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RESEARCH

Monitoring and detection of feral cats on Auckland Island

Alistair S. Glen[1*], Rachael L. Sagar[2], Talia Brav-Cubitt[1] and Paul M. Jacques[2]

[1]Manaaki Whenua – Landcare Research, Private Bag 92170, Auckland 1142, New Zealand
[2]Department of Conservation, PO Box 743, Invercargill 9840, New Zealand
*Author for correspondence (Email: glena@landcareresearch.co.nz)

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Abstract: In order to conserve important biodiversity values, eradication of feral cats (*Felis catus*) is planned on Auckland Island in the New Zealand subantarctic region. This eradication will require detailed knowledge of the abundance, distribution, movement behaviour and detection probability of cats on the island. We investigated these parameters on a peninsula at the northern end of the island using live trapping, camera trapping, and scat searches with and without detection dogs. Here, we compare the results of these methods, and discuss their utility for the planned eradication. Four cats were captured and fitted with GPS collars. Camera traps with 500 m spacing detected all these individuals on multiple occasions, and at multiple locations. At least 12 other individuals were also captured on camera. Excluding every second camera (to simulate 1000 m spacing) resulted in failure to detect 32% of known individuals. Population density estimates from camera trapping varied from 0.7–1.0 cats km^{-2}. Humans found 29 cat scats, and dogs found 33. Genetic analysis estimated that these came from a minimum of ten individuals. Camera trapping should be repeated during the operational and confirmation phases of the eradication to monitor spatial and temporal variation in cat density, detect survivors, and help confirm eradication success. Scat collection, with and without dogs, can supplement data from camera trapping. With larger sample sizes of scats, DNA profiling may also allow cat abundance to be estimated.

Keywords: camera trapping, detection probability, eradication, *Felis catus*, invasive species

Introduction

Feral cats (*Felis catus*) are among the greatest threats to global biodiversity (Doherty et al. 2016). Their impacts are particularly severe on islands, which are often biodiversity hotspots with high proportions of endemic and/or endangered species. Where feasible, eradicating feral cats from islands is an effective way to protect insular biodiversity (Campbell et al. 2011; Medina et al. 2011).

Auckland Island in the New Zealand subantarctic island region is listed as a World Heritage Area (World Heritage Convention 1998), Important Bird Area (Birdlife International 2021) and World Centre of Floristic Diversity (IUCN 2017). The island is the most biologically rich of New Zealand's subantarctic islands, supporting more than 500 species including 38 native bird species, nine of which are island endemics (Miskelly et al. 2020). In order to conserve this important biodiversity, the Department of Conservation (DOC) plans to eradicate feral cats (as well as mice, *Mus musculus*, and feral pigs, *Sus scrofa*) from the island (Horn et al. 2022; Russell et al. 2022).

In order to eradicate a pest population, the following criteria must be met (Bomford & O'Brien 1995): (1) all individuals in the target population must be placed at risk by the removal method(s) used; (2) the rate of removal must be greater than the rate of population growth at all population densities; (3) risk of reinvasion must be close to zero; (4) target animals must be detectable at low population densities; and (5) benefits of eradication must exceed the costs. Ensuring that these criteria are met requires detailed knowledge of the target population, including abundance, spatial distribution, movement behaviour and detection probability (Fisher et al. 2015).

To inform eradication feasibility and operational planning, we investigated the density, movement behaviour and detection probability of feral cats near the northern end of the island. Detection methods included camera trapping, live trapping and scat searches (with and without detection dogs). Here, we estimate the population density and spatial detection parameters of feral cats using camera traps. We then compare the camera trapping results with those of the other methods, illustrating the advantages and disadvantages of each monitoring technique and their utility for the eradication of cats from Auckland Island.

There are two spatial detection parameters (Efford 2004). The first (g_0) is the probability of detecting an individual on any given day if a detection device is placed at the centre of its home range. The second (σ) is the spatial scale over which detection probability declines with increasing distance from the centre of the home range (Efford 2004). Knowledge of these parameters will help guide placement of devices for cat removal and monitoring. This information can also be used during the confirmation phase of an eradication to interpret surveillance results and estimate probability of eradication success (Anderson et al. 2013; Samaniego-Herrera et al. 2013; Russell et al. 2017).

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Methods

Study area

Auckland Island (45 891 ha), part of the Auckland Island group (50.69°S, 166.08°E), lies 465 km south of New Zealand's South Island. Our study focussed on the Deas Head area (1350 ha), a peninsula at the northern end of the island (Fig. 1). Habitat on Deas Head includes a mixture of tussock grassland, moorland, dense shrubland dominated by *Myrsene divaricata*, īnaka (*Dracophyllum longifolium*), and rātā (*Metrosideros umbellata*) and coastal rātā forest (Johnson & Campbell 1975).

Live trapping

Between 28 November and 14 December 2018 cats were targeted with a network of 174 Victor® 1.5 soft-jaw leghold traps (Woodstream Corporation, Lititz, USA). Trapping density varied across the study area but all habitat types were sampled. Traps were baited alternately with pieces of rabbit (*Oryctolagus cuniculus*) and barracouta (*Thyrsites atun*) meat, and baits were replaced every third day. Most traps (>95%) were set in 'cubbies', whereby bait is placed at the back of a corral of sticks carefully placed to guide a cat's fore-paw onto the trigger plate of the trap. A small number of traps were set as 'trail sets', whereby a pair of traps are set on a game trail with a bait in between. A small number of sticks are placed strategically to guide a cat onto the trap. These sets were used sparingly due to the higher risk of catching non-target animals compared with cubby sets. Traps were checked daily in accordance with the NZ Animal Welfare Act 1999.

Upon capture cats were restrained using a cat-grabber (Ketch-All, San Luis Obispo, USA) and Kevlar lined gauntlets

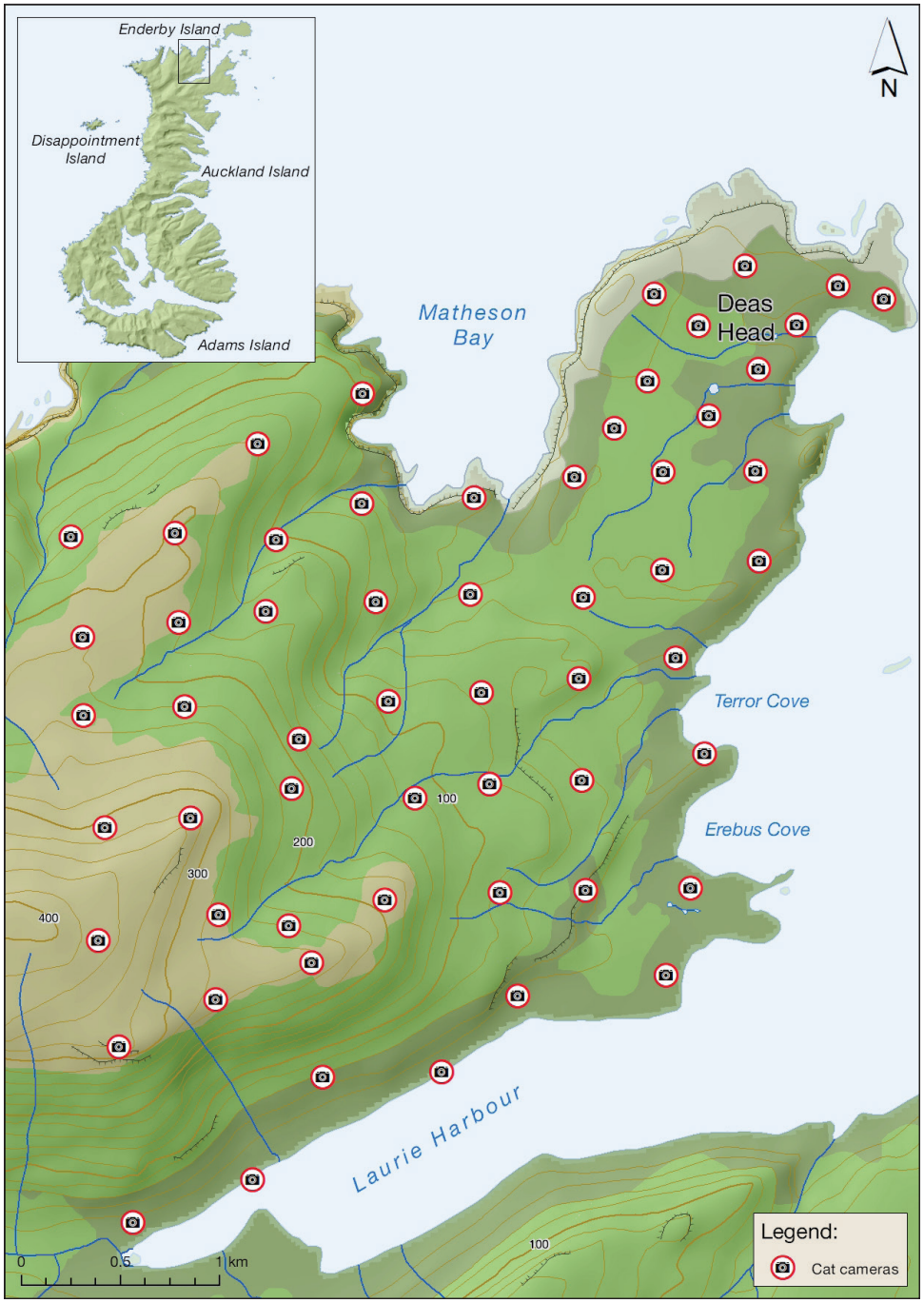

Figure 1. Map of the study area at Deas Head, Auckland Island, showing the locations of camera traps.

(HexArmor, Grand Rapids, Michigan, USA), and sedated by trained staff using an intramuscular injection of a mixture of Ketamine (Phoenix Pharm Distributors Ltd, New Zealand) and Domitor (Zoetis New Zealand Ltd). Four cats were fitted with GPS-collars: one Sirtrack/Lotek™ Iridium Lite Track 130 (130 g), and three Sirtrack/Lotek ™ Lite Track (60 g). Collars were fitted according to cat weight, and were <5% of the body mass of each cat (Recio et al. 2010). Collars were marked with 1–3 reflectors to aid identification of individuals in photographs. Unique patterns were also bleached into the fur to aid individual identification (Fig. 2a). Following the methods of Nathan (2016), we used a mixture of MYHD #908 Extra Light Silver Blonde hair dye mixed with MYHD 40 vol. developer (My Hairdresser, Sydney, Australia). Figure 2b shows an example of a cat identifiable by its unique pattern of reflectors and fur bleaching. A mouth swab was taken from each cat for DNA analysis and comparison with scats (see below). Swabs were stored in vials containing Longmire buffer (Longmire et al. 1997) at room temperature until analysis. Two additional cats were trapped at the end of the study period (late February–early March 2019) and mouth swabs were collected as above.

Camera trapping

Between January and March 2019, we deployed 58 camera traps (Bushnell Aggressor "No-glow"; Bushnell Corporation, Overland Park, Kansas) across an area of c. 1350 ha on Deas Head (Fig. 1). Four cats had previously been captured in this area and fitted with GPS collars.

Among the 58 camera traps, 53 were placed in an 'soft grid' formation with c. 500 m spacing. Field-staff had freedom to re-locate cameras within 100 m of the pre-determined point if a good site for detecting cats was found, e.g. well-defined game trails, habitat boundaries or localised food sources. An additional five cameras were placed within the home range of one of the GPS-collared cats ('MB'), creating a grid with c. 250 m spacing over part of the study area (Fig. 1). The location of each camera was recorded using GPS.

Cameras were fastened to wooden posts 15 cm above the ground, facing horizontally towards a bait post c. 2.5–3.5 m away. Bait posts were smeared with cat food (Whiskas Ocean Loaf®) and a muslin bag containing cat food was tacked to the top of each post. Posts were re-baited twice (approximately every 10 days) during the monitoring period. On the first

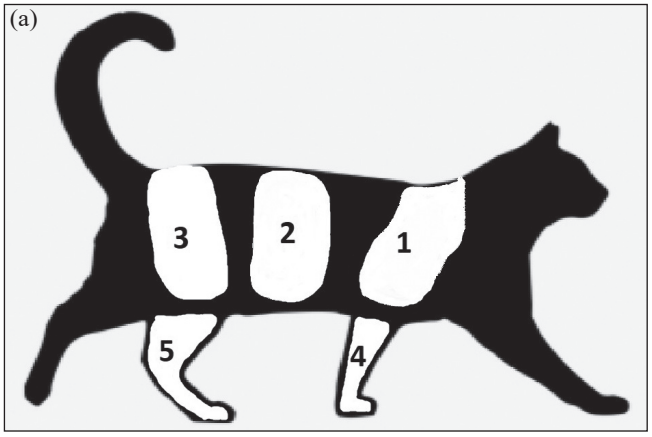

Figure 2. Unique patterns (a) were bleached into the fur of GPS-collared cats by applying hydrogen peroxide to one or more of the areas illustrated. In addition, each GPS collar had 1, 2 or 3 reflectors. Identification of individual cats in unclear images (b) was aided by observing the bleaching pattern and number of reflectors. For example, the animal below could be identified by the bleaching around the hips, and having 3 reflectors.

re-baiting, a piece of salted rabbit was nailed to each post in addition to the cat food.

Cameras operated 24 hours a day and were set to take three images when triggered by motion, with a delay of 1 s between triggers. The infrared flash was set to low intensity, and image size was set to high definition. We recorded the dates and times at which each camera detected a cat. Where possible, individual cats were identified based on natural and/or artificial markings.

The camera trap data and GPS co-ordinates for each camera were combined to create spatially explicit capture histories (Efford 2004). Repeated photographs of the same cat on the same camera within a day were treated as a single detection, unless the cat was recorded on another camera before returning to the first one. Capture histories were compiled for the 28 days from 2 February to 1 March 2019, and were analysed using spatially explicit capture recapture (SECR) modelling in Programme DENSITY 5.0 (Efford et al. 2004; Efford 2012). A GIS shape file of the island's coastline was used to create a habitat mask defining ocean as non-habitat, and a spatial buffer was placed around the camera trap grid. Buffer width was set by multiplying the root pooled spatial variance (RPSV) observed in the spatial capture histories by a factor of four. The appropriateness of this buffer width was tested using the 'evaluate SECR log likelihood' function in DENSITY 5.0 (Efford 2012).

Initially, the entire data set was analysed, then selected data were discarded and the analysis re-run to simulate different camera spacing, explore the influence of one individual cat with an atypical capture history, and test how the results may have been affected by failure to identify some individual cats. Seven scenarios were modelled (Table 1).

Opportunistic scat collection

Between 28 November and 14 December 2018 (collaring trip) and between 27 January and 9 March 2019 (monitoring trip) all staff were instructed to collect any cat scat they encountered within the study area. Scats were collected into a zip-lock bag, labelled with GPS co-ordinates for the point of collection, and stored in a −20°C freezer until analysis.

Cat detection dogs

Between 27 February and 9 March 2019 two cat detection dogs and their handlers (DOC conservation dog team) searched approximately half of the camera detection grid to detect live cats and locate scats. Each dog team covered approximately the same area on separate days. GPS tracks were collected daily for each dog team. A GPS point was collected for each cat detection and scat collected. Scats were bagged and stored in a −20°C freezer until analysis.

DNA analysis

All cat scats and mouth swabs were sent to EcoGene® (Manaaki Whenua – Landcare Research, Auckland, NZ) for genetic profiling and sexing. Scats that were visually assessed as being too dry and degraded for genetic profiling were not processed. Wet swabs were taken from the outside of each remaining scat. DNA was extracted from the scat and mouth swabs using either the QIAamp 96 DNA QIAcube HT kit (Qiagen), the QIAamp DNA Mini Kit (Qiagen), or the DNeasy Blood & Tissue Kit (Qiagen) following the manufacturer's instructions.

Genetic profiling was performed by amplifying 11 microsatellite markers and a sex-specific locus developed for domestic cats (Butler et al. 2002). PCRs consisted of 5 µL of 2x Type-it Multiplex PCR Master Mix (Qiagen), 2 µL of primer mix (Table 2), 2 µL of genomic DNA, and PCR grade water up to a total reaction volume of 10 µL. Thermocycling conditions largely followed those recommended for use with the Type-it Microsatellite PCR Kit (Qiagen) and consisted of an initial activation step at 95°C for 5 mins; followed by 40 cycles

Table 2. Cat microsatellite marker names (as per Butler et al. 2002) and their final concentrations per forward and reverse primer in the primer mix used for genetic profiling of feral cats on Auckland Island.

Marker name	Final concentration of each primer (µM)
F53	0.12
C08	0.12
B04	0.12
G11	0.18
FCA441	0.05
D09	0.03
F124	0.16
C12	0.16
C09	0.16
F85	0.2
D06	0.16
SRY	0.02

Table 1. Description of the seven different modelling scenarios used to estimate the spatial detection parameters g_0 and σ for feral cats on Auckland Island, New Zealand subantarctic region.

Scenario	Description
i	All cat detections from all cameras
ii	Cat detections from all 53 cameras in the 500 m grid (i.e. excluding data from the five 'extra' cameras deployed within the home range of the known individual 'MB')
iii	Cat detections from the 27 even-numbered cameras in the 500 m grid (simulating a 1000 m grid spacing)
iv	Cat detections from the 26 odd-numbered cameras in the 500 m grid (again, simulating a 1000 m grid spacing)
v	Cat detections from all 53 cameras in the 500 m grid, excluding detections of one individual – a juvenile that was detected repeatedly, then thought to have died or emigrated before the end of the study
vi	Cat detections from all 53 cameras in the 500 m grid, excluding five detections in which the individual could not be confidently identified
vii	A repeat of scenario vi, but including two detections thought probably to represent the same individual

of denaturation at 95°C for 30 secs, annealing at 60°C for 90 secs, and extension at 72°C for 60 secs; and a final extension step at 60°C for 30 mins. Resulting microsatellite amplicons were visualised under ultraviolet (UV light) using GelRed™ stained 2% agarose gels, and electrophoresed using a 3500xL Genetic Analyser (Applied Biosystems). Fragment sizes were scored using GeneMapper v5.0 (Applied Biosystems).

Mouth swabs were processed in singlicate. Scat samples were initially amplified once to test for amplification success. For samples where at least one marker amplified, two more replicates were conducted. Consensus profiles were taken from across the three replicates, where alleles were required to be present in at least two replicates to be included.

The Multilocus Matches function within the program GenAlEx v 6.503 (Peakall & Smouse 2006, 2012) was used to assist with the identification of potential matches between samples. Profiles with seven or more markers were used for matching, with seven being determined as a suitable threshold based on probability of identity estimates calculated using the Multilocus Prob. Identity function in GenAlEx v 6.503. All potential profile matches were manually checked, with all profiles being compared against each other to identify similarities in observed genotypes at each marker. To accommodate the possibility of allelic drop-out among genotypes originating from scat samples, for any given marker where two individuals were each homozygous for different alleles, or where a heterozygote and a homozygote had an allele in common, these were still considered potential matches. Genotypes were excluded as coming from the same individual where at least three different alleles were present across each pair of genotypes being compared at a particular marker. These methods of exclusion were also used to estimate the minimum number of individuals represented by the profiles generated from the scat samples. The presence of multiple individuals was also noted where three individuals were all homozygous for different alleles at the same marker, which assisted with this estimate.

Results

Camera trapping

Sixteen individual cats were confidently identified from the camera trap images based on natural and artificial markings. A further five images were tentatively identified from partial or unclear images. These may have been new or previously identified individuals. All four cats GPS-collared on Deas Head were detected on two or more cameras. One additional cat captured and GPS-collared outside the study area also appeared once on camera.

Using data for all cameras and individual cats, DENSITY 5.0 estimated a population of 21 cats (95% CI ± 0.8), with RPSV = 866 m. Therefore, a buffer width of 3600 m was chosen (c. 4 × RPSV; see methods). Doubling the buffer width had minimal effect on the estimated log likelihood, indicating that this was an appropriate buffer.

For each of the seven modelled scenarios, Table 3 summarises the number of encounters, number of individual cats detected, population density estimate, and spatial detection parameter estimates.

Among the scenarios modelled, estimated population density of cats on Deas Head ranged from 0.7 to 1.0 cats km^{-2} (Fig. 3a). Excluding the five additional cameras in the home range of MB reduced the density estimate from 1.0 to 0.9 cats km^{-2} (Fig. 3a, Scenarios i and ii), and led to a slight increase in precision, as indicated by the shorter error bars for Scenario ii. Omitting data from every second camera to simulate a 1000 m grid spacing produced slightly lower and less precise density estimates (Fig. 3a, Scenarios iii and iv). The simulated 1000 m grids also detected 32% fewer individual cats.

By definition, omitting some individual cats from the analysis led to lower density estimates (Fig. 3a, Scenarios v–vii). However, there was a slight improvement in precision when the unidentified individuals were omitted (Scenarios vi and vii).

Estimates of g_0 ranged from 0.015 to 0.06 (Fig. 3b). The full data set provided the lowest and most precise estimate of g_0. The two scenarios simulating a camera grid with 1000 m spacing (Fig. 3b, Scenarios iii and iv) produced estimates of g_0 that were higher, but less precise, than those obtained

Table 3. Numbers of encounters of feral cats, numbers of individual cats, and estimates of population density and spatial detection parameters for feral cats on Auckland Island under seven modelled scenarios.

Scenario	Description	Encounters	Individuals	Cats per km^2 (95% CI)	g_0 (95% CI)	σ (95% CI)
i	All detections, all cameras	91	21	1.0 (0.6–1.6)	0.015 (0.010–0.022)	842 (679–1045)
ii	All detections, 500 m grid only	79	19	0.9 (0.6–1.5)	0.03 (0.02–0.04)	700 (591–829)
iii	Even-numbered cameras	43	13	0.7 (0.4–1.3)	0.06 (0.04–0.09)	575 (466–709)
iv	Odd-numbered cameras	36	13	0.8 (0.4–1.4)	0.03 (0.02–0.05)	646 (492–848)
v	Excluding kitten	75	18	0.8 (0.5–1.4)	0.03 (0.02–0.04)	729 (608–873)
vi	Excluding five cats not positively identified	75	15	0.7 (0.4–1.2)	0.04 (0.03–0.06)	687 (585–807)
vii	Excluding four unidentified cats but including one probable identification	76	16	0.8 (0.5–1.2)	0.04 (0.02–0.05)	686 (585–803)

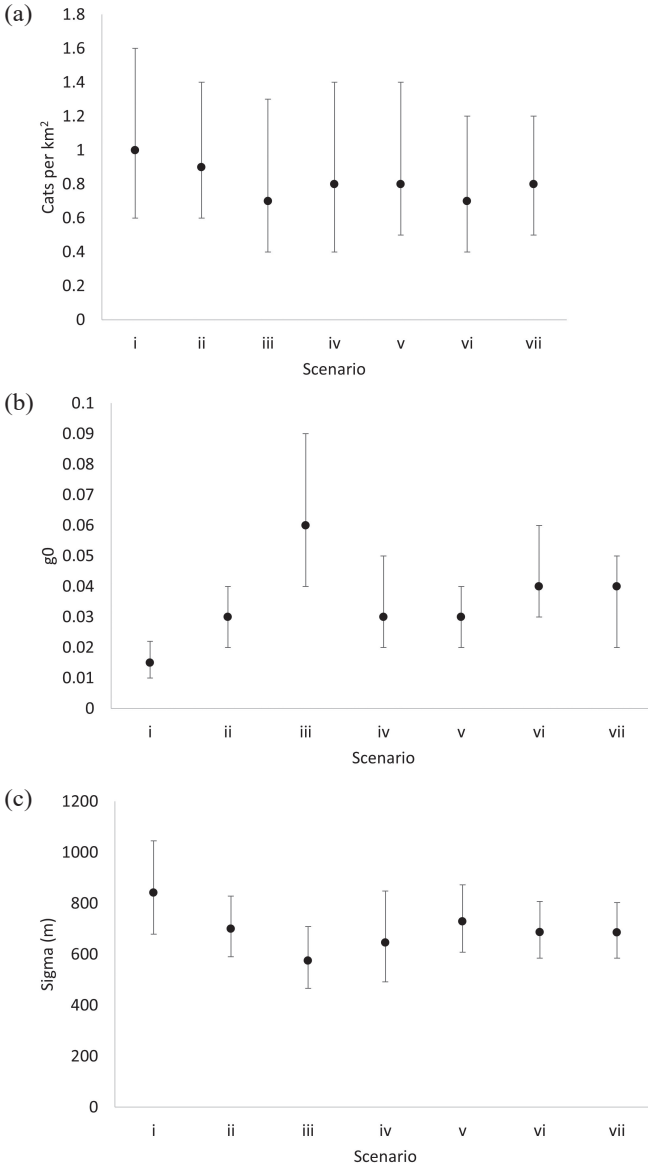

Figure 3. Estimates (with 95% confidence interval) of (a) population density; (b) daily detection probability at the centre of the animal's home range (g_0), and; (c) the spatial detection parameter (σ) for feral cats on Deas Head, Auckland Island.

using the 500 m grid. Omitting the unknown individuals (Scenarios vi and vii) also led to estimates of g_0 that were higher but less precise.

Estimates of σ ranged from 575 to 842 m (Fig. 3c). Inclusion of the five additional cameras in the home range of MB (Fig. 3c, Scenario i) led to a higher and more imprecise estimate than those from the 500 m grid (Scenario ii). Parameter estimates from the simulated 1000 m grids (Scenarios iii and iv) were slightly lower than those from the 500 m grid. Excluding the kitten (Scenario v) or the unidentified individuals (Scenarios vi and vii) had little effect on the estimates of σ.

Scat collection

Humans found 29 scats, and dogs 33 scats (n = 62). The dog teams also recorded nine cat detections not associated with scats, when the dogs detected scent trails. On two of these occasions the cat was also sighted by the handler.

Forty-nine of 62 scats were deemed fresh enough for DNA testing. Full or partial profiles were obtained from 27 (55%) of these, with 16 meeting the threshold for matching (seven or more markers). We estimated that the scat samples came from a minimum of 10 individuals, based on the number of genetic profiles where we could confidently exclude the possibility of them originating from the same individual.

Of the genetic profiles obtained from mouth swabs of the six trapped cats at Deas Head, four were matched with confidence to profiles obtained from the scat samples, and two with lower confidence. One individual cat was matched to three scats, one was matched to two scats, two cats were matched to one scat, and two cats were tentatively matched (i.e. could not be excluded) to one scat. The genetic profiling data are presented in Appendix S1 (see Supplementary Material).

Discussion

Eradication of feral cats requires site-specific knowledge of animal behaviour, prey sources, habitat and detection probability (Fisher et al. 2015). Live trapping, camera trapping, and scat searches with and without dogs all yielded information that will be valuable for eradication planning and evaluating eradication success on Auckland Island.

Estimates of population density, distribution and detection parameters of feral cats will inform trapping and monitoring efforts throughout the eradication project. For example, numbers and locations of traps, bait stations and monitoring devices will be guided by our estimates of the spatial detection parameters g_0 and σ, as discussed below.

Our trials showed camera traps were an effective tool for detecting feral cats on Auckland Island; all GPS-collared cats resident in the study area were detected on multiple occasions, and by more than one camera. Importantly, the cat with the smallest known home range (Rodriguez-Recio et al. 2022) was detected on two cameras. This cat was a female whose condition indicated she was raising kitten(s) during the study period. The smallest home ranges of cats from Auckland Island were found to be breeding female cats in summer (Rodriguez-Recio et al. 2022). We speculate their movement is constrained at this time by the need to provision young, and more reliable prey sources are available (Rodriguez-Recio et al. 2022).

Mark-recapture analysis can readily be applied to camera trap data for species with unique markings, e.g. tigers *Panthera tigris* (Karanth 1995; Karanth & Nichols 1998). However, this analysis can be problematic for feral cats, which sometimes lack unique coat patterns (e.g. uniform black). Even a low level of misidentification can distort population estimates (Otis et al. 1978). However, our estimates varied little with the inclusion or exclusion of images in which individuals were tentatively identified (Fig. 2, Scenarios ii, vi and vii), suggesting that our results can be interpreted with confidence. This may have been due in part to the fact that 80% of the positively identified cats (12 of 16) had tabby coats. Individual identification was also aided by artificial marks on the fur and GPS collars of some cats.

Density estimates from all modelled scenarios were between 0.7 and 1.0 cats km^{-2}. Camera trapping and SECR modelling were also used to estimate population density of feral cats on Kangaroo Island, South Australia. Estimates in various parts of the island ranged from 0.06–3.27 (mean 0.37) cats km^{-2} (Hohnen et al. 2020). Our estimates are higher than the mean estimate on Kangaroo Island, but well within

the range of estimates reported by Hohnen et al. (2020), and typical of large islands (e.g. Legge et al. 2017).

Population density of mice reached a peak in February 2019 (Sagar et al. 2022), which coincides with our camera trapping. In the central South Island of New Zealand, cat populations are driven by prey availability, with a 6-month time lag (Cruz et al. 2013). It is not known whether cat density on Auckland Island is driven by mouse abundance. However, repeated camera trapping on Deas Head in winter 2019 showed no evidence of a peak in cat density (unpubl. data).

All but one of the modelled scenarios produced estimates of g_0 between 0.015 and 0.04, suggesting that a camera placed at the centre of a cat's home range had a 1.5–4% chance of detecting the cat on any given day. These estimates will help managers decide how much monitoring effort is needed for a high probability of detecting cats, if present.

Our simulated scenarios also showed that doubling the spacing between cameras from 500 m to 1000 m would have caused a substantial loss of information. Both scenarios simulating a 1000 m grid detected 13 individuals, compared to 19 for the 500 m grid; a reduction of 32%. This is consistent with the modelled estimates of σ, which were >500 m and <900 m for all modelled scenarios.

Although effective, camera traps have some limitations for monitoring cats on Auckland Island. There was evidence of behavioural variability among individuals; for example, some cats closely investigated baits whereas others showed no apparent interest. Some cats also showed signs of wariness towards the cameras. Similarly, pen trials by Glen et al. (2013) found that three of six cats fled after triggering camera traps, and one individual subsequently avoided the camera. Such behaviours could be problematic, particularly in the mopping-up and confirmation stages of an eradication. Aversive responses could be caused by light and/or sound emitted by camera traps (Glen et al. 2013; Meek et al. 2014). The choice of camera traps to use, and the design of future camera traps, should seek to minimise such aversive stimuli.

Camera detection trials on Auckland Island highlighted that processing photos and data from landscape-scale camera networks is prohibitively labour intensive. Thus, camera trapping is not currently feasible at the proposed scale for the Auckland Island eradication project, nor would it allow rapid detection and response to target individuals. Automated processing of image data is required to triage falsely triggered images (no animal present) as a minimum, and preferably to identify images where cats are present. Software for automated analysis of camera trap images is becoming increasingly reliable (Falzon et al. 2014, 2020; Norouzzadeh et al. 2018), and will greatly improve cost-effectiveness.

Strategic placement of camera traps near roads, trails or habitat edges can increase detection probability of feral cats (Nichols et al. 2019; Geyle et al. 2020). Many well-defined game trails are present in tussock, scrub and rātā habitat on Auckland Island, kept open by pigs, hoiho/yellow-eyed penguin (*Megadyptes antipodes*) and whakahao/sealions (*Phocarctos hookeri*) (PMJ & RLS pers. obs.). Utilising a soft grid allowed for placement of cameras at sites that looked more likely for detecting cats, and most cameras were placed on a well-used game trail. Evidence from trapping, dog searches, scat collection and cameras all suggest that game trails are frequently used by cats. As an obvious landscape feature that can readily be identified by field staff, game trails should be targeted for siting the majority of detection and removal devices during the eradication.

Cats are known to use cliffy areas on Auckland Island (Rodriguez-Recio et al. 2022), which extend c. 40 km along the western and northern coasts of Auckland Island and up to 400 m high. Camera trapping in such areas will be limited by accessibility, though helicopters can be used to service cameras on lower slopes or ledges. Ranging analysis revealed that such areas formed only part of cats' home ranges (Rodriguez-Recio et al. 2022), so strategic placement of cameras at cliff access points may yield important detections. In addition, some cameras will be placed overlooking bait piles in locations deemed strategically important for detecting cats (Cox et al. 2019; Hohnen et al. 2020), and other aerial techniques such as helicopter-mounted thermal imaging will be used to detect cats on the west coast.

Home range size of feral cats is negatively related to prey availability and density of conspecifics (Recio & Seddon 2013; Bengsen et al. 2016). Following the proposed eradication of mice on Auckland Island (Horn et al. 2022), prey availability will be reduced, and cat population density may also be reduced via secondary poisoning (eating toxic mice) (e.g. Gillies & Pierce 1999). Therefore, we would predict that cats will increase the size of their home ranges. Assuming the same density of cameras, this would mean more cameras per home range, resulting in increased detection probability of individuals.

We would also expect cats to become more strongly motivated by hunger after mouse eradication, increasing the attractiveness of food lures (Garvey et al. 2020). Therefore, traps or cameras placed near bait piles (see above) or other localised food sources (e.g. bird nesting sites) should have increased probabilities of detection / capture following mouse eradication.

Previous studies have used identification of individual animals through scat DNA to estimate population density by capture-mark-recapture analysis (e.g. Marks et al. 2009; Thompson et al. 2011; Fuller et al. 2016). The low numbers of 'recaptures' (scats that generated useable genetic profiles and matched to the same individual) in our data precluded this type of analysis. However, larger numbers of scats could provide a useful method of enumerating cats on the island in future. During the confirmation phase of the eradication, comparing DNA from any scats collected with DNA from previously trapped cats may help build confidence in confirming eradication success.

A previous trial (Russell et al. 2018) found that non-invasive hair sampling was ineffective in obtaining DNA samples from feral cats on Deas Head. This might partially reflect that sampling took place during a likely period of low cat abundance (numbers of mice were very low at this time; Russell et al. 2018). Placement of hair traps could also be improved using more recent knowledge of cat behaviour on Auckland Island. For example, trapping (Harper 2010) and GPS telemetry (Rodriguez-Recio et al. 2022) have revealed that cats spend much of their time in coastal forest and scrub, but traverse tussock to access seasonal prey.

Conclusions

Camera trapping should continue during the planning, operational, and confirmation phases of the cat eradication on Auckland Island. At a minimum, camera trapping should be in place prior to the eradication of mice (via toxic cereal bait; Russell et al. 2019; Horn et al. 2022), followed by a cat-specific vertebrate toxic agent (VTA) (Cox et al. 2022). This will show what level of knockdown has been achieved through primary (cat VTA) and secondary poisoning, and may provide

insight into behavioural changes as population density reduces. Ideally, cameras should be placed no further than 500 m apart in a soft grid. If resources do not permit this, an alternative may be to set cameras at every even-numbered grid point for 2 weeks, then at every odd-numbered grid point for 2 weeks. Throughout eradication operations, camera trapping should be supplemented by other detection methods, including scat searches with and without dogs.

Camera trapping and SECR modelling, as used in this study, should be conducted in other areas of the island, and repeated as cats are removed, to explore how spatial detection parameters change with population density. Ranging behaviour, and therefore detectability of individuals, is likely to increase as population density decreases, as was observed with cats on Dirk Hartog Island, Western Australia (D. Algar, pers. comm.). However, the detection network has to be designed for the worst-case scenario to minimise the possibility of cats with small home ranges avoiding detection. Therefore, we recommend 500 m spacing be used throughout.

Spatially explicit data from camera trapping, scat DNA and other sources could also be used for proof of eradication modelling (Anderson et al. 2013; Ward et al. 2016) during the confirmation phase of the operation.

Author contributions

RLS and PMJ designed the study and undertook fieldwork; ASG and TB-C analysed the data; and ASG wrote the manuscript with input from RLS, PMJ and TB-C.

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References

Anderson DP, Ramsey DSL, Nugent G, Bosson M 2013. A novel approach to assess the probability of disease eradication from a wild-animal reservoir host. Epidemiology and Infection 141: 1509–1521.

Bengsen AJ, Algar D, Ballard G, Buckmaster T, Comer S, Fleming PJS, Friend JA, Johnston M, McGregor H, Moseby K, Zewe F 2016. Feral cat home-range size varies predictably with landscape productivity and population density. Journal of Zoology 298: 112–120.

Birdlife International 2021. Country profile: New Zealand. http://www.birdlife.org/datazone/country/new-zealand (accessed 9 February 2021).

Bomford M, O'Brien P 1995. Eradication or control for vertebrate pests? Wildlife Society Bulletin 23: 249–255.

Butler JM, David VA, O'Brien SJ, Menotti-Raymond M 2002. The MeowPlex: a new DNA test using tetranucleotide STR markers for the domestic cat. Profiles in DNA 5: 7–10.

Campbell KJ, Harper G, Algar D, Hanson CC, Keitt BS, Robinson S 2011. Review of feral cat eradications on islands. In: Veitch CR, Clout MN eds. Turning the tide: the eradication of invasive species. Proceedings of the international conference on eradication of island invasives. Occasional Paper of the IUCN Species Survival Commission 28. Gland, Switzerland, IUCN. Pp. 37–46.

Cox F, Jacques P, Kirby-Crowe M, Ware J 2019. Maukahuka Pestfree Auckland Island – 2019 winter trials operational report. Internal Report – Department of Conservation. Wellington, Department of Conservation Te Papa Atawhai.

Cox FS, Jacques PM, Kirby-Crowe MS, Murphy EC 2022. Field palatability and degradation of a selection of feral cat bait matrices on Auckland Island. New Zealand Journal of Ecology 46: 3495.

Cruz J, Glen AS, Pech RP 2013. Modelling landscape-level numerical responses of predators to prey: the case of cats and rabbits. PLoS One 8: e73544.

Doherty TS, Glen AS, Nimmo DG, Ritchie EG, Dickman CR 2016. Invasive predators and global biodiversity loss. Proceedings of the National Academy of Sciences USA 113: 11261–11265.

Efford M 2004. Density estimation in live-trapping studies. Oikos 106: 598–610.

Efford MG 2012. DENSITY 5.0: software for spatially explicit capture-recapture. Dunedin, University of Otago.

Efford MG, Dawson DK, Robbins CS 2004. DENSITY: software for analysing capture–recapture data from passive detector arrays. Animal Biodiversity and Conservation 27: 217–228.

Falzon G, Meek PD, Vernes K 2014. Computer-assisted identification of small Australian mammals in camera trap imagery. In: Meek P, Fleming P eds. Camera trapping: wildlife management and research. Collingwood, CSIRO Publishing. Pp. 299–306.

Falzon G, Lawson C, Cheung KW, Vernes K, Ballard GA, Fleming PJS, Glen AS, Milne H, Mather-Zardain A, Meek PD 2020. ClassifyMe: a field-scouting software for the identification of wildlife in camera trap images. Animals 10: 58.

Fisher P, Algar D, Murphy E, Johnston M, Eason C 2015. How does cat behaviour influence the development and implementation of monitoring techniques and lethal control methods for feral cats? Applied Animal Behaviour Science 173: 88–96.

Fuller AK, Sutherland CS, Royle JA, Hare MP 2016. Estimating population density and connectivity of American mink using spatial capture–recapture. Ecological Applications 26: 1125–1135.

Garvey PM, Banks PB, Suraci JP, Bodey TW, Glen AS, Jones CJ, McArthur C, Norbury GL, Price CJ, Russell JC, Sih A 2020. Leveraging personality, motivations, and sensory cues for effective predator management. Trends in Ecology & Evolution 35: 990–1000.

Geyle HM, Stevens M, Duffy R, Greenwood L, Nimmo

DG, Sandow D, Thomas B, White J, Ritchie EG 2020. Evaluation of camera placement for detection of free-ranging carnivores; implications for assessing population changes. Ecological Solutions and Evidence 1: e12018.

Gillies CA, Pierce RJ 1999. Secondary poisoning of mammalian predators during possum and rodent control operations at Trounson Kauri Park, Northland, New Zealand. New Zealand Journal of Ecology 23: 183–192.

Glen AS, Cockburn S, Nichols M, Ekanayake J, Warburton B 2013. Optimising camera traps for monitoring small mammals. PLoS One 8: e67940.

Harper GA 2010. Diet of feral cats on subantarctic Auckland Island. New Zealand Journal of Ecology 34: 259–261.

Hohnen R, Berris K, Hodgens P, Mulvaney J, Florence B, Murphy BP, Legge SM, Dickman CR, Woinarski JCZ 2020. Pre-eradication assessment of feral cat density and population size across Kangaroo Island, South Australia. Wildlife Research 47: 669–676.

Horn SR, Sagar RL, Frank VK, Cox FS, Jacques PM, Ware J, Hanley-Nickolls R, Leask EP, MacDonald NL, Kirby-Crowe MS, Le Lievre ME, Broome KG 2022. The next frontier: assessing the feasibility of eradicating mammalian pests from Auckland Island. New Zealand Journal of Ecology 46: 3500.

IUCN 2017. New Zealand sub-antarctic islands. https://worldheritageoutlook.iucn.org/explore-sites/wdpaid/168239 (accessed 5 February 2021).

Johnson PN, Campbell DJ 1975. Vascular plants of the Auckland Islands. New Zealand Journal of Botany 13: 665–720.

Karanth KU 1995. Estimating tiger *Panthera tigris* populations from camera-trap data using capture-recapture models. Biological Conservation 71: 333–338.

Karanth KU, Nichols JD 1998. Estimation of tiger densities in India using photographic captures and recaptures. Ecology 79: 2852–2862.

Legge S, Murphy BP, McGregor H, Woinarski JCZ, Augusteyn J, Ballard G, Baseler M, Buckmaster T, Dickman CR, Doherty T, Edwards G, Eyre T, Fancourt BA, Ferguson D, Forsyth DM, Geary WL, Gentle M, Gillespie G, Greenwood L, Hohnen R, Hume S, Johnson CN, Maxwell M, McDonald PJ, Morris K, Moseby K, Newsome T, Nimmo D, Paltridge R, Ramsey D, Read J, Rendall A, Rich M, Ritchie E, Rowland J, Short J, Stokeld D, Sutherland DR, Wayne AF, Woodford L, Zewe F 2017. Enumerating a continental-scale threat: how many feral cats are in Australia? Biological Conservation 206: 293–303.

Longmire JL, Maltbie M, Baker RJ 1997. Use of 'lysis buffer' in DNA isolation and its implication for museum collections. Occasional Papers, The Museum, Texas Tech University 163: 1–3.

Marks CA, Gigliotti F, McPhee S, Piggott MP, Taylor A, Glen AS 2009. DNA genotypes reveal red fox (*Vulpes vulpes*) abundance, response to lethal control and limitations of contemporary survey techniques. Wildlife Research 36: 647–658.

Medina FM, Bonnaud E, Vidal E, Tershy BR, Zavaleta ES, Donlan CJ, Keitt BS, Le Corre M, Horwarth SV, Nogales M 2011. A global review of the impacts of invasive cats on island endangered vertebrates. Global Change Biology 17: 3503–3510.

Meek PD, Ballard G-A, Fleming PJS, Schaefer M, Williams W, Falzon G 2014. Camera traps can be heard and seen by animals. PLoS One 9: e110832.

Miskelly CM, Elliot GP, Parker GC, Rexer-Huber K, Russ RB, Taylor RH, Tennyson AJD, Walker KJ 2020. Birds of the Auckland Islands, New Zealand subantarctic. Notornis 67: 59–151.

Nathan HW 2016. Detection probability of invasive ship rats: biological causation and management implications. Unpublished PhD thesis. Auckland, University of Auckland.

Nichols M, Ross J, Glen AS, Paterson A 2019. An evaluation of systematic versus strategically-placed camera traps for monitoring feral cats in New Zealand. Animals 9: 687.

Norouzzadeh MS, Nguyen A, Kosmala M, Swanson A, Palmer MS, Packer C, Clune J 2018. Automatically identifying, counting, and describing wild animals in camera-trap images with deep learning. Proceedings of the National Academy of Sciences 115: E5716–E5725.

Otis DL, Burnham KP, White GC, Anderson DR 1978. Statisitical inference from capture data on closed animal populations. Wildlife Monographs 62: 1–135.

Peakall R, Smouse PE 2006. GENALEX 6: genetic analysis in Excel. Population genetic software for teaching and research. Molecular Ecology Notes 6: 288–295.

Peakall R, Smouse PE 2012. GenAlEx 6.5: genetic analysis in Excel. Population genetic software for teaching and research-an update. Bioinformatics 28: 2537–2539.

Recio MR, Mathieu R, Maloney R, Seddon PJ 2010. First results of feral cats (*Felis catus*) monitored with GPS collars in New Zealand. New Zealand Journal of Ecology 34: 288–296.

Recio MR, Seddon PJ 2013. Understanding determinants of home range behaviour of feral cats as introduced apex predators in insular ecosystems: a spatial approach. Behavioral Ecology and Sociobiology 67: 1971–1981.

Rodriguez-Recio M, Sagar RL, Chan L, Cox FS, Jacques PM 2022. Spatial ecology meets eradication of feral cats on Auckland Island. New Zealand Journal of Ecology 46: 3493.

Russell JC, Binnie HR, Oh J, Anderson DP, Samaniego-Herrera A 2017. Optimizing confirmation of invasive species eradication with rapid eradication assessment. Journal of Applied Ecology 54: 160–169.

Russell JC, Horn SR, Harper GA, McClelland P 2018. Survey of introduced mammals and invertebrates on Auckland Island, March–April 2015. DOC Research and Development Series 352. Wellington, Department of Conservation. 17 p.

Russell JC, Griffiths R, Bannister WM, Le Lievre ME, Cox FS, Horn SR 2019. Mouse bait uptake and availability trials on Falla Pennisula, Auckland Island. DOC Research and Development Series 363. Wellington, Department of Conservation. 11 p.

Russell JC, Horn SR, Broome KG 2022. Restoration of New Zealand subantarctic islands. New Zealand Journal of Ecology 46: 3482.

Sagar RL, Cox FS, Horn SR, Russell JC 2022. Population trends of mice during tussock mast seeding on Auckland Island. New Zealand Journal of Ecology 46: 3497.

Samaniego-Herrera A, Anderson DP, Parkes JP, Aguirre-Muñoz A 2013. Rapid assessment of rat eradication after aerial baiting. Journal of Applied Ecology 50: 1415–1421.

Thompson CM, Royle JA, Garner JD 2011. A framework for inference about carnivore density from unstructured spatial sampling of scat using detector dogs. Journal of Wildlife Management 76: 863–871.

Ward DF, Anderson DP, Barron MC 2016. Using spatially

explicit surveillance models to provide confidence in the eradication of an invasive ant. Scientific Reports 6: 34953.
World Heritage Convention 1998. New Zealand Sub-Antarctic Islands. http://whc.unesco.org/en/list/877/ (accessed 2 March 2018).

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Supplementary Material

Additional supporting information may be found in the online version of this article:

Appendix S1. Genetic profiling data from scats and mouth swabs collected from feral cats (*Felis catus*) on Auckland Island, New Zealand subantarctic region.

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