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Mouse bait uptake and availability trials on Falla Peninsula, Auckland Island

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Abstract

Auckland Island is the last of the New Zealand subantarctic islands to have introduced mammals, including pigs (*Sus scrofa*), cats (*Felis catus*) and mice (*Mus musculus*), and its large size makes mouse eradication logistically challenging. Therefore, it has been suggested that a lower bait sowing rate than is typically used for island rodent eradications should be applied and that eradication should be undertaken during summer, despite this being the rodent breeding season and alternative food being more readily available. In February 2019, we evaluated the effectiveness of this proposal by applying 4 kg/ha of non-toxic cereal bait containing the fluorescent dye pyranine across Falla Peninsula, Auckland Island, and trapping mice for 7 days using 13 live and kill trapping grids to determine their population status, density, home range size and bait uptake. In addition, bait availability was concurrently monitored along 30 transects. Mice were initially neophobic towards the trapping devices and thereafter were captured at low rates across both trap types. Mouse density varied greatly across the grids (range = 26.4–105.6 mice/ha) and was independent of habitat type, and the home range radius of mice was estimated to be 34 m, although this was based on only one grid in coastal forest, where there was a medium density of mice. Bait was still available on the ground in a potentially palatable condition at a density of >1.2 kg/ha at 9 nights after bait application. Only 2 of 232 mice (<1%) that were caught within the treatment area showed no evidence of consuming bait, both of which were very small juveniles caught in tussock grassland. Therefore, we believe they would have been vulnerable to a second application of bait approximately 4 weeks later once they were mature.

Keywords: conservation, eradication, mice, rodent, bait application, pyranine, Auckland Island, subantarctic

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1. Introduction

The eradication of introduced mammals is commonly undertaken as a first step towards the ecological restoration of islands around the world (Russell & Holmes 2015; Jones et al. 2016). Mammals have been eradicated from New Zealand's offshore islands for over 100 years, with an increased focus on this during the last 50 years (Towns & Broome 2003; Clout & Russell 2006; Russell & Broome 2016), resulting in approximately one-third of New Zealand's islands now being free of all invasive mammals (Towns et al. 2013) and a keen interest in removing these species from additional islands (Russell et al. 2015).

New Zealand's subantarctic islands are listed as a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site, and Auckland Island (46 000 ha) is the last island in the region to have introduced mammals. Pigs (*Sus scrofa*), cats (*Felis catus*) and mice (*Mus musculus*) have been present on the main island since its discovery by Europeans in 1806 and have had a devastating impact on its fauna and flora (Russell et al. in press). Consequently, the eradication of these invasive species is being pursued and the feasibility of such a large-scale project is currently being evaluated by the New Zealand Department of Conservation (DOC).

On the main islands of New Zealand, animal control operations with 1080 have moved towards using the lowest possible sowing rate to achieve biodiversity or disease management outcomes (Nugent et al. 2011; Nugent & Morriss 2013). However, managers generally opt to use higher sowing rates for eradications with brodifacoum on islands to minimise the risk of eradication failure (Pott et al. 2015). For example, ship rats (*Rattus rattus*) and mice were eradicated from 13 182-ha Macquarie Island in May to June 2011 using two applications of bait at sowing rates of 12–22 kg/ha (Springer 2016), and mice were eradicated from 2025-ha Antipodes Island in June to July 2016 using two applications of bait at sowing rates of 16 kg/ha and 8 kg/ha respectively (Horn et al. 2019). Furthermore, rats and mice were eradicated from independent eradication units on South Georgia Island that together covered 96 800 ha using a multi-year phased approach that involved one application at a rate of 2–6.5 kg/ha for Norway rats (*Rattus norvegicus*) in March 2011, and one application at a rate of 1.5–5 kg/ha for Norway rats and 10 kg/ha for mice in both March–May 2013 and February–March 2015 (Martin & Richardson 2019).

DOC's current agreed best practice for the eradication of mice on islands is two applications of cereal bait containing brodifacoum at a rate of 8 kg/ha (Broome et al. 2019), which would pose significant logistical challenges for the proposed eradication of mice from Auckland Island due to the large amount of bait that would need to be transported and applied by aerial delivery within the available weather windows to ensure its exposure to every single mouse. However, rodent eradications on islands near to Auckland Island have previously been achieved using lower sowing rates. For example, Norway rats were eradicated from 11 300-ha Campbell Island/Motu Ihupuku in June 2001 using one application of bait at a sowing rate of 6 kg/ha (McClelland 2011), and mice were eradicated from 710-ha Enderby Island in February 1993 using two applications of bait at a sowing rate of 5 kg/ha (which was increased to 10 kg/ha over 100 ha during the first drop and over 20 ha during the second drop) (Torr 2002). Furthermore, previous studies on Auckland Island have revealed that the population density of mice is generally low with associated low capture rates (see Russell et al. (2018) for a summary). Therefore, it is possible that mice could be eradicated from Auckland Island using a low bait sowing rate.

The aim of this study was to examine the feasibility of using a low sowing rate on Auckland Island and applying this during the summer, when there are longer daylight hours and more settled weather, and thus an increased opportunity for helicopter operations to be completed in one season.

2. Methods

2.1 Study site

This study was carried out on Falla Peninsula on the east coast of Auckland Island (Fig. 1). The 951-ha peninsula has an elevation of 284 m and narrows to a 258-m-wide bottleneck from coast to coast, making it a suitable setting for minimising the risk of mouse immigration, which was important as previous bait uptake studies have been unable to rule this out as a potential factor explaining the lack of bait uptake by some individuals. It was also necessary to remove all pigs from the peninsula, as a single pig could have consumed enough bait to prevent one or more mice from being exposed. Therefore, this was achieved by erecting a temporary electric fence across the narrowest point of the peninsula to discourage and indicate reinvasion and then undertaking aerial hunting aided by a thermal imaging camera and a team of six ground hunters with dogs in January 2019.

2.2 Trapping grids and transects

In February 2019, 12 grids of 7 × 7 traps were established around Falla Peninsula spaced at 10-m intervals across three habitats: coastal forest dominated by rātā (*Metrosideros umbellata*), scrub dominated by dracophyllum (*Dracophyllum longifolium*) and rātā around the coast and myrsine (*Myrsine divaricata*) on slopes, and tussock (*Chionochloa antarctica*) on the tops (Table 1; Fig. 1).

Figure 1. Locations of the mouse (*Mus musculus*) trapping grids, transects and bait application area on Falla Peninsula, Auckland Island. Note that an additional trapping grid was located in tussock to the west of this area.

Table 1. Numbers of live and kill trapping grids and tracking tunnel and bait availability transects in each habitat on Falla Peninsula, Auckland Island.

HABITAT	LIVE	KILL	TRANSECT
Coastal forest	1	5	2
Scrub	1	2	2
Tussock	2	2	2

Three live trapping grids (using Longworth traps) were initially established adjacent to Falla Peninsula in an area that would not be exposed to the bait treatment. These were run for 7 nights prior to bait application, with all mice that were captured on the final 2 nights being euthanised by cervical dislocation. At the same time, nine kill trapping grids (using Victor traps) were established on Falla Peninsula at least 500 m from the untreated land to be opened following bait application. The first live trapping grid that was established in tussock (west of the map in Fig. 1) did not catch any mice, so a second live trapping grid was established in tussock on Falla Peninsula to be run concurrently with the kill traps.

In addition, five 1-m-wide and 25-m-long subtransects were established at 25-m intervals along each of six 250-m-long transects across the three habitats (n = 30; Table 1) to examine bait availability. Ten tracking tunnels were also placed along each of the six transects at 25-m intervals in December 2018 (n = 60) and run three times for 1 night each on 6 December 2018, 14 January 2019 and 6 February 2019 to establish baseline tracking rates of mice.

2.3 Bait trial

The proposed eradication treatment being tested was two aerial applications of bait at a sowing rate of 4 kg/ha with twice the sowing rate applied within 40 m of the coast through the use of a deflector shield and an additional bait application of 2 kg/ha between 40 m and 110 m inland of the coast and on all slopes >50°. This treatment was simulated using a single application of non-toxic Pestoff™ 20R cereal pellets containing the fluorescent dye pyranine (0.2%) at the prescribed rates. The pellets were aerially applied in fine weather along flight lines that were 45 m apart to achieve a 50% overlap of 90-m baiting swaths across the whole of Falla Peninsula. Bait application was completed on 6 February 2019 over a period of 8 h, which included calibration of the low sowing rate (Fig. 1).

The kill trapping grids were opened 2 days following bait delivery and trapping was undertaken for the following 7 nights (i.e. on nights 3–9 following bait delivery) across all kill trapping grids, as well as on the second tussock live trapping grid on Falla Peninsula (see section 2.2). All mice that were captured on these grids were considered to have been exposed to the bait application. In addition, bait availability was monitored over the same period by placing five c. 2-g bait pellets along each of the twenty-five 1-m-long subtransects to simulate an average sowing rate of 4 kg/ha. The location of each individual bait was marked by placing a flag in the ground nearby, and daily checks were undertaken during which the number of bait pellets remaining was recorded to the nearest half and the bait condition was assessed using the Craddock scale (Craddock 2003).

2.4 Post-mortem analysis

All mice that were killed were necropsied and their sex, reproductive status (presence of descended testes, lactating nipples or embryos), weight (to the nearest 0.5 g), head–body length and total length (to the nearest 1 mm) were recorded. In addition, the presence of the fluorescent dye pyranine was assessed for mice that were caught in the bait treatment area by using an ultraviolet (UV) light to search for evidence of pyranine externally followed by internal dissection if this was inconclusive. For those mice that were captured in the second tussock live trapping grid, both the mice and trap contents were inspected for pyranine using a UV torch and then cleaned.

2.5 Data analysis

The density of mice across all trapping grids was estimated using spatially explicit capture–recapture models with half-normal detection curves fitted in the package secr in the R software (Borchers & Efford 2008). Known deaths (on kill trapping grids) or accidental deaths (on live

trapping grids) were incorporated into these models. Because no recaptures could occur on the kill trapping grids, the scale of movement (σ) was only estimated from the live trapping grids and it was assumed that the ranging behaviour was the same between the live and kill trapping grids. Here, 2σ was considered a proxy for the home range radius and the 95% area of activity was calculated as $\pi(2.45\sigma)^2$. Since different trap types were used in the live and kill trapping grids, the capture probability at the centre of the home range (g_0) was expected to differ between the two grid types. Because different age classes (i.e. adult versus juvenile) could not be clearly distinguished, we used body weight on first capture as a proxy for age. Therefore, the spatially explicit capture–recapture models incorporated the session covariates 'session', 'habitat' and 'trap type' and the individual covariates 'sex' and 'weight' and were compared using Akaike's information criterion (AIC).

Conditional likelihood models were used to incorporate the individual covariates, but neither sex nor weight were included in the preferred model (AIC model weight < 5%). Therefore, when calculating g_0, we focused on the full likelihood models in which density was estimated directly. However, both mouse density and the device type capture probability were partially confounded in our experimental design (i.e. we were unable to determine whether there were more mice in the kill trapping grids or the kill traps had higher capture probabilities), so we were unable to reliably estimate these without making an additional assumption. Therefore, we first constructed a model in which density was assumed to be constant within each habitat type (and hence across the live and kill trapping grids within the same habitat), allowing us to distinguish the capture probability between trap types.

Differences in the sex ratio and body size of mice among habitats and over time were also tested using linear models implemented in the R software.

3. Results

3.1 Mouse population parameters

During the trapping period, we captured a total of 274 individual mice – 42 in the live trapping grids (24 of which were necropsied but excluded from further analysis) and 232 in the kill trapping grids (all of which were necropsied). Trapping rates in the kill traps increased across the 7 days of trapping from 24 mice on the first 2 nights to 42 on the last night (with 441 trap nights per night). Neither the size nor the weight of the mice that were captured on the kill trapping grids significantly varied among habitats or over time (all $P > 0.05$), so all morphological measurements were pooled across kill trapping grids for further analysis (Table 2; Fig. 2).

The body weights of the mice were normally distributed, indicating that we captured all age and size classes. Most male mice that were > 15 g and female mice that were > 20 g (which equated to 40% of females) were reproductively active, having obvious testes and being pregnant or having lactating nipples, respectively. At the extremes, 2.5% of mice weighed ≤ 10 g and 12% weighed

Table 2. Weights and lengths of adult mice (*Mus musculus*) trapped on the kill trapping grids on Falla Peninsula, Auckland Island, in February 2019. Values are means with the ranges in parentheses. Age classes could not be distinguished. Adults are defined as > 72 mm body length. M, male; F, female (including any embryos).

SEX	*n*	WEIGHT (g)	HEAD–BODY LENGTH (mm)	TOTAL LENGTH (mm)
M	137	22.7 (10.5–33.0)	91 (72–103)	172 (137–203)
F	83	22.4 (11.5–41.0)	88 (73–106)	168 (141–200)

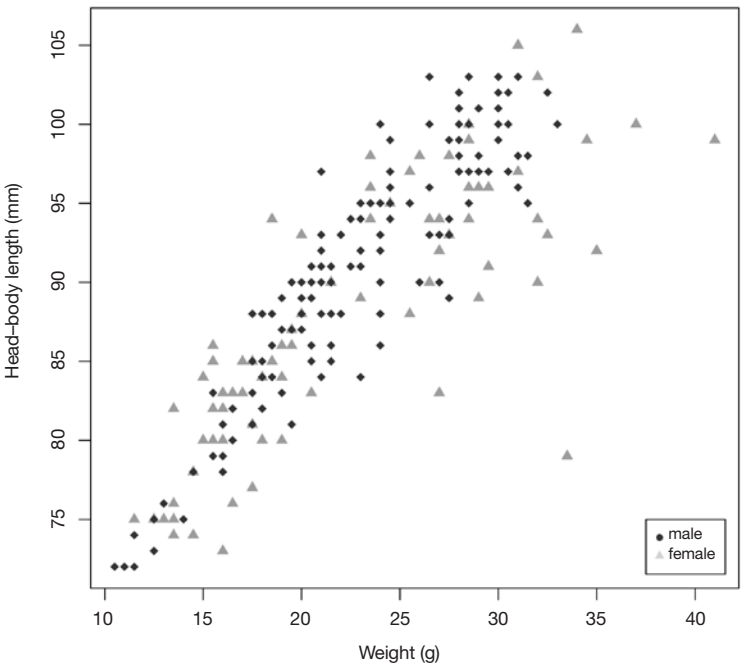

Figure 2. Head–body length (mm) versus weight (g) of adult mice (*Mus musculus*) trapped on the kill trapping grids on Falla Peninsula, Auckland Island, in February 2019. Adults are defined as >72 mm body length. Black diamonds, males; grey triangles, females (including any embryos).

≥30 g, with mice from both these extremes usually being found in tussock habitat. The sex ratio of trapped mice was male biased at a ratio of approximately 2:1 males:females (M:F) in both the coastal forest (74 M : 44 F) and scrub (43 M : 20 F) but was even in the tussock habitat (28 M : 23 F).

Only 12 mice were captured more than once in the live trapping grids, equating to a total of 16 recaptures: ten on the coastal live trapping grid and two on the second tussock live trapping grid. Therefore, a single pooled σ across all grids was assumed in all models. However, it should be noted that although the estimate of σ was reliable (17.19; 95% confidence interval (CI) = 12.25–24.12), this was predominantly based on only one trapping grid in one habitat (coastal forest). The model in which it was assumed that density was constant within habitats showed that there was only a small difference in capture probability between trap types (Longworth: 0.006; Victor: 0.009). The final model estimated mouse density for each grid while holding g_0 and σ constant. This showed that the density estimates varied widely across the grids, ranging from 26.4 to 105.6 mice/ha, with no significant difference among habitats ($P > 0.05$). Based on the home range radius, the average home range of mice on Auckland Island is approximately 0.56 ha.

Tracking cards in tunnels recorded 0% tracking when they were run on the same day as installation in December but >85% when tracking was repeated using the same tunnels in January and February (Table 3).

Table 3. Tracking rates of mice (*Mus musculus*) over 1 night in tunnels that were set along two transects in each habitat on Falla Peninsula, Auckland Island.

HABITAT	DECEMBER (%)	JANUARY (%)	FEBRUARY (%)
Coastal forest	0	85	95
Scrub	0	95	100
Tussock	0	90	100

3.2 Bait uptake and availability

Of the 244 mice that were trapped in the bait treatment area (kill trapping grids + second tussock live trapping grid), only two individuals (< 0.1%) had an absence of pyranine indicating that they had not consumed bait. Both of these mice were very small juveniles (< 10 g) and were captured in the tussock habitat on nights 4 and 9 following bait application.

Bait availability declined slowly but linearly over 9 nights ($P < 0.001$) from 4 kg/ha to an average of 2.67 kg/ha, with a minimum of 1.2 kg/ha and a 99% lower CI limit of 0.6 kg/ha (Fig. 3). Following best practice, we had 2 clear nights after bait application, but this was then followed by a substantial rain event of 119 mm between nights 3 and 5. However, the baits maintained their consistency during this time based on a visual assessment using the Craddock scale (Craddock 2003), scoring an average of 3 (on a scale of 1–6) after 9 nights, although they were likely to have started to become less palatable by the end of the monitoring period, as 129 mm of rain fell over the 9 nights.

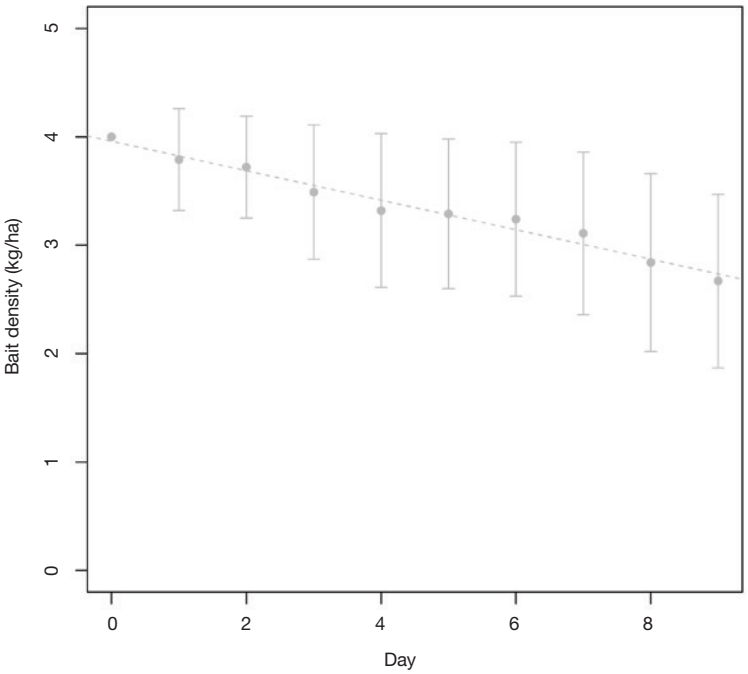

Figure 3. Bait availability over 9 nights following bait application. Error bars are standard errors of the mean.

4. Discussion

At the time of this trial, the mice on Auckland Island were in the middle of their summer breeding period. However, the lack of a clear recruitment pulse suggested that the population had asynchronous breeding that commenced in early summer. Although the densities of mice varied greatly across our trapping grids, they could be considered high for Auckland Island, especially when compared with trapping efforts that were carried out in autumn 2015 (Russell et al. 2018). This is likely due to the present trial corresponding with a tussock masting event, which only occurs every 4–5 years on average and was one of the strongest in decades. Similarly, previous trapping that was undertaken in winter 2007 was also suspected to have followed a mast seeding event (Harper 2010). Although the average body size of the mice that were trapped on Auckland Island was not exceptional, a small number of very large individuals were captured. These mice were larger than those that were found on Antipodes Island (Russell 2012), where they have not been present for as long, and were approaching the size of those on Gough Island, where mouse gigantism has previously been recorded (Cuthbert et al. 2016).

The final model assumed that density varied independently across all grids and found substantial inter-site variation in mouse density that was not obviously related to habitat type. In addition, because of our low recapture rates in the live trapping grids, we were only able to obtain a reliable estimate of σ, and hence home range size, for the coastal forest habitat. Based on the estimated average home range of just over half a hectare, each mouse's home range should contain over 1000 baits at an application rate of 4 kg/ha. However, juvenile mice are known to have smaller home ranges than adults (Russell 2012) and there would be substantial home range overlap among individuals that would lead to bait competition.

The mice on Auckland Island appeared to exhibit higher levels of wariness than other populations (Clapperton 2006), particularly in relation to the time since device installation. Tracking tunnels that were installed and run on the same day in December, which is contrary to best practice, did not detect any mice but subsequently tracked much higher rates later in the season. Therefore, this may partially explain why the kill trapping grids that were installed prior to being set had relatively and consistently higher trapping rates than the live trapping grids, which were also opened on the same day as installation. Two pigs also broke through the fence and entered our trial area on the peninsula on 10 February 2019 during the week of kill trapping. One of these pigs was observed to have faeces containing pyranine on 10 February, while the second was sighted on 12 February. Although one of these pigs destroyed three traps in the southern coastal forest trapping grid on the night of 13 February, neither is assumed to have otherwise affected this study.

Two of the 244 mice that were captured in our trial showed no evidence of having consumed bait. Similarly, on Gough Island, 2.5% of mice failed to consume biomarked bait at application rates of 15.7 and 7.9 kg/ha, although this was in a very small study area and was potentially confounded by immigration from outside the bait application treatment area (Wanless et al. 2008), with a subsequent study finding 100% bait uptake by resident mice at an application rate of 16 kg/ha (Cuthbert et al. 2011). By contrast, there was 100% bait uptake on Antipodes Island at an application rate of 16 kg/ha (Elliott et al. 2015) and on Steeple Jason Island at an application rate of 7.5–7.7 kg/ha (Rexer-Huber et al. 2013).

There are a number of possible explanations for why these very young mice did not take the bait, which are presented here in no particular order. First, these mice may have only very recently emerged from the nest and thus had fewer nights of exposure to bait before being trapped. Second, these mice may have had smaller home ranges than larger mice, reducing the likelihood that they would encounter bait. Third, these mice may have been sub-dominant and so access to bait may have been restricted by dominant individuals. Fourth, these mice may not have yet

learnt about appropriate food choices, especially if their mothers had been killed earlier in the trapping operation. We cannot determine which of these non-mutually exclusive hypotheses is more likely and note that the majority of mice within this size class had consumed bait.

While the proposed bait application sowing rate of 4 kg/ha is low, it is not unprecedented. A reinvading population of mice was successfully eradicated from 88-ha Motuareronui / Adele Island, Abel Tasman National Park, in August 2017 using a single application at a rate of 3 kg/ha, and mice were successfully eradicated from Enderby Island in summer using two applications at rates of 5 kg/ha (with a higher sowing rate of 10 kg/ha over 100 ha) (Torr 2002). Although we did not undertake a second bait application in the present trial because it is generally precluded in bait uptake studied where lethal sampling is necessary, we suspect that a second round of bait application at a sufficient interval after the first (e.g. 4 weeks) would allow any very young mice that were not exposed to bait during the first application to mature such that they would consume bait following the second application. Furthermore, this 4-week period should still be soon enough after the first application to avoid the complications of increased food resources that can occur when there are eradication survivors (Kappes et al. 2019) and to prevent those juveniles that survived from breeding themselves (Nathan et al. 2015). Our findings also suggest that we require a greater understanding of the population biology of rodents if we intend to eradicate them when they are reproductively active. This has not previously been an issue for mouse eradications, which are typically carried out in winter (Elliott et al. 2015), but is increasingly being recognised as a research issue for eradications in the tropics, where rodents breed all year round (Russell & Holmes 2015).

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