A successful mouse eradication explained by site-specific population data

J.W.B. MacKay1, E.C. Murphy2, S.H. Anderson1, J.C. Russell1, M.E. Hauber3,4, D.J. Wilson4, and M.N. Clout1

1 School of Biological Sciences, University of Auckland, Private Bag 92019, Auckland, New Zealand.
2 Research & Development, Department of Conservation, Christchurch, New Zealand.
3 Department of Psychology, Hunter College of the City University of New York, 695 Park Ave, New York, NY 10065, USA.
4 Landcare Research, Private Bag 1930, Dunedin 9054, New Zealand.

Abstract Invasive rodents have been responsible for the extinction of many species on islands. House mouse (Mus musculus) eradication attempts have been less successful than introduced rat (Rattus spp.) eradication attempts and research is needed to identify the reasons for this disparity. We studied, and successfully eradicated, a mouse population on a small (6 ha) island in northern New Zealand in an attempt to characterise possible behavioural factors influencing eradication outcome. We monitored pre-eradication mouse movements with radio-tracking and trapping to provide guidance on grid-spacing for bait stations, which are a common tool used in rodent eradication and reinvasion monitoring protocols. Mouse densities on the island were estimated during three capture-mark-recapture (CMR) sessions in January, March and May 2008. Mice were then trapped almost to extinction in August 2008 and poison baits were used to eradicate the survivors. Removal trapping data combined with WaxTag interference rates provided a final density estimate of mice in winter (August in New Zealand), the period when most eradication is attempted. Densities on the island ranged from 8.8-19.2 mice/ha, with home ranges varying from 0.15-0.48 ha. Eradication success was monitored intensively using tracking tunnels and WaxTags and was confirmed in December 2008 using a trained rodent monitoring dog. Information gathered during this study can be used to make recommendations to improve the success of future mouse eradication attempts. One of the key recommendations is to identify areas of complex habitat (such as dense ground cover) where mice may not come into contact with poison and adjust eradication methods to specifically target such areas.

Keywords: House mouse, Mus musculus, density estimate, home range estimate

INTRODUCTION

The house mouse (Rodentia: Mus musculus) became commensal early in human history (Cuéchi and Vigne 2006), was then widely spread by human activity (Cuéchi 2008; Searle et al. 2009), and is now one of the most widely distributed mammal species (Rowe 1973; Pocock et al. 2005). House mice (hereafter: mice) spread disease (Langton et al. 2001), consume cultivated crops (Stenseth et al. 2003), and prey on native fauna such as birds, lizards, and invertebrates (Howald et al. 2005; St Clair 2011). Some of the worst impacts of mice on native ecosystems are seen on islands where native fauna and flora evolved without mammals (Diamond 1989; Angel et al. 2009).

There have been numerous attempts to eradicate mice. However, the global failure rate for these attempts on islands is 38% (MacKay et al. 2007), compared with only 5% for Norway rats (Rattus norvegicus) and 8% for ship rats (R. rattus) (Howald et al. 2007). These failures raise the question: why are mice harder to eradicate than rats? Our study was designed to investigate some of the possible behavioural reasons for these failed eradications.

New Zealand is an oceanic archipelago of 297 islands (≥5ha) inhabited by a native flora and fauna that evolved in the absence of terrestrial mammals (Atkinson and Cameron 1993). Mice first arrived in New Zealand in 1824 following a shipwreck and are now present across the whole country (Ruscoe and Murphy 2005) after multiple colonisation events from diverse sources (Searle et al. 2009). Because mice in New Zealand islands have detrimental impacts on native flora and fauna (e.g., Newman 1994; Miller and Miller 1995; Miller and Webb 2001; Wilson et al. 2007b), there have been 28 eradication attempts (Howald 2009; MacKay et al. 2007), 16 of which succeeded and 12 failed (MacKay et al. 2007).

Information about mouse populations on New Zealand islands is scarce in the literature. There are few estimates of mouse population densities (White and King 2006) on ‘mainland’ New Zealand or on its offshore islands, and home range sizes and nightly movement distances have rarely been studied. This paper describes the first detailed study of a population of house mice during an eradication on a small New Zealand island. We used trapping and radio-tracking to determine densities and movements throughout the year and also collected demographic information about the population for comparison with other studies. These data were then employed to design a successful mouse eradication using trapping and poisoning during the Austral winter, when mouse eradications are typically attempted.

METHODS

This study took place on Saddle (Te Haupa) Island in the Hauraki Gulf, New Zealand (36˚31’S, 174˚47’E; Fig. 1). The island is long and narrow (650 m by 50–150 m wide; C. 6 ha), has steep cliffs around the littoral area, and reaches 35 m above sea level. Norway rats were eradicated from the island by poisoning in 1989 (Howald et al. 2007) and mice were detected shortly afterwards (Tennyson and...
Table 1 Summary of trapping visits to Saddle Island, New Zealand. CMR=Capture-mark-recapture

<table>
<thead>
<tr>
<th>Month</th>
<th>No. trap-nights</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>5</td>
<td>CMR</td>
</tr>
<tr>
<td>March</td>
<td>4</td>
<td>CMR</td>
</tr>
<tr>
<td>May</td>
<td>4</td>
<td>CMR</td>
</tr>
<tr>
<td>July</td>
<td>1 (4 nights of telemetry)</td>
<td>Radio-tracking</td>
</tr>
<tr>
<td>August</td>
<td>4</td>
<td>Removal trapping</td>
</tr>
</tbody>
</table>

Taylor (1999). It is not known whether mice were present concurrently with Norway rats or invaded following Norway rat eradication. Further details of the island's history, fauna and flora are provided by Tennyson and Taylor (1999).

We established a grid of 62 stations (Fig. 1) at 25 m intervals on the island in October 2007. This grid was used to place traps for live capture, stations for poison bait, other devices for monitoring mouse activity, and as an aid for navigation during night work. A Longworth live capture mouse trap (Chitty and Kempson 1949) was set at each station five times between January and August 2008 (Table 1). Each trap contained Dacron fibre for bedding, with peanut butter on a carrot disk and oats as bait.

Capture-Mark-Recapture protocol

Traps were checked daily during each four- or five-night Capture-Mark-Recapture (CMR) session. Captured mice were weighed, sexed, and had a numbered tag (National Band and Tag Co., Newport, Kentucky, USA) attached to each ear. After tagging, the animals were released at their capture site. The tag numbers of previously marked animals were recorded and the presence of torn ears was noted. Lost tags were replaced only when missing from both ears.

Radio-tracking

Traps were set to catch mice for fitting with radio collars on 16 July 2008 (Table 1) and captured animals were processed according to the protocol above. Only mice >12 g were used for telemetry. At this weight the 0.6 g transmitters were ≤5% of mouse body weight and therefore unlikely to affect mouse behaviour (Pouliquen et al. 1990, Mikesci and Drickamer 1992). From the captured animals, four males and two females were selected for radio-tracking according to their capture location, to achieve a spread of animals across the whole island. Six animals were the maximum number that could be effectively tracked simultaneously. Animals were transferred to a plastic bag and anaesthetised with a piece of cotton wool soaked in anaesthetic. Mice were then weighed, sexed, and any ear tags present on 16 July 2008 (Table 1) and captured animals were euthanased by cervical dislocation.

Table 2 Monitoring visits to Saddle Island following poison application.

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>19/08/08</td>
<td>Poison bait distributed on the island in bait stations and hand-spread on cliffs.</td>
</tr>
<tr>
<td>16/09/08</td>
<td>Poison bait stations checked and location of chewed blocks recorded; WaxTags and ink tracking tunnels baited with chocolate nut spread deployed on alternate lines across island.</td>
</tr>
<tr>
<td>18/09/08</td>
<td>Detection devices checked; wax poison block placed in each tracking tunnel giving 31 more bait stations. Total bait density including pellets and blocks approximately 4 kg/ha.</td>
</tr>
<tr>
<td>26/09/08</td>
<td>Poison bait stations removed from island; WaxTags and tracking tunnels left in place; poison in tracking tunnels left in place. Eradication confirmation with trained rodent dog Occi; poison removed from tracking tunnels; traps set around small area of possible mouse scent (since considered to be a response by the dog to skink scent (M. Ritchie pers. comm. 19/01/10))</td>
</tr>
<tr>
<td>03/12/08</td>
<td>Traps and devices checked</td>
</tr>
<tr>
<td>15/12/08</td>
<td></td>
</tr>
</tbody>
</table>
Island invasives: eradication and management

to shelter the poison blocks but to allow easy access to mice. Wax blocks in bait stations were not replaced and were removed from the island on 26 September 2009 (Table 2). Total bait density of wax blocks and pellets was approximately 4 kg/ha. Following poison application, the island was intensively checked (Table 2) using 31 ink-based footprint tracking tunnels (Gotcha Traps, Warkworth, New Zealand and Connovation Ltd., Auckland, New Zealand) and 31 WaxTags set at trap stations on alternate lines across the island. Two unsecured poison blocks were placed in each tracking tunnel on 18 September 2008 to create 31 further bait stations. These blocks were left in place until 3 December 2008 when the island was checked by a Department of Conservation rodent detection dog ‘Occi’ (handler: Miriam Ritchie). Rodent detection dogs are commonly used in New Zealand and around the world to aid in the confirmation of eradication success or failure (Gsell et al. 2010).

Analysis

Four estimates of mouse population size on the island were calculated using two methods. Estimates for January, March, and May were calculated using closed-capture models in program MARK (White and Burnham 1999). Trapping data from August were analysed using a removal trapping catch effort method augmented by independent index data from WaxTags to reduce bias (Russell et al. 2009). For this augmented removal estimate we assumed multiple mice could interfere with a single WaxTag. Analysis in MARK followed Wilson et al. (2007a), with three covariates used to model heterogeneity in the data. Two categorical variables (sex and age) and one continuous variable (weight) were used as covariates in four models incorporating both behavioural response to trapping and variation in capture probability between trap nights. Mice are difficult to classify as adults or juveniles based on external characteristics, so we classified animals weighing less than 12 g as juveniles. This weight was chosen based on the mean weight of non-fecund mice recorded during a study at nearby Tawharanui Open Sanctuary (Goldwater 2007). Six covariate combinations (none; sex; weight; age; sex and weight; sex and age) were tested for each model. The model-averaging procedure in MARK was used to calculate population estimates based on all models except those where parameters were identified as singular or standard errors of estimates were very large or zero. Confidence limits (95%) of the averaged estimate were adjusted to take into account the actual number of mice caught in each trapping session (White et al. 1999). Population estimates were converted into density estimates (mice/ha) by dividing the estimate by 6 ha, the area of the island. MARK was also used to obtain a rudimentary survival estimate. Capture data were pooled for all sessions (except the single night of trapping in July) to estimate monthly survival, maximum lifetime and mean lifetime.

Information on animal home ranges and ranging behaviour was collected through trapping records and radio-tracking. Home ranges were calculated for all individuals that were trapped five or more times, and trapping records for the radio-tracked individuals were combined with radio-tracking data to calculate home-range sizes for these animals. Average movements were described from radio-tracking data alone. Movement information was compared to habitat observations from the island to investigate whether different habitat affected movements. Home ranges were estimated using harmonic mean estimation in Ranges7 (South et al. 2005). We estimated a 95% range core to avoid outlying fixes biasing the range size estimate upwards (Moro and Morris 2000). Ranges7 was also used to summarise animal movements and to estimate the area of the island sampled by traps assuming each trap had a ‘circle of influence’ with a radius equivalent to the average male or average female between fix movements. The combined area of the circle of influence for each trap was compared with the total island area to obtain an estimate of the proportion of the island sampled by traps.

RESULTS

Demographics

Between January and August, 154 mice were caught and tagged on the island (Table 3). Many unmarked individuals entered the population in March resulting in a relatively low recapture rate which then generally increased through the year (Table 3). Many mice were captured only in a single session; six were caught in four trapping sessions, and none in all five. There was a relatively high rate of tag loss between trapping sessions and 41 mice lost both ear tags between trapping sessions. This meant that each session had to be treated separately in CMR analysis. Three mice caught in January were captured and killed in August, indicating that they were at least 8 months old at time of death. Six mice died in traps during trapping sessions prior to August and 51 mice were trapped and killed in August, leaving 97 animals of unknown fate. Assuming tag loss was random, rudimentary survival analysis gave a monthly survival estimate of 0.6, a maximum lifetime of 26 months and a mean life span of 5 months. Tag loss between sessions will have biased the survival estimate downwards.

Pregnant or lactating female mice (indicated by prominent nipples) were recorded only in January and March. By July, most animals caught were at least 12 g in weight and were classified as adults, which suggests that breeding had ceased at least a month earlier. The proportion of females caught tended to decrease through the year with females representing only 27% of the animals caught during removal trapping in August (Table 4).

Population size

Because models with age covariates consistently ranked higher than models with weight covariates (based on Akaike’s information criterion; Burnham and Anderson 2002), weight models were deleted before model averaging. The estimated population size varied between 53 and 115 individuals and was highest in March (Fig. 2). Confidence intervals were wide for population estimates in January and March because of the relatively high number of animals caught only once in these sessions (42% and 52% respectively). In May, this group decreased to only 24%. The removal trapping and WaxTag dataset produced a population estimate with very narrow confidence intervals. This August population estimate was 53 animals, whereas 51 mice were actually removed. Mouse densities therefore varied between 8.8 and 19.2 mice/ha (Table 5).

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**Fig. 2** Number of mice caught (open) and estimated population size (closed) with 95% confidence interval (CI) shown for each trapping session where population size was estimated.
Average home-range size (± SE) from radio-tracking data for female mice was 0.19 ± 0.04 ha (n=2) and for male mice was 0.38 ± 0.07 ha (n=4) (Table 6). Radio-tracked mice returned to the same den site at the end of each tracking night and males M2 and M3 had dens within 1 m of each other underneath the same karo (*Pittosporum crassifolium*) bush. Eighteen further home ranges were obtained using trapping information from animals that had been trapped five or more times (range 5–10 locations). Combining trapping and radio-tracking data gives average home range size (± SE) of 0.28 ± 0.05 ha for female mice (n=9) and 0.23 ± 0.03 ha for male mice (n=15). The animals with the smallest home ranges and lowest mean distance between fixes were in areas of the island with more understorey; generally with dense shrub cover or a combination of open grass and shrubs. Larger home ranges and movements were associated with more open areas of the island with sparse understorey.

Average movement between fixes (± SE) for radio-tracked females was 15.8 ± 7.0 m and for males was 24.9 ± 4.9 m. Five of the six tracked mice moved over 25 m at least once during the four-night tracking period, so were likely to have encountered a bait station (spaced 25 m apart). The sixth animal had a maximum movement between consecutive fixes of 23.5 m (Table 6). The maximum distance recorded between fixes was 142 m travelled by a male mouse in just over 2 h. Based on these values, GIS analysis suggested that the trapping grid ‘circle of influence’ covered 78.7% of the island for females and 95.7% for males.

### Eradication and monitoring

Removal trapping ended on 7 August 2008. Of 62 WaxTags, 18 were chewed over 13 nights between the end of trapping and poison being laid on 19 August. Chewed tags were located between lines 1 and 7 at the north of the island and 15 and 23 at the south, with no sign of mouse activity in between. Poison bait taken from stations was minimal; although 13 out of 62 bait stations showed signs of interference when they were checked on 16 September, only two of these showed conclusive signs of interference by mice and the remaining 11 could have been due to invertebrates. The distribution of bait take from bait stations closely matched that of chewed WaxTags. No further signs of mice were found after this and the eradication was confirmed as successful on 3 December (Miriam Ritchie, Department of Conservation pers. comm.). Ongoing monitoring throughout 2009 did not detect any mice other than those released deliberately during a study into mouse invasion behaviour (J. MacKay, unpublished data).

### Rat incursions

In March 2008, rat sign was detected on the island and four DOC 200 traps were deployed. A large male Norway rat was captured on 14 May 2008. No further rat sign was detected until rat-tracked tracking cards were found on 3 December 2008. However, a trained rodent dog showed no reaction to the cards suggesting that the prints were older than 15 days, this being the length of time for which rodent scent persists (Gsell et al. 2010). No further evidence of rats has been found on the island. During mouse trapping in March 2008 (four nights) and May (two nights) an average of five mouse traps per night were pulled apart by the rat and were therefore unavailable for mouse trapping. All traps that had been pulled apart had mouse droppings inside them, so it appears that the rat was targeting traps that had caught mice.

### DISCUSSION

Mice were successfully eradicated from Saddle Island, New Zealand, using a combination of removal trapping and poisoning. By gathering a large amount of data about the mouse population prior to eradication, we can now assess why the eradication was successful.

### Demographics

The main predators of mice in New Zealand are stoats (*Mustela erminea*) and cats (*Felis catus*) (Ruscoe and Murphy 2005) both of which are absent from Saddle Island. Mouse population dynamics on the island were therefore influenced largely by food availability and climatic factors. Live trapping revealed a biased sex ratio of mice; 65% were males. During removal trapping in August, 73% were males. Male biased sex ratios have been recorded in some other trapping studies of mice in New Zealand (Ruscoe and Murphy 2005). The alternative scenario, that sex ratios of mouse populations are generally at parity but that trapability differs between the sexes (Efford et al. 1988), is not supported by our data. Our removal estimate of 53 mice on Saddle Island at the time of eradication, when 51 mice (37 males) were captured and removed, also supports the conclusion that in August there was a male bias in the population. The bias may have been caused by differentially greater mortality of females due to the physiological demands of breeding (Calow 1979).

Rodent eradication attempts generally occur in winter when natural food availability is low and rodent populations have declined (Howald et al. 2007). Mice do not normally breed over winter in New Zealand, except in mast seeding years (years where certain tree species produce vast quantities of seeds, Ruscoe and Murphy 2005). There was no evidence of mice breeding on Saddle Island over the study winter so it is unlikely that young animals were in nests and not exposed to poison bait.
Ranges, movements, and habitat

The average home ranges of animals recorded in this study fall in the middle range of those reported elsewhere in New Zealand. For example, in forest with multiple pests in the Orongorongo Valley, east of Wellington, mouse home ranges averaged 0.6 ha (Fitzgerald et al. 1981). At Tawharanui Open Sanctuary north of Auckland, where mice are the only rodent species present, home range lengths were <40 m (Goldwater 2007). One criterion for successful eradication is that every animal must be able to come into contact with a kill device (poison bait or trap) during a feasible trapping period. Because of logistical constraints, sample sizes of tracked animals were low (n=6), but the resulting information was consistent with the live-trapping data. As part of eradication planning, areas of complex habitat should be identified and eradication methods adapted to ensure all mice living in these areas have access to bait.

We endorse the value of genetic samples collected before an eradication attempt to distinguish between failed eradication and reinvasions (Abdelkrim et al. 2007, MacKay et al. 2007). Combining removal trapping and detection devices allowed an accurate density estimate to be calculated (Russell et al. 2009) and if time and resources are available, a grid of snap traps could provide genetic samples and data to accurately estimate mouse population size.

Trapping followed by poisoning proved to be an effective method of mouse eradication on a 6 ha island. A 25 m grid was adequate in this instance, and five out of the six mice radio-tracked moved over 25 m between fixes at least once during a four-night tracking period. A 25 m grid of bait stations has been used to eradicate mice from 253 ha Flat Island in Mauritius (Bell 2002), but successfully scaling up to larger islands will depend on terrain and vegetation, as generating and maintaining a grid of traps and/or bait stations is very labour-intensive.

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