House mice on islands: management and lessons from New Zealand

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Abstract The impacts of house mice (*Mus musculus*), one of four invasive rodent species in New Zealand, are only clearly revealed on islands and fenced sanctuaries without rats and other invasive predators which suppress mouse populations, influence their behaviour, and confound their impacts. When the sole invasive mammal on islands, mice can reach high densities and influence ecosystems in similar ways to rats. Eradicating mice from islands is not as difficult as previously thought, if best practice techniques developed and refined in New Zealand are applied in association with diligent planning and implementation. Adopting this best practice approach has resulted in successful eradication of mice from several islands in New Zealand and elsewhere including some of the largest ever targeted for mice; in multi-species eradications; and where mouse populations were still expanding after recent invasion. Prevention of mice reaching rodent-free islands remains an ongoing challenge as they are inveterate stowaways, potentially better swimmers than currently thought, and prolific breeders in predator-free habitat. However, emergent mouse populations can be detected with conventional surveillance tools and eradicated before becoming fully established if decisive action is taken early enough. The invasion and eventual eradication of mice on Maud Island provides a case study to illustrate New Zealand-based lessons around mouse biosecurity and eradication.

Keywords: biosecurity, eradication, impacts, invasive rodents, Maud Island

INTRODUCTION

The house mouse (*Mus musculus*) established in New Zealand (NZ) around 1830, about 550 years after the first rodent to arrive, the Pacific rat or 'kiore' (*Rattus exulans*), 60 years after Norway rats (*R. norvegicus*) and 30 years before ship rats (*R. rattus*) (Atkinson, 1973). Mice in New Zealand have traces of ancestry from three subspecies – *Mus musculus domesticus*, *M. m. castaneus* and *M. m. musculus* – however *M. m. domesticus* is the dominant subspecies (King, et al., 2016; Veale, et al., 2018). The hybridisation of subspecies could have occurred before or after the mice arrived in NZ (Veale, et al., 2018).

Today mice are widespread and common throughout NZ but not as common as ship rats. Mice increase in numbers quickly in response to pulses of food and reductions in ship rat abundance (Elliott & Kemp, 2016).

Rodent colonisations of smaller islands in the NZ archipelago have different histories influenced by past human visitation and proximity to the largest islands 'North' and 'South' considered 'mainland' by New Zealanders. Of the 1065 islands >1 ha (excluding the mainland), mice established on about 42 of them (Ruscoe & Murphy 2005; Department of Conservation (DOC), unpublished data).

Action against mice for biodiversity protection goals began with efforts by NZ Wildlife Service with rodent-proof packaging of stores destined for rodent-free islands. The first eradication of mice in NZ occurred in 1984 on 2 ha Whenuakura Island, although the project targeted Norway rats, not mice (Veitch & Bell 1990).

In 1989 the first deliberate attempts to eradicate mice from islands occurred on Mana 217 ha (Hook & Todd, 1992), Rimariki 22 ha (Veitch & Bell, 1990), and Allports 16 ha, (Brown, 1993). We can identify 36 attempts to remove mice from NZ islands larger than 1 ha, 28 of them succeeded and eight failed (Appendix 1). Mice have reinvaded seven of the 28 from which they were eradicated. Some of the eradication failures could possibly be attributed to reinvasion. These figures update NZ data presented by MacKay, et al., (2007) and Howald, et al. (2007) who included eradication attempts worldwide where the eradication of mice was not always a stated goal and where the presence of mice on the island prior to eradication remained unproven.

In this paper, we explore three questions related to the management of mice on islands for biodiversity protection:

1. What do we know about the impacts of mice on NZ island ecosystems?
2. What have we learnt about eradicating mice from islands and what do we now consider best practice in NZ?
3. What have we learnt about preventing mice from establishing new populations on NZ islands?

We use the invasion of Maud Island by mice in 2013 and their successful eradication in 2014 as a case study to illustrate our lessons.

IMPACTS OF MICE

Mice often inhabit islands with other invasive species which can confound efforts to quantify mice impacts. Predators, particularly rats, can have a marked influence on the behaviour and densities of mice while simultaneously reducing and masking mice impacts (Bridgman, 2012). Removal of mice in these situations often requires simultaneous removal of other invasive mammals, thereby continuing the confusion over how to attribute recovery to the absence of mice and not the other species involved.

On islands where mice are the only invasive mammal present they usually attain higher densities, exhibit different behaviours and therefore have more conspicuous impacts on native biodiversity (Angel, et al., 2009).

Mice as bird predators

Mice eat small bird's eggs. Frogley (2013) filmed them eating quail (*Coturnix japonica*) (30 × 24 mm), zebra finch (*Taeniopygia guttata*) (14 × 9 mm) and canary (*Serinus canaria*) eggs (16 × 11 mm) from unattended used nests placed on the forest floor. Fewer of the quail eggs tested were eaten, suggesting they are near the size limit for mice to break into. Over 400 hours of filming six natural forest bird nests in podocarp-broadleaved forest at Maungatautari resulted in observation of only a single mouse visit (Watts, et al., 2017).

In: C.R. Veitch, M.N. Clout, A.R. Martin, J.C. Russell and C.J. West (eds.) (2019). Island invasives: scaling up to meet the challenge, pp. 100–107. Occasional Paper SSC no. 62. Gland, Switzerland: IUCN.

Smaller seabirds such as some storm petrel species appear more vulnerable to egg and sometimes chick predation by mice although some studies suggest this has little effect on productivity (Campos & Granadeiro, 1999). Shore plover (*Thinornis novaeseelandia*) breed very successfully on Waikawa Island with mice at high densities. There is no evidence of egg predation on shore plover (egg size 37 × 26 mm) or white-faced storm petrels (*Pelagodroma marina*) (egg size 36 × 26 mm) on Waikawa Island in the presence of high mouse numbers (H. Jonas & J. Dowding pers. comm.).

The evidence for other impacts on birds in NZ is more circumstantial, for example differences in abundance of snipe (*Coenocorypha aucklandica*) and black-bellied storm petrels (*Fregetta tropica*) on Antipodes Island with mice and rodent-free islands such as Adams and Bollons (Miskelly, et al., 2006; Imber, et al., 2005).

Mice as reptile predators

On Mana Island removal of grazing livestock led to an increased mouse population due to improved habitat from rank grass. The McGregor's skink (*Oligosoma macgregori*) population declined and mice were seen eating skinks in pitfall monitoring traps. Following the eradication of mice in 1989 McGregor's skink numbers increased and they became more conspicuous (Newman, 1994).

Norbury, et al. (2014) followed the fate of translocated Otago skinks (*Oligosoma otagense*) in a fenced site which contained mice as the only mammalian predator. They observed mice attacking 25 cm adult skinks but noted skink survival rates were adequate for population persistence.

Romijn (2013) compared the capture rates of ornate skinks (*Oligosoma ornata*) between sites with and without mice present (without other predators). The site with mice had periodic control of mice to maintain densities below 21 per100 trap-nights. He found population increases at both sites but significantly higher rates in the site with no mice.

Mice were implicated in the suppression of recruitment in a shore skink (*O. smithi*) population at Tawharanui fenced sanctuary (Wedding, 2007).

Mice as invertebrate predators

Invertebrates are an important part of the broad diet of mice (Ruscoe & Murphy, 2005). St Clair (2011) compiled the known impacts of invasive rodents on island invertebrates including a range of NZ species influenced by mice.

Watts, et al. (2017) conducted a large-scale treatment switch experiment at Maungatautari in 2011–2016. Two fenced enclosures in forest had all mammalian pests removed except mice. At one site they eradicated mice and at the other allowed mice to increase. Results suggested mice suppressed beetles, spiders, earthworms and weta in both abundance and size.

Mice impacts on vegetation

Williams, et al. (2000) found mice destroy all seed they eat, rather than acting as seed dispersers. On the New Zealand mainland, seed predation by mice may affect regeneration of kauri (*Agathis australis*) (Badan, 1986), pingao (*Desmoschoenus spiralis*) and sand tussock (*Poa triodioides*) (Miller & Webb, 2001). Mouse predation on mountain beech (*Fuscospora cliffortioides*) and rimu (*Dacrydium cupressinum*) seeds not only reduces rates of seedling establishment, but may also alter the composition of forests over time (Wilson, et al., 2007). Seed predation by mice may also impede ecological restoration efforts, for example inhibiting a tree planting programme on Mana Island (Hook & Todd, 1992).

Watts, et al. (2017) found no significant impact of mice on forest seedling establishment over their five-year study. However, they noted their (predator fenced) mainland study site has been subject to modification by a range of introduced mammals for hundreds of years prior to the beginning of the study.

Other biodiversity impacts by mice

Two studies reported observations of mice eating the eggs of a NZ native fish, inanga (*Galaxias maculatus*) (Baker, 2006; Hickford, et al., 2010).

Besides the direct impacts discussed above, mice also influence other predators who use them as a food source. For example, stoats (*Mustela erminea*) will include mice in their diet. In beech (*Fuscospora* spp.) dominated forest, mast seeding events lead to high populations of mice followed by increased stoat populations with consequent impacts on native species (King & Murphy, 2005).

Mice may also provide an important year-round food resource for larger predators on islands with strongly seasonal primary food resources such as colonial nesting seabirds. They may therefore 'artificially' sustain higher predator populations through the non-seabird nesting periods.

MOUSE ERADICATION

Since 1989 developments in mouse eradication methodologies in New Zealand mirrored those of rat eradications (Towns & Broome, 2003; Broome, 2009; Russell & Broome, 2016). Aerial broadcast baiting was consistently chosen for eradications targeting mice on islands larger than 40ha (Appendix 1).

Mouse susceptibility to brodifacoum is highly variable. For example, Cuthbert, et al. (2011) had two Gough Island mice survive doses of 2.44 and 5.41 mg/kg, respectively. These individuals were subsequently offered more bait in no-choice tests and died after ingesting 12.2 and 7.14 mg/kg. Three (of 10) mice from Lord Howe Island survived doses of 5.2 mg/kg in a no-choice bait test (D. Priddel pers. comm.). A subsequent trial using 30 wild-caught Lord Howe mice allowed to feed *ad libitum* for three days resulted in 100% mortality (A. Walsh pers. comm.).

Mice usually die from about five days following the first application. For example, MacKay, et al. (2007) found no sign of surviving mice on Adele Island eight days after bait application. However, they can survive much longer (see case study) and in one laboratory trial, a warfarin-resistant mouse survived a total of 65 days after first feeding on brodifacoum laced bait (Rowe & Bradfield, 1976).

Bridgman (2012) studied the behaviour of mice in the presence of ship rats. She found ship rats strongly influenced the movements of mice, reducing home ranges and nutrition levels. This has implications for eradication projects targeting both rats and mice, reinforcing the need for comprehensive bait coverage and well-spaced multiple bait applications to allow for the dominant rats to die off and theoretically 'free up' the movement of any mice remaining.

Some projects failed to eradicate mice because they did not explicitly target them. For example, on Mokoia Island in 1989 an eradication project targeting Norway rats using bait stations spaced at 50 × 50 m subsequently found mice on the island (P. Jansen, pers. comm.). Because the eradication was designed around the home range of Norway rats, mice survived and became detectable after the rat population had crashed.

Eradications of mice on islands in NZ progressed through the 1990s with mixed success (MacKay, et al., 2007). The review of mouse eradication projects by MacKay, et al., in 2007 could not find a consistent operational factor contributing to eradication failure but recommended robust planning of future projects to rule out operational errors, thereby providing better insight into the cause of failures.

Following this recommendation, a project to eradicate mice from three islands (Adele, Tonga, Fisherman) in Tasman Bay in 2007 strictly adhered to the current agreed best practice methodology for mouse eradications (Golding, 2010). The Island Eradication Advisory Group (IEAG), a technical advisory group of the NZ Department of Conservation, updates and maintains a document providing technical advice to project managers in the planning, implementation and monitoring of rat eradications on islands (Broome, et al., 2017a).

The IEAG consider best practice for mouse eradications to be similar to that used for rats with the following changes:

Bait applications use 50% overlap on both the first and second application (cf. for rats where 50% overlap is recommended for the first application and 25% for the second) (Fig. 1).

Bucket flow rates remain at or above 4 kg/ha (cf. for rats where bucket flow rates of 3 kg/ha are permissible). With 50% overlaps as in 1 above, this means applying a minimum of 8 kg/ha on the ground in each application.

The interval between applications is extended to a minimum of 14 days (cf. for rats where more flexibility in timing of the second application is permissible).

The IEAG has recently developed a best practice document incorporating these elements with other advice borrowed from the rat best practice (Broome, et al., 2017b). Since the Tasman Bay project, all subsequent mouse eradications following this advice have succeeded. including one of the largest (Macquarie 12,800 ha); multi-species eradications (Macquarie, and Rangitoto/Motutapu 3,809 ha) and a still-establishing mouse population (Maud 309 ha – see case study).

Changes 1 and 2 recognise the smaller territories of mice than rats and strive to ensure all mice encounter bait. Relatively few mouse home range studies have occurred on NZ islands (Ruscoe & Murphy, 2005). MacKay, et al. (2011) measured home ranges varying from 0.15–0.48 ha on Saddle Island. Radio-tracking found animals living in areas with dense shrub and grass cover had smaller ranges and mean nightly movements than those living in areas with tall canopy and minimal ground cover. Elsewhere on the NZ mainland in the absence of other mammalian predators and competitors, Goldwater, et al. (2012) estimated densities of 160 mice/ha in rank kikuyu grass (*Pennisetum clandestinum*) immediately after other mammals were eradicated, but density has since greatly declined.

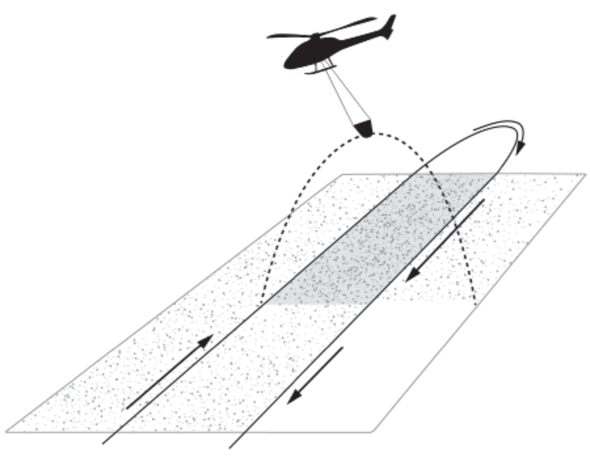

Fig. 1 50% overlap when aerially sowing bait. Arrows indicate centres and direction of two consecutive sowing lines. The dark shaded area shows the area of overlap between the first and the (half-completed) second line.

Eradication designs must cater for not only the smallest home range (rather than the mean) but also the smallest foraging movements by mice over the limited period that bait is available in palatable condition. At 8 kg/ha the 2 g baits used in NZ would in theory be on the ground at 0.4 baits/m^2 providing ample opportunity for mice to encounter baits, especially after a second application.

Keeping bucket flow rates relatively high (possum control operations using the same equipment routinely use rates around 1 kg/ha), reduces the risk of interruptions in bait flow out of the bucket. Such interruptions in flow are potentially fatal to eradication success as they would not be mapped by the helicopter's GPS navigation recording system, and therefore could go unnoticed.

Change 3 acknowledges mice as light and erratic feeders compared to rats (Clapperton, 2006). Extending the period of bait availability, compared to a rat eradication, is desirable to ensure all mice have access to lethal doses before bait is consumed by other fauna or environmentally degraded. Brown (1993) found mice initially reluctant to take bait presented in bait stations on Allports and Motutapu Islands. They often 'sampled' small portions of baits over several nights before full-scale consumption ensued. He described a gradual spread of consumption from a focal point, speculating that social interactions between mice encouraged more to try the new food resource presented.

To counter the risk of mice being present but undetected in the presence of rats, some projects have deliberately designed their baiting strategy to mice eradication standard. For example, the rodent eradication (ship rats and kiore) on Great Mercury Island was designed to mouse eradication best practice standards despite no confirmed evidence of mice. The island operated as a pastoral farm with minimal biosecurity precautions for over 50 years so it was difficult to believe mice had not arrived during this time. The project sponsors found it cost effective risk management to assume mice were present and design the project accordingly (Corson & Hawkins, 2016).

MOUSE BIOSECURITY

Keeping islands free of mice presents ongoing challenges in quarantine, surveillance and responding to arrivals. Pathways for invasion include cargo and personal luggage landed on the island, vessels and aircraft of all sizes, and swimming or rafting to islands.

Vulnerabilities to these pathways differ between islands but some islands may also be less susceptible to establishment of a mouse population following incursion. For example, Secretary, Kapiti, Stewart, Raoul and Campbell Islands have records of mice arriving, without evidence of meaningful action to respond, and yet failing to subsequently establish populations (DOC unpublished data). At the time all of these large islands had rats or stoats present, potentially providing a form of biological defence against mouse establishment. Weka (*Gallirallus australis*) may also play a role where they occur on islands. For example, on rat-free Tarakaipa Island mice were barely detectable in the presence of weka (DB pers. obs.). Weka held in captivity eagerly attacked mice entering their pen (CG pers. obs.). Conversely, the subsequent eradication of such predators could, in theory, increase the vulnerability of the island to invasion by mice. Further research into this phenomenon is warranted.

The probability of establishment can relate to propagule pressure (Lockwood, et al., 2005). Because rodent populations fluctuate seasonally in NZ with peaks in late summer, the risk of invasion could increase at this time of year. Additionally, mast seeding events in some forests can produce superabundant populations of mice which increase propagule pressure on nearby islands. For example, mice were successfully eradicated from Adele Island in 2007 and a biosecurity system installed. In the 2014/15 summer a significant mast seeding event occurred in the adjacent Abel Tasman National Park where mice became abundant. In February 2015 they were discovered on Adele. Attempts to eliminate them by localised trapping around points of detection failed and a population re-established (CG pers. obs.).

Mice as stowaways

Mice are inveterate stowaways with numerous records of their discovery in cargo destined for islands. The DOC invasion incidents database has 24 records of mice reaching islands amongst cargo between January 2010 and June 2017. Two more were intercepted on vessels en route to pest-free islands. Mice have been discovered in visitor day packs, in kayaks and nesting in under-seat dingy flotation. Container, building and vessel openings must be <6 mm to restrict mouse access. Of equal importance is the vigilance required to ensure doors, lids and hatches remain closed when not in use.

Quarantine measures to prevent mice reaching islands require constant vigilance by people involved. Careful checking of cargo, using rodent-proof containers for transport and control measures on board vessels are key components. These precautions can be enhanced by good rodent management and habitat control at ports and minimising the quantity of equipment transferred to islands (e.g. by having field equipment remain on-island).

Mice swimming to islands

Mice are often thought of as poor swimmers relative to rats (Russell & Clout, 2005). However, Evans, et al. (1978) found mice would readily enter water and swim. A fisherman saw a number of mice 600 m from shore in Lake Monowai while night fishing during the 2009 mouse plague (CG pers. comm..). Fishermen anecdotally report them in trout guts (James & Fox, 2017) and they have been found live in coastal flood debris (DB pers. obs.). The maximum distance over water that mice can cross unassisted remains unknown and therefore the pathway should not be assumed unimportant when considering biosecurity risks for an island.

Pomona and Rona Islands in Lake Manapouri were both assumed a ‘safe’ distance offshore (500 m and 600 m respectively) but both were reinvaded by mice within a decade of successful eradication, probably by swimming or rafting on flood debris. These re-invasions coincided with beech masting events when mice reached high abundance on the mainland.

Detection methods

We can readily detect mice at low densities, in the absence of other rodent species, using a range of tools including footprint tracking tunnels, chew cards and other bait interference methods, snap traps and trained detection dogs. Nathan, et al. (2013) studied mouse detection on Saddle Island (6 ha) during an experimental invasion event in which a male and a female mouse were released on the rodent-free island. They readily detected mice by both tracking tunnels and wax tags, even during the initial phases of the invasion.

Invading mice can move large distances. For example, pairs of mice sequentially released at opposite ends of Saddle Island (approximately 400 m apart), increased their nightly movements two-fold, and range sizes ten-fold, relative to movements on this island prior to the mouse eradication. This allowed them to rapidly and reliably encounter each member of the opposite sex (MacKay, 2011).

A mouse invading pest-free Moturua Island initially tracked inked footprint tracking cards in October 2011 and was finally trapped in late 2011. On one occasion this animal travelled at least 750 m between tracking tunnels over a 36-hour period (KB unpublished data).

Mice established on islands in relatively high numbers can hinder the detection of newly invading rats by ‘swamping’ detection tools. For example, they cover ink tracking cards on Waikawa Island within a few nights which can obscure the footprints of an invading rat. Mice usually do not trigger DOC200 stoat and rat traps but steal the bait, rendering the trap less attractive. These mouse-induced limitations delayed the detection of a Norway rat incursion on Waikawa Island in 2012, indicated by a dramatic decline in the critically endangered NZ shore plover. The rat was never caught and only retrospectively identified with the help of a rodent detection dog by the discovery of a nest containing bird remains and Norway rat fur and droppings (EM unpublished data).

Incursion response

Responding to the discovery of invading mice on a pest free island is challenging due to the potential delay between incursion and discovery through periodic surveillance checks. Nathan, et al. (2015) demonstrated the urgency of responding to a mouse invasion by experimentally releasing one male and one female mouse on Saddle Island. They subsequently bred and the mouse population reached the island’s carrying capacity within five months. Routine surveillance discovered invading mice on Adele Island in February 2015, potentially months after arrival. Despite intensive trapping around points of detection the incipient population could not be eliminated.

CASE STUDY MAUD ISLAND

Biosecurity

Before 2013 rodents had never established on Maud Island (309 ha) in the Marlborough Sounds. Consequently, it has some highly rodent-vulnerable native species including some not found elsewhere, such as the Maud Island frog (*Leiopelma pakeka*), and others restricted to a handful of nearby pest-free islands.

Keeping pests from reaching Maud has long been a priority. Landing is restricted and DOC staff are present year-round. Stoats are considered the biggest invasive threat because they can swim the 900 m from the mainland and have done so on at least three occasions. Traps targeting stoats and rats are throughout the island and checked regularly. A quarantine store at the mainland DOC ranger station is used to check cargo destined for Maud or other pest free islands. Extra precautions are taken to prevent chytrid fungus – a pathogen implicated in the worldwide decline of frog populations (Berger, et al., 1999) – from reaching Maud.

In 2006, a mouse was killed by the Maud Island resident ranger when turning garden compost. An incursion response using mouse traps and a trained rodent detection dog failed to find further sign of mice after several weeks.

In October 2013, a mouse was captured in visitor accommodation on the island. An incursion response immediately deployed traps, detection devices and a rodent detection dog. Several mice were trapped around the buildings. The dog handler reported mice in several places across the island. Breeding was confirmed from necropsied animals. The youngest mice were in age class 1 (0–1 months in age) and the eldest in age class 6 (8–10 months) suggesting the first invaders arrived about a year previously and they had bred through the winter, which is uncommon in NZ.

DNA analyses found the Maud Island population highly inbred, suggesting the population arose from a single incursion. Although the mice were a genetic subset of the mainland population, their point of origin could not be established (E.M. & R. Fewster, unpublished data).

With an emerging picture of an established mouse population across the island, the incursion response team were forced to admit their efforts had begun too late and a whole island eradication was required.

To understand how mice had reached the island and remained undiscovered for long enough to establish, an independent review of biosecurity procedures was undertaken (Kennedy & Chappell, 2013). This found several weaknesses, including a lack of devices capable of killing or detecting mice on the island or on the ranger's boat, that was pulled onto a slipway on the island when not in use. The focus on stoats and rats allowed mice to go unnoticed. Some staff regularly visiting the island bypassed quarantine standards.

The review could not identify the pathway for the mouse incursion but made many recommendations for improvement which were actioned prior to the eradication. The island's biosecurity plan has recently been re-written to capture these new practices and give more authority to biosecurity rangers to enforce standards.

Eradication

In 2014, mouse eradication best practice was successfully applied to eradicating the newly established population of mice on Maud Island. Challenges included the abundance of natural food available to the expanding mouse population, and the presence of residential buildings requiring careful management of domestic foodstuffs and waste to minimise access to alternative food after toxic baiting.

A helicopter applied 8 kg/ha on 23 July 2014 followed by 8 kg/ha 23 days later (15 August) with strict adherence to the current agreed best practice described above. Two mice were trapped on Maud on 19 August, 27 days after the first bait application. Both had bait in their stomachs. A badly decayed male mouse was taken from a snap trap on 22 September and a female trapped the next day. This sexually mature female showed no signs of past or present breeding and appears to have survived about 60 and 37 days after the first and second bait applications, respectively. An intensive trapping grid (10 m × 10 m) was installed around each capture site covering about one hectare. No further mice were caught.

We estimated the age (from tooth eruption and wear) of the last mouse caught to be five months, meaning it could have lived through all bait applications. Bait was freely available from July to October, so these individuals must have encountered it. Although a range of trap baits were used, the snap traps which caught each mouse were baited with a Pestoff 20R pellet as used for the aerial baiting, indicating no aversion to the bait.

Testing of all four trapped mice revealed brodifacoum liver residues in three of them of 4.65–8.82 mg/kg. Considering liver values probably resulted from higher doses due to losses through excretion and metabolism (Eason & Wickstrom, 2001), these mice probably received many times the published LD50 for mice of 0.52 mg/kg (O'Connor & Booth, 2001). Maggots from the more decomposed male caught 22 September contained 2.35 mg/kg. DNA testing found these mice to be clearly from the original Maud invasion, not a new independent invasion.

Extensive monitoring over the subsequent two years no further survivors but a further incursion in 2018 has once again established a mouse population on the island. Mouse trapping on the island after bait application was intended as indicative monitoring only and had limited coverage of the island. We assume other mice survived in un-trapped areas long after bait application. These animals presumably acquired a lethal dose of brodifacoum and died without reproducing.

The successful eradication of an expanding population of mice from Maud is an indication of high bait acceptance despite other natural food being available in relative abundance. Camera footage from some of the buildings on Maud showed mice taking large quantities of bait placed in trays during the eradication and presumably caching it (CB pers. obs.).

CONCLUSION

Mice remain on many large islands in New Zealand and around the world. The techniques used in NZ to eradicate mice have been successful and could readily be applied to other temperate islands of similar size with a good chance of success. Biosecurity measures to protect islands from mouse invasion are challenging and mice must be considered a real threat to all rodent free islands, regardless of previous invasion history.

Biosecurity lessons:

Quarantine standards must apply to everyone to be effective. The pre-eminence of biosecurity over other duties of island staff and managers needs regular reinforcement to create an organisational culture which can sustain high biosecurity standards over time.

All potential threats and all potential pathways need to be assessed and multiple layers of protection established: i.e. quarantine checking, pest proof containerisation, hygiene of transportation, targeted surveillance, capability and readiness for incursion response.

Independent review of procedures can give valuable insights into opportunities for improvements and should be done proactively and routinely.

The risk of successful mouse invasions may be influenced by island predators (or lack thereof) and mouse abundance at potential source populations.

Eradication lessons:

The current agreed best practice used in NZ has a very good track record of success (>90% in known outcomes) against mice on temperate islands. This is far better than previously published review figures which did not present data on the quality of planning and delivery or discriminate between operations deliberately targeting mice and those targeting other species where mice also occur.

Mice can take a long time to succumb to the cumulative effects of small doses of brodifacoum and some individuals may require significantly higher doses than others. A baiting strategy which prolongs the availability of toxicant to mice has a better chance of success. In NZ this is usually achieved with two well-spaced bait applications but a third application is also an option.

Bait application rates need to allow for other bait consumers when multiple target species are involved and must not fall below the ability of sowing equipment to spread bait 100% reliably.

Where the presence of mice is likely but unproven due to suppression by other species, it is prudent to design the eradication assuming their presence, rather than discover that they have survived a rat eradication and thrived in the absence of rats or other predators.

Eradication is feasible against newly established and expanding populations of invading mice, especially if current agreed best practice is followed.

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Appendix 1 Mouse eradications on NZ islands >1ha. F or R = failed or reinvaded and S (R) = successful but subsequently reinvaded.

Region	Mice targeted	Island	Area (ha)	DOC best practice	Eradication start date	Eradication status	Primary baiting method	Secondary baiting method	References
Coromandel	Y	Whenuakura	2	NA	1983	Successful	Bait station	NA	Veitch & Bell, 1990; Newman, 1985
Cook Strait	Y	Mana	217	NA	1989	Successful	Bait station	Aerial broadcast	Hook & Todd, 1992; Newman, 1994
Marlborough	Y	Allports	16	NA	1989	Successful	Bait station	NA	Brown, 1993
Marlborough	Y	Motutapu	2	NA	1989	Successful	Bait station	NA	Brown, 1993
Lake Rotorua	N	Mokoia	136	NA	1989	Failed	Bait station	NA	MacKay, et al., 2007
Kaituna Bay	Y	Rimariki	22	NA	1989	Successful	Bait station	NA	Veitch & Bell, 1990
Kaipara Harbour	Y	Moturemu	5	NA	1992	Successful	Bait station	NA	Clout & Russell, 2006
Subantarctic	N	Enderby	710	NA	1993	Successful	Aerial broadcast	NA	Torr, 2002
Coromandel	N	Hauturu	10	NA	1993	F or R	Bait station	Hand broadcast	Glassey, 2006
Hauraki Gulf	Y	Te Haupa	6	NA	1993	Failed	Bait station	NA	Clout & Russell, 2006
Coromandel	Y	Motutapere	46	NA	1994	Successful	Aerial broadcast	Bait station	Clout & Russell, 2006

Appendix 1 (continued) Mouse eradications on NZ islands >1ha. F or R = failed or reinvaded and S (R) = successful but subsequently reinvaded.

Region	Mice targeted	Island	Area (ha)	DOC best practice	Eradication start date	Eradication status	Primary baiting method	Secondary baiting method	References
Hauraki Gulf	Y	Browns	60	NA	1995	Successful	Aerial broadcast	NA	Veitch, 2002a
Lake Wanaka	Y	Mou Waho	140	NA	1996	Successful	Aerial broadcast	NA	McKinlay, 1999
Whangarei Harbour	Y	Matakohe	37	NA	1996	F or R	Aerial broadcast	NA	MacKay, et al., 2007
Lake Rotorua	Y	Mokoia	136	NA	1996	F or R	Aerial broadcast	Hand broadcast	Clout & Russell, 2006; Owen, 1998
Hauraki Gulf	Y	Motuihe	179	NA	1997	Successful	Aerial broadcast	NA	Veitch, 2002b
Whangarei Harbour	Y	Matakohe	37	NA	1997	F or R	Aerial broadcast	NA	MacKay, et al., 2007; Ritchie, 2000
Whangarei Harbour	Y	Matakohe	37	NA	1998	F or R	Aerial broadcast	NA	Clout & Russell, 2006; Ritchie, 2000
Lake Rotorua	Y	Mokoia	136	NA	2001	S (R)	Aerial broadcast	Hand broadcast	MacKay, et al., 2007
Whangarei Harbour	Y	Matakohe	37	NA	2001	F or R	Bait station	NA	Clout & Russell, 2006
Canterbury	N	Quail	85	NA	2002	Failed	Bait station	Hand broadcast	Bowie, et al., 2011
Lake Rotomahana	Y	Patiti	13	NA	2004	Failed	Bait station	NA	Bancroft, 2004
Marlborough	Y	Blumine	377	NA	2005	Successful	Aerial broadcast	NA	MacKay, et al., 2007
Coromandel	Y	Ohinau	46	NA	2005	Successful	Aerial broadcast	NA	Chappell, 2008
Marlborough	Y	Pickersgill	96	NA	2005	Successful	Aerial broadcast	NA	MacKay, et al., 2007
Lake Manapouri	Y	Rona	60	Y	2007	S (R)	Aerial broadcast	NA	Shaw & Torr, 2011
Lake Manapouri	Y	Pomona	262	Y	2007	S (R)	Aerial broadcast	NA	Shaw & Torr, 2011
Tasman Bay	Y	Adele	88	Y	2007	S (R)	Aerial broadcast	NA	Golding, 2010
Tasman Bay	Y	Fisherman	4	Y	2007	S (R)	Aerial broadcast	NA	Golding, 2010
Tasman Bay	Y	Tonga	8	Y	2007	S (R)	Aerial broadcast	NA	Golding, 2010
Hauraki Gulf	Y	Te Haupa	6	N	2008	Successful	Bait station	Hand broadcast	MacKay, et al., 2011
Fiordland	Y	Coal	1,163	Y	2008	Successful	Aerial broadcast	NA	Brown, 2013
Hauraki Gulf	Y	Motutapu	1,509	Y	2009	Successful	Aerial broadcast	Bait station	Griffiths, et al., 2015
Hauraki Gulf	Y	Rangitoto	2,311	Y	2009	Successful	Aerial broadcast	Bait station	Griffiths, et al., 2015
Canterbury	Y	Quail	85	Y	2009	F or R	Aerial broadcast	Hand broadcast	Bowie, et al., 2011
Hauraki Gulf	Y	Te Haupa	6	N	2010	Successful	Trapping	Bait station	MacKay, et al., 2011
Dusky Sound	Y	Indian	167	Y	2010	Successful	Aerial broadcast	NA	Department of Conservation, 2011
Hauraki Gulf	Y	Rotoroa	140	Y	2013	Successful	Aerial broadcast	NA	Fraser, et al., 2013
Marlborough	Y	Maud	309	Y	2014	Successful	Aerial broadcast	NA	This paper
Subantarctic	Y	Antipodes	2,012	Y	2016	Successful	Aerial broadcast	NA	Horn, et al. (these proceedings)