Review of rat invasion biology

Implications for island biosecurity

SCIENCE FOR CONSERVATION 286

Department of Conservation
Te Papa Atawhai

Review of rat invasion biology

Implications for island biosecurity

J.C. Russell, D.R. Towns and M.N. Clout

SCIENCE FOR CONSERVATION 286

Published by
Science & Technical Publishing
Department of Conservation
PO Box 10420, The Terrace
Wellington 6143, New Zealand

Cover: Norway rat swimming. *Photo: Gen-Yu Sasaki.*

Science for Conservation is a scientific monograph series presenting research funded by New Zealand Department of Conservation (DOC). Manuscripts are internally and externally peer-reviewed; resulting publications are considered part of the formal international scientific literature.
Individual copies are printed, and are also available from the departmental website in pdf form. Titles are listed in our catalogue on the website, refer www.doc.govt.nz under *Publications*, then *Science & technical*.

ISSN 1173–2946 (hardcopy)
ISSN 1177–9241 (web PDF)
ISBN 978–0–478–14410–9 (hardcopy)
ISBN 978–0–478–14411–6 (web PDF)

This report was prepared for publication by Science & Technical Publishing; editing by Helen O'Leary and layout by Amanda Todd. Publication was approved by the Chief Scientist (Research, Development & Improvement Division), Department of Conservation, Wellington, New Zealand.

In the interest of forest conservation, we support paperless electronic publishing. When printing, recycled paper is used wherever possible.

CONTENTS

Review of rat invasion biology

Implications for island biosecurity

J.C. Russell[1], D.R. Towns[2] and M.N. Clout[1]

[1] School of Biological Sciences, University of Auckland, Private Bag 92019, Auckland Mail Centre, Auckland 1142, New Zealand
Email: j.russell@auckland.ac.nz

[2] Research, Development & Improvement Division, Department of Conservation, Private Bag 68908, Newton, Auckland 1145, New Zealand

A B S T R A C T

In this paper, we review and analyse how three species of invasive rat (*Rattus rattus*, *R. norvegicus* and *R. exulans*) disperse to and invade New Zealand offshore islands. We also discuss the methods used to detect and prevent the arrival of rats on islands. All species of invasive rat can be transported by ship. However, rats can also swim to islands. Swimming ability varies greatly between individual rats, and is probably a learned trait; it is unlikely to be affected by variation in sea temperature in this region. Norway rats (*R. norvegicus*) are the best swimmers and regularly swim up to 1 km. Therefore, to prevent recurrent swimming invasions of islands, source populations may need to be controlled. Since islands differ in their attributes and individual rats differ in their behaviours, multiple devices need to be used to detect and prevent the invasion of islands, including poisons, traps, passive detection devices and trained dogs. In New Zealand, 85% of rat incursions have been successfully intercepted using traps and/or poisons. Any response should cover at least a 1-km radius around the point of incursion. If trapping, it is recommended that jaw traps are used. If using poison, it is recommended that hand-spread, short-life, highly palatable bait of the maximum permissible toxin concentration in small pellet form is used; if bait stations are used, large wooden tunnels that have a line of sight through them are recommended. To intercept invasions early, it is recommended that island surveillance is undertaken at least annually (preferably every 6 months).

Keywords: bait, island biosecurity, New Zealand, poison, *Rattus exulans*, *R. norvegicus*, *R. rattus*, rodents, swimming, traps

Russell, J.C.; Towns, D.R.; Clout, M.N. 2008: Review of rat invasion biology: implications for island biosecurity. *Science for Conservation 286*. Department of Conservation, Wellington. 53 p.

1. Introduction

Island biosecurity refers to the policies and measures taken to protect insular biodiversity and ecosystems from non-native species (Russell et al. 2008). Three rat species—the Pacific or Polynesian rat (*Rattus exulans*), the Norway or brown rat (*R. norvegicus*), and the ship or black rat (*R. rattus*)—have together invaded over 80% of the world's oceanic island groups (Atkinson 1985). These invasive rats may pose the greatest threat to island biodiversity in New Zealand and elsewhere in the world (Moors et al. 1992; Towns et al. 2006; Jones et al. 2008). This report provides a global review of invasive rat island biosecurity, while drawing specifically on New Zealand experiences and including an analysis of rodent incursion responses in New Zealand. Many of the data reported are based on the outcomes of a larger scientific research project investigating the invasion ecology of rats on New Zealand islands (Russell 2007).

The major components of island biosecurity are prevention, detection and responses to incursions. These all share the objective of stopping the establishment of invasive species. An 'incursion' is when a species is believed to have arrived on an island, but where a self-sustaining island-wide population has not established. An 'invasion' is what follows an incursion, where a species colonises an entire island. A third category, 'incident', is used to describe an incursion where evidence is equivocal (e.g. no body or reliable sign such as droppings or footprints are provided), or where a 'near miss' occurs and a species was intercepted prior to arrival on an island. A recent review of invasion studies (Puth & Post 2005) found that only a small proportion of them focused on incursions before they became an invasion, yet this is the critical time in which to eradicate an invading species.

1.1 BACKGROUND

Invasive rats have now been removed from many islands around the world, including some larger than 1000 ha in area (Clout & Russell 2006; Howald et al. 2007). However, rats have reinvaded some islands about a decade after eradications were completed (Clout & Russell 2008). Early detection of such invasions is crucial, especially on large islands where the costs of repeated whole-island eradication campaigns are substantial. Unfortunately, the processes involved in the invasion of islands by rats are so poorly understood that all islands are potentially at risk. Furthermore, the use of islands close to the mainland for conservation purposes is compromised because their reinvasion (by rats swimming to them) is currently regarded as inevitable.

General 'best practice' guidelines, such as those produced by the Department of Conservation (DOC 2006), are useful for island biosecurity. However, for such guidelines to have greater relevance, the efficacy of island biosecurity methods needs to be tested in the context of the pathways and vectors of rat invasion (Rulz et al. 2003). The objectives of our study reflect this need.

1.2 OBJECTIVES

The objectives of this study were to:

- Review the processes involved in dispersal to and invasion of islands by invasive rats, with reference to how they may affect island biosecurity practice
- Review the approaches and tools used for the detection and prevention of invasive rat arrival on islands
- Analyse all records of rodent incursions and reinvasions on New Zealand islands
- Recommend tools and approaches for island biosecurity to prevent rat invasions, thereby allowing the development of region-specific best practice manuals

2. Methods

We reviewed the relevant international scientific literature on the biology and control of introduced rats, with particular emphasis on swimming ability and dispersal, and control and eradication on islands. In addition, unpublished DOC reports and discussion with DOC staff across New Zealand were used to develop specific case examples of eradications, incursions and island biosecurity methods. We also compiled and analysed all recorded incursions of rodents to islands in New Zealand (Appendix 1).

Islands recently invaded by rats around New Zealand were visited by the authors to evaluate island biosecurity practice. These comprised Goat I., Haulashore I., Moturemu I., Motutapere I., Noises Is., Pearl I., Tawhitinui I., and Ulva I. James Russell also participated in the following (New Zealand) rodent workshops: Landcare Research rodent research—strategic planning workshop (19 March 2004, Lincoln); Tawharanui open sanctuary rodent workshop (29 June 2005, Tawharanui); DOC rodent research workshop (16–17 March 2006, Christchurch); and DOC rodents and island invasion workshop (22–23 August 2006, Omaui).

On the basis of the site visits and using information from the workshops, pathways of rat dispersal and invasion were reviewed and their relative risks quantified in New Zealand as well as in an international context. Current approaches and tools for rat island biosecurity were then assessed.

3. Results

3.1 DISPERSAL AND INVASION

The pathways and processes by which invasive rats disperse to and colonise islands will affect the likelihood of an island being invaded (Atkinson 1985; Drake 2004; Russell et al. 2007a). Island biosecurity must assess the risk of invasion for any particular island or group of islands, and consider how this risk is to be managed (Andersen et al. 2004; Bartell & Nair 2004). The greatest problem has been in comparing the relative merits of various island biosecurity systems, when very few rat invasions have actually been detected. The absence of rat invasion alone does not necessarily mean that biosecurity systems in place are effective; it may simply be that invasion rates are low.

Island-specific factors must be considered at a regional level, and include variables such as distance offshore, marine conditions (e.g. water temperature, currents, marine predators), island traffic (e.g. shipwreck risk and visitation rate), landing and entry points, local drivers of population biology (e.g. dispersal cues from the mainland and to islands), and faunal elements (e.g. the presence of other rodent species or predators, which might affect the likelihood of establishment). Analyses of the current distribution of introduced rats on islands (e.g. Russell & Clout 2004) to perform risk assessments have limited power for predicting future invasion risks to islands, since risk factors may change over time. However, examination of islands that have never been historically invaded by rats, despite changing pressures, can indicate factors that may have kept rats away. These island-specific variables are not considered any further in this review.

The species of invasive rat that might invade an island must also be considered (O'Connor & Eason 2000), because different species behave differently with regard to movement, habitats and their interactions with devices (Daniel 1978; Moors et al. 1992). Sometimes the species of invading rat may be unknown, so an island biosecurity system that caters for a range of species will be necessary (Spurr et al. 2006, 2007). Invading rats at low density on a pristine island will also behave very differently from established populations on the mainland (O'Connor & Eason 2000; Dilks & Towns 2002) or survivors of eradications (Howald et al. 1999; Thomas & Taylor 2002).

In the following sections, we discuss recent invasions and invasion pathways (sections 3.1.1–3.1.2), consider dispersal by vessels and swimming (sections 3.1.3–3.1.4), and finally examine the process of island invasion (section 3.1.5).

3.1.1 Recent invasions

The distribution of invasive rat species on the world's major island groups was collated by Atkinson (1985), who described the large-scale, human-mediated rat movements of all three invasive rat species (*R. rattus*, *R. norvegicus* and *R. exulans*) during the last 3000 years. By 1985, invasive rats had reached 82% of the world's 123 major islands and island groups. Of these invasions, 24% were by Pacific rats, 50% by ship rats and 36% by Norway rats. The rate of invasion was then estimated at 6.57 islands per 20-year period, with a prolific

period of invasions on Pacific islands following World War II. Since Atkinson's (1985) paper, there have been seven new invasions of previously rat-free islands (Table 1).

Reporting bias probably underestimates the true rate of invasions, which will also be influenced by the declining number of historically rat-free islands available (although recent eradications are increasing the number of contemporary rat-free islands). With the addition of these seven recent invasions of previously rat-free islands (Fig. 1), the average invasion rate is now 5.89 islands per 20-year period. Assuming a constant invasion rate (modelled by a stationary Poisson process), this is not a significant change ($P = 0.107$); and as Atkinson (1985) stated, the spread of rats to islands is continuing. Some oceanic islands in the Seychelles from which rats had been eradicated have since been reinvaded, and a further 18 cases of reinvasions of 11 near-shore islands by swimming have been reported (rats were subsequently re-eradicated from these islands) (see Appendix 1 in Howald et al. 2007).

TABLE 1. RECENT INVASIONS (SINCE 1980) OF RATS ON PREVIOUSLY RAT-FREE ISLANDS.

DATE	RAT SPECIES	ISLAND	LOCATION	REFERENCE
1980s	*R. norvegicus*	Rabida	Galapagos	Dexter et al. 2004
1986–89	*R. rattus*	Toro	Corsica	Martin et al. 2000
1995	*R. norvegicus*	Frégate	Seychelles	Thorsen et al. 2000
1996–97	*R. rattus*	St. Anne islets	French West Indies	Pascal et al. 2004
1999	*R. rattus*	Clipperton	Baja Peninsula	Pitman et al. 2005
2000	*R. rattus*	Fatu Hiva	Marquesas	Towns et al. 2006
2000	*R. tanezumi*	McKean	Phoenix	M. Thorsen, DOC, pers. comm. 2006

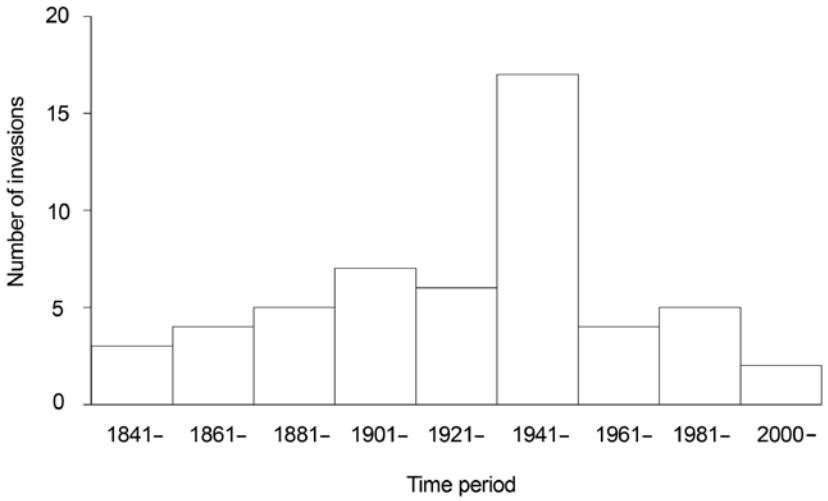

Figure 1. Number of invasions of historically rat-free islands (i.e. excluding islands where rats reinvaded after previous eradication) (extended from Atkinson 1985: figure 7).

3.1.2 Invasion pathways

At a global scale, rats can only be transported across water by human means. Their distribution at this scale provides a powerful tool for inferring invasion pathways, especially when coupled with well-documented arrival times. These data also allow inferences to be drawn about relationships between pest species introductions and species' extinctions (Blackburn et al. 2004; Towns et al. 2006), which are important for prioritising eradications and island biosecurity (Jones et al. 2008). Conservation managers are often focused on a much smaller scale, usually no more than at the archipelago level. At this scale, rats can also invade islands through self-dispersal, which makes inferring invasion pathways based on distributions difficult because of the inability to distinguish between human-assisted and self-dispersed introduction (Johnson 1962; Atkinson 1986; Atkinson & Taylor 1991). As an example, Norway rats have reinvaded the Noises Is in New Zealand up to six times since the 1980s. Earlier reinvasions were attributed to eradication failure (Moors 1985), because boat transport was ruled out as a possibility and the islands were outside the known swimming distance of Norway rats, which, as inferred from their distribution, was considered to be 300 m (Taylor, R.H. 1984), or up to 600 m in warmer waters (Atkinson 1986). However, more recent assessments of reinvasion patterns indicate that these distances were probably underestimates (Innes 2005; Russell & Clout 2005). With more data, it is apparent that swimming rather than eradication failure was the most likely cause of reinvasions of the Noises Is (JCR, unpubl. data). Establishing whether an island is at risk of invasion only by rat transport on vessels, or additionally by rats swimming, is an important first step in island biosecurity.

3.1.3 Transport on vessels

Accidental transport aboard ocean-going vessels allowed rats, along with many other pest species, to overcome the geographic barrier that water presented to them (Russell et al. 2004). Rats were able to travel hundreds to thousands of kilometres around the world on ships. Shipwrecks are a common pathway for rat establishment on islands, with examples including ship rats on Lord Howe I. (Hindwood 1940); Norway rats on Raoul I. (Sykes et al. 2000); ship rats on Clipperton I. (Pitman et al. 2005); and Asian ship rats (*R. tanezumi*) on McKean I. (M. Thorsen, DOC, pers. comm. 2006). However, not all rat-infested shipwrecks will lead to established rat populations (Spennemann 1997). Rat invasion by accidental transport was considered the greatest threat to island conservation in the 1980s (Moors et al. 1992).

Atkinson (1985) estimated the proportions of ship and Norway rats on ocean-going vessels from dates of island invasion and some observations of rats on vessels. Before 1700, when islands in the Indian and Atlantic Ocean were first discovered by Europeans, ship rats were the dominant invader. For the period 1700–1850, Norway rats became the primary island invader, particularly as islands in the Pacific were first being discovered. Only after 1850, were both rat species documented invading new islands, implying they were both present on ocean-going vessels (Fig. 2).

Since 1975, the proportions of ship and Norway rats aboard ocean-going vessels have been about equal (Fig. 2). Recent records of rats on vessels reflect the

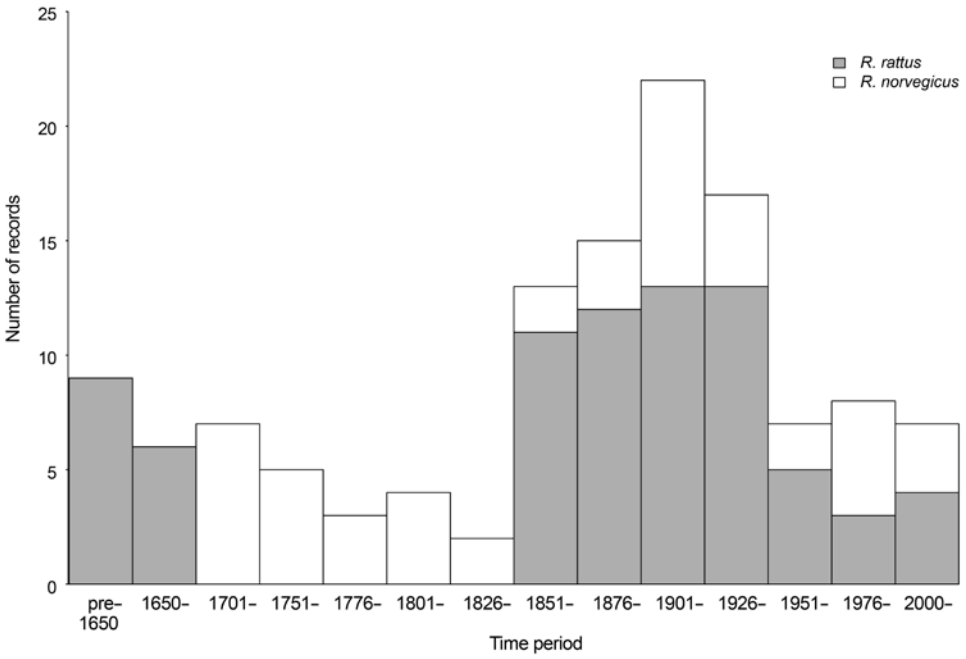

Figure 2. Changes in the proportion of *R. rattus* and *R. norvegicus* aboard ocean-going vessels between 1500 and today (n = 125 records). All available dated records of identified species reaching islands are combined with a smaller number of dated records of identified rats aboard ships (extended from Atkinson 1985: figure 5).

dominant species in the areas from where records are available. They include recent invasions of Norway rats in the Seychelles (1990s), ship rats in the Pacific (2000s), and some records of rats on vessels from Alaska and New Zealand, where quarantine standards and detection rates are high.

In New Zealand, there are also records of unknown rat species swimming from moored boats to islands, and escaping from cargo being landed on islands (Appendix 1). In addition, rats have been reported on vessels before threatening any particular island. In 1949, a ship rat was caught onboard the New Zealand scientific study vessel MV *Alert* as it moored in Duck Cove, off Resolution I., New Zealand (LM1083, Te Papa Museum Collection). In 1995, a Pacific rat was found on the DOC vessel *Hauturu*. In 2001, two Norway rats were killed on the DOC vessel *Jester* during a mainland irruption when many rats were observed swimming from islands to boats moored 100–200 m offshore from Stewart I./Rakiura (Harper 2005). In 2003, an unknown species of rat was killed on the DOC vessel *Renown* in Blanket Bay, Fiordland.

Wharves and associated buildings can act as focal points for detecting rats associated with vessels. For example, all six rat incursions on rat-free Mokoia I. in New Zealand were observed around the wharf area (Appendix 1). Poison take from bait stations at a large international wharf in the city of New Plymouth, New Zealand, increased rapidly after the docking of ships; this was presumably either caused by rats on board the vessel disembarking or neighbouring rats being attracted by the vessel landing (Parkes et al. 2004). However, increased numbers of detections around areas of human presence could be an artefact of the greater human activity in these areas.

Good records of the accidental transport of rats are also available from islands in Alaska. In 1992, the Korean shipping vessel F/V *Chil Bo San No. 6* was wrecked off Unalaska I. (137 849 ha) and unidentified rats were observed escaping onto the island, which was already infested by Norway rats. On the rat-free Pribilof Is, rat incursions have been recorded from vessels ever since monitoring began

on St. Paul I. in 1993 (Sowls & Byrd 2002). Nine Norway rats (the dominant species in the region) have been found in the 13 years since monitoring began: six caught in traps (all males), two carcasses recovered from foxes on the island, and one dead rat found in cargo. One bag of poison was also eaten, but no body ever located, and Arctic foxes were twice seen carrying what was thought to be a rat, but confirmation was not possible. Invasive rats have been detected on five vessels moored off the Pribilof Is, and two rat-infested ships have been evicted from the harbour on St. Paul I. The offshore floating fish processor *Yardarm Knot* was confirmed as rat infested (with a breeding population) and was taken to dry dock and its rats eradicated. In nearby Dutch Harbor on Unalaska/Amaknak I., the US Fish and Wildlife vessel *Tiglax* and the fish processor vessel *Arctic Star* had Norway rats trapped on board before arriving at St. Paul I. In most Alaskan cases, the rats were probably lone 'hitch-hikers' that had recently arrived on board rather than established breeding populations (A. Sowls & P. Dunlevy, US Fish and Wildlife Service, pers. comm. 2006). The construction of a wharf in the early 1990s may have been responsible for the increase in rat incursions on St. Paul I. (Sowls & Byrd 2002). Wharf construction may also have increased the likelihood of rat invasions in the Hawaiian Islands (Atkinson 1977) and elsewhere around the world (Moors et al. 1992; Spennemann 1997; Russell & Clout 2004).

3.1.4 Dispersal by swimming

Most rodents can swim when necessary and have been recorded doing so both in the wild (Blair 1939; Schmidly & Packard 1967; Stock 1972; Forys & Dueser 1993; Giannoni et al. 1994) and in experimental studies (Dagg & Windsor 1972; Esher et al. 1978; Carter & Merritt 1981). As animal ethics has increasingly (and fairly) become more important during studies of animals, studies of swimming ability to exhaustion (under wild or lab conditions) have become less common. Nonethless, those that have been conducted provide insights into the capability of rats to disperse over water.

Dagg & Windsor (1972) recorded Norway rats swimming at speeds of up to 1.4 km/h for a few seconds in laboratory tanks. Lund (1978 in Møller 1983) stated that '[Norway] rats are able to stay in water for 3 days, swimming up to 0.75 km' in northern Europe. Austin (1948) inferred that Norway rats must be able to swim up to 0.8 km to reach insular tern colonies near Cape Cod, USA. Russell et al. (2005) recorded a radio-collared adult male Norway rat swimming over 400 m from one rat-free island to another, across open water. Rats (described as 'generally Norway rats') have also been recorded swimming 100–200 m from Stewart I./Rakiura to vessels moored offshore during a period of heavy population irruptions (Harper 2005).

A physiological understanding of swimming ability can be gained by considering laboratory studies of (Norway) rats. In their account of dispersal of rats in the tropics, Spennemann & Rapp (1989) reviewed many studies of the physiological capabilities of swimming in laboratory Norway rats. Such studies usually test the effect of a treatment such as diet, chemical or physical change on the ability of rats to swim. Following Spennemann & Rapp (1989), swimming times used here have been based only on control treatments.

Eleven studies reliably assessed swimming time of invasive rat species, in water temperatures ranging from 2°C to 42°C (Table 2). Temperatures above 30°C are

unlikely to be found in the ocean, but are included in Table 2 for comparative purposes when determining the functional relationship between swimming ability and temperature.

Studies of Norway rat swimming ability consistently found high variability amongst individuals (Le Blanc 1958; Baker & Horvath 1964; Dawson et al. 1968). Tan et al. (1954) suggested that Norway rats swimming in water at body temperature died from fatigue or starvation after 50 h, whereas those in water of other temperatures

TABLE 2. SWIMMING TIMES (UNTIL THERE WAS SOME MEASURE OF FAILURE SUCH AS DROWNING) OF VARIOUS RAT SPECIES IN WATERS OF DIFFERENT TEMPERATURES.

TEMP (°C)	TIME*	*n*	REFERENCE	NOTES
R. norvegicus				
42	14.1 min†	10	Baker & Horvath 1964	
41	20 min	7	Richter 1957	
41	22 min	–	Tan et al. 1954	
37	50 h	–	Tan et al. 1954	
37	> 45 min†	10	Baker & Horvath 1964	
37	> 30 min†	8	Dawson et al. 1968	
36	> 120 min	14	Erschoff 1951	Combined diets
35	60 h	10	Griffith 1960	Wild, immediately after capture
35	6.0 h	10	Griffith 1960	Wild, kept in cages for 60 days
35	36.9 h	10	Griffith 1960	
35	60 h (60–80 h)	7	Richter 1957	
32	>90min	6	LeBlanc 1958	
29	> 90min	6	LeBlanc 1958	
22	20.8 ± 6.9 min	6	Dawson et al. 1968	Trained
22	15.7 ± 2.8 min	7	Dawson et al. 1968	Untrained
22	15 min	7	Richter 1957	
20	24.7 min (15–39 min)	8	Erschoff 1951	Normal diet
20	13.3 min (5–29 min)	12	Erschoff 1951	Basal diet (liver)
20	12.6 min†	10	Baker & Horvath 1964	
19	29 ± 7 min	6	LeBlanc 1958	
18	29 ± 4 min	6	Dumm & Ralli 1950	
17	10 min	7	Richter 1957	
17	8.6 min	–	Tan et al. 1954	
16	10.6 min† (8.2–14.5 min)	4	Dawson et al. 1968	
9	9 ± 1 min	6	LeBlanc 1958	
2	5.6 min† (5.0–6.0 min)	3	Dawson et al. 1968	
R. rattus				
22	13 min (0–51 min)	8	Jackson & Strecker 1962	Wild
21	46.3 min (17–92 min)	3	Spennemann & Rapp 1987, 1989	Wild
R. exulans				
22	41 min (0–154 min)	6	Jackson & Strecker 1962	Wild
17	10 min (6–17 min)	9	Whitaker 1974	Wild

* Time given ± SD or with range if known.

† With additional weight (a 10-g thermometer in Baker & Horvath (1964) and a 8-g catheter in Dawson et al. (1968)).

died from failure to regulate their own body temperature. However, Griffith (1960) concluded that rats ultimately died of depression (giving-up), and that swimming ability was improved in rats that had developed better stress-coping mechanisms through learning from repeated exposure to swimming. Taylor (1986) reported that wild Norway rats on subantarctic Campbell I. were only present on islands less than 50 m from the shore. Sea temperature around Campbell I. is around 10°C in summer, which may be near the lower limit of water temperatures that Norway rats can tolerate.

Bruner & Vargas (1994) specifically investigated the effect of water temperature on swimming ability (rather than merely manipulating temperature as a proxy for stress). They observed a clear U-shaped relationship between rat swimming activity and temperature (Fig. 3), with a minimum at 23°C. High rates of activity were used as an indicator for likelihood of drowning ($n = 50$). At the boundaries of 14°C and 47°C, activity levels indicated that no rats would survive for longer than about 25 min. While there were clear differences between the initial swimming abilities of individuals, rats in subsequent trials learned to lower their activity levels and swim for longer periods.

Contrary to the results obtained by Richter (1957) and the review by Spennemann & Rapp (1989), Bruner & Vargas (1994) found that swimming time increased monotonically for water temperatures up to 40°C (Fig. 4). This is possibly due to differences between active swimming ability (optimal around 23°C) and passive survival (optimal around 36°C). Dawson et al. (1968) found that that the stroke rates of swimming Norway rats increased as temperature decreased. Gray (1951) additionally found that drowning time (the time between last breath and death) for Norway rats was more rapid when water was at body-temperature ($n = 72$), suggesting that in colder waters rats would take longer to drown.

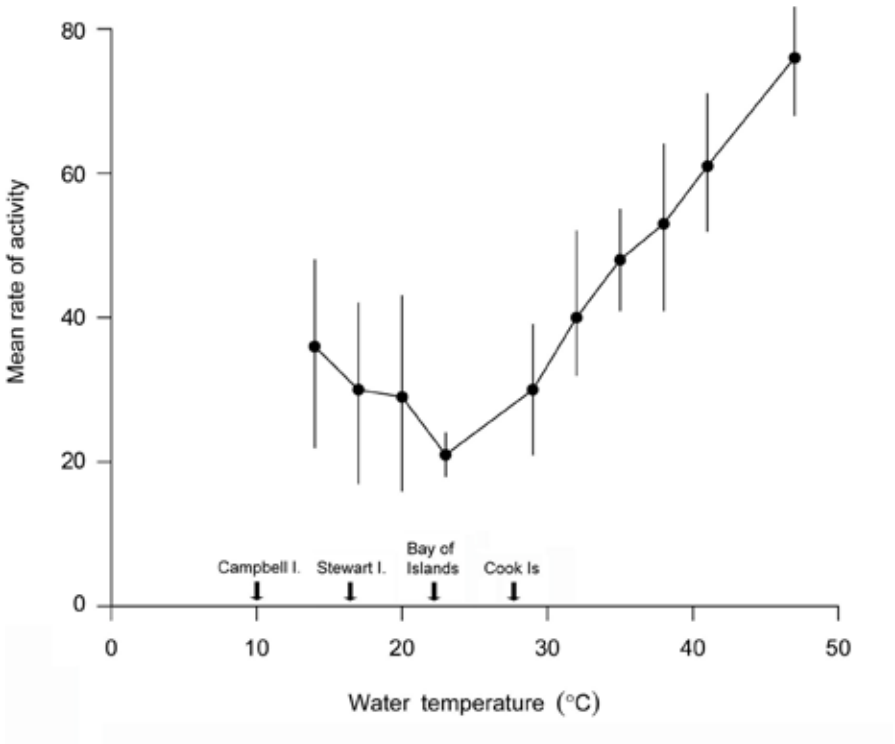

Figure 3. Relationship between mean (± standard deviation) rate of activity and water temperature ($n = 5$ rats per data point). Rate of activity was measured as interruptions per min. Data from Bruner & Vargas (1994: figure 7), with permission from Elsevier. Arrows indicate summer sea temperatures for various island groups.

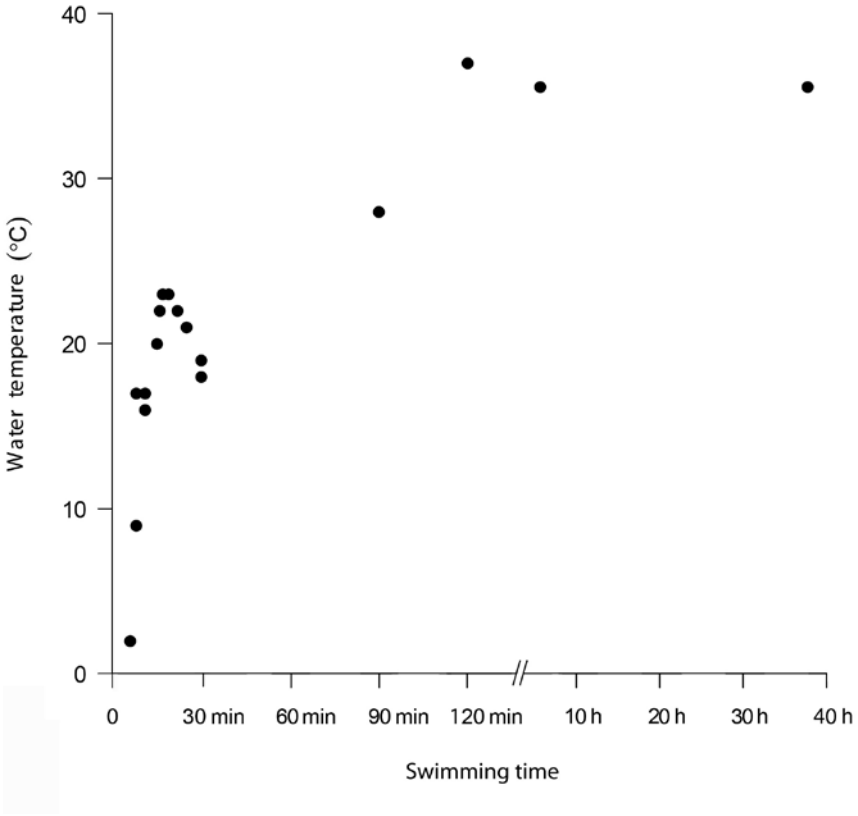

Figure 4. Relationship between swimming time and water temperature. Data from Spennemann & Rapp (1989: table 1).

McArdle & Montoye (1966) tested 51 juvenile laboratory (Norway) rats swimming to exhaustion (sinking for longer than 10 s) in water temperatures of 34–35°C over a period of 4 months. Their subjects also had weights (2% to 7% bodyweight) attached to bring swimming times into a range suitable for laboratory experiments (e.g. a 10-min average; McArdle 1967). Maximum swim time was negatively correlated with body weight (i.e. small rats swam better), although other studies have found no difference with age (Erschoff 1951). Rat swimming ability became more predictable after repeated exposure to swimming trials and the first swim did not accurately reflect an individual rat's potential ability. Orientation also improved after previous swimming trials. McArdle & Montoye (1966) concluded that swimming ability was a learned trait.

Three field-based studies of invasive rat swimming ability have been published. Jackson & Strecker (1962) studied ship and Pacific rats off Ponape I. in the tropical Caroline Is of the South Pacific. Both species orientated poorly towards land, with most individuals being lost from sight to wind and current effects. After 15 min, most rats were submerging for 'brief periods'. Whitaker (1974) also studied Pacific rats on a hot, calm day in the temperate Mokohinau Is in New Zealand. Mean swimming distance was 66 m (10–130 m). Spennemann & Rapp (1987, 1989) studied ship rats in tropical waters with a moderate wind off Tongatapu I. in Tonga. Only one rat (of $n = 9$) reached the shore from a distance of 5 m, while for all others released further offshore, orientation was poor. Rats swam against the current for 5–10 min and did not usually swim actively for longer than 10–20 min. Three rats drifted a total of 1 km during the experiment.

Objects offered as floating debris were generally ignored. The authors concluded that rats could colonise islands up to 1 km offshore, but were highly unlikely to colonise islands further than 3 km offshore. In all three field-based studies, the authors concluded that in general rats were weak swimmers, made little or no progress against wind or current, and had difficulty orientating to shore. However, there was large variation between individuals in each study, with some rats being very adept swimmers.

3.1.5 Island invasion

A small number of colonising or surviving rats can complete the invasion of large areas in less than 2 years (Ecke 1954; Cowan et al. 2003). Pacific rats were believed to have been eradicated from Coppermine I. (90 ha) in New Zealand in March 1993. In May 1993 they were re-detected and 9 months after their supposed eradication they were widespread once again across the entire island (DRT, unpubl. data). Ship rats invaded the northern half of Taukihepa/Big South Cape I. (939 ha) in New Zealand in 1 year, and invaded the entire island in just over 2 years (Atkinson & Bell 1973). Frégate I. (210 ha) in the Seychelles was entirely invaded 26 months after an incursion (Thorsen et al. 2000). Two years after detection, the Norway rat population on tiny Moturemu I. (5 ha) in New Zealand was structurally similar to other much longer established insular Norway rat populations, despite colonisation by only a few individuals (Russell et al. in press).

Such information has led DOC to apply a 2-year 'lay-down' period following believed/reported eradication before an island is revisted and successful eradication is confirmed. After 2 years, any survivors would be readily detectable. However, this lay-down period means there is no scope for reaction to survivors or new colonists during these 2 years. More recently, adaptive monitoring methods have been trialled on perceived high-risk islands such as Pearl I., which is 225 m offshore from Stewart I./Rakiura, New Zealand. Rats were expected to reinvade the island following eradication, and DOC initiated 3-monthly monitoring on the island to intercept reinvaders (Russell et al. 2007b). This monitoring would also have facilitated detection of any survivors. Eradications with a non-negligible chance of failure or reinvasion will require island biosecurity to be implemented immediately following eradication to allow interception of survivors or reinvaders.

A simple deterministic model of invasion by a single pregnant Norway rat was constructed to estimate population growth rates and relate these to island biosecurity monitoring. The model used published data on birth rates from Norway rat populations in New Zealand (Innes 2005), but assumed no mortality, and hence gives a liberal estimate of population size. Following successful invasion by a single pregnant Norway rat, there was rapid population expansion in two to three stages corresponding to successive generations within 1 year (Fig. 5). The model demonstrates the importance of incorporating rat population biology into the timing of island biosecurity surveillance. Six-monthly checks, for example, allow one or possibly even two failed detections while still allowing for a response before rats have invaded an entire island. This timeframe also allows management action for vulnerable species to be undertaken before rats can affect them.

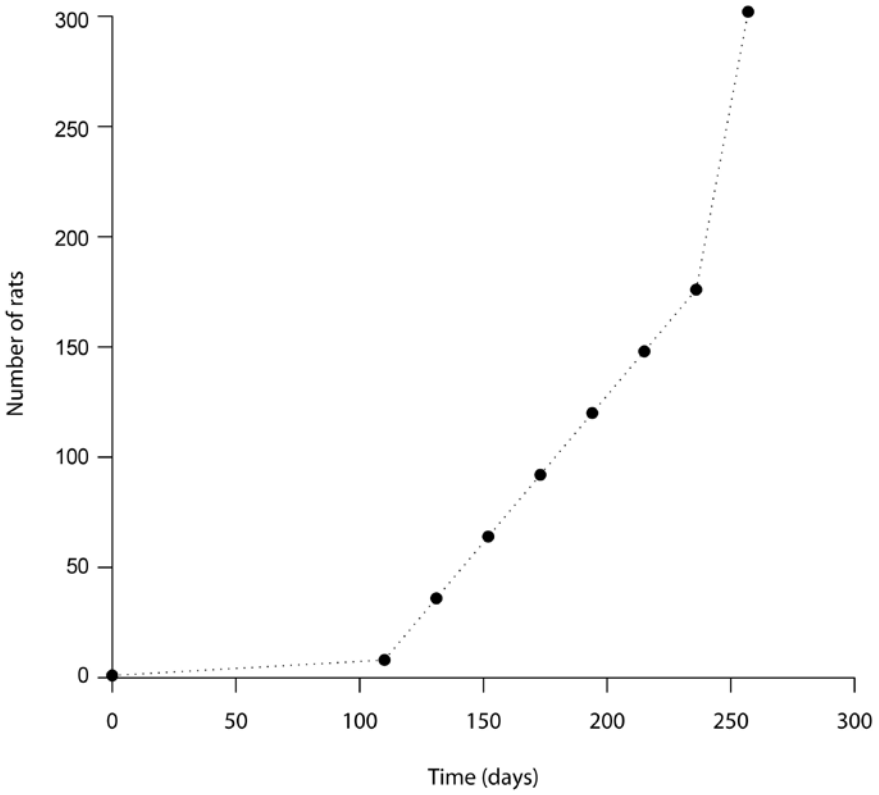

Figure 5. Invasion from a single pregnant female Norway rat colonist. Changes in gradient represent F1 and F2 generations entering the breeding pool. The model assumes deterministic growth with no mortality.

In some cases, rats may successfully establish a breeding population that island biosecurity maintains at an ongoing low density (Thorsen et al. 2000; Russell & Clout 2005). This may be indicated by a high incidence of rat detection, and (in temperate regions) detecting rats in winter, when they are hungry, rather than summer and autumn, when they are more likely to swim to islands. If rats are already well established before being detected, it may be necessary to attempt eradication on a rapidly expanding population, in which case success may be difficult to achieve (e.g. Thorsen et al. 2000).

It is possible to create mechanistic models of island invasion by rats, calibrated by using data on rat swimming ability and invasion success rates. Coutts (2005) created a Microsoft Excel-based mechanistic model with two components: one for rats swimming to islands and a second for rat populations establishing on islands. The model predicted that many rat arrival events were not followed by invasion, because of the stochastic nature of population establishment from a small number of founders (Coutts 2005). However, the modelling approach requires accurate data for calibration; without this it offers only a limited theoretical approach to rat invasion management.

Islands that have already been invaded by one rodent species may have a lower likelihood of being invaded by another, new invasive rat species, through an incumbent advantage (Roberts 1991; Russell & Clout 2004). Hence, following eradication of one species, the likelihood of invasion by any invasive rat species may increase. Even for the same species, unfamiliar individuals may be rejected from an island population (e.g. Granjon & Cheylan 1989), affecting genetic estimates of migration prior to eradication (Abdelkrim et al. 2007).

3.2 DETECTION AND PREVENTION

Since eradication became widely developed as a conservation tool in the 1980s, there has been increasing awareness of island biosecurity, which is the need to detect and prevent rats invading new islands or reinvading islands from which they have been eradicated. The first authoritative treatment of the prevention of rat invasion of islands was provided by Moors et al. (1989, 1992), who focused on ships as the vectors of spread. Austin (1948) had previously described some of the first attempts to remove invading rats from small islets on which seabirds breed, recommending gassing burrows, instead of using traps (which performed poorly) or poisons (which gave diminishing returns after their first application). Wace (1986) reported a lack of techniques for responding to invasions, and argued that further research was urgently required. Moors et al. (1992) reiterated concerns that tools available to detect or control very low rat populations, and stop rodents from reinvading offshore islands, were limited and often unproven. These concerns have persisted (Innes 1992; Dilks & Towns 2002; Airey & O'Connor 2003).

The key to successful island biosecurity is the ability to detect rats at low density (Dilks & Towns 2002). However, there are differences in the susceptibility of rats to interception depending on rat population density. At high density, rats are almost exclusively controlled through exploiting their lack of food resources, by generally baiting traps or using toxic baits. At low density, and especially on a pristine island with abundant food, rats will no longer be limited by food supply (Dilks & Towns 2002). This might evoke novel behaviours in the invader (Russell et al. 2005). Tools that successfully control and eradicate rats at high density may no longer be suitable for intercepting rats as they invade islands.

In the context of detecting new invasions, the following sections review island biosecurity approaches and procedures (section 3.2.1), and then consider the different tools that can be used in biosecurity, with regard to their suitability for low-density populations (sections 3.2.2–3.2.6).

3.2.1 Approaches and procedures

The three basic units of island biosecurity are quarantine, surveillance and contingency responses. Quarantine involves minimising the possibility of rat transport and incursions before, during and after landing on an island (Burbidge 2004). Surveillance refers to actions taken to monitor for rats both on and off islands (e.g. on boats or at points of departure). A contingency response is a calculated (and usually expensive and laborious) exercise to eliminate the invading rats when there has been a quarantine breach or surveillance detection (e.g. Wace 1986; Jansen 1989; Russell et al. 2008).

All three aspects of island biosecurity must be maintained and regularly audited to ensure that they comply with the highest degree of best practice (e.g. DOC 2006). Failure to maintain adequate island biosecurity regimes inevitably leads to reinvasions (e.g. Merton et al. 2002). The prevention of incursions through pre-departure quarantine is the first and most powerful step in island biosecurity (Leung et al. 2002). Post-arrival quarantine on an island, in secured, rodent-proof 'quarantine rooms', provides an additional opportunity to intercept incursions early. For example, on Hauturu/Little Barrier I. in northern

New Zealand, all arrivals are given a final inspection inside such a quarantine room. However, on some islands this may require building a structure, which might not be appropriate. Quarantine and surveillance require an ongoing long-term commitment in order to reliably detect possible invaders and intervene earlier and hence more successfully.

Many rat-free islands now have permanent rodent invasion surveillance systems. Provided that these are checked regularly, and there has been a long enough period of monitoring rat-free status, an empirical picture of the rate of rat incursions can be developed. For example, in 1996, Norway rats were eradicated from Ulva I. (Thomas & Taylor 2002), which is a 270-ha open sanctuary 800 m offshore from Stewart I./Rakiura, in southern New Zealand. However, subsequently annual incursions have been detected and eliminated (Appendix 1). The incursions are countered on Ulva I. by an island-wide grid of traps and bait stations that are serviced monthly. Unfortunately, such data on vulnerability to reinvasion may only become available many years after a successful eradication, cannot distinguish between swimming or accidental transport, and are not available to those planning eradications. Biosecurity on Ulva I. is now based on knowledge of the origins and frequency of incursions, and the speed and form of response required.

For mounting contingency responses, knowledge of invader behaviour at low density plays a vital role (Dilks & Towns 2002). Quantifying maximum movements of invaders is necessary for determining optimal device placement (O'Connor & Eason 2000). Rats with large home-ranges are least likely to succumb to poisoning (Cowan et al. 2003). Movements of invading rats change with respect to the time since arrival, and stationary home-ranges may not be established until many weeks after arrival (Russell 2007). Initially, movements can be erratic and occasionally long-distance (Russell et al. 2008). In addition, range size and dispersal may be affected by island habitat types, and may differ between species. If an incursion of many individuals is detected, delimiting the extent of the island that has been invaded will be vital (e.g. Thorsen et al. 2000; Morris 2002). The specifics of rat behaviour during an incursion means that all tools used for 'normal' rat control and eradication (at higher densities) must be reconsidered for these low-density invaders (e.g. Russell et al. 2005).

The appropriate balance between all three types of island biosecurity will be determined by the relative risks of islands being invaded, and the resources available to conservation managers. For some islands, it may be more appropriate to utilise only one or two particular island biosecurity approaches (e.g. Russell et al. 2007a).

3.2.2 Poison and bait stations

Poisons delivered as baits are the most cost-effective way to remove rats across large areas. They are used to eradicate rats from islands (Towns & Broome 2003) and to control rats where eradication is not practical (Howard 1987; Cowan et al. 2003). The most common types of rat poisons are 'second generation' anticoagulants delivered in wax or cereal form, which have a delayed onset of symptoms and can kill after one dose (Moors et al. 1992). These were developed to overcome resistance to first generation anticoagulants in long-term controlled urban populations. On islands without native land mammals, secondary poisoning

of non-target mammals from anticoagulants is not a major issue. However, as a result of non-target poisoning risks, poisons have not been so readily used for conservation in other parts of the world, unless suitable systems of delivery to the target rat species have been available (e.g. Erickson et al. 1990; Morris 2002; Pascal et al. 2005).

Approximately ten poisons are commonly used for rat control or eradication on islands around the world (Table 3; see Fisher 2005), and several studies have assessed their efficacy (O'Connor & Eason 2000; Donlan et al. 2003; Airey & O'Connor 2003; Fisher et al. 2003). Resistance to first generation anticoagulants was first observed in Norway rats in 1958 (Boyle 1960), and to second generation anticoagulants shortly after their development in the 1980s (Quy et al. 1995; Pelz et al. 2005). Long-term use of poisons for island biosecurity may lead to the development of poison-resistance, which would preclude further use of this tool, as was found for mice on Lord Howe I. (Parkes et al. 2004).

TABLE 3. ANTI-COAGULANT POISON COMPOUNDS USED FOR RAT CONTROL OR ERADICATION.

GEN*	POISON	BRAND NAMES
1	Chlorophacinone†	
1	Coumatetralyl	Racumin®
1	Diphacinone	Ditrac®
1	Pindone	
1	Warfarin	
2	Brodifacoum	Pestoff®, Talon®
2	Bromadiolone	Contrac®, Ridrat®, Rentokil®
2	Difenacoum†	
2	Difethialone	
2	Flocoumafen	Storm®

* Generation of poison.
† Not registered in New Zealand.

The delivery of toxic baits is either through bait stations, or through ground or aerial broadcast on islands with no species of conservation concern. Bait stations are designed to identify the poison to humans (for safety and management), shield baits from the elements, prevent excessive loss of poison within the ecosystem to non-target species (either by-kill or resilient species), and allow poison to be preferentially dispensed to the target species (Kaukeinen 1989; Moors et al. 1992; Inglis et al. 1996). Because many island eradication operations are ground-based (Thomas & Taylor 2002), bait stations used for eradication are often subsequently used for island biosecurity (e.g. Orueta et al. 2005). However, if this is done without any assessment of the suitability of bait stations for island biosecurity, or because a grid system is already in place, there may be poor interception rates for new incursions.

Rat behaviour plays a major interactive role with the efficacy of poisons and bait stations in control operations (Jackson 1972). The most widely considered rat behavioural phenomenon is neophobia, which is the avoidance of an unfamiliar object in a familiar place (Barnett 1958). This is generally evoked in rodents by the unfamiliar objects within which food is presented, rather than by novel food itself (Mitchell 1976; Cowan 1983; Inglis et al. 1996), and has long been a problem for rodent control (Clapperton 2006).

Non-commensal rats may not be as neophobic as their urban-dwelling counterparts, because of generations of existence in the absence of humans and control operations (Cowan 1983; Taylor & Thomas 1993), but this suggestion requires further investigation to separate the various confounding factors. Generally, the extent of neophobia varies considerably among species, populations, sexes, ages and individuals, and across time (Cowan & Barnett 1975; Cowan 1977, 1983; Mitchell 1976; Mitchell et al. 1977; Moors 1985; Inglis et al. 1996; Thorsen et al.

2000). Neophobia can last from a few days (Moors et al. 1992), to weeks (Chitty & Southern 1954), or may never be overcome by some individuals during the course of a control or eradication attempt. The phenomenon of neophobia has been reviewed elsewhere (Brigham & Sibley 1999; Clapperton 2006).

There are several reviews on the effects of poison (particularly brodifacoum) on non-target species (Eason & Spurr 1995; Erickson & Urban 2004; Hoare & Hare 2006). These include effects on other bird and mammal species (Eason et al. 2002; Brakes & Smith 2005), invertebrates (Booth et al. 2001), and a case-study on marine ecosystems (Primus et al. 2005). Continuous use of poison baits for island biosecurity may pose risks to non-target wildlife (Hoare & Hare 2006), which must be considered if this approach is used. Using poison for surveillance also requires long-life baits, which are often less palatable (Morriss et al. 2008). Although wrapping poison baits in tin foil or plastic bags increases longevity and decreases non-target interference, it significantly decreases palatability, rendering it an ineffective island biosecurity tool (Airey & O'Connor 2003). Baits generally retain their toxic efficacy for up to 12 months. Over 12 months, palatability remains relatively high for ship rats, but declines markedly for Norway rats; however, baits that appear unpalatable are still readily eaten by wild rats in captivity (Morriss et al. 2008).

Poor success with ongoing poison operations in the United Kingdom appears to be better explained by population size differences, range sizes and the presence of alternative food rather than poison resistance in rats (Cowan et al. 2003). Therefore, research into rodent interception and control at low densities is currently shifting away from the type of poison used to the design of bait station delivery devices (Inglis et al. 1996). Trials of bait station designs have found that wild Norway rats show the greatest delays in using stations when there are complex internal baffles, and that plastic construction probably also decreases use (Moors 1985; Kaukeinen 1987). Tunnel type designs that Norway and ship rats can see through are preferred (Spurr et al. 2006, 2007). No effect of colour (for plastic stations and covers) has been demonstrated in rats, although it has been found in other invasive mammals (Hamilton 2004; Clapperton 2006).

In an island biosecurity context, some bait station designs increase the entry and bait consumption rates for Norway and ship rats; but not all rats are guaranteed to succumb to poison, even at toxin concentrations as high as 50 ppm (Spurr et al. 2006, 2007). The percentage of rats consuming a lethal dose of weathered baits during first encounter was below 20% in laboratory studies of Norway and ship rats (Morriss et al. 2008). Although weathered long-life baits in island sentinel bait stations remain palatable to ship rats, no long-life bait is currently available that has suitable palatability and would be successful at preventing Norway rat invasion of islands (Morriss et al. 2008).

The best contingency response to rodent invasion may be to avoid using bait stations altogether, and instead to hand (or aerially) broadcast highly palatable but short-life baits around the area of invasion (DOC 2006; Russell et al. 2008). This circumvents the constraints imposed by bait stations, but is only possible where broadcasting is legally permitted. As regulation by government agencies around the world on poison use increases, novel targeted methods of rodent eradication, such as biocontrol or immunocontraceptions, are also being re-considered (Jackson & van Aarde 2003), as well as the development and registration of alternative poisons.

3.2.3 Traps

Unlike bait stations, traps provide a non-toxic elimination method, supply a carcass (which is vital for identification of the invading species or for scientific analysis; e.g. Abdelkrim et al. 2007), and confirm the removal of trapped animals (Moors et al. 1992; O'Connor & Eason 2000). Intense trapping prior to poison-use, including with live traps, has been common in French eradications of islands (Pascal et al. 2005). However, because they are labour intensive to operate, rat-trapping alone usually fails in eradication attempts—except on islands of < 10 ha (Moors et al. 1992; Pascal et al. 1996; Wittenberg & Cock 2001: 190; Courchamp et al. 2003).

TABLE 4. TYPES OF RAT TRAPPING DEVICES.

TRAP	BRAND NAME
Snap	Eze-set™, Victor™, T-Rex™, Ka Mate™
Jaw	Fenn, DOC150 & 200
Live	Tomahawk™, Sherman™, Elliot™

Various trap designs are available (Table 4), but all are based on the fundamental concept that when bait is taken, a trigger is set-off (from the action of applying weight on a pedal), which kills or contains the animal. Traps can be covered to prevent interference or inadvertent capture of non-target animals. However, even with covered traps, rodent-sized fauna (particularly seabirds, crabs and reptiles) can still be regularly caught and killed. Wire mesh covered traps have had a higher trapping success than closed covers in high-density Norway rat populations, but at a cost of increased non-target capture (Weihong et al. 1999). In addition, traps beneath wire-mesh covers are more exposed to the environment, requiring frequent bait-change and sometimes being inadvertently set-off and generating a false indication of possible rat presence. Therefore, wire-mesh covers are not recommended if traps are being used for surveillance. Future trap designs may incorporate a solid bait that has to be removed to trigger the trap, preventing accidental triggering (B. Thomas, Ka Mate Traps Ltd, pers. comm. 2007).

It is not clear whether live traps have greater capture rates than kill traps, because there may be species-specific differences in capture rates (Wiener & Smith 1972; Woodman et al. 1996; Lee, L.L. 1997). For example, Norway rats may avoid live traps (Moors et al. 1992), while ship rats may be more readily caught in them (Smith et al. 2006). Mesh-wall live traps have greater capture rates than closed-wall live traps, although the occupants are subject to environmental conditions (O'Farrell et al. 1994). Live traps have been used as part of a contingency response on Gough I., in the South Atlantic Ocean, where caged, sterilised albino laboratory (Norway) rats were used to attract possible invading rats (Wace 1986). These 'Delilah' traps were subsequently tested on high-density ship rat populations on neighbouring Tristan da Cunha I., but performed worse than control live-traps without rats in terms of inter-species attraction. Further work is required to determine if this system has potential for attracting the same species, and if the sex of the caged animal has any effect. If the species of invading rat is unknown, use of 'Delilah' traps is not recommended (Wace 1986). Live traps are generally not used for island biosecurity because of animal welfare requirements

to check traps daily. Traps must meet appropriate welfare requirements (O'Connor & Eason 2000), and when tested some traps fail to do so (e.g. Poutu & Warburton 2005).

Some baits are better than others at attracting rats into traps. However, no single bait stands out among the suitable ones (Moors et al. 1992). Poorly performing baits are often still used because of extraneous factors, such as increased field-longevity. Choosing the bait most suitable for attracting rats is important, even if this involves a trade-off with other desirable factors such as longevity, availabilty or cost. The palatability and attractiveness of various types of baits have been reviewed elsewhere (Lund 1988; Clapperton 2006), but a mix of peanut butter and rolled oats, possibly with some meat content, performs well for short-term (contingency) trapping of rats. No ultimate bait type exists (Clapperton 2006), and changing bait types over time to cater for individual variation in rat preference may be necessary if one type does not work (Moors et al. 1992). Although traps have many positive qualities for biosecurity, they can fail when alternative food sources are available (Dilks & Towns 2002; Drever 2004).

Traps may be used to combine detection and trapping in one action on large islands where traps can be regularly checked but an island-wide grid is not suitable (DOC 2006). Since a rat, or its sign, seen on these large islands may be from an individual that has since moved elsewhere, it is important to combine detection with elimination. However, if the goal is surveillance, a suitable long-life bait will be necessary to maximise the attracting properties of the trap. Norway rats, in particular, can be wary of mechanical metal devices (Moors et al. 1992), and can attempt to dig alternative entrances under trap covers to avoid walking over the trap itself to acquire the bait (Russell 2007). Eggs are commonly used as long-life bait for stoat trapping using jaw traps, and have been successfully used for invading rats (Russell et al. 2007b). On islands where biosecurity requires monitoring for both mustelids and rats, jaw traps baited with eggs in wooden boxes are the preferred tool (King & Edgar 1977).

When traps are used as a contingency response tool to confirm the number and species of invading rats, jaw traps are superior (Innes et al. 2001). Large Norway rats can escape from snap-traps (Hollands 2002); therefore, unless invading rats are known to be ship rats, snap traps are not recommended for island biosecurity (DOC 2006). When using traps in a contingency response, it may be beneficial to pre-bait traps that are not set until the invader is known to be visiting the traps and eating the bait (Moors et al. 1992). Natural materials such as logs can be used to guide animals into the trapping area ('hazing'). A natural inclination to place as many traps out as possible in the hope of maximising the likelihood of capturing the animal should be avoided. For wide-ranging invaders, trappability is more likely to be a function of whether a rat enters a trap, rather than whether it encounters a trap. Trappability depends on the type and placement of the trap, its cover and baiting, and also on the individual rat. Accordingly, as with all devices in island biosecurity for rats, a wide and sparse coverage of one to two appropriate devices per hectare will be more useful than smaller areas saturated with devices that are ineffective (DOC 2006).

3.2.4 Passive detection devices

Passive devices that record rat presence non-invasively are commonly used as an activity index in rat monitoring programmes (Quy et al. 1993; Brown et al. 1996; Whisson et al. 2005). They fall under a number of broad categories (Table 5).

TABLE 5. METHODS OF PASSIVE RAT DETECTION.

TYPE	FORM
Gnaw	Stick, wax, fruit
Tracking	Substrate, ink, hair
Sign	Footprints, faeces, burrows, feeding, sighting

Gnaw devices exploit the desire of rats to gnaw substances that may possibly prove nutritious. Rats leave characteristic incisor marks measuring 2–3 mm in width (Fig. 6). Devices generally consist of a base substance (wood or wax) either infused with an attractive flavouring such as oils, or baited on top of an unscented device. They are commonly known as gnaw sticks, wax blocks or wax tags (Thomas et al. 1999), although candles, soap bars and fruit often perform similarly (Taylor et al. 1999; Weihong et al. 1999; Drever 2004). There are no published studies comparing the performance of different gnaw devices (Clapperton 2006). The greatest limitation of gnaw devices is that they require hungry rats to test if something is food. They have performed well at high densities for monitoring purposes (McFadden 1991), but (as with bait stations) they are often converted to devices for monitoring reinvasion (Jansen 1989).

Figure 6. Rat (*Rattus* spp.) gnaw on waxtag. Note the characteristic 2–3 mm double incisors.

Field experience of gnaw sticks (wood soaked for days in oils) suggests they can remain attractive for 2 years, but only to Norway rats (McFadden 1991). Compared to traps and natural signs, gnaw sticks were the most useful, but not infallible, means of detecting reinvasion of the Noises Is in New Zealand (Moors 1985). On Ulva I., blocks of butter performed better than gnaw sticks for detecting low densities of rats following eradication, but gnaw sticks detected subsequent reinvaders (Taylor et al. 1999). In recent trials with intentionally released rats, gnaw sticks performed poorly compared to wax devices and tracking tunnels (Russell et al. 2008), and oiled wood is not a preferred attractant (Weihong et al. 1999). Trials on Moturemu I. found that only wax tags lured with peanut butter were attractive to high-density Norway rats, compared to those using fish oil, 'blaze' (flour and icing sugar) or no lure at all (control). These wax tags detected additional Norway rats that had evaded eradication trapping (Russell et al. in press). Gnaw devices will have a reduced appeal to rats when alternative food is abundant, although they probably perform better than traps overall for Norway rats (Taylor et al. 1999; Drever 2004). Gnaw devices with infused flavouring have greater longevity than those that require baiting, but this may be a trade-off with appeal to rats (Russell 2007).

Tracking devices are the other common method of passive detection. Even without any devices, tracks can often be preserved in substrates such as sand and mud (Moors et al. 1992; Ratz 1997). Rats leave characteristic pad prints in a 2-3-2 pattern (Fig. 7). Initially, smoked-papers and complex ink formulations were used inside a dry tunnel that was baited similarly to traps (Lord et al. 1970; King & Edgar 1977; Innes & Skipworth 1983). However, recent technological advances have allowed the mass production of tracking cards—white cards with a screen-sprayed ink section that can remain active for over 4 months (Griffiths 2006), but probably not much longer, depending on the environment.

Tracking tunnels are more effective than traps at detecting rats (Innes & Skipworth 1983) and are a popular invasion detection device (Jansen 1989; Burbidge 2004; Russell et al. 2005). As with bait stations, larger tunnels that animals can see through are probably preferred (Loukmas et al. 2003). However, like other passive monitoring devices, it can be difficult to distinguish between rat species with tracking tunnels (Ratz 1997). Even when a species' identity is known, tracking tunnels only provide an index of population size (Quy et al. 1993). Recent advances in computer image scanning technology have made it possible to detect species-specific patterns in footprints that are not immediately obvious to the human eye (Yuan et al. 2005). With further development of this technology, it may become possible to consistently determine which rat species has been tracked, and possibly also determine individuals from foot morphology (such as age and sex). With high enough resolution, it may then be possible to determine the number of rats that have tracked each card with reasonable accuracy.

The major drawbacks of tracking type devices are that they require baiting for accurate detection (Moors et al. 1992), and there are still no suitable long-life attractant baits for this purpose. Poison baits can be used to create an integrated device, but problems of long-life bait palatability and residual toxicity in the ecosystem can remain. Non-target species (e.g. inquisitive birds, reptiles and especially insects), which are more abundant on rat-free islands, also heavily track these cards immediately following baiting. Often when cards are recovered, it is impossible to distinguish any species-specific track patterns upon them. If a fine mesh cover is placed over tunnel entrances to prevent insect interference, invading rats will probably be deterred from entering the tunnel (Cook 2002).

Figure 7. Rat (*Rattus* spp.) footprints on ink tracking card (Tawhitinui I.). Note the central pad lies on the same axis as the outer two pads (dotted line).

Rodent sign also acts as a passive indicator of rat presence (Moors et al. 1992; Zimmerman & Friedman 2000). This can include direct sightings, nesting sites and faeces (not necessarily in the same location), footprints (Taylor et al. 1999), runways, burrows, and feeding signs, such as characteristic predation on fauna or nuts (Wilmhurst & Higham 2004). Generally, such signs are only opportunistically discovered, and the likelihood of finding them for a small number of invading rats is very low (Moors et al. 1992). The observer must be fairly confident of his/her assessment of the sign to surmise that it was caused by rats. Photographic evidence and, where possible, the collection (and preservation) of samples for verification by other experts is important. Advances in forensic analysis now permit DNA isolation from sign (Russell et al. 2005). In this case, it is vital that samples are appropriately stored in ethanol. Genetic methods provide a powerful means to determine the species, and possibly sex, of invading rats (Robins et al. 2007). Further work may then reveal the source populations from which invaders are departing, allowing more targeted biosecurity (Russell et al. 2007b).

Another sign-based method, which has also been used as a population index, is recording unaccompanied food (bait) take (Chitty 1942). By leaving a small amount of food at a known location (e.g. peanut butter smears on trees, nuts or meat on the ground), it is possible to rapidly assess rat presence (Russell et al. 2005). Food stations present none of the neophobia-generating elements of other devices, can be rapidly deployed over large scales, and readily checked the following day, especially if food items are placed in a readily identified pattern so that any disturbance (even if not eaten) is easily recorded. The greatest constraint of such methods is that they require daily checks because of disturbance by the environment (weather) or non-target animals (e.g. birds or insects), and even then, interpreting what caused the disturbance can remain conjectural. This method has been successfully used to detect invading rats around buildings and campsites (Russell et al. 2005; Russell et al. 2007b).

Hudson & Davis (1980) provided calculations to distinguish Norway rat faeces from those of ship rats, using the expression:

$$y = 100\,L/W^3$$

with length (L) and width (W) measured to the nearest 0.1 mm. If the mean value of y from a sample of at least five pellets is < 20, then one can state with 95% confidence that the pellets are from Norway rats. Zimmerman & Friedman (2000) provided a key to distinguish rat faeces from those of other mammals, reptiles and insects.

3.2.5 Integrated approaches

In an effort to cater for the large variation in individual rat behaviour, some island managers have combined baiting, trapping and passive detection into rat 'motels', first pioneered on Tawhitinui I., in New Zealand (Taylor, D.P. 1984). Large boxes, preferably of wood (Fig. 8), act as bait stations, protecting their contents from the elements and human interference. The stations may also act as an attractive shelter and nesting area to rats that encounter them. Any nesting material added can be routinely collected and searched for rodent sign. Various devices can be placed within the 'motel'. Baffles can be added, although as with bait stations and tracking tunnels, this may reduce use. Traps (baited and un-baited) and/or poison can then be added. If the 'motel' is lifted > 30 cm off the ground, it may restrict access by mice and allow only rats to enter (Baker et al. 1994), which is important on mouse-invaded islands where rat biosecurity can be compromised by persistent mouse interference with devices. Rodent 'motels' may have much potential for island biosecurity, but they require field-testing to assess how successfully they detect invading rats. Recent experiences in laboratory trials have been promising (Spurr et al. 2007), but mixed results have been found in the field on Iona I., Pearl I. and Tawhitinui I., depending on how often 'motels' were serviced and whether or not they were baited.

Technology is creating added scope for integrated tools such as the 'Scentinel®' tunnel, which incorporates a tunnel, weigh station, toxin dispenser and camera (King et al. 2005). Beyond those methods already described, there is scope for others that are not currently used widely in island biosecurity for rats. These include hair tubes (Suckling 1978; Lindenmayer et al. 1999) and the use of live rats in a 'Judas rat' context, where live animals are released to locate conspecifics (Wace 1986).

Figure 8. Rodent motel containing sawdust, snap-trap and tracking card (Tawhitinui I.).

3.2.6 Trained dogs

Trained dogs are increasingly being used in conservation biology as effective detection tools for tracking both animals and their sign (Smith et al. 2001; Bester et al. 2002; Brown 2005; Miskelly & Fraser 2006). Preliminary studies show that, once properly trained, dogs accurately differentiate between targets (Smith et al. 2003). Rodent-detecting dogs operate through detecting the extent and strength of rodent scent, and behaving accordingly (e.g. whining or scraping). Rats leave scent trails including urine as part of their nightly activities (Galef & Buckley 1996), although the nature of these trails can differ between sexes (Natynczuk & Macdonald 1994) and species. Norway rats use specific runs, whereas ship rats use an entire territory (Telle 1966). The chemical components of rat urine have recently been identified (Selvaraj & Archunan 2002). The persistence of scent in the wild, and its variation with climate and interaction with spatial area appears to affect rodent dog efficacy. Preliminary work suggests that rodent sign in the form of female-soiled sawdust lasts no longer than 1 week in exposed temperate forested island environments, but retains its scent for at least 1 week inside buildings (Russell 2007). Price (1977) found that as urine aged over a 24-h period, its scent became more potent, and that domestic rat scents provide an equivalent surrogate for wild rat scent. Further research is required into the longevity and prevalence of rat odours at low density, and mechanical methods to detect rat scent.

DOC manages a 'predator dog programme', in which dogs are trained to detect predators of native wildlife. Dogs trained to detect rodents are used as tools for monitoring the status of rodent-free or possibly invaded offshore islands (Dilks & Towns 2002). Dogs are worked around sites of interest (e.g. coastal landings or sites of possible rodent sign). Regular visits with dogs to rodent-free islands of conservation importance are becoming standard practice for island biosecurity in New Zealand. Although the dogs are trained to rapidly hunt out any rodent, their primary use is in detection and not control, because rats can easily evade the dogs by burrowing (*R. norvegicus*) or climbing trees (*R. rattus*). Dogs rarely give false positives, but can result in false negatives or inconclusive results, when the handler does not 'read' the dog as suggesting rodents are present, or if the dog did not display recognised behaviour. Another cause of false negatives (also the case for any detection tool) is when the dog is not worked in the actual area that rodents are present. Therefore, recording areas where rodent dogs have searched using GPS could help minimise the number of searches in such areas.

In New Zealand, dogs become certified to work on conservation projects through a two-stage process: gaining interim certification when both dog and handler are assessed as having an effective relationship and the dog is under good control, and full certification once the dog displays good hunting ability on the target species and suitable non-target behaviour (i.e. ignores seabirds in burrows, etc.). Predator dog handlers in New Zealand tend to favour small breeds such as fox-border terrier crosses, which are more convenient than larger dogs to transport and land on islands (many islands have treacherous rocky shore landings). Because of the subjective nature of this type of monitoring, it is extremely difficult to quantify and calibrate the accuracy of rodent detection dogs, although successes achieved through their use suggest they can be a powerful conservation tool (Russell et al. 2005).

3.3 NEW ZEALAND INCURSIONS AND INVASIONS

Examination of data on rodent incursions on New Zealand islands indicates that there have been a total of 36 unique rat incursion records on 25 New Zealand islands since records began (Appendix 1). These comprise 15 records of Norway rats, 7 of ship rats, 1 of Pacific rats and 13 of unknown rat species. An additional 18 mouse incursions have been recorded, and on four islands rat reinvasion was so frequent that individual records were not presented. Forty interceptions or contingency responses (usually using poison and/or traps) have been made against 26 of the rat incursions in New Zealand (Table 6).

TABLE 6. SUCCESS RATE OF RESPONSES TO RAT INCURSIONS IN NEW ZEALAND SINCE RECORDS BEGAN.

RESPONSE	SUCCESS*		TOTAL
	YES	NO	
Trap	12 (13)	8 (7)	20
Poison	5 (10)	9 (4)	14
Carcass	4	–	4
Manual†	2	0	2

* Success denotes recovery of the carcass of the invading rat. Brackets indicate values when, without a carcass, no further sign was considered a success.

† Manual denotes the animal was killed directly by a person.

When traps were used either in surveillance or for a contingency response, they were successful in 65% of cases, compared to only 36% of responses where poison was used and a carcass was recovered. The success rate of poison increased to 71% when no further sign was considered a success. Two responses involved chasing a rat as it escaped from the landing vessel and killing it, and four incursions simply recorded a rat carcass washed up on the beach (presumably a dead swimmer). Overall, 85% of incursion responses using traps and/or poison successfully prevented reinvasion.

Ten incursion responses using either traps or bait stations were only considered successful because no further sign was observed. However, for two of these islands, reinvasion occurred within 3 years, suggesting rats had in fact evaded detection. The one record of a Pacific rat incident relates to faeces found 6 years after this species was eradicated from Kapiti I. These figures inevitably underestimate the actual rate of rat incursions on New Zealand islands, as for many islands lone rats may arrive but not establish a population before dying out naturally (e.g. Roberts 1991).

On Limestone I. (Whangarei Harbour), Moturoa I. (Bay of Islands), Pearl I. and Ulva I. (both Stewart I./Rakiura), incursions are annual events, considered as single records where bait stations and traps both successfully prevent reinvasion. These four islands all lie either in the far north or south of New Zealand, between 300 m and 800 m offshore, and are almost exclusively reinvaded by Norway rats. Pest control on the adjacent mainland is considered necessary to reduce incursion rates. Unusually high incursion rates on these islands have sometimes been responded to with repeated island-wide eradication to prevent a population establishing. Most incursions on these islands were detected between December and June (Russell & Clout 2005), in the southern hemisphere's summer and autumn, although this may have been confounded by the increased trappability of rats during this period due to higher population densities and decreasing food resources following summer (Innes et al. 2001).

In New Zealand, there have been 9 reinvasions of ship rats on 8 islands and 20 reinvasions of Norway rats on 12 islands from which they had been previously eradicated (Appendix 2). In almost all cases, swimming was the most likely invasion pathway. For five of these reinvasions, it was believed that incursions shortly beforehand had been intercepted successfully, given no further sign (Appendix 1). Most reinvasions occurred only a few years after eradication, although some did not occur until well over a decade later (Fig. 9). The mean time until reinvasion was just over 7 years ($n = 9$) for ship rats but only 4.5 years ($n = 19$) for Norway rats. Generally, reinvasion appears to lag behind eradication by about 10 years (Clout & Russell 2008). For most islands, some form of biosecurity was in place, but they were reinvaded either because the invasion rate was so high it could not be prevented, or because by the time rat presence was confirmed rats were already successfully breeding. In all cases, the only response could be repeated island-wide eradication.

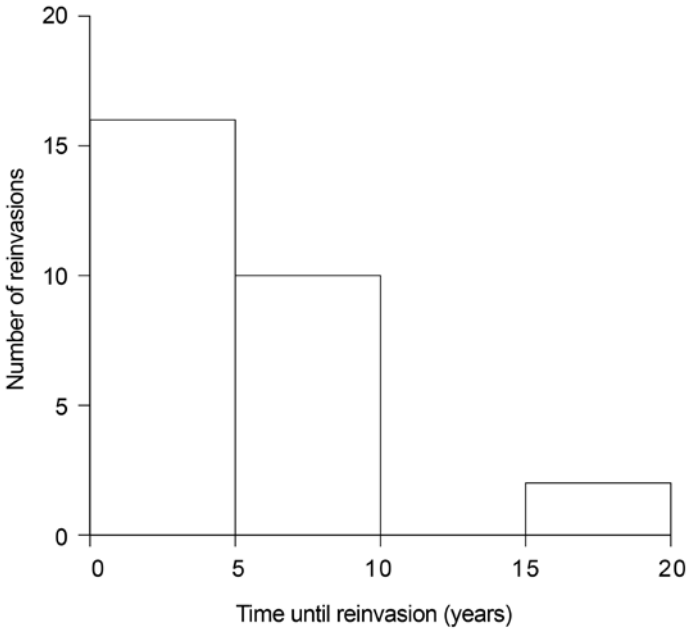

Figure 9. Time until reinvasion of islands in New Zealand from which rats have been eradicated.

4. Discussion

Rats are one of the most widespread invasive vertebrates, and threaten indigenous species and communities on islands throughout the world (Atkinson 1985; Towns et al. 2006). Despite long being recognised as a threat, the global rate of *de novo* rat invasions of islands has not changed significantly in the past century. Instead, the rate or rat invasion of islands may be increasing as more islands become rat-free through eradication, but are subsequently reinvaded. Preventative measures against these invasions by rats are referred to as island biosecurity and are improving around the world, although these measures have not prevented some recent invasions.

Traditionally, prevention measures have focused on the transport of rats by vessels. Any species of rat could be transported by vessel to an island, but although anecdotes suggest rat prevalence on ships is non-negligible, precise data are not usually available (though see Russell et al. 2007a). As vessels are an important vector of rat invasions, biosecurity measures must be undertaken onboard to minimise the risk of transporting rats. Knowledge of which rat species are most likely to be found on vessels in a region will assist in species-specific island biosecurity planning.

Reinvasion by swimming is also occurring at increasing rates, often decades after eradication has taken place. Water temperature appears to have multiple functional relationships with rat swimming ability. Norway rats appear to swim most actively at temperatures of c. 23°C, and although they can passively survive longer in warmer temperature up to body temperature of 36°C, they take longer to drown in colder waters. These temperature results will affect the mode (active or passive) of swimming dispersal to islands by invasive rats, which has been theoretically demonstrated to affect which islands in an archipelago are at greater risk of invasion (Coutts 2005). The ranges of swimming speeds and times reported from laboratory studies suggest, conservatively, that if Norway rats can swim at speeds of 1.4 km/h and for 45 min, then they could certainly swim distances of 1 km routinely, and undoubtedly further in favourable conditions. Invasive rats, particularly Norway rats, are capable of swimming in a wide range of water temperatures, including most sea temperatures encountered in temperate and tropical regions. Only in subarctic and subantarctic waters is the swimming ability of invasive rats likely to be impaired.

Contrary to evidence from dispersal and in the laboratory, the few studies of invasive rat swimming ability in the wild suggest that rats have a very poor swimming ability. There is an important need to identify whether this apparent anomaly is because forced trials are not representative of an animal's true potential, or that the ability to swim far is a highly variable, rare and learnt trait in rats (e.g. see Jackson & Strecker 1962). If swimming ability is generally poor in rats, then the rate of rats attempting to swim to islands and not being successful may be an order of magnitude greater than those recorded as arriving on islands.

Island biosecurity for invasive rats must consider the likelihood of rat invasion, and then weigh the value and vulnerability of islands and their native biodiversity

against the cost of various biosecurity options for the different invasive species (Russell et al. 2007a). Accurately assessing the risk of invasion on an island remains difficult. Invasion risk may be evaluated *a priori* through genetic evaluation of migration rates, or through island monitoring for reinvaders, though both methods involve risk and inaccuracy (Abdelkrim et al. 2007). Which level of island biosecurity is chosen will depend heavily on the geography and land use of an island, and frequency of visits to it. Island managers will often have to make trade-off decisions about what and how many devices to use, and how best to apply limited resources to obtain maximum island biosecurity coverage (Russell et al. 2008).

Whether islands are rat free or have been invaded by rats in the past, surveillance should be regularly undertaken, as distributions of invasive rats can change rapidly. For example, in just 20 years the distribution of invasive rodents in the Bay of Islands archipelago in New Zealand changed from dominance by Norway rats to recent undetected invasion by ship rats (Moller & Tilley 1986; King 2005). Identifying the invasive rodent status of islands, and checking regularly for new invasions, remains a priority for conservation managers (Moors et al. 1992). Six-monthly biosecurity surveillance allows monitoring in different seasons, and provides a number of opportunities for early detection and localised response (Myers et al. 2000) before the entire island is invaded; a process that takes about 2 years. Most detections of invading rats are in late summer and early autumn, which coincides with a peak in post-breeding numbers, a decline in available food in high-density populations (Møller 1983), and an increased likelihood of detection. Hungry rats are most readily caught in winter (Innes et al. 2001).

For recurrent incursions by swimming, biosecurity efforts might involve ongoing rat control in the adjacent source population (Abdelkrim et al. 2007; Russell et al. 2007b). Norway rats are significant predators in the intertidal zone (Navarrete & Castilla 1993; Harper 2006), which could present them with regular opportunities to develop swimming ability (McArdle & Montoye 1966). If swimming is a learnt ability, then targeting rats with intensive control before they learn to swim, to concurrently maintain a low population density and minimise dispersal pressure, should decrease incursion rates. The species composition of source populations will also suggest which rat species is likely to invade (Dilks & Towns 2002). The cost/benefit of 'mainland' control to reduce invasion pressure warrants further investigation. In effect, the efforts of mainland control should provide value at least as great as any extra effort required to intercept incursions through island biosecurity.

Rat invasions of very large islands can be rapid, and managers must be prepared to respond equally rapidly when survivors of an eradication, or reinvaders, are first detected. Managers should aim to eliminate every individual. Detection and elimination of rats at low densities is vital in these responses, and it should be remembered that rats may change their behaviour at low density and focus on locating conspecifics (Russell et al. 2005). This low-density behaviour could be exploited to intercept invading rats. Furthermore, dietary requirements of rats could be exploited for baits, especially for species such as Norway rats, which are often coastal intertidal foragers (Navarrete & Castilla 1993; Harper 2006).

On large islands, it may also be necessary to define the extent of area to be searched, and maximise the likelihood of detection within this area (Koopman

1957; Stone 1975; Cacho et al. 2006). Early recommendations for contingency response to shipwrecks suggested a 200-m radius of devices on a 30-m grid (Jansen 1989; Moors et al. 1992). Current experience of wide-ranging invaders suggests that radius should extend to at least 1000 m (1 km), but at a grid-spacing of only one or two devices per hectare. Saturating the area with devices can evoke neophobia in an invader that has only recently familiarised itself with its new environment (Cowan 1983; Inglis et al. 1996; Russell et al. 2005).

Rat behaviour is highly variable between individuals (Jackson & Strecker 1962; Cowan 1977; Gliwicz 1980; Moors et al. 1992; Galef & Buckley 1993; Bruner & Vargas 1994; Bramley et al. 2000; Dall et al. 2004). Therefore, no single method will detect and eliminate all invaders (Moors et al. 1992; Russell et al. 2005, 2008). The most robust island biosecurity systems will, therefore, be based on integrated methods that combine as many of the techniques described here as possible (DOC 2006). Such an approach has been used on the rat-free Pribilof Is in Alaska, with pre-border inspections on ships and post-border traps and poison stations around the wharf. In over 450 000 trap-nights since 1993, traps have performed better than poisons. Invading rats have been intercepted on boats and the island, but no sign of an established population has been found (Sowls & Byrd 2002). In New Zealand, traps and poisons (as well as passive monitoring) have been equally successful at detecting and eliminating invading rats, although the use of poisons is based on the assumption that no further sign constitutes success. This assumption can be dangerous given evidence that some animals can evade detection for prolonged periods (Russell et al. 2005). In New Zealand, 85% of responses to incursions have been successful. These experiences also suggest that the most robust systems will comprise permanent surveillance systems incorporating detection and elimination followed by contingency responses when an incursion is detected (Thorsen et al. 2000; Russell et al. 2008).

There is still a need to find methods for eradication and island biosecurity that are capable of operating in the presence of non-target species such as small mammals (Howald et al. 2005; Phillips et al. 2007), inquisitive birds (Taylor et al. 1999; Thorsen et al. 2000) and land crabs (e.g. Brakes & Smith 2005), which are all known to interfere with devices and poisons. This may require novel approaches that exploit the behaviour of invasive rats, such as the propensity for Norway rats to dig (Spurr et al. 2006), ship rats to climb (Morris 2002), or invasive rats to jump (Baker et al. 1994). At the same time, this exploitation of behavioural ecology cannot come at the cost of device efficiency. Some novel combinations of tools are yet to be explored. 'Judas rats' may work particularly well in tandem with rodent dogs on very large islands, where dogs can locate approximate areas of rat activity, and 'Judas rats' can then exactly locate den sites or 'Delilah' traps can attract them. Following the development of any novel methods, it will be imperative to test them under real conditions of invading rats on rat-free islands (Russell et al. 2008) or at least very similar laboratory conditions (Spurr et al. 2006, 2007; Morriss et al. 2008)

Search-effort models for invasive rats should be developed, which incorporate the unique population biology of each species and cater for the behaviour of invading rats or the survivors of failed eradications (Dilks & Towns 2002). Models should be calibrated on both unintentional (e.g. Thorsen et al. 2000) and experimental (e.g. Russell et al. 2005) invasion events.

Contingency kits consisting of a variety of detection and elimination devices should be accessible to all rat-free islands, preferably stored on the islands and with enough equipment to react to multiple incursions simultaneously. These kits should be regularly checked and maintained with a fresh supply of poison baits and functioning traps. For example, on Tiritiri Matangi I., in northern New Zealand, traps, bait stations, poison and tracking tunnels are stored and maintained by the island managers and have been used in the past to respond to suspected incursions.

In New Zealand, all islands are at some risk of invasion from any species of rat transported by vessel. However, the greatest threat to inshore islands less than 500 m offshore is that they are accessible to ship rats and Norway rats by swimming; islands > 500 m offshore are currently most likely to be invaded by Norway rats, which can cross up to 2 km of open water. The variation across New Zealand in records of rat swimming distances suggests that susceptibility to rat invasions varies with local conditions and, therefore, requires specific consideration within any archipelago. Trying to apply general rules may be fraught with difficulty, especially around the 1–2 km limit of Norway rat swimming ability.

Islands can be maintained free of rats, even where there are high reinvasion rates, but this requires an ongoing commitment to island biosecurity, sometimes to the extent that considering an island 'eradicated' of rats has little meaning. Inshore islands with high incursion rates are more appropriately considered extensions of the mainland where, as with their mainland counterparts, reinvasion should be considered inevitable.

5. Recommendations

The recommendations provided here are not intended to be globally prescriptive but include those that are implicit as a result of our review. Island biosecurity should be designed on a regional basis with specific biosecurity plans for different island groups. Island biosecurity should be implemented in consultation with appropriate experts (e.g. DOC's Island Eradication Advisory Group) and be regularly, independently audited and adapted to changes in best practice knowledge both nationally and from specific island experiences. Practitioners should not implement novel methods that have not been tested. Although the recommendations here have been developed for rats, some of them apply equally to mice, although the invasion ecology and methods of detection and control for mice can differ considerably from those for rats.

The following recommendations have been made based on the data presented and reviewed in this paper, and implicit as a result of the review.

5.1 APPROACHES AND PROCEDURES

- Island biosecurity should consist of pre- and post-border actions, which are made up of quarantine, surveillance and contingency responses.
- Quarantine, surevillance and contingency responses should use a combination of methods to cater for individual variation in rat behaviours and behavioural changes associated with low population densities.
- Risk assessment and island biosecurity plans for islands should be developed and implemented (e.g. Jansen 1989; Brown 1992).

5.2 QUARANTINE

- Rat populations should be maintained at low density around sites of possible departure (by vessel or swimming).
- All cargo destined for rat-free islands should be packed in rodent-proof containers, packed inside a rodent-proof room and not be left unattended, especially overnight when rats are most active.
- All vessels visiting islands should contain permanent rodent control devices.
- Ships should preferably moor offshore and transport cargo to islands, or minimise berthing times.
- Extra measures, such as pre- and post-border traps and poison stations, should be taken around wharves to minimise the risk of rats embarking onto and disembarking from vessels.
- Rodent-proof quarantine rooms should be established on islands for final inspections, and should be equipped with tools to manually eliminate any rats detected.

5.3 SURVEILLANCE

- Biosecurity devices should be established prior to rat arrival to maximise the likelihood of early interception and avoid neophobia in invading rats.
- Device grids should be spaced at around 1–2 per hectare, given that rats roam widely during initial invasion.
- Island biosecurity surveillance should be conducted at least every 6 months. Invading rats can establish a large population in < 1 year, and by 2 years will have invaded an entire large island.
- Surveillance should take place during late summer to early winter when rats are most likely to be detected invading islands.
- Bait station design should be a large wooden tunnel with line-of-sight through it.
- Highly palatable long-life bait should be used for island sentinel bait stations.
- Toxin concentration in poison baits should be as high as possible, to minimise the quantity that invading rats must consume for a lethal dose.

5.4 CONTINGENCY RESPONSE

- Contingency responses to incursions should cover at least a 1-km radius around the point of incursion.
- Suspected evidence of rat incursions (e.g. faeces, hairs, chewing, etc.) should be preserved and independently verified by invasive rat experts.
- Contingency kits should be immediately available (e.g. stored on islands) for incursion responses, and regularly serviced.
- Suspected incursions (e.g. shipwrecks) must be responded to rapidly in order to detect rats before they move away from landing sites.
- Hand-spread, short-life, highly palatable bait in small pellet form is the preferred response to an incursion.
- Jaw traps should be used in any contingency response to a rat invasion, since large rats (e.g. Norway rats) can escape from some snap traps.
- Certified, trained, rodent detection dogs provide an alternative tool to locate invading rats, and should be used in conjunction with other methods to successfully detect rat incursions.

6. Acknowledgements

This project was funded by DOC (Science Investigation No. 3585). Thanks to Fin Buchanan for information on predator dogs, Dave Spennemann for information on swimming ability, and Art Sowls and Peter Dunlevy for data on Alaskan islands. Phil Moors provided discussion on his work on the Noises Is. and Mike Thorsen discussion on modes of island invasion. Charlie Daugherty, Helen O'Leary, Keith Broome and an anonymous reviewer read the entire manuscript and provided valuable feedback. Thanks to all DOC staff for their contributions and discussion.

7. References

Abdelkrim, J.; Pascal, M.; Samadi, S. 2007: Establishing causes of eradication failure based on genetics: case study of ship rat eradication in Ste. Anne archipelago. *Conservation Biology 21*: 719–730.

Airey, A.T.; O'Connor, C.E. 2003: Consumption and efficacy of rodent baits to Norway rats. *DOC Science Internal Series 148*. Department of Conservation, Wellington, New Zealand. 9 p.

Alley, P. 2002: Mokoia rodent response—debrief notes. Department of Conservation, Rotorua, New Zealand (unpublished). 2 p.

Andersen, M.C.; Adams, H.; Hope, B.; Powell, M. 2004: Risk assessment for invasive species. *Risk Analysis 24*: 787–793.

Asquith, P. 2004: Moturoa Island predator status report 2004. Unpublished report. 4 p.

Atkinson, I.A.E. 1977: A reassessment of factors, particularly *Rattus rattus* L., that influenced the decline of endemic forest birds in the Hawaiian Islands. *Pacific Science 31*: 109–133.

Atkinson, I.A.E. 1985: The spread of commensal species of *Rattus* to oceanic islands and their effects on island avifaunas. Pp. 35–81 in Moors, P.J. (Ed): Conservation of island birds. *International Council for Bird Preservation Technical Publication No. 3*. ICBP, Cambridge, UK.

Atkinson, I.A.E. 1986: Rodents on New Zealand's northern offshore islands: distribution, effects and precautions against further spread. Pp. 13–40 in Wright, A.E.; Beever, R.E. (Eds): The offshore islands of northern New Zealand. *Department of Lands and Survey Information Series No. 16*. Department of Lands and Survey, Wellington, New Zealand.

Atkinson, I.A.E.; Bell, B.D. 1973: Offshore and outlying islands. Pp. 372–392 in Williams, G.R. (Ed): The natural history of New Zealand: an ecological survey. Whitcoulls Ltd, Wellington, New Zealand.

Atkinson, I.A.E.; Taylor, R.H. 1991: Distribution of alien mammals on New Zealand islands. Contract report 91/50. DSIR Land Resources, Lower Hutt and Nelson, New Zealand.

Austin, O.L. 1948: Predation by the common rat (*Rattus norvegicus*) in the Cape Cod colonies of nesting terns. *Bird-banding 19*: 60–65.

Aviss, M. 2006: Mouse incident on Maud Island, bottom house compost bin. Department of Conservation, Picton, New Zealand (unpublished). 7 p.

Baker, M.A.; Horvath, S.M. 1964: Influence of water temperature on oxygen uptake by swimming rats. *Journal of Applied Physiology 19*: 1215–1218.

Baker, R.; Bodman, G.; Timm, R. 1994: Rodent-proof construction and exclusion methods. Pp. B-137–B-150 in Hygnstrom, S.; Timm, R.; Larson G. (Eds): Prevention and control of wildlife damage. Cooperative Extension Service, University of Nebraska, Lincoln, USA.

Barnett, S.A. 1958: Experiments on neophobia in wild and laboratory rats. *British Journal of Psychology 49*: 195–201.

Bartell, S.M.; Nair, S.K. 2004: Establishment risk for invasive species. *Risk Analysis 24*: 833–845.

Bell, B.D. 1978: The Big South Cape Islands rat irruption. Pp. 33–45 in Dingwall, P.R.; Atkinson, I.A.E.; Hay, C. (Comps): The ecology and control of rodents in New Zealand nature reserves. *Department of Lands and Survey Information Series No. 4*. Department of Lands and Survey, Wellington, New Zealand.

Bell, B.D. 1989: The removal of problem animals from islands. Pp. 97–100 in Burbidge, A. (Ed): Australian and New Zealand islands: nature conservation values and management. Department of Conservation and Land Management, Western Australia.

Bester, M.N.; Bloomer, J.P.; van Aarde, R.J.; Erasmus, B.H.; van Rensburg, P.J.J.; Skinner, J.D.; Howell, P.G.; Naude, T.W. 2002: A review of the successful eradication of feral cats from sub-Antarctic Marion Island, Southern Indian Ocean. *South African Journal of Wildlife Management 32*: 65–73.

Beveridge, A.E.; Daniel, M.J. 1966: A field trial of a new rat poison, compound S-6999, on brown rats. *Proceedings of the New Zealand Ecological Society 13*: 40–42.

Blackburn, T.M.; Cassey, P.; Duncan, R.P.; Evans, K.L.; Gaston, K.J. 2004: Avian extinction and mammalian introductions on oceanic islands. *Science 305*: 1955–1958.

Blair, W.F. 1939: A swimming and diving meadow vole. *Journal of Mammalogy 20*: 375.

Booth, L.H.; Eason, C.T.; Spurr, E.B. 2001: Literature review of the acute toxicity and persistence of brodifacoum to invertebrates. Pp. 1–9 in: Literature review of the acute toxicity and persistence of brodifacoum to invertebrates and studies of residue risks to wildlife and people. *Science for Conservation 177*. Department of Conservation, Wellington, New Zealand. vi + 23 p.

Boyle, C.M. 1960: Case of apparent resistance of *Rattus norvegicus* Berkenhout to anticoagulant poisons. *Nature 188*: 517.

Brakes, C.R.; Smith, R.H. 2005: Exposure of non-target small mammals to rodenticides: short-term effects, recovery and implications for secondary poisoning. *Journal of Applied Ecology 42*: 118–128.

Bramley, G.N.; Waas, J.R.; Henderson, H.V. 2000: Responses of wild Norway rats (*Rattus norvegicus*) to predator odors. *Journal of Chemical Ecology 26*: 705–719.

Brigham, A.J.; Sibley, R.M. 1999: A review of the phenomenon of neophobia. Pp. 67–84 in Cowan, D.P.; Feare, C.J. (Eds): Advances in vertebrate pest management. Filander Verlag, Furth, Germany.

Brown, D. 1992: A rodent contingency plan in action—Maud Island. P. 37 in Veitch, C.R.; Fitzgerald, M.; Innes, J.; Murphy, E. (Comps): Proceedings of the national predator management workshop. Department of Conservation, Wellington, New Zealand.

Brown, J. 2005: Sniffing with precision: detection dogs push the limits of field-monitoring techniques. *Conservation in Practice 6*: 35–36.

Brown, K.P.; Moller, H.; Innes, J.; Alterio, N. 1996: Calibration of tunnel tracking rates to estimate relative abundance of ship rats (*Rattus rattus*) and mice (*Mus musculus*) in a New Zealand forest. *New Zealand Journal of Ecology 20*: 271–275.

Bruner, C.A.; Vargas, I. 1994: The activity of rats in a swimming situation as a function of water temperature. *Physiology & Behavior 55*: 21–28.

Burbidge, A.A. 2004: Montebello Renewal: Western Shield review—February 2003. *Conservation Science Western Australia 5*: 194–201.

Cacho, O.J.; Spring, D.; Pheloung, P.; Hester, S. 2006: Evaluating the feasibility of eradicating an invasion. *Biological Invasions 8*: 903–917.

Cameron, E.K. 1998: Bot Soc trips to the Noises (Hauraki Gulf) and an updated species list. *Auckland Botanical Society Journal 53*: 25–35.

Carter, J.L.; Merritt, J.F. 1981: Evaluation of swimming ability as a means of island invasion by small mammals in coastal Virginia, USA. *Annals of the Carnegie Museum 50*: 31–46.

Chappell, R. 2004: Motutapere Island rodent invasion 2004. Department of Conservation, Coromandel, New Zealand (unpublished). 3 p.

Chitty, D. 1942: A relative census method for brown rats (*Rattus norvegicus*). *Nature 150*: 59–60.

Chitty, D.; Southern, H.N. 1954: Control of rats and mice. Clarendon Press, Oxford, UK. 305 p.

Clapperton, B.K. 2006: A review of the current knowledge of rodent behaviour in relation to control devices. *Science for Conservation 263*. Department of Conservation, Wellington, New Zealand. 55 p.

Clout, M.N.; Russell, J.C. 2006: The eradication of mammals from New Zealand islands. Pp. 127–141 in Koike, F.; Clout, M.N.; Kawamichi, M.; De Poorter, M.; Iwatsuki, K. (Eds): Proceedings of the international conference on assessment and control of biological invasion risks. IUCN, Gland, Switzerland and Cambridge, UK.

Clout, M.N.; Russell, J.C. 2008: The invasion ecology of mammals: a global perspective. *Wildlife Research 35*: 180–184.

Cook, J. 2002: Pest surveillance of the Noises Islands, Hauraki Gulf. New Zealand School of Outdoor Studies, Auckland, New Zealand (unpublished).

Cooksley, I. 2002: Rodent droppings investigation report. Department of Conservation, Wellington, New Zealand (unpublished). 9 p.

Courchamp, F.; Chapuis, J.-L.; Pascal, M. 2003: Mammal invaders on islands: impact, control and control impact. *Biological Reviews 78*: 347–383.

Coutts, S. 2005: A stochastic computer simulation of island group colonisation by *Rattus norvegicus* in small near shore island systems: specifically Tia Island and the Boat Group. Unpublished MSc thesis, University of Otago, Dunedin, New Zealand. 158 p.

Cowan, D.P.; Quy, R.J.; Lambert, M.S. 2003: Ecological perspectives on the management of commensal rodents. Pp. 433–439 in Singleton, G.R.; Hinds, L.A.; Krebs, C.J.; Spratt, D.M. (Eds): Rats, mice and people: rodent biology and management. Australian Centre for International Agricultural Research, Canberra, Australia.

Cowan, P.E. 1977: Neophobia and neophilia: new-object and new-place reactions of three *Rattus* species. *Journal of Comparative Physiology and Psychology 91*: 63–71.

Cowan, P.E. 1983: Exploration in small mammals: ethology and ecology. Pp. 147–175 in Archer, J.; Birke, L.I.A. (Eds): Exploration in animals and humans. Van Nostrand-Reinhold, Berkshire, UK.

Cowan, P.E.; Barnett, S.A. 1975: The new-object and new-place reactions of *Rattus rattus* L. *Zooloogical Journal of the Linnaean Society 56*: 219–234.

Dagg, A.I.; Windsor, D.E. 1972: Swimming in northern terrestrial mammals. *Canadian Journal of Zoology 50*: 117–130.

Dall, S.R.X.; Houston, A.I.; McNamara, J.M. 2004: The behavioural ecology of personality: consistent individual differences from an adaptive perspective. *Ecology Letters 7*: 734–739.

Daniel, M.J. 1978: Population ecology of ship and Norway rats in New Zealand. Pp. 145–152 in Dingwall, P.R.; Atkinson, I.A.E.; Hay, C. (Comps): Ecology and control of rodents in New Zealand nature reserves. *Department of Lands and Survey Information Series No 4*. Department of Lands and Survey, Wellington, New Zealand.

Dawson, C.A.; Nadel, E.R.; Horvath, S.M. 1968: Cardiac output in the cold-stressed swimming rat. *American Journal of Physiology 214*: 320–325.

de Lange, P.J.; McFadden, I. 1995: Additions and comments on the flora and fauna of Motukahakaha Island, Hauraki Gulf, Auckland. *Auckland Botanical Society Journal 50*: 22–26.

Dexter, N.; Dowler R.C.; Flanagan, J.P.; Hart, S.; Revelez, M.A.; Lee Jr., T.E. 1980: The influence of feral cats *Felis catus* on the distribution and abundance of introduced and endemic Galápagos rodents. *Pacific Conservation Biology 10*: 210–215.

Dilks, P.J.; Dunn, E. 1978: Report on a visit to Campbell Island 1977–78, with recommendations on bird banding. Ecology Division, DSIR (unpublished).

Dilks, P.J.; Towns, D.R. 2002: Developing tools to detect and respond to rodent invasions of islands: workshop report and recommendations. *DOC Science Internal Series 59*. Department of Conservation, Wellington, New Zealand. 19 p.

DOC (Department of Conservation) 2006: Island biosecurity best practice manual. Department of Conservation, Wellington, New Zealand (unpublished). 40 p.

Donlan, C.J.; Howald, G.R.; Tershy, B.R.; Croll, D.A. 2003: Evaluating alternative rodenticides for island conservation: roof rat eradication from the San Jorge Islands, Mexico. *Biological Conservation 114*: 29–34.

Drake, J.M. 2004: Allee effects and the risk of biological invasion. *Risk Analysis 24*: 795–802.

Drever, M.C. 2004: Capture rates of Norway rats (*Rattus norvegicus*) in a seabird colony: a caveat for investigators. *Northwestern Naturalist 85*: 111–117.

Dumbell, G.S. 1998: Mokoia Island ecological management strategy—revised draft. Applied Ecology Ltd, Auckland, New Zealand (unpublished). 73 p.

Dumm, M.E.; Ralli, E.P. 1950: Influence of panethonic acid on the response of adrenalectomised and intact rats to stress. *Federation (of American Societies for Experimental Biology) Proceedings 9*: 34–35.

Eason, C.T.; Murphy, E.C.; Wright, G.R.G.; Spurr, E.B. 2002: Assessment of risks of brodifacoum to non-target birds and mammals in New Zealand. *Ecotoxicology 11*: 35–48.

Eason, C.T.; Spurr, E.B. 1995: Review of the toxicity and impacts of brodifacoum on non-target wildlife in New Zealand. *New Zealand Journal of Zoology 22*: 371–379.

Ecke, D.H. 1954: An invasion of Norway rats in southwest Georgia. *Journal of Mammalogy 35*: 521–525.

Efford, M.G.; Karl B.J.; Moller, H. 1988: Population ecology of *Mus musculus* on Mana Island, New Zealand. *Journal of Zoology, London 216*: 539–563.

Erickson, W.A.; Marsh, R.E.; Halvorson, W.L. 1990: A roof rat bait station that excludes deer mice. *Wildlife Society Bulletin 18*: 319–325.

Erickson, W.; Urban, D. 2004: Potential risks of nine rodenticides to birds and nontarget mammals: a comparative approach. United States Environmental Protection Agency, Washington, USA. 225 p.

Erschoff, B.H. 1951: Beneficial effect of liver feeding on swimming capacity of rats in cold water. *Proceedings of the Society for Experimental Biology and Medicine 77*: 488–491.

Esher, R.J.; Wolfe, J.L.; Layne, J.N. 1978: Swimming behavior of rice rats (*Oryzomys palustris*) and cotton rats (*Sigmodon hispidus*). *Journal of Mammalogy 59*: 551–558.

Fisher, P. 2005: Review of house mouse (*Mus musculus*) susceptibility to anticoagulant poisons. *DOC Science Internal Series 198*. Department of Conservation, Wellington, New Zealand. 19 p.

Fisher, P.; O'Connor, C.; Wright, G.; Eason, C.T. 2003: Persistence of four anticoagulant rodenticides in the livers of laboratory rats. *DOC Science Internal Series 139*. Department of Conservation, Wellington, New Zealand. 19 p.

Forys, E.A.; Dueser, R.D. 1993: Inter-island movements of rice-rats (*Oryzomys palustris*). *American Midland Naturalist 130*: 408–412.

Galef Jr., B.G.; Buckley, L.L. 1993: Individual differences in responses of Norway rats to social induction of food preferences. *Behavioural Processes 30*: 309–316.

Galef Jr., B.G.; Buckley, L.L. 1996: Use of foraging trails by Norway rats. *Animal Behaviour 51*: 765–771.

Giannoni, S.M.; Borghi, C.E.; Martínez-Rica, J.P. 1994: Swimming ability of the Mediterranean pine vole *Microtus (Terricola) duodecimcostatus*. *Acta Theriologica 39*: 257–265.

Gliwicz, J. 1980: Island populations of rodents: their organisation and functioning. *Biological Reviews 55*: 109–138.

Granjon, L.; Cheylan, G. 1989: Le sort des rats noirs (*Rattus rattus*) introduits sur une île, tévélé par radio-tracking. *Comptes rendus de l'Académie des Sciences, série III 309*: 571–575.

Gray, S.W. 1951: Respiratory movements of rat during drowning and influence of water temperature upon survival after submersion. *American Journal of Physiology 167*: 95–102.

Griffith, W.J. 1960: Responses of wild and domestic rats to forced swimming. *Pschological Reports 6*: 39–49.

Griffiths, R. 2006: Hauturu kiore eradication: post eradication target species monitoring and assessment of operational success. Department of Conservation, Warkworth, New Zealand (unpublished). 6 p.

Hamilton, B. 2004: Using colour to increase stoat (*Mustela erminea*) trap catch. *DOC Science Internal Series 187*. Department of Conservation, Wellington, New Zealand. 15 p.

Harper, G.A. 2005: Heavy rimu (*Dacrydium cupressinum*) mast seeding and rat (*Rattus* spp.) population eruptions on Stewart Island/Rakiura. *New Zealand Journal of Zoology 35*: 155–162.

Harper, G.A. 2006: Habitat use by three rat species (*Rattus* spp.) on an island without other mammalian predators. *New Zealand Journal of Ecology 30*: 321–333.

Hindwood, K.A. 1940: The birds of Lord Howe Island. *Emu 40*: 1–86.

Hoare, J.M.; Hare, K.M. 2006: The impact of brodifacoum on non-target wildlife: gaps in knowledge. *New Zealand Journal of Ecology 30*: 157–167.

Hollands, N. 2002: Mokoia rat diary. Department of Conservation, Rotorua, New Zealand (unpublished). 3 p.

Howald, G.R; Donlan, C.J.; Galván, J.P.; Russell, J.C.; Parkes, J.; Samaniego, A.; Wang, Y.; Veitch, C.R.; Genovesi, P.; Pascal M.; Saunders, A.; Tershy B. 2007: Invasive rodent eradication on islands. *Conservation Biology 21*: 1258–1268.

Howald, G.R.; Faulkner, K.R.; Tershy, B.; Keitt, B.; Gellerman, H.; Creel, E.M.; Grinnell, M.; Ortega, S.T.; Croll, D.A. 2005: Eradication of black rats from Anacapa Island: biological and social considerations. Pp. 299–312 in Garcelon, D.K.; Schwemm, C.A. (Eds): Proceedings of the sixth California Islands symposium. Institute for Wildlife Studies, Arcata, USA.

Howald, G.R.; Mineau, P.; Elliott, J.E.; Cheng, K.M. 1999: Brodifacoum poisoning of avian scavengers during rat control on a seabird colony. *Ecotoxicology 8*: 431–447.

Howard, W.E. 1987: Rodent-free using permanent bait stations. Pp. 147–154 in Richards, C.G.J.; Ku, T.Y. (Eds): Control of mammal pests. Taylor & Francis, London, UK.

Hudson, L.W.; Davis, R.A. 1980: Discriminate functions to aid identification of faecal pellets of *Rattus norvegicus* and *Rattus rattus*. *Journal of Stored Products Research 16*: 103–104.

Inglis, I.R.; Shepherd, D.S.; Smith, P.; Haynes, P.J.; Bull, D.S.; Cowan, D.P.; Whitehead, D. 1996: Foraging behaviour of wild rats (*Rattus norvegicus*) towards new food and bait containers. *Applied Animal Behaviour Science 47*: 175–190.

Innes, J. 1992: An introduction to rodents in New Zealand. Pp. 27–29 in Veitch, C.R.; Fitzgerald, M.; Innes, J.; Murphy, E. (Comps): Proceedings of the national predator management workshop. Department of Conservation, Wellington, New Zealand.

Innes, J.G. 2005: Norway rat. Pp. 174–187 in King, C.M. (Ed): The handbook of New Zealand mammals. Oxford University Press, Melbourne, Australia.

Innes, J.G.; King, C.M.; Flux, M.; Kimberley, M.O. 2001: Population biology of the ship rat and Norway rat in Pureora Forest Park, 1983–1987. *New Zealand Journal of Zoology 27*: 57–78.

Innes, J.G.; Skipworth, J.P. 1983: Home ranges of ship rats in a small New Zealand forest as revealed by trapping and tracking. *New Zealand Journal of Zoology 10*: 99–110.

Jackson, T.P.; van Aarde, R.J. 2003: Advances in vertebrate pest control: implications for the control of feral house mice on Marion Island. *South African Journal of Science 99*: 130–136.

Jackson, W.B. 1972: Biological and behavioural studies of rodents as a basis for control. *Bulletin of the World Health Organisation 47*: 281–286.

Jackson, W.B.; Strecker, R.L. 1962: Ecological distribution and relative numbers. Pp. 45–63 in Storer, I.E. (Ed): Pacific Island rat ecology: report of a study made on Ponape and adjacent islands 1955–1958. *Bulletin 225*. Bernice P. Bishop Museum, Honolulu, USA.

Jansen, P. 1989: Rodent invasion plan. *Miscellaneous Report No. 3*. Department of Conservation, Bay of Plenty, New Zealand. 14 p.

Johnson, D.H. 1962: Rodents and other micronesian mammals collected. Pp. 21–38 in Storer, I.E. (Ed): Pacific Island rat ecology: report of a study made on Ponape and adjacent islands 1955–1958. *Bulletin 225*. Bernice P. Bishop Museum, Honolulu, USA.

Jones, H.P.; Tershy, B.R.; Zavaleta, E.S.; Croll, D.A.; Keitt, B.S.; Finkelstein, M.E.; Howald, G.R. 2008: Severity of the effects of invasive rat on seabirds: a global review. *Conservation Biology 22*: 16–26.

Kaukeinen, D.E. 1987: Evaluation of rodent bait station use under controlled conditions. Pp. 103–114 in Shumake, S.A.; Bullard, R.W. (Eds): Vertebrate pest control and management materials, 5th volume. ASTM STP 974. American Society for Testing Materials, Philadelphia, USA.

Kaukeinen, D.E. 1989: Rodent bait stations. *Journal of Food Protection 52*: 756–757.

King, C.M.; Edgar, R.L. 1977: Techniques for trapping and tracking stoats (*Mustela erminea*); a review, and a new system. *New Zealand Journal of Zoology 4*: 193–212.

King, C.M.; Martin, R.D.; McDonald, R.M.; Tempero, G.; Dekrout, A.; Holmes, S.; Stirnemann, M. 2005: Automated monitoring for detection of small mammal pests. Pp. 106–107 in Parkes, J; Statham, M; Edwards, G. (Comps): Proceedings of the 13th Australasian vertebrate pest conference. Landcare Research, Lincoln, New Zealand.

King, E. 2005: Results summary of the second rodent survey in the Eastern Bay of Islands. Department of Conservation, Kerikeri, New Zealand (unpublished). 7 p.

Koopman, B.O. 1957: The theory of search III: the optimum distribution of searching effort. *The Journal of the Operations Research Society of America 5*: 613–626.

Lander, R. 2004: Norway rat found on Mokoia Island. Department of Conservation, Rotorua, New Zealand (unpublished). 2 p.

Le Blanc, J.A. 1958: Effect of chlorpromazine on swimming time of rats at different temperatures. *Proceedings of the Society for Experimental Biology and Medicine 98*: 648–650.

Lee, L.L. 1997: Effectiveness of live traps and snap traps in trapping small mammals in Kinmen. *Acta Zoologica Taiwanica 8*: 79–85.

Lee, M. 1997: Rat eradication programme Rotoroa Island—report. Auckland, New Zealand (unpublished). 3 p.

Lee, M. 1999: Biota of seven islets off Waiheke Island, Inner Hauraki Gulf. *Tane 37*: 99–136.

Leung, B.; Lodge, D.M.; Finnoff, D.; Shogren, J.F.; Lewis, M.A.; Lamberti, G. 2002: An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proceedings of the Royal Society of London B 269*: 2407–2413.

Lindenmayer, D.B.; Incoll, R.D.; Cunningham, R.B.; Pope, M.L.; Donnelly, C.F.; MacGregor, C.I.; Tribolet, C.; Triggs, B.E. 1999: Comparison of hairtube types for the detection of mammals. *Wildlife Research 26*: 745–753.

Lord, R.D.; Vilches, A.M.; Maiztegui, J.I.; Soldini, C.A. 1970: The tracking board: a relative census technique for studying rodents. *Journal of Mammalogy 51*: 828–829.

Loukmas, J.J.; Mayack, D.T.; Richmond, M.E. 2003: Track plate enclosures: box designs affecting attractiveness to riparian mammals. *American Midland Naturalist 149*: 219–224.

Lund, M. 1988: Selection of baits and their distribution. Pp. 261–268 in Prakash, I. (Ed): Rodent pest management. CRC Press, Boca Raton, USA.

MacKay, J.W.B.; Russell, J.C. 2005a: Eradication of ship rats from Goat Island. University of Auckland, Auckland, New Zealand (unpublished). 13 p.

MacKay, J.W.B.; Russell, J.C. 2005b: Ship rat *Rattus rattus* eradication by trapping and poison-baiting on Goat Island, New Zealand. *Conservation Evidence 2*: 142–144.

Martin, J.L.; Thibault, J.C.; Bretagnolle, V. 2000: Black rats, island characteristics, colonial nesting birds in the Mediterranean: consequences of an ancient introduction. *Conservation Biology 14*: 1452–1466.

McArdle, W.D. 1967: Metabolic stress of endurance swimming in the laboratory rat. *Journal of Applied Physiology 22*: 50–54.

McArdle, W.D.; Montoye, H.J. 1966: Reliability of exhaustive swimming in the laboratory rat. *Journal of Applied Physiology 21*: 1431–1434.

McFadden, I. 1991: Rat invasion—Noises Islands. Department of Conservation, Auckland, New Zealand (unpublished). 3 p.

McMurtrie, P. 2006a: Rats on Resolution. Department of Conservation, Te Anau, New Zealand (unpublished). 3 p.

McMurtrie, P. 2006b: Resolution rat trip report. Department of Conservation, Te Anau, New Zealand (unpublished). 5 p.

McSweeney, G. 1984: Snares Islands need greater protection. *Forest and Bird 15(2)*: 38.

Merton, D.; Climo, G.; Laboudallon, V.; Robert, S.; Mander, C. 2002: Alien mammal eradication and quarantine on inhabited islands in the Seychelles. Pp. 182–198 in Veitch, C.R.; Clout, M.N. (Eds): Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group, IUCN, Gland, Switzerland and Cambridge, UK.

Miskelly, C.M.; Fraser, J.R. 2006: Campbell Island snipe (*Coenocorypha* undescribed sp.) recolonise subantarctic Campbell Island following rat eradication. *Notornis 53*: 353–359.

Mitchell, D. 1976: Experiments on neophobia in wild and laboratory rats: a reevaluation. *Journal of Comparative and Physiological Psychology 90*: 190–197.

Mitchell, D.; Beatty, E.T.; Cox, P.K. 1977: Behavioral differences between two populations of wild rats: implications for domestication research. *Behavioral Biology 19*: 206–216.

Møller, A.P. 1983: Damage by rats *Rattus norvegicus* to breeding birds on Danish islands. *Biological Conservation 25*: 5–18.

Moller, H.; Tilley, J.A.V. 1986: Rodents and their predators in the eastern Bay of Islands. *New Zealand Journal of Zoology 13*: 563–572.

Moors, P.J. 1981: Norway rat studies on the Noises Islands, and proposals for future rat research. New Zealand Wildlife Service, Auckland, New Zealand (unpublished). 7 p.

Moors, P.J. 1985: Eradication campaigns against *Rattus norvegicus* on the Noises Islands, New Zealand, using brodifacoum and 1080. Pp. 143–155 in Moors, P.J. (Ed): Conservation of island birds. *International Council for Bird Preservation Technical Publication No. 3*. ICBP, Cambridge, UK.

Moors, P.J. 1987: Norway rats on Motuhoropapa Island, Noises group, Hauraki Gulf. New Zealand Wildlife Service, Auckland, New Zealand (unpublished). 2 p.

Moors, P.J.; Atkinson, I.A.E.; Sherley, G.H. 1989: Prohibited immigrants: the rat threat to island conservation. World Wide Fund for Nature, Wellington, New Zealand. 32 p.

Moors, P.J.; Atkinson, I.A.E.; Sherley, G.H. 1992: Reducing the rat threat to island birds. *Bird Conservation International 2*: 93–114.

Morris, K.D. 2002: The eradication of the black rat (*Rattus rattus*) on Barrow and adjacent islands off the north-west coast of Western Australia. Pp. 219–225 in Veitch, C.R.; Clout, M.N. (Eds): Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group, IUCN, Gland, Switzerland and Cambridge, UK.

Morriss, G.A.; O'Connor, C.E.; Airey, A.T.; Fisher, P. 2008: Factors influencing acceptance and efficacy of toxic baits in ship rats, Norway rats and house mice. *Science for Conservation 282*. Department of Conservation, Wellington, New Zealand. 26 p.

Myers, J.H.; Simberloff, D.; Kuris, A.M.; Carey, J.R. 2000: Eradication revisited: dealing with exotic species. *Trends in Ecology & Evolution 15*: 316–320.

Natynczuk, S.E.; Macdonald, D.W. 1994: Analysis of rat haunch odor using dynamic solvent effect and principal component analysis. *Journal of Chemical Ecology 20*: 1859–1866.

Navarrete, S.A.; Castilla, J.C. 1993: Predation by Norway rats in the intertidal zone of central Chile. *Marine Ecology Progress Series 92*: 187–199.

O'Connor, C.E.; Eason, C.T. 2000: Rodent baits and delivery systems for island protection. *Science for Conservation 150*. Department of Conservation, Wellington, New Zealand. 25 p.

O'Farrell, M.J.; Clark, W.A.; Emmerson, F.H.; Juarez, S.M.; Kay, F.R.; O'Farrell, T.M.; Goodlett, T.Y. 1994: Use of a mesh live trap for small mammals: are results from Sherman live traps deceptive? *Journal of Mammalogy 75*: 692–699.

Orueta, J.F.; Aranda, Y.; Gómez, T.; Tapia, G.G.; Sanchez-Mármol, L. 2005: Successful eradication of invasive rodents from a small island through pulsed baiting inside covered stations. *Biological Invasions 7*: 141–147.

Owen, K. 1992: Mokoia Island—rat sighting. Department of Conservation, Rotorua, New Zealand (unpublished). 1 p.

Owen, K. 1996: Mokoia Island rat sighting. Department of Conservation, Rotorua, New Zealand (unpublished). 1 p.

Parkes, J.; Ruscoe, W.; Fisher, P.; Thomas, B. 2004: Benefits, constraints, risks and costs of rodent control options on Lord Howe Island. Landcare Research, Lincoln, New Zealand (unpublished). 46 p.

Pascal, M.; Brithmer, R.; Lorvelec, O.; Vénumière, N. 2004: Conséquences sur l'avifaune nicheuse de la réserve naturelle des îlets de Sainte-Anne (Martinique) de la récente invasion du rat noir (*Rattus rattus*), établies à l'issue d'une tentative d'éradication. *Revue Écologie (Terre Vie) 59*: 309–318.

Pascal, M.; Siorat, F.; Cosson, J.F.; Burin des Roziers, H. 1996: Éradication de populations insulaires de Surmulot Archipel des Sept-Îles-Archipel de Cancale: Bretagne, France. *Vie et Milieu—Life and Environment 46*: 267–283.

Pascal, M.; Siorat, F.; Lorvelec, O.; Yéson, P.; Simberloff, D. 2005: A pleasing consequence of Norway rat eradication: two shrew species recover. *Diversity and Distributions 11*: 193–198.

Pelz, H.-J.; Rost, S.; Hünerberg, M.; Fregin, A.; Heiberg, A.-C.; Baert, K.; MacNicoll, A.D.; Prescott, C.V.; Walker, A.-S.; Oldenburg, J.; Müller, C.R. 2005: The genetic basis of resistance to anticoagulants in rodents. *Genetics 170*: 1839–1847.

Phillips, R.B.; Harris, D.B.; Snell, H.L. 2007: Bait stations for detection and control of alien rats in the Galapagos. *Journal of Wildlife Management 71*: 2736–2742.

Pitman, R.L.; Ballance, L.T.; Bost, C. 2005: Clipperton Island: pig sty, rat hole and booby prize. *Marine Ornithology 33*: 193–194.

Poutu, N.; Warburton, B. 2005: Potential killing effectiveness of Sturgeon rat/stoat trap. *DOC Research & Development Series 203*. Department of Conservation, Wellington, New Zealand. 7 p.

Price, E.O. 1977: Urine-marking and the response to fresh vs. aged urine in wild and domestic Norway rats. *Journal of Chemical Ecology 3*: 9–25.

Primus, T.; Wright, G.; Fisher, P. 2005: Accidental discharge of brodifacoum baits in a tidal marine environment: a case study. *Bulletin of Environmental Contamination and Toxicology 74*: 913–919.

Puth, L.M.; Post, D.M. 2005: Studying invasion: have we missed the boat? *Ecology Letters 8*: 715–721.

Quy, R.J.; Cowan, D.P.; Prescott, C.V.; Gill, J.E.; Kerins, G.M.; Dunsford, G.; Jones, A.; MacNicoll, A.D. 1995: Control of a population of Norway rats resistant to anticoagulant rodenticides. *Pesticide Science 45*: 247–256.

Quy, R.J.; Cowan, D.P.; Swinney, T. 1993: Tracking as an activity index to measure gross changes in Norway rat populations. *Wildlife Society Bulletin 21*: 122–127.

Ratz, H. 1997: Identification of footprints of some small mammals. *Mammalia 61*: 431–441.

Richter, C.P. 1957: On the phenomenon of sudden death in animals and man. *Psychosomatic Medecine 19*: 191–198.

Roberts, M. 1991: Parasitological evidence for the presence of other rodent species on 'kiore only' islands. *Journal of the Royal Society of New Zealand 21*: 349–356.

Robins, J.H.; Hingston, M.; Matisoo-Smith, E.; Ross, H.A. 2007: Identifying *Rattus* species using mitochondrial DNA. *Molecular Ecology Notes 7*: 719–729.

Roorda, M. 1981: No shore-leave for rats. *Forest and Bird 13(12)*: 39–40.

Rulz, G.M.; Carlton, J.T.; Ruiz, G.M. 2003: Invasive species: vectors and management strategies. Island Press, Washington, DC, USA.

Russell, J.C. 2005: Introduced mammal survey of Haulashore Island and recommendations. University of Auckland, Auckland, New Zealand (unpublished). 4 p.

Russell, J.C. 2007: Invasion ecology of rats on New Zealand islands. Unpublished PhD thesis, University of Auckland, Auckland, New Zealand. 226 p.

Russell, J.C.; Abdelkrim, J.; Fewster, R.M. in press: Early colonisation population structure of a Norway rat invasion. *Biological Invasions*.

Russell, J.C.; Beaven, B.M.; MacKay, J.W.B.; Towns, D.R.; Clout, M.N. 2008: Testing island biosecurity systems for invasive rats. *Wildlife Research 35*: 215–221.

Russell, J.C.; Clout, M.N. 2004: Modelling the distribution and interaction of introduced rodents on New Zealand offshore islands. *Global Ecology & Biogeography 13*: 497–507.

Russell, J.C.; Clout, M.N. 2005: Rodent incursions on New Zealand islands. Pp. 324–330 in Parkes, J.; Statham, M.; Edwards, G. (Comps): Proceedings of the 13th Australasian vertebrate pest conference. Landcare Research, Lincoln, New Zealand.

Russell, J.C.; Clout, M.N.; Towns, D.R. 2007a: Early detection and eradication of invading rats. Pp. 268–272 in Witmer, G.W.; Pitt, W.C.; Fagerstone, K.A. (Eds): Managing vertebrate invasive species: proceedings of an international symposium. USDA/APHIS/WS, National Wildlife Research Center, Fort Collins, USA.

Russell, J.C.; MacKay, J.W.B. 2005: Ship rat reinvasion of Tawhitinui Island. University of Auckland, Auckland, New Zealand (unpublished). 10 p.

Russell, J.C.; McArdle, B.H.; Clout, M.N. 2004: Island biogeography and the species richness of inroduced mammals on New Zealand offshore islands. *Journal of Biogeography 31*: 653–664.

Russell, J.C.; Miller, S.D.; MacInnes, H.E.; Fewster, R.M. 2007b: Genetic fingerprinting of rats from Pearl Island. University of Auckland, Auckland (unpublished). 16 p.

Russell, J.C.; Towns, D.R.; Anderson, S.H.; Clout, M.N. 2005: Intercepting the first rat ashore. *Nature 437*: 1107.

Schmidly, D.J.; Packard, R.L. 1967: Swimming ability in pocket mice. *Southwest Naturalist 12*: 480–482.

Selvaraj, R.; Archunan, G. 2002: Chemical identification and bioactivity of rat (*Rattus rattus*) urinary compounds. *Zoological Studies 41*: 127–135.

Smith, D.A.; Ralls, K.; Davenport, B.; Adams, B.; Maldonado, J.E. 2001: Canine assistants for conservationists. *Science 291*: 435.

Smith, D.A.; Ralls, K.; Hurt, A.; Adams, B.; Parker, M.; Davenport, B.; Smith, M.C.; Maldonado, J.E. 2003: Detection and accuracy rates of dogs trained to find scats of San Joaquin kit foxes (*Vulpes macrotis mutica*). *Animal Conservation 6*: 339–346.

Smith, D.G.; Shiinoki, E.K.; Vanderwerf, E.A. 2006: Recovery of native species following rat eradication on Mokoli'i Island, O'ahu, Hawai'i. *Pacific Science 60*: 299–303.

Sowls, A.L.; Byrd, G.V. 2002: Preventing rat introductions to the Pribilof Islands, Alaska, USA. P. 413 in Veitch, C.R.; Clout, M.N. (Eds): Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group, IUCN, Gland, Switzerland and Cambridge, UK.

Spennemann, D.H.R. 1997: Distribution of rat species (*Rattus* spp.) on the atolls of the Marshall Islands: past and present dispersal. *Atoll Research Bulletin 446*: 1–18.

Spennemann, D.H.R.; Rapp, G. 1987: Swimming capabilities of the black rat (*Rattus rattus*) in tropical lagoonal waters in Tonga. *Alafua Agricultural Bulletin (Western Samoa) 12*: 17–19.

Spennemann, D.H.R.; Rapp, G. 1989: Can rats colonise oceanic islands unaided? An assessment and review of the swimming capabilities of the genus *Rattus* with particular reference to tropical waters. *Zoologische Abhandlungen 45*: 81–91.

Spurr, E.B.; Morriss, G.A.; Turner, J.; O'Connor, C.E.; Fisher, P. 2007: Bait station preferences of ship rats. *DOC Research & Development Series 271*. Department of Conservation, Wellington, New Zealand. 21 p.

Spurr, E.B.; O'Connor, C.E.; Morriss, G.A.; Turner, J. 2006: Bait station preferences of Norway rats. *DOC Research & Development Series 255*. Department of Conservation, Wellington, New Zealand. 18 p.

Stock, A.D. 1972: Swimming ability in kangaroo rats. *Southwest Naturalist 17*: 98–99.

Stone, L.D. 1975: Theory of optimal search. Academic Press, New York, USA. 260 p.

Suckling, G.C. 1978: A hair sampling tube for the detection of small mammals in trees. *Australian Wildlife Research 5*: 249–252.

Sykes, W.R.; West, C.J.; Beever, R.E.; Fife, A.J. 2000: Kermadec Islands flora—special edition. Manaaki Whenua Press, Lincoln, New Zealand. 259 p.

Tan, E.M.; Hanson, M.E.; Richter, C.P. 1954: Swimming time of rats with relation to water temperature. *Federation (of American Societies for Experimental Biology) Proceedings 13*: 151–152.

Taylor, D.P. 1984: The identification and detection of the rats in New Zealand and the eradication of ship rats on Tawhitinui Island. Unpublished diploma dissertation thesis, Lincoln College, Lincoln, New Zealand. 73 p.

Taylor, G.A. 1986: The ecology of Norway rats on Campbell Island. Ecology Division, Department of Scientific and Industrial Research, Lower Hutt, New Zealand (unpublished). 169 p.

Taylor, G.A.S. 1989: A register of northern offshore islands and a management strategy for island resources. *Northern Region Technical Report Series 13*. Department of Conservation. 126 p.

Taylor, R.H. 1975: What limits kiore (*Rattus exulans*) distribution in New Zealand? *New Zealand Journal of Zoology 2(4)*: 473–477.

Taylor, R.H. 1978: Distribution and interactions of rodent species in New Zealand. Pp. 135–143 in Dingwall, P.R.; Atkinson, I.A.E.; Hay, C. (Comps): The ecology and control of rodents in New Zealand nature reserves. *Department of Lands and Survey Information Series No. 4*. Department of Lands and Survey, Wellington, New Zealand.

Taylor, R.H. 1984: Distribution and interactions of introduced rodents and carnivores in New Zealand. *Acta Zoologica Fennica 172*: 103–105.

Taylor, R.H.; Chadderton, L.; Thomas, B.W. 1999: An eradication campaign against Norway rats on Ulva Island; and trial of the 'rolling front' technique. Department of Conservation, Invercargill, New Zealand (unpublished).

Taylor, R.H.; Thomas, B.W. 1993: Rats eradicated from rugged Breaksea Island (170 ha), Fiordland, New Zealand. *Biological Conservation 65*: 191–198.

Telle, H.J. 1966: Beitrag zur kenntnis der verhaltensweise von ratten, vergleichend dargestellt bei *Rattus norvegicus* und *Rattus rattus*. *Zeitschrift für Angewandte Zoologie 53*: 129–196. (Available in English as Technical Translation 1608, Translation Section, National Science Library, National Research Council of Canada, Ottawa, Ontario.)

Thomas, B.W.; Taylor, R.H. 2002: A history of ground-based rodent eradication techniques developed in New Zealand, 1959–1993. Pp. 301–310 in Veitch, C.R.; Clout, M.N. (Eds): Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group, IUCN, Gland, Switzerland and Cambridge, UK.

Thomas, M.D.; Brown, J.A.; Henderson, R.J. 1999: Feasibility of using wax blocks to measure rat and possum abundance in native forest. *Proceedings of the New Zealand Plant Protection Conference 52*: 125–129.

Thorsen, M.; Shorten, R.; Lucking, R.; Lucking, V. 2000: Norway rats (*Rattus norvegicus*) on Frégate Island, Seychelles: the invasion; subsequent eradication attempts and implications for the island's fauna. *Biological Conservation 96*: 133–138.

Towns, D.R.; Atkinson, I.A.E.; Daugherty, C.H. 2006: Have the harmful effects of introduced rats on islands been exaggerated? *Biological Invasions 8*: 863–891.

Towns, D.R.; Broome, K.G. 2003: From small Maria to massive Campbell: forty years of rat eradications from New Zealand islands. *New Zealand Journal of Zoology 30*: 377–398.

Veitch, C.R. 2002: Eradication of Norway rats (*Rattus norvegicus*) and house mouse (*Mus musculus*) from Motuihe Island, New Zealand. Pp. 353–356 in Veitch, C.R.; Clout, M.N. (Eds): Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group. IUCN. Gland, Switzerland and Cambridge, UK.

Veitch, C.R.; Bell, B.D. 1990: Eradication of introduced animals from the islands of New Zealand. Pp. 137–146 in Towns, D.R.; Daugherty, C.H.; Atkinson, I.A.E. (Eds): Ecological restoration of New Zealand islands. *Conservation Sciences Publication No. 2*. Department of Conservation, Wellington, New Zealand.

Wace, N.M. 1986: The rat problem on oceanic islands—research is needed. *Oryx 20*: 79–86.

Waite, E.R. 1909: Vertebrata of the subantarctic Islands of New Zealand. In Chilton, C. (Ed): The subantarctic Islands of New Zealand. Philosophical Institute of Canterbury, Wellington, New Zealand.

Ward, S. 2000: Mouse report, Comalco Lodge, Maud Island, June/July/August 2000. Department of Conservation, Picton, New Zealand (unpublished). 1 p.

Ward, S. 2005: Rats on Tawhitinui Island. Department of Conservation, Picton, New Zealand (unpublished). 2 p.

Watson, J.S. 1961: Mammals. Pp. 132–135 in Hamilton, W.S. (Ed): Little Barrier Island (Hauturu). 2nd. ed. *Bulletin 137*. N.Z Department of Scientific and Industrial Research, Wellington, New Zealand.

Weihong, J.; Veitch, C.R.; Craig, J.L. 1999: An evaluation of the efficiency of rodent trapping methods: the effect of trap arrangement, cover type, and bait. *New Zealand Journal of Ecology 23*: 45–52.

Whisson, D.A.; Engeman, R.M.; Collins, K. 2005: Developing relative abundance techniques (RATs) for monitoring rodent populations. *Wildlife Research 32*: 239–244.

Whitaker, A.H. 1974: Report on a visit to the Mokohinau Islands, Hauraki Gulf, 20 November to 4 December 1973. Department of Lands and Survey, Wellington, New Zealand (unpublished).

Wiener, J.G.; Smith, M.H. 1972: Relative efficiencies of four small mammal traps. *Journal of Mammalogy 53*: 868–873.

Williams, D. 1997: Rat sighting Mokoia Island. Department of Conservation, Rotorua, New Zealand (unpublished). 2 p.

Wilmshurst, J.M.; Higham, T.F.G. 2004: Using rat-gnawed seeds to independently date the arrival of Pacific rats and humans in New Zealand. *The Holocene 14*: 801–806.

Wilson, G. 2003: Unpublished file notes on the eradication of Norway rats from The Noises. Department of Conservation, Auckland, New Zealand (unpublished).

Wittenberg, R.; Cock, M.J.W. 2001: Invasive alien species: a toolkit of best prevention and management practices. CAB International, Wallingford, UK. 228 p.

Woodman, N.; Timm, R.M.; Slade, N.A.; Doonan, T.J. 1996: Comparison of traps and baits for censusing small mammals in neotropical lowlands. *Journal of Mammalogy* 77: 274–281.

Yuan, G.; Russell, J.; Klette, R.; Rosenhahn, B.; Stones-Havas, S. 2005: Understanding tracks of different species of rats. Pp. 493–499 in McCane, B. (Comp.): Proceedings of image and vision computing New Zealand 2005. University of Otago, Dunedin, New Zealand.

Zimmerman, M.L.; Friedman, S.L. 2000: Identification of rodent filth exhibits. *Journal of Food Science 65*: 1391–1394.

Appendix 1

RODENT INCURSIONS ON NEW ZEALAND ISLANDS

Records of rodents reaching New Zealand islands but not establishing populations. Rodent status is the status at the time of the incursion.

Appendix 1

ISLAND	LOCATION	DISTANCE OFFSHORE	RODENT STATUS	POTENTIAL INVADER	DATE	CIRCUMSTANCES	REFERENCES
Campbell I.	Subantarctic	600 km	*R. norvegicus*	*Mus*	1907	Possibly present at homestead and government depots.	Waite 1909; Taylor 1978
			R. norvegicus	*Mus*	1978	Observed on southeast harbour beach but could not be caught.	Dilks & Dunn 1978
Codfish I. (Whenuahou)	Stewart I./Rakiura	3.1 km	*R. exulans*	*R. norvegicus*	1984	One male caught in possum trap.	McSweeney 1984; Bell 1989
			R. exulans	*R. rattus*	1994	Dead male found on high-tide line, probably drowned swimming from moored fishing boat.	A. Roberts, pers. comm.
Goat I.	Hauraki Gulf	100 m	Rodent free	*Rattus* spp.	Oct 2005	Wax tag found gnawed on landing point adjacent to mainland 3 months after eradication; traps and poison laid but no further sign.	MacKay & Russell 2005a
Hauturu/Little Barrier I.	Hauraki Gulf	21.5 km	*R. exulans*	*Mus*	1950s	One brought ashore in stores and killed.	Watson 1961
Hokianga I.	Ohiwa Harbour	275 m	Rodent free	*R. norvegicus*	Dec 2005	Norway rat snap-trapped in hut during post-eradication monitoring.	D. Paine, pers. comm.
Kapiti I.	Wellington	5.2 km	*R. exulans* and *R. norvegicus*	*Mus*	?	Landed on occasions, failed to establish.	Taylor 1978
			R. exulans and *R. norvegicus*	*Mus*	1970	Mummified specimen found in whare.	L. Rodda, pers. comm.
			Rodent free	*Rattus* spp.	1998	Missing bait from station; trapping undertaken, no further sign.	C. Giddy, pers. comm.
			Rodent free	*R. norvegicus*	1998	Corpse found by black-back gull colony.	C. Giddy, pers. comm.
			Rodent free	*R. exulans*	June 2002	Faeces found and genetically identified as kiore; poison laid and monitoring undertaken but no further sign; assumed old faeces from eradication.	Cooksley 2002
Koi I.	Hauraki Gulf	250 m	Rodent free	*R. norvegicus*	Aug 1999	Green faeces found; ate old Talon and presumably died.	Lee 1999
Korapuki I.	Coromandel	5.8 km	Rodent free	*R. rattus*	1988	Virgin female 'Virginia' trapped after 1986 kiore eradication follow-up	Dilks & Towns 2002; Towns & Broome 2003
Limestone I.	Whangarei Harbour	550 m	*Mus*	*R. norvegicus*	1999–ongoing	Reinvade from mainland annually, occasionally establish population; grid (36 Fenn traps/800 bait stations) prevents establishment.	P. & C. Mitchell, pers. comm.
Mana I.	Wellington	2.5 km	*Mus*	*R. norvegicus*	1974/75	One brought ashore in bales of hay and killed.	M. Meads, pers. comm.
			Mus	*Rattus* spp.	1976–78	Jumped overboard, reached shore and killed.	Veitch & Bell 1990
			Mus	*R. norvegicus*	1978	Partly eaten carcass on shore.	Efford et al. 1988

Continued on next page

Appendix 1—continued

ISLAND	LOCATION	DISTANCE OFFSHORE	RODENT STATUS	POTENTIAL INVADER	DATE	CIRCUMSTANCES	REFERENCES
			Mus	*Rattus* spp.	1981	Dead rat found in high-tide drift line, about 300 m south of jetty.	M. Meads, pers. comm.
			Rodent free	*Mus*	1992	One female from packed stores killed on boat before reaching island.	T. Hook, pers. comm.
Mangere I.	Chatham Is	850 km	Rodent free	*Mus*	1970s	Adult female and nest of young in equipment brought ashore by dinghy	Bell 1978, 1989
Maud I. (Te Hoiere)	Marlborough Sounds	850 m	Rodent free	*Mus*	June 2000	Green faeces found in equipment in lodge; trapping undertaken, no further sign.	Ward 2000
			Rodent free	*Mus*	Apr 2006	Male adult mouse observed in compost heap and trapped; further monitoring (traps, tunnels, dogs) revealed no further sign.	Aviss 2006
Mokoia I.	Lake Rotorua	2.1 km	*R. norvegicus*	*Mus*	< Mar 1965	Extremely low numbers and confined to the vicinity of the huts.	Beveridge & Daniel 1966
			Mus	*Rattus* spp.	Apr 1992	Sighted around jetty; no sign in trapping June 1994 and 1995.	Owen 1992; Dumbell 1998
			Mus	*R. norvegicus*	1995	Observed around hut, traps and poison laid, body of very large virgin female found in hole on beach.	Dumbell 1998
			Mus	*Rattus* spp.	Mar 1996	Sighted around jetty.	Owen 1996; Dumbell 1998
			Mus	*Rattus* spp.	Dec 1997	Sighted around jetty.	Williams 1997; Dumbell 1998
			Rodent free	*Rattus* spp.	Feb 2002	Detected in tracking tunnels; traps and tunnels laid out, dogs used; further sign in traps and tunnels; presumed dead from trap injury.	Alley 2002; Hollands 2002
			Rodent free	*Mus*	Mar 2002	Tracks found in tunnels; juvenile caught in April, possible offspring of an August 2001 eradication survivor, or recent invader.	Hollands 2002
			Rodent free	*R. norvegicus*	Mar 2004	Dead male found near jetty, liver contained brodifacoum.	Lander 2004
Motuhoropapa I.	Hauraki Gulf	2.2 km	Rodent free	*R. norvegicus*	1987	Carcass of young female found in old trap; sign on two islets.	Moors 1987
Moturemu I.	Kaipara Harbour	2.5 km	Rodent free	*R. norvegicus*	1999	Sign reported by T. Wilson; poison and traps laid; no further sign until 2002 invasion.	T. Wilson, pers. comm.

Continued on next page

Appendix 1—continued

ISLAND	LOCATION	DISTANCE OFFSHORE	RODENT STATUS	POTENTIAL INVADER	DATE	CIRCUMSTANCES	REFERENCES
Moturoa I.	Bay of Islands	375 m	*Mus*	*R. norvegicus*	1996–ongoing	Reinvade from mainland annually, occasionally establish population; grid (48 Fenn traps/60 bait stations) prevents establishment	Asquith 2004; P. Asquith, pers. comm.
Ohinau I.	Coromandel	4.5 km	*R. exulans*	*Mus*	2002–05	Low numbers present around northwest bay campsite.	R. Chappell, pers. comm.
Otata I.	Hauraki Gulf	2.3 km	Rodent free	*R. norvegicus*	2005	Male escaped from controlled release on neighbouring Motuhoropapa, sign reported by owners; traps and poison laid, rat trapped 6 weeks later.	Russell et al. 2005
Pearl I.	Stewart I./Rakiura	300 m	Rodent free	*R. norvegicus* and *R. rattus*	2006–ongoing	High reinvasion rate from mainland; grid (Fenn traps, snap-traps, tracking tunnels, rodent motels) present adjacent to Whale Passage.	M. Wylie, pers. comm.
Pitt I.	Chatham Is	850 km	*Mus*	*Rattus* spp.	1996/7	Swam from moored fishing vessel.	Dilks & Towns 2002
Poutama I.	Stewart I./Rakiura	275 m	Rodent free	*Rattus* spp.	1984	Rat sign reported by muttonbirders and seen by A. Cox; poison laid, no further sign.	Bell 1989; Veitch & Bell 1990
Rakino I.	Hauraki Gulf	1.5 km	Rodent free	*Mus*	Jan 2006	Passenger with 3 pet mice in cage refused passage on Pine Harbour ferry to island, following a phone call weeks earlier.	J. MacKenzie, pers. comm.
Rangatira I.	Chatham Is	850 km	Rodent free	*Mus*	1998	Possible mouse sighting.	Dilks & Towns 2002
Raoul I.	Kermadec Is	900 km	*R. exulans* and *R. norvegicus*	*Mus*	1972	One pregnant female carried ashore in stores and killed.	Taylor 1978; Veitch & Bell 1990
Resolution I.	Fiordland	500 m	*Mus*	*Rattus* spp.	1986	Suspected Norway rat footprints in sand; no further sign.	McMurtie 2006a
			Mus	*R. rattus*	May 2006	Male caught in trapline at Fixed Head (southern coast of island); trapping and monitoring undertaken across island, no further sign.	McMurtrie 2006b
Rolla I.	Fiordland	250 m	Rodent free	*R. rattus*	2005	Caught in double set Mark 4 Fenn traps monitoring for stoats.	H. Edmonds, pers. comm.
Secretary I.	Fiordland	925 m	Rodent free	*Mus*	Nov 2006	Seen in Gut Hut by DOC staff; poison, traps and tunnels laid, intensive trapping follow-up.	K-A. Edge, pers. comm.
Snares I.	Subantarctic	105 km	Rodent free	*Rattus* spp.	1950s	Rat jumped from boat onto island during landing of scientific party.	Roorda 1981

Continued on next page

Appendix 1—continued

ISLAND	LOCATION	DISTANCE OFFSHORE	RODENT STATUS	POTENTIAL INVADER	DATE	CIRCUMSTANCES	REFERENCES
Stevensons I.	Lake Wanaka	150 m	*Mus*	*R. norvegicus*	Apr 2006	Rat seen in April, DOC told in June, two male rats caught in Fenn traps in July; used meat, as peanut butter bait taken by mice.	C. Golding, pers. comm.
Stewart I./Rakiura		27 km	All 3 rat spp.	*Mus*	?	Landed in stores on several occasions.	Taylor 1975
Takangaroa I.	Hauraki Gulf	1.8 km	Rodent free	*R. norvegicus*	1987	Sign reported by owners and seen by G. Taylor; poison laid, no further sign.	Taylor 1989; Veitch & Bell 1990
Taukihepa/ Big South Cape I.	Stewart I./Rakiura	1.5 km	Rodent free	*R. rattus*	1955	One female with active corpora lutea trapped near beach; no further sign till 1963.	Bell 1978
Tawhitinui I.	Marlborough Sounds	475 m	Rodent free	*R. rattus*	1986–2000	Old sign found in 'rat motel', trapping undertaken; no further sign till invasion detected in 2004.	Dilks & Towns 2002; Ward 2005
Tiritiri Matangi I.	Hauraki Gulf	3.4 km	*R. exulans*	*Mus*	1986	Brought ashore in stores and killed.	Roberts 1991
			Rodent free	*R. norvegicus*	Sept 2007	Sign found on mainland ferry, trip cancelled; traps and poison laid, rat caught following day.	L. Clayton, pers. comm.
Titi I.	Marlborough Sounds	1.9 km	Rodent free	*Rattus* spp.	June 2006	Lower bait station missing baits and possible gnaw and rodent poo; rodent dog finds no sign—probably a false alarm from weta.	M. Aviss, pers. comm.
Ulva I.	Stewart I./Rakiura	800 m	Rodent free	*R. norvegicus*	1997–ongoing	Reinvade from mainland annually; grid (69 snap-traps and bait stations) prevents establishment.	Dilks & Towns 2002; Taylor et al. 1999; B. Beaven, pers. comm.
Unnamed I.	Blanket Bay (off Secretary I.)	2.6 km	Rodent free	*R. rattus*	June 2006	Fresh droppings and poison take; poison and traps laid, male and female caught in Fenn traps on islet in August.	A. Cox, pers. comm.
Unnamed I.	Lake Hauroko	1.0 km	Rodent free	*R. norvegicus*	Mar 2006	Mottled petrel colony, decomposed male found in Fenn trap.	A. Cox, pers. comm.

Appendix 2

RODENT REINVASIONS ON NEW ZEALAND ISLANDS

ISLAND	LOCATION	AREA (ha)	ERADICATION DATE	ERADICATION LEADER	REINVASION DATE	REFERENCES
Rattus rattus						
Awaiti I.	Marlborough Sounds	2	1982	D. Taylor	c. 2001	Taylor 1984; Russell & MacKay 2005
Duffers Reef	Marlborough Sounds	2	1983	D. Taylor	c. 1990	D. Brown, pers. comm.
Goat I.	Hauraki Gulf	9	1994	T. Wilson	1996	MacKay & Russell 2005b
Goat I.	Hauraki Gulf	9	2005	J. Russell	2007	J. Russell, pers. comm.
Haulashore I.	Nelson	6	1991	R. Taylor, B. Thomas	c. 2000	Russell 2005
Hokianga I.	Ohiwa Harbour	8	2005	D. Paine	2006	D. Paine, pers. comm.
Iona I.	Stewart I./Rakiura	7	2004	M. Wylie	2005	M. Wylie, pers. comm.
Motutapere I.	Coromandel	45	1996	P. Thomson	2002	Chappell 2004
Tawhitinui I.	Marlborough Sounds	22	1984	D. Taylor	c. 2001	Taylor 1984; Russell & MacKay 2005; Ward 2005
Rattus norvegicus						
Karamuramu I.	Hauraki Gulf	7	1999	J. McCallum	2005	J. Russell, pers. comm.
Limestone I.	Whangarei Harbour	37	1998	J. Craw	2004	C. Bishop, pers. comm.
Motuhoropapa I.	Hauraki Gulf	9	2001	G. Wilson	2002	Wilson 2003
Motuhoropapa I.	Hauraki Gulf	9	1997	I. McFadden	2001	Cameron 1998
Motuhoropapa I.	Hauraki Gulf	9	1991	I. McFadden	1996	Cameron 1998
Motuhoropapa I.	Hauraki Gulf	9	1984	P. Moors	1991	Moors 1985, 1987
Motuhoropapa I.	Hauraki Gulf	9	1981	P. Moors	1983	Moors 1985, 1987
Motuhoropapa I.	Hauraki Gulf	9	1978	P. Moors	1981	Moors 1981, 1985
Motuihe I.	Hauraki Gulf	179	1988	?	1997	Veitch 2002
Moturemu I.	Kaipara Harbour	5	1994	I. McFadden	2002	J. Russell, pers. comm.
Moturoa I.	Bay of Islands	157	1993	P. Asquith	1997	Asquith 2004
Otata I.	Hauraki Gulf	22	2001	G. Wilson	2002	Wilson 2003
Otata I.	Hauraki Gulf	22	1991	I. McFadden	2001	Cameron 1998
Otata I.	Hauraki Gulf	22	1981	P. Moors	1991	Moors 1985, 1987
Otata I.	Hauraki Gulf	22	1979	P. Moors	1980	Moors 1981, 1985
Pakatoa I.	Hauraki Gulf	29	1993	M. Lee	1997	M. Lee, pers. comm.
Pakihi (Sandspit) I.	Hauraki Gulf	114	198?	J. McCallum	1991	J. McCallum, pers. comm.
Pearl I.	Stewart I./Rakiura	512	2005	M. Wylie	2006	M. Wylie, pers. comm.
Rotoroa I.	Hauraki Gulf	90	1997	M. Lee	c. 1999	Lee, M. 1997; M. Lee, pers. comm.
Unnamed in Ruthe Passage	Hauraki Gulf	0.6	1992	M. Lee	1994	de Lange & McFadden 1995

How do rats invade offshore islands and how can we stop them?

Invasive rats may pose the greatest threat to island biodiversity in New Zealand. It is now known that not only are rats transported by ship, but they can also swim to islands, with Norway rats being able to cross up to 2 km of open water. Multiple devices need to be used to detect and prevent the invasion of islands, including poisons, traps, passive detection devices and trained dogs. This report reviews the ways in which three species of rat disperse to and invade New Zealand offshore islands, and the approaches and tools available to detect and prevent the arrival of rats on these islands.

Russell, J.C.; Towns, D.R.; Clout, M.N. 2008: Review of rat invasion biology: implications for island biosecurity. *Science for Conservation 286*. 53 p.

New Zealand Government