Testing island biosecurity systems for invasive rats

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Abstract. Rats continue to invade rat-free islands around the world, and it remains difficult to successfully intercept them before they establish populations. Successful biosecurity methods should intercept rats rapidly, before they can establish a population. Current island biosecurity practice employs techniques used for high-density rat eradication, assuming that they will be equally effective on low-density invaders. However, such approaches are often untested. Adult male Norway rats (*Rattus norvegicus*) were individually released onto forested rat-free islands in New Zealand to test methods of detecting and eliminating a single invader. Only half the rats released were caught within a two-week timeframe, although the mean time to interception was just under 14 days. Permanent island biosecurity surveillance systems performed better than contingency responses. Success rates were higher on islands where complete coverage could be obtained, although surveillance systems using multiple devices eventually detected most invading rats. For some rats a change of methods was necessary. Single invading rats left a rat-free island despite the presence of excessive natural food resources. With surveillance systems comprising an array of tested island biosecurity devices, and where necessary a contingency response using alternative methods, it should be possible to maintain islands as rat-free even when they have a high reinvasion rate.

Introduction

Because of their isolation, islands often support unusual or endemic species that become the focus for conservation (Towns *et al*. 1990; Mittermeier *et al*. 2005). The most significant threats to these unique ecosystems come from invasive species (Courchamp *et al*. 2003). The detection and elimination of invasive species is therefore fundamental to conservation of island systems. The arrival of an individual invasive organism is known as an incursion (Russell and Clout 2005). However, if the arriving individual reproduces or additional individuals arrive a population can become established to form an invasion. The detection of incursions and the prevention of invasions are now widely referred to as biosecurity (Jay *et al*. 2003).

Invasive rats are present on over 80% of the world's island groups and have had tremendous negative effects on biodiversity (Towns *et al*. 2006). Eradication of invasive rats is now possible on large islands (Howald *et al*. 2007), restoring large areas of habitat for species reintroduction and conservation (e.g. Burbidge 2004). However, rats continue to invade islands where they have never been (Thorsen *et al*. 2000; Pitman *et al*. 2005) and from which they have previously been eradicated (Burbidge 2004; Clout and Russell 2006). Effective island biosecurity is vital (e.g. Sowls and Byrd 2002) but until recently there has been very little testing of methods for detecting and eliminating invading rats. Thus, our capacity to respond to invading rats remains underdeveloped (Wace 1986; Moors *et al*. 1992; Dilks and Towns 2002). Previously, island biosecu-

rity centred on the same traps and bait stations that effectively eradicate high-density populations of rats. This assumes that devices work as efficiently at low densities while rats are invading as they do at high densities when rats are established (e.g. Orueta *et al*. 2005). The fallacy of this assumption has now been demonstrated on islands invaded by rats despite the presence of biosecurity devices such as bait stations at likely points of entry (Thorsen *et al*. 2000; Chappell 2004).

A realistic field test of devices used to detect or intercept rodent incursions is vital. Such tests could be achieved by the intentional release of rats onto rat-free islands (Dilks and Towns 2002). However, such an approach is possible only if there is 100% confidence that released rats can be removed. This means that biosecurity tests will be possible only on relatively small islands.

We released radio-collared adult male Norway rats (*Rattus norvegicus*) on two small pest-free, forested, offshore islands in northern New Zealand, and one large pest-free, forested island in southern New Zealand (Fig. 1). Rats had recently been eradicated from all three islands. We then assessed the performance of island biosecurity systems against a known number of rats. Permanent surveillance methods, used for island 'border control', were contrasted with contingency response methods, which are a reaction to suspected rat invasion such as shipwrecks. In all cases, male rats were released in order to minimise the risk of population establishment.

Materials and methods

Southern New Zealand

Ulva Island (259 ha; 46°18′S, 168°08′E) in Paterson Inlet, 800 m offshore from Stewart Island/Rakiura in southern New Zealand, was cleared of Norway rats in a campaign initiated in 1992, and declared successful in 1997 (Thomas and Taylor 2002). Several species of threatened birds have since been reintroduced to the island, but Norway rats have been recorded arriving at a rate of approximately one per year. The surveillance system on Ulva consists of 52 Victor Professional snap-traps (Pest Management Services, Waikanae, New Zealand) with expanded pedals in corflute tunnels, baited with peanut butter and a chicken egg, and 17 plastic 'Protecta' bait stations (Bell Industries), containing Pest-Off brodifacoum waxed blocks (Animal Control Products Ltd, Wanganui, New Zealand). These are checked monthly.

Norway rats used for release in southern New Zealand were obtained from wild populations around the outskirts of the township of Oban on Stewart Island, where they coexist with ship rats (*R. rattus*), kiore (*R. exulans*) and feral cats (*Felis catus*). Eight live-capture cage traps (Bell Laboratories), baited with peanut butter and meat, were placed in forested gullies and near streams. Rats were held for a maximum of 48 h before release, during which time they were surgically desexed in case they evaded detection and encountered other Norway rats, which would risk population establishment. Released rats were fitted with a 3.9-g removable cable-tie collar with an external 100-mm aerial (Sirtrack Electronics, Havelock North, New Zealand).

Northern New Zealand

Hawere/Goat Island (9.3 ha; 36°16′S, 174°48′E), 50 m offshore from the north-eastern coast of the North Island, is well within the swimming range of rats, which have been present on the island since at least 1970 (Esler 1975). In 1994, ship rats were eradicated from the island but were redetected in 1996. Ship rats were eradicated again by trapping, and the island confirmed rat-free in 2005 (MacKay and Russell 2005).

Motuhoropapa Island (9.5 ha), in the Noises island group (36°41′S, 174°59′E), Hauraki Gulf, has been repeatedly re-invaded by Norway rats following eradication trials (Moors 1985a, 1985b). Rodent biosecurity comprising snap-traps and 'gnaw sticks' (Moors 1985a) detected Norway rats at high densities, but did not indicate the presence of reinvading rats until a population was already established. More recently, a permanent grid of white plastic (Philproof Pest Control Services, Hamilton, New Zealand) bait stations (*n* = 17), tracking tunnels (*n* = 12) and candles was established across the island and checked annually. Norway rats were last eradicated from The Noises in 2002. The current surveillance system on Motuhoropapa consisted of a 100-m grid (~2 devices ha^{-1}) of 17 recessed Mark IV Fenn traps (Pest Management Services Ltd, Waikanae, New Zealand) covered with leaf litter, under double-entrance black Philproof covers closed at one end. Devices were baited with peanut butter and meat behind the buried trap, encouraging rats to move over the traps.

Norway rats used for release in northern New Zealand were obtained from a wild population on Pakihi Island (114 ha; 36°54′S, 175°09′E), Hauraki Gulf, where they coexist with
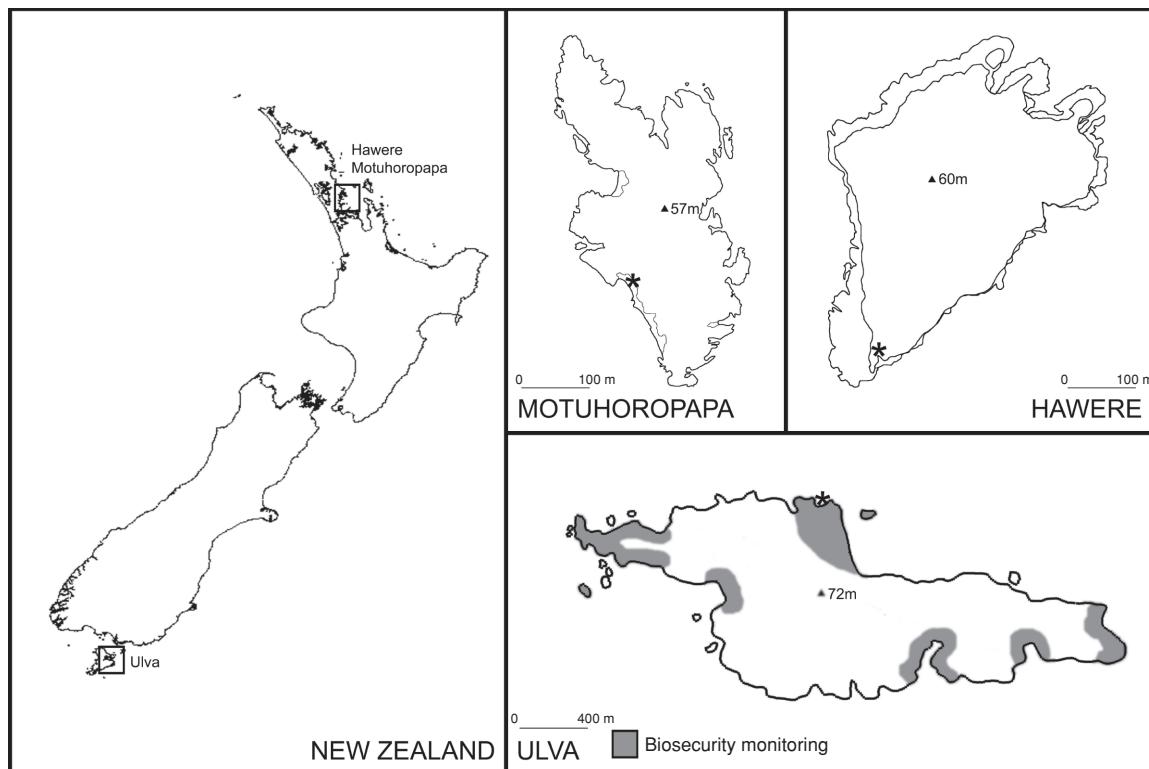

Fig. 1.   Forested rat-free islands used for experimental release of male Norway rats. Asterisks indicate release sites.

mice (*Mus musculus*). Pakihi Island consists of pasture and pine plantation, and ~10 ha of coastal native forest. Some unoccupied dwellings are scattered across the island. Thirty live-traps (Tomahawk, WI, USA), baited with chocolate paste, were placed along hedgerows and left in place for the entire study. Live-captured rats were transferred to a clear plastic bag, where they were anaesthetised using isoflurane delivered into the bag via a hand-pumped bottle system. Once anaesthetised, rats were sexed, measured and weighed (500-g scale, Pesola, Baar, Switzerland) as in Cunningham and Moors (1996). Healthy adult male rats suitable for transfer and release were radio-collared with a 6.4-g bolted brass internal-aerial collar (Bio-track, Dorset, UK) and a 1-mm tail-tip sample was collected in 70% ethanol for genetic finger-printing. Rats were held in a purpose-constructed, steel-mesh box and given shelter and sawdust, with liberal amounts of food and water. Rats were held for 48 h before release.

Releases

In total, nine adult male Norway rats were released in southern New Zealand over the summers of 2001–2004. The mean weight of Norway rats released, where measured, was 263 g (s.d. = 51 g, *n* = 4). Individual Norway rats were released in the afternoon on the Ulva Island wharf. Each rat was tracked immediately following release until either he died or a signal was no longer received, at which time a new rat was released. Here we tested a surveillance system only (Table 1).

Seven adult male Norway rats were released in northern New Zealand. Two were released on Hawere over summer 2005–2006 (*n* = 2) and five were released on Motuhoropapa over the summers of 2004–2005 (*n* = 1) and 2005–2006 (*n* = 4). The mean weight of Norway rats released was 335 g (s.d. = 36 g, *n* = 7). Individual rats were released at dusk on the main landing beaches of the islands. They were then tracked using a TR4 receiver (Telonics, Mesa, AZ, USA) with a Yagi 3-stage folding antenna (Sirtrack Electronics, Havelock North, New Zealand), as part of a study on the movement of invading rats in novel environments (Russell 2007). After ~3–4 weeks on the island, and once rats had established a stable home range, efforts were made to detect and then eliminate each rat.

On Hawere, a contingency response consisting of 15 waxtags (Thomas *et al*. 1999), 15 tracking tunnels (Brown *et al*. 1996), each baited with peanut butter, and 15 gnaw sticks (McFadden 1991), was tested. These were laid alternately in an approximate 50-m grid across the island, similar to a standard contingency response to suspected rat invasion, to confirm rat presence. Once rats were detected, traps and hand-spread poison were laid in their area of activity. Here we tested a contingency response only (Table 1).

On Motuhoropapa the current biosecurity system was used for all but the first rat (reported elsewhere in Russell *et al*. 2005). If rats were not caught in the first week using the surveillance system, a contingency response using rodent dogs, hand-spread poison and live-traps with bait and sawdust impregnated with female rodent scent was implemented. The contingency response comprised using interference sign and simultaneously poisoning the rat by placing out 10-g 'smears' of peanut butter each with a 2-g Pestoff 20R pellet (Animal Control Products Ltd, Wanganui, New Zealand). These were placed on tree trunks just above ground level within 200 m of the rat's den site (as determined from radio-telemetry). A 400-g rat would need to eat 5.2 g of brodifacoum pellets to have taken an LD_{50} (0.27 mg kg^{-1}) dose (Airey and O'Connor 2003). Furthermore, since 30% of consumed bait can pass right through the gut unabsorbed, a chronic feed over many nights is more likely to be fatal than a single acute dose (B. Simmons, Animal Control Products Ltd., pers. comm.). The rat would need to consume at least an estimated six 20R pellets to ensure lethal poisoning. Live-traps baited with bacon rind, chocolate paste and fresh sawdust soiled by female laboratory rats were also set. Trained Department of Conservation rodent dogs were then used to locate the rat's area of activity and, where possible, a corpse. Here we tested a surveillance system (one week) with an additional contingency response (one week) (Table 1).

The distribution of time to interception of rats across all islands was compared with an exponential distribution. The exponential distribution models the waiting time until an event occurs (in this case interception) where the probability of an event occurring is constant across time. Where the fate of rats was not known (i.e. right-censoring of interception times), the last date of detection was used. On all islands, methods were considered successful if the rat was intercepted within two weeks of commencement of biosecurity operations.

Results

The mean time to interception for all rats eventually intercepted was 13.8 days (median 4.5 days), with ~50% of rats that were successfully released (*n* = 13) intercepted within 14 days (Fig. 2). Excluding the first rat released on Motuhoropapa under a different biosecurity system, there was no evidence that the time taken to intercept rats (*n* = 12) differed from an exponential distribution (χ^2 = 1.47, d.f. = 3, *P* = 0.71).

On Ulva Island, three rats were caught within the two-week specified time-frame, and one was not (Table 2). A native flightless rail (*Gallirallus australis*) contributed to the death of one invader. Three rats were unaccounted for, although two rats later found dead but without collars in the surveillance system were possibly rats U5 and U7. One rat died upon release. Rats released on Ulva spent 2–3 days around the area of release,

Table 1.   Surveillance and contingency response systems tested on islands

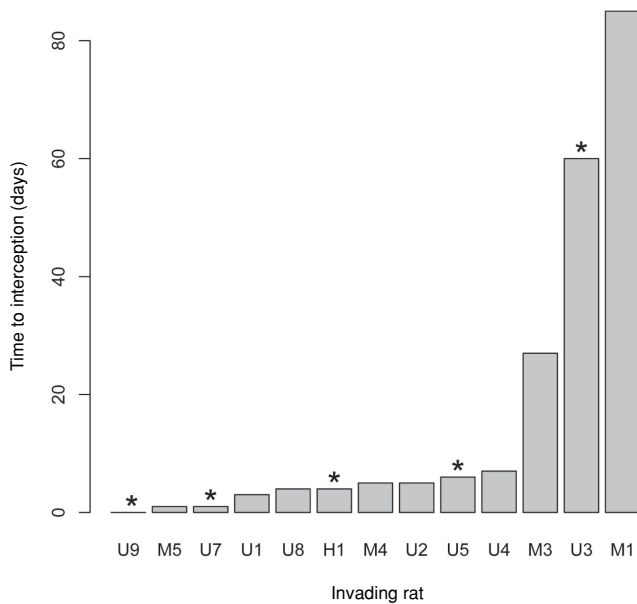| Island	Method	Devices
Ulva	Surveillance	Kill-traps + bait stations
Hawere	Contingency	Detection devices followed by kill-traps + poison + trained dogs
Motuhoropapa	Surveillance	Kill-traps
	Contingency	Hand-spread poison + live-traps with rodent-scented sawdust + trained dogs

Fig. 2. Time to interception of invading Norway rats released on islands. Asterisks indicate last confirmed presence of rat (no interception).

following which some individuals remained near the release site, whereas others embarked on a wider exploration, moving up to 1250 m from the site of release. Three rats (U4, U5 and U8) moved larger distances (in the order of kilometres), although one later returned to the original site of release. The bodies of rats U4 and U8 were recovered shortly after their deaths and both rats had lost weight over the short period (<1 week) between their release and recapture.

On Hawere Island, one rat was successfully detected but not eliminated by a contingency response, while another rat left the island prematurely. Rat H1 interfered with six tracking tunnels (40%) and five waxtags (33%), confirming rat presence. Subsequent efforts over the following two weeks to locate the rat (traps, poisons and rodent dogs) found no further sign. It was therefore presumed that the rat had swum to the nearby mainland, and all devices were removed. Rat H2 was located on the adjacent mainland beach before a contingency response could be initiated.

On Motuhoropapa Island, two rats were caught within the two-week time-frame, and one was caught using alternative methods (Table 3). One rat died upon release. Rat M3 on Motuhoropapa evaded the surveillance grid but was eliminated by the contingency response. This rat ate a lethal dose of poison and its corpse was then located by rodent dogs to confirm successful elimination. On release, rat M3 weighed 328 g; upon retrieval of the body 49 days later, it weighed 441 g. This equates to a weight gain of over 16 g (almost 5%) per week and 33% overall. A substantial amount of subcutaneous fat was observed upon autopsy.

Discussion

Testing surveillance systems when a known number of rats are present on an island is a powerful method for validating the performance of biosecurity techniques. We found that invading rats had variable susceptibilities to biosecurity methods. Most released individuals that remained on the islands either died or were eventually captured, although only half the rats released were intercepted within our target of 14 days. However, the mean time to interception was around this timeframe. Rats that took a long time to catch required a change of methods, an array of devices and more intensive effort. Even confirming rat presence was at times very difficult. Similar difficulties were found for detecting and killing invading Norway rats on Frégate Island, Seychelles (Thorsen *et al.* 2000).

The exponential pattern for interceptions suggests that the probability of intercepting a rat on an island could be constant across time. However, as an unlikely event on any particular day some rats may, by chance alone, take a very long time to intercept. Detection could be confounded by other factors though (e.g. for rats that were never intercepted). Individuals that were recaptured soon after release had lost weight, possibly due to trauma from containment and release into a novel environment. In contrast, the rat caught 49 days after release showed a 33% weight gain. This staggering increase in bodyweight over such a short time highlights a complicating factor on rodent-free islands: an abundance of uncontested food resources. The longer an island has remained rat-free, the more abundant its palatable natural food resources will become. This abundance of food resources probably competes with artificial baits and lures used on devices (Moors 1985*b*; Dilks and Towns 2002; Hoare and

Table 2.   Outcome of adult male Norway rats released on Ulva Island, 2001–2004

Rat	Weight (g)	Date	Distance[A] (m)	Days[B]	Success	Fate
U1	–	May 2001	100	3	Yes	Ate poison and then caught in trap.
U2	–	May 2001	100	5	Yes	Ate poison and died.
U3	–	Apr. 2002	100	>60	No	Took up residence in building. Not caught despite extra traps being installed. Collar failed after 2 months.
U4	290	Nov. 2002	980	7	Yes	Caught in trap 150 m from release site.
U5	–	Nov. 2002	1250	>6	–	Collar lost after 6 days, possibly caught in surveillance grid 4 months later.
U6	–	May 2003	0	0	–	Drowned attempting to get ashore.
U7	220	Nov. 2004	n.a.	>1	–	Collar lost after 10 min, possibly caught in surveillance grid 10 days later.
U8	220	Nov. 2004	1340	4	–	Found dead, killed by weka.
U9	321	Dec. 2004	–	–	–	Dead or collar lost.

[A]Maximum distance ranged from release site.
[B]From release to capture/death.

Table 3.   Outcome of adult male Norway rats released on Motuhoropapa and Hawere Island, 2004–2006

Rat	Weight (g)	Date	Island	Days[A]	Success	Fate
M1	265	Nov. 2004	Motuhoropapa	85	–	Evaded contingency response, swam to Otata, caught in trap.[B]
M2	329	Oct. 2005	Motuhoropapa	0	–	Died on release.
M3	328	Oct. 2005	Motuhoropapa	27	Yes	Evaded grid, poisoned.[C]
H1	341	Dec. 2005	Hawere	>4	?	Collar failed, detected after 1 month, swam to mainland?[C]
M4	383	Feb. 2006	Motuhoropapa	~5	Yes	Collar failed shortly after release, caught in grid.
H2	353	Feb. 2006	Hawere	>34	–	Found on mainland coast after 1 month.[C]
M5	343	Mar. 2006	Motuhoropapa	~1	Yes	Caught in grid by trap under hut.

[A]From instigation of biosecurity to capture/death/leaving island (i.e. not including 3 weeks radio-tracking).
[B]See Russell *et al*. (2005).
[C]See text.

Hare 2006). Poor detection of invading rats may also be caused by neophobia (Cowan 1977; Brigham and Sibley 1999), either as device aversion or bait aversion. Because peanut butter on tree trunks was readily consumed whereas detection and trapping devices were avoided, the devices rather than the baits are the most likely cause of neophobia in our study. Similar results have been reported from laboratory trials (Inglis *et al*. 1996). This problem can be overcome using pre-established surveillance grids. Our field results and those in the laboratory indicate that rats are less likely to demonstrate neophobia towards devices when they are present in an entirely novel environment (Russell 1983). Over longer periods (weeks), neophobia towards novel devices in a familiar environment should decline, given that most rats eventually overcome neophobia, at least when they are at high densities where food is limited (Moors *et al*. 1992; Inglis *et al*. 1996). For example, juvenile Norway rats born into the invading population on Frégate Island were less neophobic than the invading adult female (Thorsen *et al*. 2000).

An additional cause of neophobia is trap aversion. Trap-shyness as a result of the experience of being previously caught is commonly observed in live-trapping studies of rats (Moors 1985*b*). Some trap aversion was therefore unavoidable in this study. Rats could also become averse to human scent present on devices, although scent should not last more than a few days after handling. This may explain why rats can be more easily trapped when devices are inspected and handled less regularly (Taylor *et al*. 1974). Detection rates can also be influenced by a spatial component, whereby rats simply do not encounter the devices. However, given that most rats explored the small northern islands within one week, it is unlikely that they would not have encountered any of the devices present. Whether rats enter the devices when they encounter them seems more important (Russell *et al*. 2005), perhaps also related to the tendancy for any rat arriving at a new location to be wary of its new environment during exploration (Cowan 1977; Russell 1983). Furthermore in the absence of competition for abundant food resources, fewer risks need be taken by a single rat whose neophobia has been exacerbated by the novel environment.

Two, and possibly three, of the nine rats released in northern New Zealand left rat-free islands after one month. Similarly, three of the nine rats released in southern New Zealand also evaded early elimination and embarked on long-distance movements of up to 2 km. Field studies of rat dispersal and detectability have previously focused on high-density populations, where juvenile dispersal is attributed to stress associated with the availability of food and territories (Macdonald *et al*. 1999; Lacey and Solomon 2003). Such conclusions may not be relevant to the behaviour of new invaders, however. The larger size of Ulva Island enabled detection of long-distance dispersal events not possible on the two small northern islands. Such dispersal events are particularly alarming for island biosecurity, as they provide for only short periods for responses to an incursion (such as a shipwreck) before invaders will disperse well beyond the landing site.

Trained dogs are able to locate direct and indirect sign (Smith *et al*. 2001), which is difficult to find for a small number of invading rats (Thorsen *et al*. 2000). Rodent dogs were used twice when other devices were unsuccessful. The dogs indicated where rats were active when all other detection methods failed. These dogs confirmed a successful poisoning by locating the rat's corpse. Potentially, dogs could be used to indicate specific areas of rodent activity on an island where control efforts should be targeted. This is particularly important on larger islands (>50 ha) where it is not possible to launch an island-wide response to a rodent incursion, and instead the response must be targeted to a recent known location of any rats. Scent is particularly important to rodents (Burwash *et al*. 1998; Bramley *et al*. 2000), and the scent to which the dogs reacted in the field was probably no older than one week. Properly trained rodent dogs can be used both for surveillance of rat-free islands and as part of a contingency response to incursions.

Our use of radio-collared rats not only tested island biosecurity systems, but also indicated movement patterns that will affect encounter rates with grids and device placement (O'Connor and Eason 2000). These results indicate that detecting and eliminating a single invading rat requires a revised view of best-practice for rodent detection. Tunnel-type devices made of natural wood and left permanently in place probably offer the least deterrent to invading rats (Spurr *et al*. 2006, 2007). Such devices need to be large enough to incorporate tracking cards, bait or traps and should be located where invading rats are most likely to be found (Russell *et al*. in press). In many cases it was difficult to reliably identify the cause of device interference, such as triggered devices and missing food smears. Non-target animals on islands can all disturb bait and devices (Thorsen *et al*. 2000). It is important that island managers can confidently identify rodent sign and persist in interception efforts despite low to zero detection rates.

An integrated surveillance approach using a variety of proven devices is the core of a successful biosecurity system, and should be able to eliminate most invading rats immediately within 14 days of arrival, especially on small islands. On larger islands a widespread surveillance grid, and persistence, are required to guarantee successful interception of invading rats. When necessary, an additional contingency response with novel methods should be used if it is believed that any surveillance system has not detected an incursion. Contingency response alone first requires that invading rats are somehow detected, which may not happen until late in an invasion. As an indication of costs, on Ulva Island monthly biosecurity surveillance costs NZ$660, whereas on Hawere Island each contingency response (two weeks) costs NZ$1540. On Motuhoropapa Island surveillance costs NZ$740 per visit, and an additional NZ$1420 per contingency response (one week). Costs include transport, labour, device maintenance and, for contingency responses, the additional use of trained dogs for one day. Costs will vary widely, however, based on transport costs and the size of islands being protected.

Provided that island biosecurity systems are regularly maintained so that the rate of interception equals the arrival rate, it should be possible to keep islands rat-free even when they have high reinvasion rates (e.g. greater than one rat per annum), although on large islands surveillance devices must be strategically placed (e.g. at points of known arrival). The susceptibility of an island to invasion and the most appropriate island biosecurity system will vary between islands. When islands have high conservation value or are regularly reinvaded, managers should consider releasing single radio-collared rats to test island biosecurity systems. This is best done immediately after the eradication of resident rats, so that strategically placed devices and an appropriate surveillance regime can be designed before other conservation values on the island are restored.

Acknowledgements

References

Airey, A. T., and O'Connor, C. E. (2003). Consumption and efficacy of rodent baits to Norway rats. DOC Science Internal Series 148. Department of Conservation, Wellington.

Bramley, G. N., Waas, J. R., and Henderson, H. V. (2000). Responses of wild Norway rats (*Rattus norvegicus*) to predator odors. *Journal of Chemical Ecology* **26**, 705–719. doi:10.1023/A:1005432322861

Brigham, A. J., and Sibley, R. M. (1999). review of the phenomenon of neophobia. In 'Advances in Vertebrate Pest Management'. (Eds D. P. Cowan and C. J. Feare.) pp. 67–84. (Filander Verlag: Furth.)

Brown, K. P., Moller, H., Innes, J., and 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.

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

Burwash, M. D., Tobin, M. E., Woolhouse, A. D., and Sullivan, T. P. (1998). Laboratory evaluation of predator odors for eliciting an avoidance response in roof rats (*Rattus rattus*). *Journal of Chemical Ecology* **24**, 49–66. doi:10.1023/A:1022384728170

Chappell, R. (2004). Motutapere Island rodent invasion 2004. Internal report, file ISL 0013. Department of Conservation, Coromandel.

Clout, M. N., and Russell, J. C. (2006). The eradication of mammals from New Zealand islands. In 'Assessment and Control of Biological Invasion Risks'. (Eds F. Koike, M. N. Clout, M. Kawamichi, M. De Poorter and K. Iwatsuki.) pp. 127–141. (IUCN: Gland.)

Courchamp, F., Chapuis, J.-L., and Pascal, M. (2003). Mammal invaders on islands: impact, control and control impact. *Biological Reviews* **78**, 347–383. doi:10.1017/S1464793102006061

Cowan, P. E. (1977). Neophobia and neophilia: new-object and new-place reactions of three *Rattus* species. *Journal of Comparative and Physiological Psychology* **91**, 63–71. doi:10.1037/h0077297

Cunningham, D. M., and Moors, P. J. (1996). Guide to the identification and collection of New Zealand rodents. Occasional Publication No. 4, 3rd edn. Department of Conservation, Wellington.

Dilks, P. J., and 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.

Esler, A. E. (1975). Goat Island, Leigh. Unpublished report. Botany Division, Department of Scientific and Industrial Research, Auckland.

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

Howald, G., Donlan, C. J., Galván, J. P., Russell, J. C., and Parkes, J., *et al.* (2007). Invasive rodent eradication on islands. *Conservation Biology* **21**, 1258–1268. doi:10.1111/j.1523-1739.2007.00755.x

Inglis, I. R., Shepherd, D. S., Smith, P., Haynes, P. J., Bull, D. S., Cowan, D. P., and Whitehead, D. (1996). Foraging behaviour of wild rats (*Rattus norvegicus*) towards new food and bait containers. *Applied Animal Behaviour Science* **47**, 175–190. doi:10.1016/0168-1591(95)00674-5

Jay, M., Morad, M., and Bell, A. (2003). Biosecurity, a policy dilemma for New Zealand. *Land Use Policy* **20**, 121–129.

Lacey, E. A., and Solomon, N. G. (2003). Social biology of rodents: trends, challenges, and future directions. *Journal of Mammalogy* **84**, 1135–1140. doi:10.1644/BLe-016

Macdonald, D. W., Mathews, F., and Berdoy, M. (1999). The behaviour and ecology of *Rattus norvegicus*: from opportunism to kamikaze tendencies. In 'Ecologically-based Rodent Management'. (Eds G. R. Singleton, L. A. Hinds, H. Leirs and Z. Zhang.) pp. 49–80. (Australian Centre for International Agricultural Research: Canberra.)

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

McFadden, I. (1991). Rat invasion – Noises Islands. Internal report, file FAU 609-01. Department of Conservation, Auckland.

Mittermeier, R. A., Gil, P. R., Hoffman, M., Pilgrim, J., Brooks, T., Mittermeier, C. G., Lamoreux, J., and da Fonseca, G. A. B. (2005).

'Hotspots Revisited: Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions.' (Conservation International; Washington, DC.)

Moors, P. J. (1985*a*). Eradication campaigns against *Rattus norvegicus* on the Noises Islands, New Zealand, using brodifacoum and 1080. In 'Conservation of Island Birds'. (Ed. P. J. Moors.) Technical Publication No. 3. pp. 143–155. (International Council for Bird Preservation: Cambridge.)

Moors, P. J. (1985*b*). Norway rats (*Rattus norvegicus*) on the Noises and Motukawao Islands, Hauraki Gulf, New Zealand. *New Zealand Journal of Ecology* **8**, 37–54.

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

O'Connor, C. E., and Eason, C. T. (2000). Rodent baits and delivery systems for island protection. *Science for Conservation* **150**. [Department of Conservation: Wellington.]

Orueta, J. F., Aranda, Y., Gómez, T., Tapia, G. G., and Sanchez-Mármol, L. (2005). Successful eradication of invasive rodents from a small island through pulsed baiting inside covered stations. *Biological Invasions* **7**, 141–147. doi:10.1007/s10530-004-9644-7

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

Russell, J. C. (2007). Invasion ecology and genetics of Norway rats on New Zealand islands. Ph.D. Thesis, University of Auckland.

Russell, J. C., and Clout, M. N. (2005). Rodent incursions on New Zealand islands. In 'Proceedings of the 13th Australasian Vertebrate Pest Conference'. (Eds J. Parkes, M. Statham and G. Edwards.) pp. 324–330. (Landcare Research: Lincoln.)

Russell, J. C., Towns, D. R., Anderson, S. H., and Clout, M. N. (2005). Intercepting the first rat ashore. *Nature* **437**, 1107. doi:10.1038/4371107a

Russell, J. C., Towns, D. R., and Clout, M. N. (in press). Review of rat invasion biology: implications for island biosecurity. Science for Conservation. Department of Conservation, Wellington.

Russell, P. A. (1983). Psychological studies of exploration in animals: a reappraisal. In 'Exploration in Animals and Humans'. (Eds J. Archer and L. I. A. Birke.) pp. 22–54. (Van Nostrand Reinhold: Cambridge.)

Smith, D. A., Ralls, K., Davenport, B., Adams, B., and Maldonado, J. E. (2001). Canine assistants for conservationists. *Science* **291**, 435. doi:10.1126/science.291.5503.435B

Sowls, A. L., and Byrd, G. V. (2002). Preventing rat introductions to the Pribilof Islands, Alaska, USA. In 'Turning the Tide: the Eradication of Invasive Species'. (Eds C. R. Veitch and M. N. Clout.) p. 413. (IUCN SSC Invasive Species Specialist Group, IUCN: Gland.)

Spurr, E. B., O'Connor, C. E., Morriss, G. A., and Turner, J. (2006). Bait station preferences of Norway rats. DOC Research & Development Series 255. Department of Conservation, Wellington.

Spurr, E. B., Morriss, G. A., Turner, J., O'Connor, C. E., and Fisher, P. (2007). Bait station preferences of ship rats. DOC Research & Development Series 271. Department of Conservation, Wellington.

Taylor, K. D., Hammond, L. E., and Quy, R. J. (1974). The reactions of captive wild rats (*Rattus norvegicus*) to human odour and to the odour of other rats. *Mammalia* **38**, 581–590.

Thomas, B. W., and Taylor, R. H. (2002). history of ground-based rodent eradication techniques developed in New Zealand, 1959–1993. In 'Turning the Tide: the Eradication of Invasive Species'. (Eds C. R. Veitch and M. N. Clout.) pp. 301–310. (IUCN SSC Invasive Species Specialist Group, IUCN: Gland.)

Thomas, M. D., Brown, J. A., and 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., and 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. doi:10.1016/S0006-3207(00)00059-8

Towns, D. R., Daugherty, C. H., and Atkinson, I. A. E. (1990). Ecological restoration of New Zealand islands. Conservation Sciences Publications No. 2, Department of Conservation, Wellington.

Towns, D. R., Atkinson, I. A. E., and Daugherty, C. H. (2006). Have the harmful effects of introduced rats on islands been exaggerated? *Biological Invasions* **8**, 863–891. doi:10.1007/s10530-005-0421-z

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