Factors Contributing to Recent House Mouse Eradication Failures on Islands: An Initial Assessment Following a Workshop in New Zealand

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ABSTRACT: Invasive house mice threaten native biodiversity on many of the world's islands. Best practice for eradicating house mouse populations from islands currently relies on bait containing the anticoagulant rodenticide brodifacoum. These baits are typically either broadcast (by hand or by helicopter in natural areas) or placed in bait stations (in human infrastructure or in areas where open broadcast is not permitted). There have been many successful mouse eradications using these methods, including 29 of 36 attempts of islands being successful (81%) in New Zealand. Following recent failed mouse eradications on Gough Island (South Atlantic, 2021) and Midway Atoll (North Pacific, 2023), a workshop was convened with 24 people attending (16 in-person, 8 on-line) from 7 countries (Australia, Canada, France, NZ, South Africa, UK, US), to discuss some hypotheses for what may have contributed to these unsuccessful outcomes. The workshop was held in Palmerston North, New Zealand, between November 27 and 29, 2023. Discussions over the three days revolved around three hypotheses. We present the key factors hypothesized for why eradications failed on these two islands. We also outline research and operational needs that were identified in the workshop that can contribute to improved outcomes for future eradications of house mice from targeted islands.

KEY WORDS: aerial application, brodifacoum, eradication failure, Gough Island, house mouse, hypotheses for eradication failure, Marion Island, Midway Atoll, mouse eradication, *Mus musculus*

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BACKGROUND

Eradication of invasive rodents from islands has been a conservation management tool used for several decades to restore island habitats and enable the recovery of native flora and fauna impacted by invasive predators (Towns and Broome 2003, Howald et al. 2007, Broome 2009, Innes et al. 2023). Rodent eradications have proven to be one of the most effective management interventions used globally for long-term habitat restoration on islands (Jones et al. 2016).

The majority of these rodent eradications targeted rats (usually ship rats *Rattus rattus*, Norway rats *R. norvegicus*, or Pacific rats *R. exulans*), partly because rats have a wider global distribution on islands, and partly because in many instances rats were considered a greater threat to island biodiversity values than other rodents such as house mice (*Mus musculus*). On some islands, rats and mice are sympatric and have been targeted for simultaneous eradication, because effectively the same methodology is used for rats and mice. This partly reflected concerns that if mice were not eradicated at the same time as rats, mouse populations could increase when released from predation and competition from rats and go on to cause further deleterious impacts on island biota (Caut et al. 2007).

Spatz et al. (2022) evaluated global eradications of invasive species from islands and found that 88% of rat eradications had been successful, compared with 72.9% of mouse eradications.

Contextually, many early mouse eradication failures were in the period when rodent eradications using the technique of aerial application of rodenticides were still being developed, and in many cases the causes of mouse eradication failure were identified in operational reviews. This led to an improving success rate as subsequent mouse eradications applied the lessons from previous failures, and for a ~15-year period from 2007, nearly all mouse eradications attempted were successful (Figure 1).

This trend of increasingly successful mouse eradications came to a halt with the failure of two projects in 2021 and 2023 – the Gough Island Restoration Project (South Atlantic) and the Midway Seabird Protection Project (North Pacific), respectively. These two islands appeared

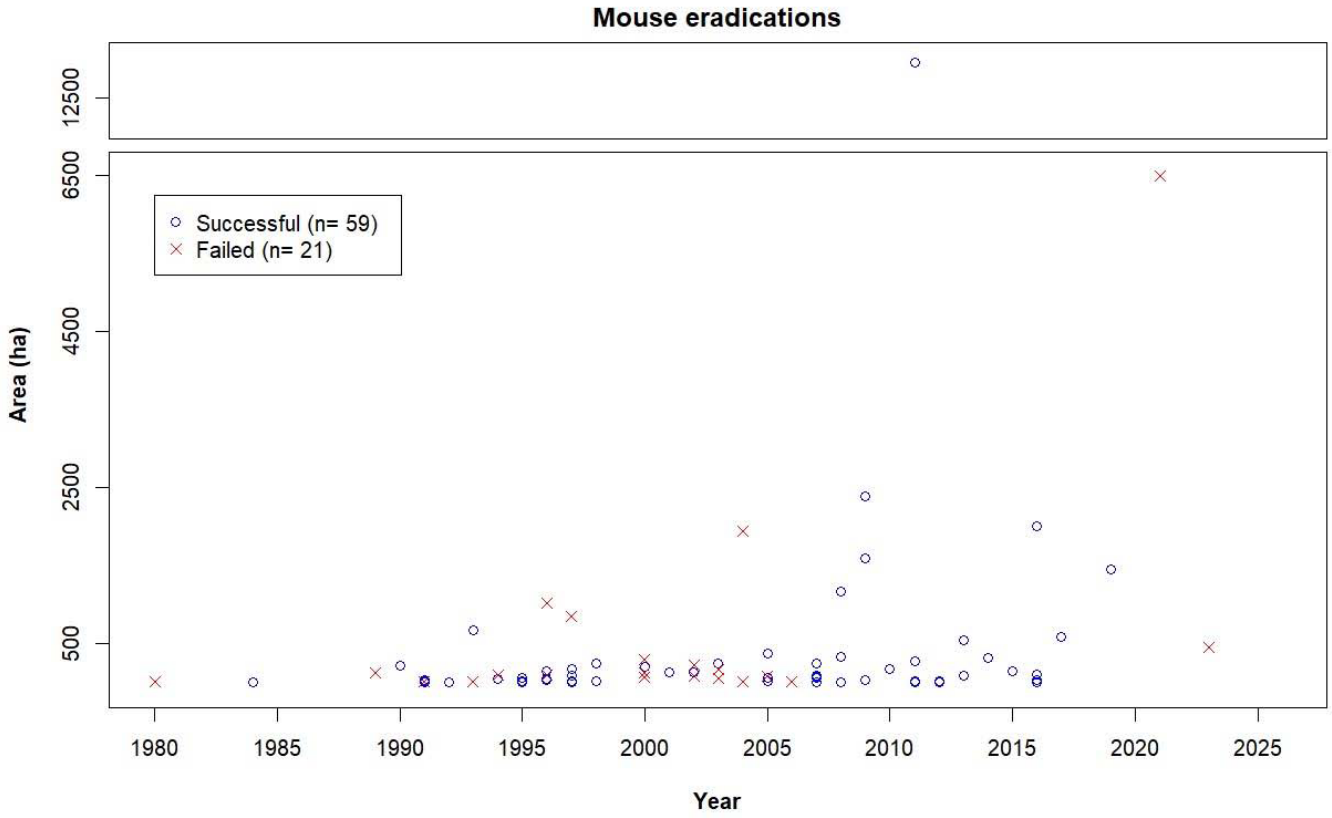

Figure 1. Mouse eradication outcomes. (Adapted by A. Samaniego from Samaniego et al. 2021)

to have very little in common in terms of climate, terrain and species assemblage, so there was no obvious common ground to point to potential reasons for the failure to eradicate mice. Gough is cool temperate, with plant and animal species associated with sub-Antarctic islands. Midway, on the other hand, is part of the Hawaiian archipelago and is tropical. The one apparent common characteristic is that in both locations, mice have developed predatory behaviour targeting seabirds, particularly albatrosses, petrels and prions. This has occurred to such an extent that breeding success of long-lived seabirds is reducing, potentially threatening long-term viability of susceptible species' populations. This observed behaviour also occurs on Marion Island (Southern Indian Ocean) where it has increased in recent years (Connan et al. 2024) since first observed in 2003 (ibid). A mouse eradication on Marion Island is currently in the planning stage, and multiple-species eradications including house mice as a target are planned for Amsterdam Island (Southern Indian Ocean, also targeting Norway rats and cats) and Auckland Island (Southern Pacific Ocean, also targeting cats and feral pigs). With better understanding of potential reasons for failure, a repeat attempt on Gough Island is intended.

MOUSE ERADICATION WORKSHOP

Rationale

To try to understand what circumstances may have contributed to the failures on Gough Island and Midway Atoll, an international Mouse Eradication Workshop was convened to identify potential contributing reasons for these failures and apply lessons to forthcoming eradications targeting mice, thus enhancing the likelihood of success. This is important for several reasons:

- Ecological gains are not realised if eradication is unsuccessful, with native biota usually gaining only brief respite before impacts resume as mouse populations recover.
- Funding for habitat restoration projects is increasingly reliant on private, philanthropic sources rather than wholly from public, government sources. Philanthropic as well as government funding sources have a higher expectation on return, therefore understanding the reasons for eradication failure and addressing the apparent causes are particularly important to maintain support.
- Reputational damage occurs if there is a perception amongst stakeholders that the methodology is ineffective, which can lead to further difficulty in raising requisite funds and support for these interventions, resulting in fewer invasive species eradications being conducted. This would reduce the use of this effective habitat restoration tool and our ability to halt declining biodiversity on islands.

The Workshop

The Mouse Eradication Workshop was held in Palmerston North, New Zealand, in November 2023. Twenty-four people attended (16 in-person, 8 on-line) from 7 countries (Australia, Canada, France, NZ, South Africa, UK, US). In addition, the NZ Department of Conservation

supported the workshop with staff to assist in facilitation and recording of discussions, and Orillion Ltd. sponsored the venue and catering.

Purpose

The long-form of the stated Workshop Purpose was "By the end of the workshop the organisers want to have a clear direction for further trials and research required to improve our understanding of what went wrong with recent failed mouse eradications. A further objective was to summarise what the most appropriate information-gathering and mitigation actions are, that should be applied to upcoming mouse eradications."

This was distilled into the following items:

1. A clear direction for trials and research to improve understanding of what went wrong.
2. Summarise information-gathering and mitigation actions for planning for upcoming mouse eradications.
3. Given what we know now - what do we do next?

Format

The workshop format followed this structure:

1) Review possible reasons for failure and agree on direction
2) Discuss hypotheses with key questions in small groups
3) Share key points with whole group
4) Go back to purpose and summarise where we got to
5) Identify research priorities and actions for upcoming projects.

The hypotheses were developed and circulated, together with relevant background reading, prior to the workshop. Three central hypotheses were identified that may have contributed to eradication failure. These were developed from a paper on eradication failures (Samaniego et al. 2021) and formed the basis for discussion throughout the workshop. In-person participants divided into three groups to discuss each hypothesis, with the on-line group forming a fourth. Each group reported back after each discussion break, for wider discussion with the whole group.

Hypotheses

The three core hypotheses each had subsidiary questions for discussion and included:

Hypothesis 1: Mice *could* not eat a lethal dose of bait

1) *Are there commonalities between different islands in terms of bait competitors?*
2) *How best to investigate bait consumption and competition (who is eating the bait and how much of it is consumed – questions around bait uptake and bait availability – for example, on both Midway and Gough there was considerable consumption of bait by invertebrates)?*
3) *What is the minimum time bait must be available in all mouse territories for all mice to access bait?*
4) *How to determine appropriate bait application/sowing rates?*

Hypothesis 2: Mice *would* not eat a lethal dose of bait

Do some mice have innate aversion to the bait?

1) *What do we know about bait aversion?*
2) *Why do we think this might/might not be an issue?*
3) *How to investigate this further?*
4) *How can this be mitigated for an eradication operation?*

Are some mice slow to switch from natural diets to bait?

1) *What do we know about preferential diet-switching?*
2) *Why do we think this might/might not be the case?*
3) *How can we investigate this further?*
4) *How can this be mitigated for an eradication operation?*

How important is the first bait application? Does surviving mouse behaviour change by the time of a second application (usually applied as part of the baiting strategy), and if so, in what ways?

1) *What do we know about bait uptake from the first application?*
2) *Why do we think this might/might not be the case?*
3) *How to investigate this further?*
4) *How can this be mitigated for an eradication operation?*

Hypothesis 3: Is there a problem with bait toxicity?

1) *Does toxicity of bait degrade more than we think (over time from manufacture until use)?*
2) *Some mice are much more tolerant and require a greater amount of toxin per body weight for a lethal dose than some other rodents - is this important in determining eradication outcomes?*
3) *Is a higher toxic concentration warranted or necessary, and what variables might influence this?*

DISCUSSION

Information about the Gough Island (including formal reviews) and Midway Atoll eradication projects was provided to workshop participants and this provided key contextual information for the workshop discussions. Other considerations discussed included the fact that both Gough and Midway mouse eradications followed broadly-agreed best practice for aerial operations. Notably, the basic methodology and materials used on Gough and Midway - including general bait types (i.e., brodifacoum in a cereal-grain matrix) - were broadly identical to those used on many successful mouse eradication projects in the preceding 15 years, although the baiting regime varies at an individual island level. While these recent eradications failed, the vast majority of mice still died. This generated questions around whether the recent eradication failures were just a coincidence after a long period of successes, or whether some aspect has changed, has previously been missed without adverse consequence, or was unique to these islands that made eradication failure more likely.

Following discussion during the workshop, it was clear that there was no immediately apparent explanation for the failures i.e., no single reason could clearly be identified for either Gough or Midway that resulted in not all mice consuming a lethal amount of bait. However, we did find support for Hypotheses 1 and 2, described in the preceding section.

This led to consideration of whether the propensity of mice to consume protein in the form of seabirds on Gough and Midway (and by projection, Marion) may have influenced the likelihood of all mice consuming sufficient grain-based bait on those islands and thus being a contributing factor in the eradication failures. On Marion Island, at least, mice have contributed to a significant reduction in invertebrate abundance in the two centuries since their establishment (Angel and Cooper 2011, McClelland et al. 2018). With a warming climate creating more favourable conditions for mouse breeding, it is an open question whether the switch to exploiting seabirds as a source of dietary protein is a response to both reduced availability of their former prey items, coupled with the food requirements (biomass) needed to support an expanding mouse population. There may be a link between reduced invertebrate populations as a result of mouse predation on islands, to a preference to higher-protein diets sourced from seabirds, with a number of individual mice finding carbohydrate-based baits less palatable. In addition, the advent of novel food items to an environment means that some individual mice may take longer than others to gain enough familiarity with the new food item to consume it in any quantity – a factor that was discussed under Hypothesis 2.

It is well established that there are a range of variables which can affect the success or failure of each operation and it's likely that the main cause of failure at Midway and Gough were different rather than the same. The landforms, vegetation, weather conditions, bait formulations used, bait exposure periods and many other variables were different between Gough and Midway, so this opens up a range of possibilities that contributed to eradication failure.

Discussion topics that workshop participants sought to explore in greater detail included characteristics of mice and bait, and implications of these for eradication success. Mice have different foraging strategies and feeding behaviours compared to rats, and typically have smaller home ranges. Whereas both rats and mice will remove bait to caches, mice tend to be nibblers and samplers and feed often, rather than consuming all of a food item at one sitting, as rats are more likely to do. They will forage around and stop for brief periods and have a few nibbles at food and then keep moving, often coming back to the same item of food later for further nibbles. This suggests that they need to find bait sufficiently palatable to want to come back to it and consume more, and consequently that encounter rates are important. This has implications for bait application rates. Mice also require a higher amount of the toxin used in most aerially-applied bait for eradication purposes (brodifacoum) to ingest a lethal dose (per unit of body weight), than do rats (Fisher 2005, Broome et al. 2021). This indicates that if mice are feeding on smaller portions, it is important that those cumulative portions contain sufficient toxin to kill each mouse, before bait availability decreases through consumption by other organisms or degradation through weathering. Given the propensity of mice to consume small amounts of food more frequently and their demonstrated (learned) behaviour of seabird predation, consideration has been given to amending bait composition, by introducing a protein component. In most rodent eradications distributing bait aerially, the bait contains the second-generation anticoagulant brodifacoum, within a matrix consisting of grains, binding agents and lures. There are two primary manufacturers of this specially-formulated bait globally (Orillion Ltd. in New Zealand, and Bell Laboratories Inc. in the USA) and both have a standard bait pellet, which is 10 mm in diameter, weighing ~2 g and containing 20 ppm (Orillion Ltd. produce Pestoff 20R) and 25 ppm (Bell Laboratories Inc. produce Brodifacoum-25D Conservation and Brodifacoum-25W Conservation) of active ingredient (brodifacoum). Orillion's 10 mm, 2 g, 20 ppm brodifacoum bait was used on Gough Island for the 2021 mouse eradication attempt (Samaniego et al. 2023). Both bait manufacturing companies also produce a smaller bait developed for mice. Individual pellet size for Bell Laboratory's mouse bait weigh (mean ± SE) 1.0 ± 0.03 g and measure 8 mm long by 10 mm diameter (n = 50; Shiels et al. 2024), and this Brodifacoum-25D Conservation formulation bait was used during the Midway mouse eradication attempt of 2023 (W. Jolley, pers. commun.). Orillion's mouse-sized pellets are 5.5 mm in diameter and weigh 0.6 g. Both bait manufacturing companies can produce baits with brodifacoum concentrations up to 50 ppm, depending on the jurisdiction for which they are intended. Typically, these higher concentration products have not been widely used for island restoration projects, mainly because mice had been successfully eradicated using the standard 2 g (20 or 25 ppm brodifacoum) baits and these had been considered proven products for eradicating mice up to this point.

Although the standard bait containing brodifacoum at 20 or 25 ppm has been used in successfully eradicating mice from islands in the period 2007-2019, changing circumstances that are not yet fully understood may warrant changing the standard bait characteristics when targeting mice. The elements that can be modified from the previous standard include bait composition, bait toxicity and bait pellet size. Given that the recent failures of mouse eradications have not been replicated in rat eradications using aerial baiting (although noting that eradication success is lower on tropical islands than on temperate islands), there may be merit in operators using bait specifically designed for mice, which will require further collaboration with bait manufacturers and operational trials to confirm both efficacy and operational suitability. Protein bait costs more to produce, but a critical aspect is the expense and long timeframes required for development and registration of new products. Relatively modest tweaking of existing bait formulations that does not require new product registration would be preferable and much quicker to be made available. However, in more heavily-regulated territories, changing a formulation usually requires a trial to prove efficacy, stability of bait and to provide information on non-target species impacts. It is not always easy or expedient to achieve a change to bait formulation, depending on the level of regulation required by the jurisdiction of the target destination.

Many pest eradication projects in the past decade or more have 'planned for success' rather than 'planned for failure'. Monitoring of environmental or operational factors during the operation has often not been widely conducted, partly due to financial constraints. As a consequence, when failure has occurred, there may be little empirical information to answer subsequent questions about what contributed to the failure. More information-gathering during aerial baiting operations is advised, both to provide information after the operation (including to rule out possible causes of failure), but also to inform real-time planning during an operation, to allow adjustments to the baiting strategy to be made.

WORKSHOP OUTCOMES

Outcomes from the workshop are still in progress, but actions identified to date are shown in Table 1. The research needs questions that were identified, discussed, and prioritized during the workshop are shown in Table 2.

CONCLUSION

Notwithstanding some potential issues identified in operational reviews of one project (a formal review has not yet been initiated for the other), both recent unsuccessful projects broadly complied with currently understood best-practice principles and practices in their operational implementation. No 'smoking gun' was identified as a sole or significant contributing cause to either eradication failure. Instead, we found support for at least two of the three hypotheses contributing to Gough and Midway mouse eradication failures: 1) Hypothesis 1: Mice *could* not eat a lethal dose of bait, and 2) Hypothesis 2: Mice *would* not eat a lethal dose of bait. Furthermore, Hypothesis 3: Is there a problem with toxicity, may have been a contributing factor in relation to Gough Island, although this was not considered conclusive.

Consumption of bait by non-target species was evident in both operations, particularly by invertebrates (slugs on Gough, cockroaches and isopods on Midway). This observation supports Hypothesis 1: Mice *could* not eat a lethal dose of bait. However, given the disparity in island characteristics (climatic, terrain, biota), the primary common factor in both failed outcomes appeared to be the learned behaviour by mice of exploiting seabirds as a source of dietary protein. This observation that more desirable natural foods, including live and dead seabirds, were chosen over the bait is evidence supporting Hypothesis 2: Mice *would* not eat a lethal dose of bait.

The Mouse Eradication Workshop was an early initiative to gather experienced eradication practitioners to discuss what may have contributed to failed mouse eradications, and how to enhance success for future projects. While no 'smoking gun' cause of failure could be identified, the importance of good foundational knowledge of the ecology of mice on target islands, robust peer-reviewed planning and trials with wide collaboration, and continued development of eradication tools and their best practice use are recommended.

WORKSHOP PARTICIPANTS

The 26 workshop participants (in-person [IP] and online [OL]) and two supporting staff represented the following agencies:

- Andrew Callender [IP], Sophie Thomas [IP], Pete McClelland [IP] - Royal Society for the Protection of Birds (UK)
- Anton Wolfaardt [IP], Keith Springer [IP] - Mouse-Free Marion Project (South Africa)
- David Will [OL], Richard Griffiths [IP], Wes Jolley [OL] - Island Conservation (USA)
- Keith Broome [IP], Stephen Horn [IP], Finlay Cox [IP], Darcy Bellanto [IP], Iain Rayner [IP] - Department of Conservation (New Zealand)
- Gerry McChesney [OL], Aaron Martin [OL] - US Fish & Wildlife Service (USA)
- Alex Wegmann [IP], Nick Holmes [OL] - The Nature Conservancy (USA)
- Aaron Shiels [IP] - US Department of Agriculture (USA)
- James Russell [OL] - University of Auckland (New Zealand)
- Araceli Samaniego [IP] – Landcare Research (New Zealand)
- Penny Fisher [OL] – Landcare Research (Australia)
- John Quigley [IP], Bill Simmons [IP] - Orillion Ltd. (New Zealand)
- Fabrice le Bouard ([IP] - France), Kerry Brown ([IP] - New Zealand), Gregg Howald ([OL] - Canada) - independent participants.

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The New Zealand Department of Conservation's support of the workshop was invaluable, in making Iain Rayner and Darcy Bellanto available to facilitate the workshop and record discussions, respectively.

Thanks also to the workshop participants who also formed the planning committee for the workshop – Keith Broome, Andrew Callender, Fabrice Le Bouard, Keith Springer, Sophie Thomas, David Will and Anton Wolfaardt.

Table 1. Mouse Eradication Workshop outcomes and progress to date.

	Outcome	Current Situation
1.	Development of a Research Plan to establish trial designs to answer some of the research questions raised during workshop discussions, including new or adjusted bait formulations.	In progress
2.	A review of the document produced by the New Zealand Department of Conservation: *Mouse eradication using aerial baiting: Current agreed best practice used in New Zealand (Version 1.0)* (Broome et al. 2019).	Awaiting further information from research investigations in (1) above
3.	Collation of workshop proceedings and publication thereof.	In progress
4.	Increased inter-agency and international cooperation to advance our understanding of potential contributing factors to mouse eradication failures and improve operational design for future mouse eradications.	A marked increase in collaboration has been evident
5.	Wider peer review of eradication planning documents to encompass a wider range of experiences from previous projects.	Ongoing

Table 2. Research priorities identified during the Mouse Eradication Workshop.

	Research Question	Priority
1	What is the minimum length of time bait needs to be available at the required density?	H
2	What attributes (demographics, genetics, location, diet) do surviving mice have?	H
3	Is mouse choice and exposure to a lethal dose a matter of encounter rate or bait preference and palatability?	H
4	Can we develop a more palatable bait for mice? e.g., protein-based	H
5	What is the highest toxin concentration that can be used without impacting palatability?	H
6	Are mice more likely to take a lethal dose if pellet size is smaller?	H
7	Does toxicity of bait degrade over time, and when exposed to different environmental conditions during transport and storage?	H
8	What is the minimum bait density required to target mice only?	M
9	How does mouse diet vary seasonally and annually with island-specific changes in food availability? And how does this affect bait acceptance?	M
10	Are multiple bait types needed?	M
11	How does mouse behaviour change after first bait application? i.e., Lower rodent density, changes in social dynamics, competition, food resources.	L
12	Under what conditions can mice be neophobic of bait?	L
13	How can non-target bait consumers be managed or deterred to reduce competition for bait – i.e., slugs, invertebrates	L
14	Are there different baiting strategies for single-species (mice) versus multi-species eradication?	L

High (H), Medium (M), Low (L)

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