployments. Cat home ranges and behaviours will likely change as the population declines during an eradication programme. For example, cats on Dirk Hartog Island, Western Australia, became more mobile as population density declined, leading to increased detectability of individuals (D. Algar, pers. comm.).

If the baits in our trial had been toxic, and we assume each consumption was lethal, we would have removed eight cats. This would correspond to a population reduction of c. 24%. Our results suggest that bait interference by rats and possums will have to be reduced if toxic baiting is to achieve a large reduction in the cat population. Similarly, in a trial of non-toxic cat baits on Kangaroo Island, South Australia, >99% of recorded bait takes were by non-target species, mainly rats and possums (Hohnen et al. 2020b). Bait interference by non-target animals also contributed to low effectiveness of a feral cat baiting programme in Western Australia (Doherty et al. 2022).

Rats and possums are also the targets of proposed eradications on Rakiura (Beaven 2008), which suggests a sequenced eradication approach would be advisable. Baiting to remove feral cats would have a higher chance of success if rat and possum populations were first reduced or eliminated. A proportion of feral cats would also be likely to consume bait laid for rats or possums (Griffiths et al. 2015). Alternatively, bait stations could be used to exclude non-target species while still allowing cats to access baits (de Burgh et al. 2021). However, this approach would significantly increase delivery effort owing to the large scale of the proposed operation and the thick forest and shrubland covering the island. Bait density could also be increased to reduce the proportion of baits consumed by non-target animals, and hence their effect on bait availability for feral cats.

Probability of consumption of both chicken and rabbit baits appeared to diminish rapidly after deployment; no baits were consumed after more than 5 days. In a similar trial on Auckland Island, Cox et al. (2022) reported that no baits were consumed by cats after 7 days. Baiting regimes should be designed to ensure all feral cats encounter bait before it becomes unpalatable. As noted, increasing bait density or reducing non-target interference will increase encounters. Further trials could aim to prolong bait palatability by deploying baits in winter when cooler weather might slow their degradation. Alternatively, baits could be replaced more frequently; perhaps after 5–7 days. Future research could also investigate altering the bait formulation to prolong palatability. However, the benefits of increased bait persistence would have to be balanced against any potential increase in risk to non-target species due to the prolonged availability of bait. However, the risk appears to be low; for example, kiwi encountered bait during our study but did not consume bait. It is unclear if prolonged exposure would increase consumption risk.

Because of the low numbers of baits encountered by cats in our trial, comparisons between chicken and rabbit baits were inconclusive. However, the model that best described the data included bait type as an explanatory variable, and estimated a higher probability of consumption for chicken baits than for rabbit baits. This result is supported by our behavioural observations, which showed that cats frequently ignored or rejected rabbit baits, whereas only one cat rejected a chicken bait. During trials on Auckland Island, Cox et al. (2022) found no difference in palatability between chicken and rabbit sausage baits. It is possible that feral cats on Rakiura, where wild rabbits are absent, are less attracted to rabbit meat due to a lack of familiarity, but this theory would not explain the lack of preference between rabbit and chicken baits on Auckland Island which is also free of rabbits. Given temporal and spatial variations in prey availability, and individual preferences, it is advisable to register both bait types so that the most appropriate bait can be chosen for local sites or conditions.

This study has shown that the population density of feral cats on the north-east coast of Rakiura was similar to other large offshore islands, and higher than previous estimates from an inland area of Rakiura. Density and detection parameter estimates from this study will help guide deployment of eradication and monitoring devices such as traps, baits and cameras. Additional research will build confidence of detection parameters for cameras, and spatial variation across Rakiura must be investigated if camera networks are to play an important part in an eradication attempt.

Non-toxic meat baits were palatable to feral cats on Rakiura, though palatability of both baits declined rapidly. In addition, bait availability for cats was significantly reduced through interference by rats and possums. Measures to reduce bait interference by non-target species should be considered to improve efficacy. Importantly, no native vertebrate species consumed baits so the risk of harming native fauna by using toxic bait should be very low. Our results show that development of a ready-made, meat-based feral cat bait should continue, and point to directions for future research to optimise bait efficacy, but also in regard to eradication planning to ensure all cats encounter fresh baits. Only with such a tool can landscape-scale cat control or eradication of feral cats from large islands be considered in New Zealand.

Author contributions

FSC, RLS and PMJ designed the study and undertook fieldwork; ASG and SWH analysed the data; and ASG wrote the manuscript with input from FSC, SWH, RLS and PMJ.

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