ERADICATING HOUSE MICE FROM ISLANDS: SUCCESSES, FAILURES AND THE WAY FORWARD

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Abstract: The house mouse (*Mus musculus*) has been spread throughout the world by the actions of humans. It causes severe impacts to native ecosystems, especially in areas where there are no native mammals. It is possible to eradicate mice from islands but they are harder to eradicate than rats. A review of reported eradication attempts found that 17 attempts on 45 islands worldwide failed; a failure rate of 38%. The effect of operational factors on eradication success was examined, but no significant model was formed. Brodifacoum is the most widely used toxicant and has a 49% success rate. Mouse eradications should be attempted wherever possible and recommendations to help increase the success of a house mouse eradication attempt are given.

Key words: brodifacoum, eradication, house mouse, invasive species, island conservation, *Mus musculus*, rodenticide.

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INTRODUCTION

The house mouse (*Mus musculus*) originated in the north of India around 900,000 years ago (Boursot et al. 1996). The species then spread in several directions, radiating to form three distinct sub-species (*M. m. domesticus, M. m. musculus* and *M. m. casteneus*) with distinct ranges (Boursot et al. 1993, Boursot et al. 1996). All sub-species show a high level of commensal behaviour (Boursot et al. 1996, Berry and Scriven 2005) but they are also able to survive away from human settlements (Berry and Scriven 2005, Ruscoe and Murphy 2005). The commensal behaviour of house mice means they have been spread throughout the world by humans, and house mice are present on all continents and many islands from the sub-Antarctic to the tropics (Berry and Scriven 2005, Ruscoe and Murphy 2005, Wanless et al. 2007, Witmer et al. 2007). The effect of introduced, invasive house mice has often been overshadowed by invasive rats (*Rattus* spp.), however (e.g., Atkinson 1985), especially where they co-exist and mice are dominated by rats (Caut et al. 2007). Non-commensal populations of house mice can have severe negative impacts on native ecosystems, especially in areas where the native biota evolved in the absence of mammals (Courchamp et al. 2003), and house mice have been recorded as damaging populations of invertebrates (Rowe-Rowe et al. 1989, Miller and Webb, 2001), lizards (Newman 1994), birds (Jones et al. 2003, Wanless et al. 2007) and seed production in forests (Wilson et al. 2007). Eradication of invasive rodents is an important management tool to redress their negative impacts and a recent review recorded that introduced house mice have been eradicated from 30 islands worldwide, using a number of different methods. Despite this progress, seven attempts failed which is a 19% failure rate, compared to a 5% failure rate for Norway rats (*Rattus norvegicus*) (Howald et al. 2007). Is there a reason that introduced mouse populations are harder to eradicate from islands than introduced rat populations? In order to answer this question, we compiled, reviewed and analysed a database of all known mouse eradication attempts. The database was compiled from the published literature, "grey" literature, and through conversations with researchers and managers involved in introduced house mouse eradication attempts (see Appendix).

ISLAND MOUSE ERADICATIONS

The first reported mouse eradication took place on Flatey Island in Iceland in 1971 (Moors 1992). Since then, there have been over 50 other attempts worldwide from Rasa Island in the Gulf of California (Tershy et al. 2002) to Enderby Island in the sub-Antarctic (Torr 2002). Different toxicants and broadcasting methods have been used in conjunction with trapping in some cases. Eradication attempts have taken place on 51 islands ranging in size from 0.7 ha Crusoe Island in New Zealand (Lee 1999) to 800 ha St. Paul Island in the French Sub-Antarctic (Micol and Jouventin 2002). Successes and failures have occurred across the full range of island sizes (see Appendix). Two eradication attempts were stopped before completion for operational reasons and six are yet to be confirmed. Eradication of house mice was achieved on 28 of 45 islands that the result is known for. However, sometimes it took more than one attempt. On Mokoia Island, New Zealand the first two operations failed but the third attempt was successful. All four operations on Limestone Island, New Zealand have failed. This gives a failure rate of 38% which is higher than reported by Howald and others (2007) and much higher than failures reported for rat species. A total of over 3,600 ha of island habitat worldwide has been cleared of mice.

We categorised each house mouse eradication attempt by four operationally defined factors which might affect the likelihood of successful eradication (Table 1). In order to identify which (if any) of these factors most influence eradication success or failure a logistic general linear model was fitted with success/failure as the response factor and details of the eradication attempt entered as explanatory variables. No significant model was formed with any combination of explanatory variables meaning there is no evidence that success or failure of mouse eradications to date has been consistently caused by any of these operational factors. Nonetheless we report success and failure rates relative to each factor.

Toxicants

Nearly all recorded mouse eradication attempts used some form of anticoagulant toxicant. These compounds are used in eradication attempts worldwide (Eason et al. 2002, Hoare and Hare, 2006) and act by inhibiting the production of clotting factors within the animal normally leading to death by internal haemorrhage within 10 days (O'Connor and Booth 2001). Seven toxicants have been used in mouse eradication attempts; three first-generation anticoagulants (diphacinone, pindone and warfarin) were used as the main toxicant in six attempts, three second-generation anticoagulants (brodifacoum, bromadiolone and flocoumafen) were used as the main toxicant in 49 attempts and an acute toxicant (1080) in one. Five attempts used multiple toxicants and two attempts followed up poisoning with trapping. Brodifacoum was used as the main or secondary toxicant in 80% of mouse eradication attempts (including multiple attempts on the same island), 49% of which were successful (45 attempts, 22 successful). Other toxicants have a higher success rate but the sample size is much lower. A single eradication attempt using 1080 (Varanus Island, Australia, 1993) is likely to have failed because it has been shown that mice can detect the presence of 1080 in baits (O'Connor et al. 2005).

Bait Delivery

Three main methods of bait delivery have been used in mouse eradication attempts. The method chosen depends on island topography, non-target issues, economics and the habitat on the island (Howald et al. 2007). Information is scarce on the earliest recorded mouse eradication attempt (Flatey

Table 1. Factors investigated in analysis of eradication attempts.

Factor	Description
Island area	Size of the island in hectares
Bait application method	Aerial, bait station or hand spreading
Toxicant (generation: 1st or 2nd generation anticoagulant)	Diphacinone (1), pindone (1), warfarin (1), brodifacoum (2), bromadiolone (2) or flocoumafen (2)
Other introduced mammals	Competitors, predators or no direct effect

Island, Iceland, 1971) but it has been assumed that bait stations were used.

1. Bait stations were used as the main method of bait delivery in 30 out of 56 eradication attempts (including multiple attempts on the same island). They were also used to supplement aerial delivery in two attempts. The grids used for bait station delivery varied in size from 10 m to 50 m; 20 m to 25 m being the most common spacing used. Bait station grids are normally maintained for 1-2 years (Thomas and Taylor 2002) but some attempts went on for much longer. Bait stations were first placed on 37 ha Limestone Island, New Zealand in 1999 and have been regularly serviced for over 6 years (J. Craw, Auckland Regional Council, New Zealand, personal communication) but mice are still present, despite three aerial attempts and one ground-based attempt, and prolonged periods of non-detection (C. Mitchell, Limestone Island Ranger, New Zealand, personal communication). Bait stations are relatively labour intensive and track maintenance can damage island habitat; particularly with smaller grid spacing; but if the support required to service bait stations is available this is a relatively effective method with 48% of eradication attempts succeeding. The largest island successfully cleared of mice using this method was 253 ha Flat Island in Mauritius using a 25 m by 25 m grid (Bell 2002).

2. Hand broadcasting of baits was used in two eradication attempts; both run by French teams, and where one attempt was successful and the other failed. Fajou Island in Guadaloupe is the largest island (120 ha) where mouse and rat eradication was attempted using this method and poisoning in this instance was supplemented by trapping (M. Pascal, National Institute for Agricultural Research, France, personal communication). A recent visit to the island found mice present at low numbers but the reason for eradication failure is unclear (M. Pascal, personal communication). Hand broadcast is a valuable method to consider when aerial broadcast is not possible and when the continued support needed to maintain a network of bait stations is unavailable. Hand broadcasting of baits has been used to supplement a number of bait station and aerial operations to ensure bait reaches all areas of islands (Stephenson et al. 1999, Merton et al. 2002).

3. Aerial broadcast of bait using helicopters is becoming more common and the preferred method of bait delivery for introduced rodent eradications (Towns and Broome 2003). This technique has been used in 25 mouse eradication attempts around the world. In some cases aerial operations have been supplemented by hand broadcast or bait stations, but the majority of attempts rely solely on bait distributed by helicopter. Forty eight percent of eradication attempts using aerial broadcast have been successful. The amount of bait distributed onto the island and the number of bait drops varies. This information is not always available but the mean quantity of bait used in 16 operations was 15.3 kg ha^{-1} (range 10-39 kg ha^{-1}). The number of drops varies between one and three. The highest bait density was used on Frégate Island in the Seychelles where the presence of crabs meant a large amount of bait had to be used (Merton et al. 2002). The flight paths of the helicopters are crucial to ensuring eradication success. Overlapping flight paths and second drops at right angles to the first are good methods of ensuring complete coverage of the island. Modern global positioning system (GPS) satellite technology allows helicopter pilots to plot locations and flight paths very accurately (Lavoie et al. 2007). Five recent eradication attempts in New Zealand had bait distributed by helicopter, but we are awaiting confirmation of success. We did not model the amount of bait used, or number of bait drops, but these operational factors, which are island-specific, may affect the outcome of eradication attempts.

Other Mammal Species

Populations of mice are significantly affected by the presence of other invasive mammal species (Innes et al. 1995, Choquenot and Ruscoe 2000). There have been a number of reported instances where mice have increased in number once rats have been eradicated or brought to low numbers (Caut et al. 2007). The presence of other mammal species may alter the behaviour of mice and make them less likely to come into contact with bait, leading to eradication failure (Innes et al. 1995). Where possible the presence of other introduced mammal species has been recorded on each island where an eradication was attempted. Twenty-seven eradications were attempted in the presence of other mammal species and 13 of these failed (48%). The mammals present were then divided into three categories – competitors (rat species); predators (cats [*Felis catus*], stoats [*Mustela erminea*], weasels[*Mustela* spp.]) and no direct effect (rabbits [*Oryctolagus cuniculus*] and brushtail possums [*Trichosurus vulpecula*]). Interactions between rats and mice are complex and poorly understood and there is likely to be an element of both competition and predation (Caut et al. 2007). Rabbits and possums have no direct impact on mouse populations but can eat bait and therefore stop mice accessing it. On Motuihe, New Zealand, high rabbit numbers may have reduced the amount of bait available to rats and mice but the eradication was still successful (Veitch 2002). Dividing the mammal species into different categories had no effect on the model.

WHY DO MOUSE ERADICATION ATTEMPTS FAIL?

In order for an eradication to succeed every house mouse on an island must have access to the toxicant. At the most basic level poor operational implementation during the baiting campaign may lead to areas of the island being missed by bait. A retrospective assessment of operational implementation effectiveness could not be included as a variable here due to its subjective nature. However, one of the main reasons for mouse eradication attempts failing could be gaps in poison coverage. An eradication attempt on St. Paul Island in the sub-Antarctic failed because a malfunction in the bait spreader led to gaps in coverage (Micol and Jouventin 2002). Similar problems with operational implementation may have occurred in other eradications and not been reported. In these cases, reasons for failure are clear and relatively simple to rectify in subsequent attempts. For some eradications, however, reasons for failure may be more complex and harder to demonstrate and resolve. Recently it has become apparent that even aerial operations using helicopters guided by GPS may leave gaps in poison coverage (Josh Kemp, Department of Conservation, New Zealand, unpublished data). Possibly some aspect of mouse behaviour means that in a number of cases some individuals are not being poisoned. These animals may not come into contact with the bait; they may find bait but not eat it (i.e., have a cereal aversion, Humphries et al. 2000) or they may have a level of toxicant resistance allowing them to survive eating the bait (e.g., mice on Lord Howe Islands are resistant to warfarin following ongoing control since 1986 (Billing 2000)). Research in laboratory situations has shown critical differences in spatial and social behaviours between wild and laboratory house mice (Augustsson and Meyerson 2004, Augustsson et al. 2005) and between different chromosomal strains of wild house mice (Ganem and Searle 1996). Behavioural differences at the subspecies level may also contribute to some of the failures.

Introduced house mice are physiologically very different from invasive rats, and able to sustain island densities orders of magnitude higher. What now seems a straightforward eradication for invasive rats, may still remain a challenge for introduced mice (Howald et al. 2007). Despite this, eradicating mice should always be attempted provided sufficient information is gathered prior to eradication to ensure correct operational implementation (i.e., bait delivery method and toxicant amounts).

We were unable to create a model predicting success or failure of a mouse eradication attempt based on operational factors. Some operational factors appear to aid success, even if this is not statistically significant. Some observations from the database are as follows:

- Following an aerial bait operation with hand spreading of poison in at risk areas or use of bait station may increase eradication success.
- Hand spreading bait in conjunction with bait stations may lead to an increased chance of success.
- Multiple toxicants may result in success. Five successful eradication attempts combined brodifacoum with another toxicant.

Bait stations spaced at around 20 m apart had the best chance of success.

FUTURE RESEARCH

Data on island house mouse populations are scarce, and only a few islands have been studied intensively (e.g., Marion Island (Avenant and Smith 2004, Ferraira et al. 2006, van Vuuren and Chown 2007) and Allports Island (Murphy 1989)). Basic information about home range sizes, ranging behaviour and densities on islands remain largely unknown, especially during critical winter months where on temperate islands mouse impacts may be greatest (Wanless et al. 2007). The effect of different habitat types on eradication attempt success is also unknown. Mice living in complex habitats with ample food may have small home ranges and not come into contact with bait. The response of mouse populations to poisoning has not been investigated on islands and nothing is known about how mouse populations re-colonise areas following a failed eradication attempt. Genetic samples should be taken prior to any eradication attempt to allow failed eradications to be distinguished from re-invasions (Abdelkrim et al. 2007). Although eradication failure is never a desirable outcome, much knowledge can still be gained from reflecting on causes of an eradication failure.

Current research on introduced house mice at The University of Auckland and elsewhere is obtaining accurate density estimates using capture-mark-recapture techniques, investigating home range size and ranging behaviour using radio-tracking and other tracking techniques, and then monitoring the response of a mouse population to poison during an experimental eradication attempt. Recent laboratory work showed that most mice died eight days after first being fed bait, while a few survived for up to 21 days (G. Morriss, unpublished data). Trapping on Adele Island in New Zealand eight days after the first poison drop failed to detect any mice over 330 trap-nights and 40 tracking-nights across the entire island (J. MacKay, unpublished data). Toxicant resistance on islands where long-term poison campaigns are taking place may also be an issue (Billing 2000) and could explain why mice are still present despite repeated attempts to eradicate them.

CONCLUSION AND RECOMMENDATIONS

Introduced house mouse eradication is an important conservation tool that should be used in order to mitigate the negative effects of introduced mouse populations on islands. Thirty eight percent of mouse eradication attempts on islands worldwide have failed, but we were unable to find a consistent simple operational explanation for these failures. Eradications should be attempted provided sufficient planning and preparation has taken place to rule out failure due to operational errors, or factors that can be controlled for. Brodifacoum is the most widely used toxicant. Poison bait has been distributed using bait stations, hand broadcast and aerial operations; each of these techniques has resulted in some successes and each technique has its merits. The presence of other mammal species on an island may affect the outcome of a mouse eradication attempt, but we detected no definitive affect on success of eradication. Further research is needed into mouse populations on islands to investigate what aspects of mouse ecology and behaviour lead to eradication failures.

Mouse eradications should always be attempted if adequate distribution of bait is feasible. However, eradications must be well planned to avoid failure. Factors to consider in order to maximise the likelihood of success include:

- Will the chosen poisoning method allow every mouse on the island access to poison?
- Take genetic samples prior to the eradication attempt. This allows the distinction to be made between eradication failure and a re-invasion and also can be used to determine sub-species.
- Consider the effects of other mammals. Will they prevent mice accessing poison?
- Will the mice eat the bait? Consider bait trials to check for poison palatability and cereal aversion.
- Are there areas which may require extra poison? Dense grassland can support very high numbers of mice and may require more poison than forest areas.

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Appendix. Eradication of house mice from islands worldwide (Updated 2007; the authors would be grateful to be made aware of any omissions or errors in this compilation.)

Part 1. Data on operations which have resulted in the eradication of house mice from islands around the world. The methods listed are: A=Aerial, B=Bait stations, H=Hand broadcast, T=Trapping. Toxicants listed are: BM=Brodifacoum, BE=Bromadiolone, DE=Diphacinone, FN=Flocoumafen, PE=Pindone, WN=Warfarin. Countries listed are: AUS=Australia, FRA=France, ICE=Iceland, MAU=Mauritius, NZL=New Zealand, POR=Portugal, ROS=Republic of Seychelles, UK=United Kingdom, US=United States. * = date confirmed after a 2 year confirmation process, # = Method not confirmed, assumed to be bait stations.

Island	Area (ha)	Country	Started	Methods	Toxicant	Completed	Reference
Beacon	1.2	AUS	1997	B	PE, BM	1997	Burbidge and Morris 2002
Bridled	22	AUS	1997	B	PE, BM	1997	Burbidge and Morris 2002
Varanus	80	AUS	1997	B	PE, BM	1997	Burbidge and Morris 2002
Surprise Island	24	FRA	2001	H	BE	2006	F. Courchamp, pers. comm.
Flatey Island	50	ICE	1971	B#	WN	1971	Moors et al. 1992
Flat Island	253	MAU	1998	B	BM	1998	Bell 2002
Ile aux Sables	8	MAU	1995	B, H	BM	1995	Bell 2002
Ile Cocos	15	MAU	1995	B, H	BM	1995	Bell 2002
Rasa Island	60	MEX	1994	A, T	BM	1994	Tershy et al. 2002
Allports (Marlborough)	16	NZL	1989	B	FN	1991*	Brown 1993
Blumine Marlborough)	377	NZL	2005	A	BN	2007*	M. Aviss pers. Comm..
Browns (Hauraki Gulf)	58	NZL	1995	A	BE	1997*	Veitch 2002a
Enderby (Auckland)	710	NZL	1993	A	BM	1995*	Torr 2002
Mana	217	NZL	1989	A, B	BM, FN	1991*	Hook and Todd 1992
Mokoia (Lake Rotorua)	135	NZL	2001	A, H	BM	2003*	Armstrong et al. 2001
Motuihe (Hauraki Gulf)	179	NZL	1997	A	BM	1999*	Veitch 2002b
Moturemu (Kaipara)	5	NZL	1992	B	BM	1994*	I. McFadden pers. comm.
Motutapere (West Coromandel)	45	NZL	1994	A, B	BM	1996*	P. Thomson pers. comm.
Motutapu (Marlborough)	2	NZL	1989	B	FN	1991*	Brown 1993
Mou Waho (Lake Wanaka)	140	NZL	1995	A, T	BM	1997*	McKinlay 1999
Ohinau (East Coromandel)	43	NZL	2005	A	BM	2006	J. Roxburgh pers. comm.
Papakohatu (Crusoe)	0.7	NZL	1996	B, T	BM	1997	Lee 1999
Pickersgill (Marlborough)	103	NZL	2005	A	BM	2007*	M. Aviss pers. comm.

Island	Area (ha)	Country	Started	Methods	Toxicant	Completed	Reference
Rimariki	22	NZL	1989	B	BM	1991	Veitch & Bell 1990
Whenuakura (Whangamata)	2	NZL	1983	B	BE	1984	Newman 1985
Selvagem Grande	200	POR	2002	B	BM, HS	2003	Oliviera et al. 2003
Frégate	219	ROS	2000	A	BM	2002	Merton et al. 2002
White Cay, Exumas-Bahamas	15	UK	1998	B	BM	1998	Hayes et al. 2004

Part 2. Data on operations which have not resulted in the eradication of house mice from an island. These operations are listed as: "incomplete" where the work is continuing or confirmation of the eradication has not been obtained; "stopped" where the work was stopped due to a management decision before the planned work was completed; "unsuccessful" where the planned programme was completed and eradication was not successful. The methods listed are: A=Aerial, B=Bait stations, H=Hand broadcast, T=Trapping. Toxicants listed are: BM=Brodifacoum, BE=Bromadiolone, DE=Diphacinone, FN=Flocoumafen, PE=Pindone, WN=Warfarin. Countries listed are: AUS=Australia, FRA=France, ICE=Iceland, MAU=Mauritius, NZL=New Zealand, POR=Portugal, ROS=Republic of Seychelles, UK=United Kingdom, US=United States.

Island	Area (ha)	Country	Started	Methods	Toxicant	Reference
INCOMPLETE						
Ile Chateau	250	FRA	2002	A	BM	M. Pascal pers. comm
Adele	87	NZL	2007	A	BM	C. Golding pers. comm.
Fisherman	4	NZL	2007	A	BM	C. Golding pers. comm.
Pomona (Lake Manapouri)	262	NZL	2007	A	BM	?
Rona (Lake Manapouri)	60	NZL	2007	A	BM	?
Tonga	8	NZL	2007	A	BM	C. Golding pers. comm.
STOPPED						
Silver (Lake Hawea)	25	NZL	1997	B	BM	S. Thorne pers. comm.
Stevensons (Lake Wanaka)	65	NZL	1997	B	BM	S. Thorne pers. comm.
UNSUCCESSFUL						
Varanus	80	AUS	1993	B	1080	Burbidge and Morris 2002
Fajou	120	FRA	2001	H	BE	M. Pascal pers. comm.
St. Paul	800	FRA	1997	A	BM	Micol and Jouventin 2002
Tromelin	100	FRA	2005	B, H	BM	?
Patiti (Banded)	12.8	NZL	2004	B	BM	Bancroft 2004

Island	Area (ha)	Country	Started	Methods	Toxicant	Reference
Haulashore	6	NZL	1991	B	BM	Thomas and Taylor 2002
Hauturu	10	NZL	1993	B, H	BM	Glassey 2006
Hokianga (Ohiwa)	8	NZL	2006	B	PE	D. Paine pers. comm.
Limestone (Matakohe)	37	NZL	1996	A	BM	Ritchie 2000
Limestone (Matakohe)	37	NZL	1997	A	BM	Ritchie 2000
Limestone (Matakohe)	37	NZL	1998	A	BM	Brackenbury 2001
Limestone (Matakohe)	37	NZL	1999	B	BM	P. and C. Mitchell pers. comm.
Mokoia	133	NZL	1989	B	BM	Owen 1998
Mokoia	133	NZL	1996	A	BM	Dumbell 1998
Quail	81	NZL	2002	B, H	BM	Bowie 2002
Te Haupa	6	NZL	1993	B	FN	T. Wilson pers. comm.
Bird Island	101	ROS	1996	B, H	BM	Merton et al. 2002
Curieuse Island	286	ROS	1996	A	BM	Merton et al. 2002
Denis	143	ROS	2000	A	BM	Merton et al. 2002
Buck	80	US	2000	B	DE	Witmer et al. 2007

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