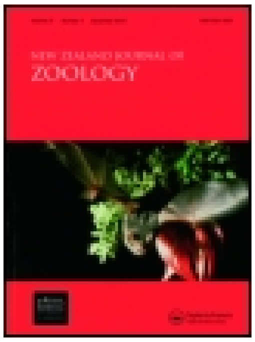

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From small Maria to massive Campbell: forty years of rat eradications from New Zealand islands

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Abstract Over the last four decades the eradication of rats from islands around New Zealand has moved from accidental eradication following the exploratory use of baits for rat control to carefully planned complex eradications of rats and cats (*Felis catus*) on large islands. Introduced rodents have now been eradicated from more than 90 islands. Of these successful campaigns, those on Breaksea Island, the Mercury Islands, Kapiti Island, and Tuhua Island are used here as case studies because they represent milestones for techniques used or results achieved. Successful methods used on islands range from bait stations and silos serviced on foot to aerial spread by helicopters using satellite navigation systems. The development of these methods has benefited from adaptive management. By applying lessons learned from previous operations the size, complexity, and cost effectiveness of the campaigns has gradually increased. The islands now permanently cleared of introduced rodents are being used for restoration of island-seabird systems and recovery of threatened species such as large flightless invertebrates, lizards, tuatara, forest birds, and some species of plants. The most ambitious campaigns have been on remote subantarctic Campbell Island (11 300 ha) and warm temperate Raoul Island (2938 ha), aimed to provide long-term benefits for endemic plant and animal species including land and seabirds. Other islands that could benefit from rat removal are close inshore and within the natural dispersal range of rats and stoats (*Mustela erminea*). Priorities for future development therefore include more effective methods for detecting rodent invasions, especially ship rats (*Rattus rattus*) and mice (*Mus musculus*), broader community involvement in invasion prevention, and improved understanding of reinvasion risk management.

Keywords kiore; Pacific rat; *Rattus exulans*; Norway rat; *R. norvegicus*; ship rat; *R. rattus*; eradication; adaptive management; Breaksea Island, Mercury Islands; Kapiti Island, Tuhua Island; rodenticide; brodifacoum; aerial spread; legal constraints; Resource Management Act 1991; invasion biology; benefits; costs; cultural issues

INTRODUCTION

In about 1962, ship rats invaded Big South Cape Island off southern New Zealand. Subsequently, the last populations of bush wren (*Xenicus longipes*) and short-tailed bat (*Mystacina robusta*) disappeared along with at least one species of large invertebrate (Atkinson 1989). This was not the first recorded invasion of islands by rats in the New Zealand archipelago (Atkinson 1973). However, it was one of the first to be documented, including an account of attempts made to save the species under threat (Atkinson & Bell 1973; Atkinson 1989). Unfortunately, these failed for all but the South Island saddleback (*Philesturnus c. carunculatus*) (Bell 1978). Given that such islands are storehouses for much of New Zealand's biodiversity (Daugherty et al. 1990), the progressive demise of unique

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remnants of the New Zealand flora and fauna to invading rodents then seemed inevitable.

Awareness of this potential ecological catastrophe formed the background for a meeting held in 1976 organised by the Department of Lands and Survey to discuss and collate information on controlling the spread of rodents into reserves (Dingwall et al. 1978). The participants came to the depressing conclusion that unless existing controls on island landings were enforced, the spread of rodents would continue unchecked. Put simply, if rats invaded an island, "the prospect of complete extermination…by conventional control methods is considered remote" (Wodzicki 1978). But in one of the great breakthroughs of New Zealand conservation biology, even as these conclusions were published, those unlikely eradications were already being achieved using methods and products available at the time.

Below, we outline how eradication of rats from New Zealand islands has progressed over 40 years from unexpected eradications on small islands of less than 5 ha to sophisticated and logistically demanding campaigns on islands of more than 11 000 ha. We also outline the financial costs and biological benefits of selected campaigns, changes in legal constraints, and examine where future efforts may focus.

For the purposes of this review we distinguish between eradication and control. Eradication involves the complete removal of a species from a location into which there is little chance of reinvasion by natural dispersal. Control is a reduction of the population size of a species, by sustained and constant effort (Parkes 1990). We also refer to adaptive management, which is viewed here as the use of new information to adjust a strategy or goal in order to learn from experience (Lessard 1998 and references therein). For example, this approach has been applied successfully in New Zealand to management of kokako (*Calleas cinerea*) (Innes et al. 1999) and to intensively managed mainland sites (Saunders & Norton 2001).

Three species of rats now occupy the New Zealand archipelago. Their introduction was closely associated with the arrival of people. The first to arrive was the Pacific rat or kiore (*Rattus exulans*), possibly with visiting voyagers from the Pacific about 2000 years ago (Holdaway 1996). If this proposal is correct, kiore were probably on the mainland of New Zealand for a considerable period before dispersing to many of the smaller islands following the establishment of permanent Polynesian colonisation in about 1200–1300 AD (Anderson 1991; McFadgen et al. 1994). Two additional species of rat were introduced subsequently by Europeans. Norway rats (*Rattus norvegicus*) dispersed from ships during exploration of New Zealand from 1769, and ship rats spread throughout New Zealand after about 1860–1890 (Atkinson 1973). The disappearance of kiore from much of mainland North and South Island coincided with the arrival of mice and ship rats (Atkinson 1973; Taylor 1975).

Distribution of rats and their effects on island species

A review by Atkinson & Taylor (1992) concluded that rats had reached at least 113 (33.5%) of the 337 islands over 5 ha. Rats also occupied numerous islands of less than 5 ha (Taylor 1989). The current pattern of rat distribution in New Zealand is influenced by several ecological and historical factors including interspecific competition, size and complexity of habitat, historical opportunity to invade, and nowadays, history of rodent eradications. Large islands (>1000 ha) may support more than one rat species, plus mice, and other predators including stoats and cats (Atkinson & Taylor 1992). Of the rat species on islands, kiore may coexist with mice and at least one other species of rat. However, kiore usually now survive only on the smaller and more distant islands, perhaps due to a lack of contact with other rats (but see Roberts 1991). Regardless of rat species present, islands less than 1500 m from the mainland are also accessible to stoats. The effects of rats on island species are therefore sometimes complicated by other species of rodents or additional predators other than rats.

Kiore have frequently survived on islands as the only introduced predatory mammal. Therefore, models of the effect of rodents without complicating effects of other pests are best constructed for New Zealand species using islands inhabited only by kiore (Atkinson & Towns 2001). Circumstantial evidence of these effects has been based on between-island comparisons and investigation of the fossil record. These methods have revealed localised extinctions of large flightless invertebrates, especially the darkling beetle (*Mimopeus elongates*) (Watt 1986), as well as large nocturnal skinks such as *Cyclodina alani* (Whitaker 1978). The decline to extinction of at least six species of passerine birds also coincided with the arrival of kiore on the mainland (Atkinson 1989; Holdaway 1999). Similarly, the shells of two species of large land

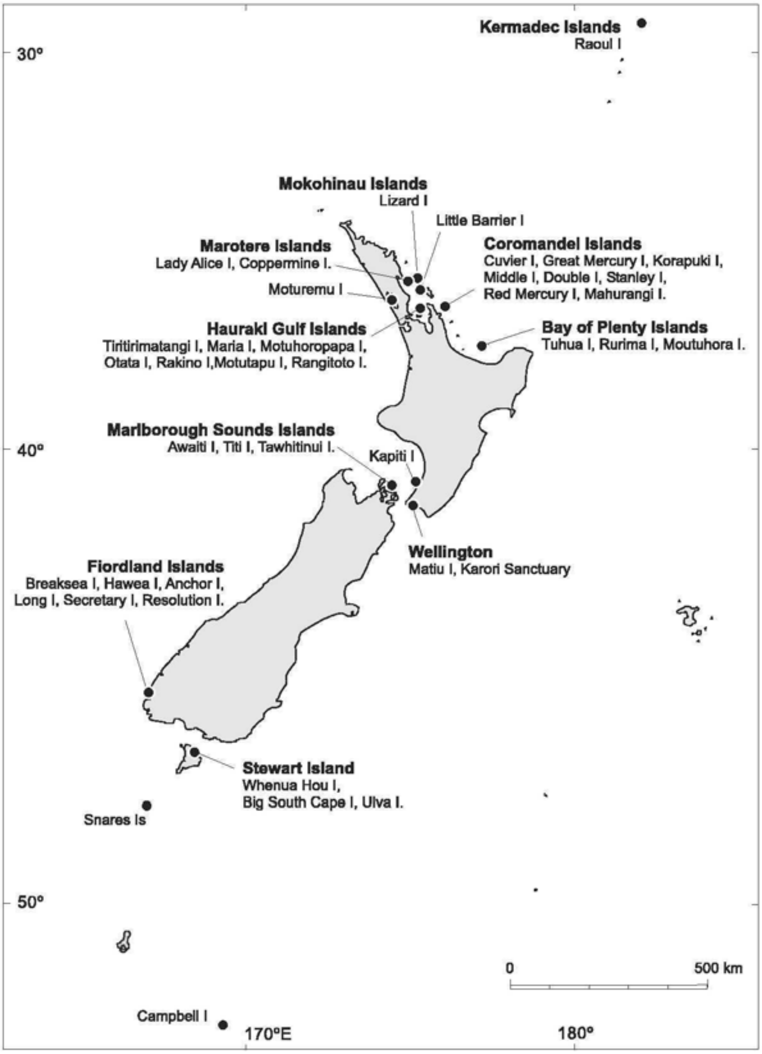

Fig. 1 Map of localities mentioned in the text and tables.

snails disappeared from subfossil deposits on Lady Alice Island (Fig. 1) soon after the appearance of rat-gnawed shells indicated an invasion by kiore (Brook 1999).

More direct evidence of the effects of kiore can be obtained by comparing regeneration on islands before and after their removal (Campbell & Atkinson 1999) and by measurement of the responses of resident species. In addition, the effects of kiore on plants have been tested using exclosure plots (Campbell & Atkinson 2002). Together, these studies indicate that kiore have suppressed the recruitment of at least 11 species of coastal broadleaf plants, ground weta (*Hemiandrus* sp.) and a selection of other flightless invertebrates (Green 2002), shoreline-inhabiting skinks (Towns 1996; Towns et al. in press), geckos (Towns 2002), tuatara (*Sphenodon punctatus*) (Atkinson & Towns 2001) and small seabirds (Pierce 2002) on the islands examined. Kiore may substantially modify forest composition on islands (Campbell & Atkinson 2002) as well as affecting the distribution of honeydew scale insects (*Coelostomidia zealandica*) by suppressing their host plants (Towns 2002).

An equivalent or larger range of organisms is vulnerable to damage by Norway rats and ship rats (Atkinson 1978; Allen et al. 1994; Innes 2001). Comparisons of the global effects of rats on island bird faunas led Atkinson (1985) to conclude: "Island avifaunas are more likely to suffer declines and extinctions if *R. rattus* is introduced than if other commensal rats become established." However, he also concluded that all three rat species have a history of devastation whenever they have invaded islands inhabited by endemic species of land birds and seabirds. Birds with limited powers of flight or that nest in burrows or holes were particularly vulnerable. Atkinson therefore proposed that all islands with vulnerable faunas should be identified and assiduously protected against invasion by all species of rats.

APPROACHES TO CONTROL AND ERADICATION

The history of ground-based *methods* used to eradicate rats from islands around New Zealand is described in detail by Thomas & Taylor (2002). Here we summarise the evolution of the technology from ground-based to aerial distribution of baits. Most importantly, the philosophical *approach* to rat invasions has developed through three stages, as illustrated below with selected examples.

Exploratory control and eradication

General awareness of the potential for rats to devastate island systems around New Zealand was raised by the 1962 Big South Cape invasion. However, there were warnings of the possible effects of rats in 1959 when hundreds of white-faced storm petrels (*Pelagodroma marina*) were found dead on Maria Island (1 ha). These deaths were attributed to an invasion of Norway rats, which disappeared at about the time of the sporadic spread of rodenticide on the island between 1960 and 1964 (Moors 1985). This was the first recorded eradication of rats from a New Zealand island. Also, because of their impacts on seabirds, Norway rats were controlled around seabird colonies on Titi Island between 1970 and 1975. Six years later it was discovered that this control had actually eradicated the rats (Thomas & Taylor 2002). In these and other examples (Table 1), the islands were mostly very small; episodic rat control was attempted in order to protect species from invading rats; the laying of baits was not systematic, and the effectiveness of the bait distribution was not routinely measured at the time. In effect, eradication of the rats was largely accidental. A more experimental approach, which also produced an unexpected result, was the inadvertent eradication of Norway rats from Motuhoropapa Island during a snap-trapping study in 1977–78 (Moors 1985).

Experimental eradication

These accidental eradications on small islands encouraged more deliberate attempts to develop eradication methods. The experimental attempts differed from exploratory bait distribution because

Table 1 Selected New Zealand islands from which rats were eradicated as an unexpected by-product of local control attempts, with data updated from Veitch (1995).

Island	Area (ha)	Year	Rat species	Method	Comments	Reference
Maria	1	1960	Norway	Hand laying of rid-rat warfarin baits	Bait distributed after rat sign had ceased	Merton in Dingwall et al. (1978)
Titi	32	1970	Norway	Hand laying of prodide warfarin baits	Attempted control of rats around seabird colonies	Thomas & Taylor (2002)
Lizard	1	1978	Kiore	Hand laying of commercial rat poison (product unknown)	Baits laid after invasion detected in 1977	McCallum (1986)
Motuhoropapa	8	1978	Norway	Snap-trapping	Part of a preliminary study of rat populations before a poisoning campaign	Moors (1985)
Moutohora	173	1986	Norway	Aerial spread of brodifacoum in Talon 20 P™ cereal baits	Toxin developed for and used against rabbits	Jansen (1993)

the quantities and effectiveness of the toxins and baits were measured. The cost-effectiveness of the methods could then be determined. The studies were conducted on small islands between 1977 and 1986 with baits delivered through self dispensing silos or bait stations (Table 2). Regardless of the delivery methods used, the two most effective rodenticides (bromadialone and brodifacoum —for descriptions see O'Connor & Eason 2000) were potent second generation anticoagulants which are single dose and have delayed onset of poisoning symptoms. These properties substantially reduce the likelihood of rodent survival by learned aversion, a common problem with fast acting poisons and those requiring multiple feeds.

Conservation-based adaptive management

Systematic eradication campaigns aimed at producing significant conservation benefits for island species began in the mid 1980s. The successful removal of Norway rats and kiore from small islands provided the impetus for larger and more complex campaigns. Some of these were motivated by ambitious requests from conservation groups for the removal of rats that either threatened resident species or in order to use islands to restore species with fragmented distributions. For example, of 12 islands on which tuatara and kiore were known to have coexisted during the last 150 years, by 1989 tuatara were extinct on four and showing signs of reduced capture rates and recruitment failure on seven (Cree et al. 1995). On three islands, the populations were estimated to be down to 20 or fewer individuals. The Tuatara Recovery Plan (Cree & Butler 1993) proposed the eradication of kiore from as many of the islands as possible, although some islands were much larger than those hitherto attempted.

Such requests provided impetus for the development of two approaches to rodent eradication on islands. One was ground-based operations using bait-stations serviced on foot, a method developed largely by the former Department of Scientific and Industrial Research (Thomas & Taylor 2002). The other was the progressive development of aerial spread of baits by helicopter. Aerial spread had been used on the mainland for control of possums, but the method

Table 2 Selected New Zealand islands from which rats were removed primarily to test eradication methods.

Island	Area (ha)	Year	Rat species	Method	Comments	Reference
Motuhoropapa	8	1981	Norway	Compound 1080 in oats and as paste, Talon 50 WB™ in bait stations and as 0.01% brodifacoum paste	Second eradication after reinvasion or irruption following 1979 snap-trapping operation	Moors (1985)
Otata	15	1981	Norway	Compound 1080 in oats and catfood, 1080 as paste, brodifacoum as Talon 50 WB™	Non-toxic pre-feed before application of 1080	Moors (1985)
Awaiti	2	1982	Ship	Talon 50 WB™ in bait stations	Continuous replacement of bait until removal by rats ceased	Thomas & Taylor (2002)
Tawhitinui	21	1983	Ship	Talon 50 WB™ in bait stations	Continuous replacement of baits until removal by rats ceased	Thomas & Taylor (2002)
Rurima	4.5	1983	Kiore	Compound 1080 and bromadiolone rodenticide in kibbled maize from bait silos	Non-toxic pre-feed used, 1080 abandoned after aversion detected	McFadden & Towns (1991)
Hawea	9	1986	Norway	Talon 50 WB™ in bait stations	Methods as above for ship rats	Taylor & Thomas (1989)

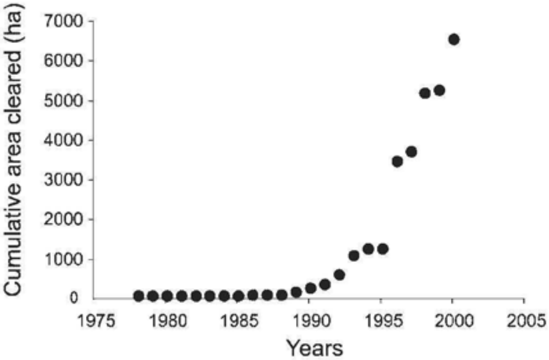

Fig. 2 Cumulative area of islands around New Zealand from which kiore have been removed over time.

was refined for use on islands by the Department of Conservation (DOC) (Table 3). Both methods were evaluated by adaptive management in the Mercury Islands (Table 4), where each island was treated as a separate experiment and the lessons learned applied to subsequent islands.

A formalised approach to adaptive management is now used by DOC for the planning and implementation of island pest eradications (Cromarty et al. 2002). Consequently, there have been incremental increases in the size and complexity of islands on which eradication of Norway rats (Clout & Veitch 2002) and kiore (Fig. 2) has been attempted. Most importantly, aerial campaigns have so far largely succeeded in removing the target rodent species.

Rather than repeat lists of all island eradications completed (McFadden et al. in Atkinson & Towns 2001; McFadden in Innes 2001), we provide below some more detailed discussions of a selection of campaigns (Table 3) that represent milestones in the development of island eradications.

CASE STUDIES OF ISLAND ERADICATIONS

1. Breaksea Island

The campaign to remove Norway rats from Breaksea Island was a landmark because the method used was a productive refinement of ground-based rat control tried elsewhere. The Breaksea campaign was preceded by a trial on neighbouring Hawea Island (Table 2) designed to confirm that ground-based rat eradication could work under the local conditions (Thomas & Taylor 2002). Following success on Hawea in 1986 (Taylor & Thomas 1989), the eradication campaign on Breaksea Island began in 1987. A network of tracks was cut so that 743 Novocoil™ bait stations could be set out at about 50 m intervals over the entire island. The baits used were the widely available Talon 50 WB™, a wax-based egg-shaped bait that contains 0.005% brodifacoum. The campaign was completed in June 1988 after 21 days of baiting at a cost of $483/ha (Taylor & Thomas 1993).

At the time, the Breaksea project was the largest planned eradication of rats undertaken in New Zealand. The use of bait stations was intended to minimise the possibility of non-target organisms being affected by the baits. However, on several occasions robins (*Petroica a. australis*) were seen entering bait stations. Two dead robins were found but were not tested for brodifacoum residues.

Breaksea Island became the largest island free of introduced predatory mammals in Fiordland National Park. The rare Fiordland skink (*Oligosoma acrinasum*) naturally recolonised once the rats had been eradicated (Thomas & Whitaker 1995). Two species of large flightless weevils, *Anagotus fairburnii* and *Hadramphus stilbocarpae*, and two species of threatened birds, South Island saddlebacks and mohua (*Mohoua ochrocephala*), were released onto the island in 1991, 1992, and 1995 (Thomas 2002; M. Willans pers. comm.).

2. Adaptive management in the Mercury Islands and Cuvier Island

The Mercury and Cuvier Islands campaigns targeted kiore on five islands between 1986 and 1993. They illustrate the evolution from ground-based to aerial operations, the clearance of progressively larger islands, gains in cost-efficiency of the methods used and increases in the range of natural resources likely to benefit (Table 4).

Korapuki Island

The first campaign was on Korapuki Island (18 ha) in 1986. Like the Breaksea Island project, it used bait stations on a 50-m grid. However, unlike Breaksea, the bait stations were automatic dispensing silos which gave a considerable saving in labour costs. A 5-day treatment of non-toxic pre-feed was used to attract kiore to the silos, the bait was kibbled maize, and the toxin applied to the baits was 0.005% bromadiolone (McFadden & Towns 1991). The total cost of the operation was $378/ha at 1991 prices. However, the operation was possibly made more

Table 3 Strategic eradication attempts against rats on New Zealand islands using adaptive management for specified conservation gains.

Island	Area (ha)	Year	Rat species	Method	Learning opportunities and eradication result	References
Breaksea	170	1988	Norway	Talon 50 WB™ in bait stations	The largest island eradication attempted thus far. Eradication successful.	Thomas & Taylor (1988); Taylor & Thomas (1993)
Mokohinau Islands	0.1–73	1990	Kiore	Aerial spread of Talon 20 P™ with follow-up ground laying of Talon 50 WB™	Trial of helicopter to spread bait. Eradication successful.	McFadden & Greene (1994)
Coppermine	80	1992	Kiore	Talon 50 WB™ in bait stations	Designed to test minimum effective bait station density. Attempt failed to eradicate rats but later successful using aerial spread.	Thomas & Taylor (2002)
Ulva	259	1992	Norway	Talon 50 WB™ in bait stations	Designed to test minimum effective bait station density, minimum bait loadings, and rolling front approaches to bait application. Eradication successful.	Anon. (1997); Thomas & Taylor (2002)
Kapiti	1965	1996	Norway + kiore	Aerial spread of brodifacoum in Talon 7–20 cereal bait	The largest island attempted thus far. Two rat species targeted. Complex non-target issues. Eradication successful.	Empson & Miskelly (1999)
Whenua Hou	1396	1998	Kiore	Aerial spread of brodifacoum in Agtech Talon 20 P™ cereal bait	Large complex project re logistics and non-targets. Test of bait type. Eradication successful.	McClelland (2002)
Tuhua	1283	2000	Norway + kiore + cats	Aerial spread of brodifacoum in Pestoff 20 R™ cereal bait	Designed to test effects of rat poisoning on cats. Eradication successful.	Hunt & Williams (2000)
Campbell	11 300	2001	Norway	Aerial spread of brodifacoum in Pestoff 20 R™ cereal bait	The largest island attempted thus far. Large complex project re logistics. New aerial spread technique. Eradication recently declared successful.	McClelland & Tyree (2002)

effective through competition for alternative food sources by rabbits.

McFadden & Towns (1991) concluded that ground-based campaigns could be difficult to coordinate on islands larger than about 50 ha although using silos may be more cost effective than other available techniques. However, in 1995 the 3100 ha Canadian island of Langara was successfully rid of Norway rats using bait stations (Taylor et al. 2000). Involving at least 30 field workers in the simultaneous servicing of the bait station grid, coordination would have been challenging in this project even though the terrain was described as low lying and slightly rolling, allowing an average 50 bait stations to be serviced per person-day (Kaiser et al. 1997). Langara remains the largest successful ground-based rat eradication in the world.

Double Island

The second campaign was undertaken on Double Island, essentially two islands of 8 and 19 ha joined at low tide by a boulder bank. The only introduced mammal present on Double Island was kiore. With no complications from other mammals, it was therefore possible to more accurately assess the effectiveness of the silos as well as the use of broadcast bait as an eradication tool. In 1989, the smaller east Double Island was treated with bait silos in the same way as Korapuki Island, and on west Double Island wheat-based pellets containing 0.005% rodenticide flocumafen (STORM™) were broadcast by hand at a rate of 18.5 kg/ha (McFadden 1992). Both methods were successful, but the lower costs of the broadcast treatment (Fig. 3) demonstrated the potential for aerial spread of baits.

Table 4 Progressive eradications of kiore (and rabbits) in the Mercury Islands using adaptive management for specified conservation gains.

Island	Area (ha)	Year	Rat species present	Method	Learning opportunities and eradication result	References
Korapuki Island	18	1986	Kiore + rabbits	Bromadiolone in kibbled maize from silos, preceded by non-toxic pre-feed	New bait and bait station type. Eradication successful.	Towns et al. (1990); McFadden & Towns (1991); Towns (2002)
East Double Island	8	1989	Kiore	Bromadiolone in kibbled maize from silos, preceded by non-toxic pre-feed; both treatments dosed with aniseed lure	Korapuki method in comparative trial with West Double. Eradication successful.	Towns et al. (1990); McFadden (1992)
West Double	19	1989	Kiore	Flocumafen blocks broadcast by hand	Comparative trial with East Double designed to simulate aerial spread. Eradication successful.	McFadden (1992)
Stanley	100	1991	Kiore + rabbits	Aerial spread of brodifacoum in Talon 20 P™ cereal baits, with follow-up hand laying of Talon 50 WB™	Aerial spread with fire fighting bucket. Non-target monitoring. Eradication successful.	Towns et al. (1993); Towns (1999)
Red Mercury	225	1992	Kiore	Aerial spread of Talon 20 P™ cereal baits, with follow-up hand laying of Talon 50 WB™	Aerial spread with fire fighting bucket. Non-target and other environmental effects monitoring. Eradication successful.	Towns et al. (1994); Towns (1999)
Cuvier	194	1993	Kiore	Aerial spread of Talon 20 P™ cereal baits	Aerial spread using bait spreader and navigational guidance. Eradication successful.	Towns et al. (1995)

Subsequent campaigns in the Mercury Islands therefore aimed to identify suitable baits, bait densities, and accurate bait spreading systems that could be used from helicopters.

Stanley Island

The first successful trial of helicopters to spread baits containing rodenticide was on the Mokohinau Islands in 1990 (Table 3). Like the Mokohinau project, the third Mercury Island project in 1991 was designed to use modified "monsoon" fire fighting buckets slung beneath helicopters to spread cereal-based pellets containing 0.002% brodifacoum (Talon 20 P™). The first of these aerial campaigns was on Stanley Island (100 ha) and targeted kiore and rabbits (*Oryctolagus cuniculus*). Unlike any previous islands, Stanley Island had a residual population of tuatara, estimated as <20 individuals and threatened by predation from kiore and forest modification by rabbits. There was also a population of saddlebacks (*Philesturnus carunculatus*), which might be attracted to the baits. Acceptance trials were conducted to test the attractiveness of baits to the saddlebacks, and there were also population studies to test for any changes in the overall abundance of saddlebacks. As a precaution, most of the tuatara were also captured and removed into captivity before the operation. In September 1991, the baits were spread by a helicopter equipped with a fire fighting monsoon bucket at an average rate of 17 kg/ha, an amount determined as sufficient to remove both kiore and rabbits (Towns et al. 1993).

This campaign was successful, for the first time removing kiore and rabbits from a New Zealand island in a single operation. However, two problems were identified during the campaign. First, baits spread by monsoon buckets tended to be concentrated along the flight path of the helicopter. This meant that follow-up spread of Talon 50 WB™ baits by hand was required to fill any possible gaps. Second, at least six native birds, five saddlebacks and one morepork (*Ninox novaeseelandiae*), were found dead after the operation. The saddlebacks most likely ingested baits directly, whereas the morepork probably succumbed through secondary poisoning by feeding on animals that had eaten baits. The saddleback deaths were not sufficient to produce a measurable increase in the annual overall mortality of the species on Stanley Island (Towns et al. 1993).

Red Mercury Island

The fourth and most complicated campaign targeted kiore on Red Mercury Island (225 ha). As on Stanley

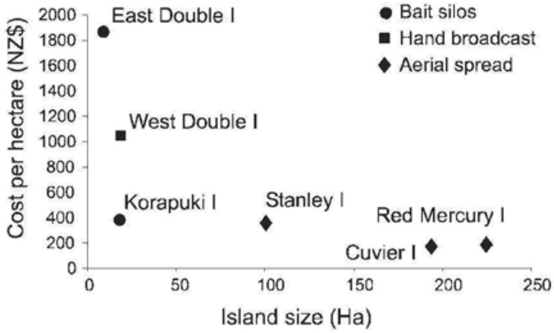

Fig. 3 Comparing relative total costs of ground baiting and aerial campaigns in the Mercury Islands with island size.

Island saddlebacks were present, and a relict population of tuatara was identified and removed to captivity. However, more importantly, a population of the endangered little spotted kiwi (*Apteryx owenii*) had been introduced to the island in 1983 (Colbourne & Robertson 1997). Transmitters were therefore fitted to nine kiwi, which were regularly checked throughout the period baits were present. A veterinary surgeon was also present in case injured birds were found, in which event they could be treated with the antidote to brodifacoum, Vitamin K_1 (Robertson et al. 1993).

In September 1992, Talon 20 P™ baits were spread by a helicopter with a monsoon bucket at an average rate of 15 kg/ha. Samples of water, soil, and invertebrates were obtained immediately after the baits were spread in order to determine the behaviour of brodifacoum in the environment. Again follow-up ground operations were required to ensure complete coverage of the island. Only one dead saddleback was found, and no kiwi showed any adverse effects. Comparisons of forest bird encounter rates and kiwi call frequencies recorded before and after the operation showed no significant differences except for increased encounter frequencies of saddlebacks after the kiore were removed (Robertson et al. 1993; H. Robertson pers. comm. 2002). The soil, water, and invertebrate samples revealed no traces of brodifacoum except in one sample of slugs obtained 2 days after the baits were laid (Morgan et al. 1996). Of more concern, samples obtained from blackbirds 8 months after the operation showed residues of brodifacoum in the liver (Towns et al. 1994). This indicated that non-toxic doses of brodifacoum were metabolised very slowly from the tissues of birds, as in mammals (Eason & Wickstrom 2001).

Cuvier Island

The final campaign in the series targeted kiore on Cuvier Island (194 ha) in September 1993. No species at risk additional to those in the Mercury Islands were identified on Cuvier Island. Like the previous two islands, Cuvier Island was inhabited by saddlebacks and a small population of tuatara estimated at <10 individuals. Aside from removal of tuatara, no special precautions for terrestrial vertebrates were undertaken. The Cuvier project advanced the technology through more consistent bait allowing distribution by helicopter using a mechanical spreader bucket and navigational guidance. These tools were beginning to be used in poison baiting operations targeting possums (*Trichosurus vulpecula*) on the mainland, and they were vital for the even distribution of baits, especially in steep areas. There were no observed losses of birds as a result of the aerial spread of baits, and the bait spreader and baits both performed as required. Consequently, it was more cost-effective than previous campaigns (Fig. 3).

The Cuvier Island campaign was the first to test the full range of techniques now used on large and topographically difficult islands, including the use of a Global Positioning System (GPS). These satellite navigation systems guide helicopter pilots along straight flight paths and map the flight path taken. Due to a malfunction, GPS was ineffective on Cuvier Island, but did become more effective in later campaigns (Towns et al. 1995).

Concluding comments on the Mercury Island projects

The Mercury Island eradications removed introduced mammals from 545 ha of island habitat and provided significant direct and indirect benefits to at least 20 species of rare plants, invertebrates, reptiles, and birds (Towns & Stephens 1997). Direct benefits were either anticipated or measured for tuatara (three populations); resident lizards (at least four species); rare lizards translocated within the islands (three species); and an endangered invertebrate (a flightless weta, now established on at least one of the islands). Most importantly, the removal of rabbits and kiore will enable natural recovery of diverse plant/invertebrate/reptile/seabird systems which, in the Mercury Group, had been reduced to a few small islands.

All of the above campaigns were conducted before the Resource Management Act 1991 (RMA) provided a formal avenue for public comment on proposals to eradicate pests from islands. Nonetheless, all campaigns were preceded by considerable consultation with various agencies and the public. The Korapuki Island and Double Island projects were conducted under the stewardship of the Hauraki Gulf Maritime Park, which had its own approval-granting process. The subsequent campaigns (Stanley Island to Cuvier Island) were conducted as a partnership between DOC and ICI Crop Care (now Zeneca) who manufactured the toxins. Included in this was consultation with iwi (local Maori people), the production of a brochure distributed to local businesses and interest groups, and newspaper and television coverage (Towns & Stephens 1997). The campaigns did generate some negative publicity, with claims that DOC needed to place a moratorium on campaigns against kiore to prevent their extinction (Jones 1992) and that DOC has an "ecological fundamentalist attitude" to introduced species (Kidson 1992).

3. Kapiti Island

The Kapiti Island campaign was unusual in several respects. First, the island is large and rugged, reaching an altitude of 520 m and covering almost 2000 ha (Table 3). Second, it was the first campaign to target kiore and Norway rats simultaneously. Third, it has permanent human inhabitants on 14.9 ha of private land at one end of the island. Fourth, the range of potential non-target species was the largest so far encountered and included weka (*Gallirallus australis*), a threatened ground-dwelling rail known to be susceptible to the baits (e.g., Brown 1997). Finally, the campaign was one of the first to be publicly notified through the RMA, which for Kapiti Island is administered by the Wellington Regional Council.

The high diversity of birds on this large island meant that more species of forest birds were likely to be vulnerable to toxic baits than in previous island campaigns. In addition to weka, there were kaka (*Nestor meridionalis*), saddlebacks, brown kiwi (*Apteryx australis*), little spotted kiwi, and North Island robins (*Petroica australis longipes*). Risk assessments indicated that weka and robins were the two species most vulnerable to baits spread by helicopter, so backup populations comprising 243 weka and 66 robins were captured and removed from Kapiti Island for the duration of the campaign. Bait acceptance trials for kiwi, robins, saddlebacks, and weka were also conducted using non-toxic baits surface coated with the biotracers Rhodamine B and Pyranine 120. In addition, bait disintegration and toxicity tests were conducted to assess the possible effects of any bait that dropped into the sea (Empson & Miskelly 1999).

Despite these measures, some local residents, an outdoors club, and an environmental group submitted objections to the proposal to the Wellington Regional Council. The objectors were uncomfortable with the use of brodifacoum because of its persistence, the indiscriminate effects of bait sown from the air, and the likely high mortality of weka. However, subject to the mitigation measures described and a range of other wildlife and marine monitoring proposals, the Wellington Regional Council consented to the campaign (Buchanan et al. 1996).

Unlike previous campaigns, baits were spread twice to ensure complete coverage of the island. The first distribution of baits was in September 1996 at 9 kg/ha, and the second was in October, 25 days later, at 5.1 kg/ha (Empson & Miskelly 1999). Surveys of coastal fish showed no measurable effects of brodifacoum. However, there were some effects on forest birds. Of the birds monitored, there was evidence of declines of kaka, kiwi, robins, morepork, and possibly kokako. As expected, there was a significant reduction in call rates of weka, indicating a population decline as a result of the spread of brodifacoum. The second most affected species appeared to be robins, especially those with territories near tracks, where they were accustomed to being fed by visitors and were therefore likely to eat baits. The remaining losses were estimated from birds carrying transmitters and ranged up to 5% for kiwi and 20% for kaka. However, such estimates are problematic for highly mobile species such as kaka, some of which may have left the island. The losses were attributable to primary poisoning for species such as saddlebacks, robins, and kaka that ate baits, secondary poisoning for birds such as moreporks that ate carcasses of dead rats, and a combination of primary and secondary poisoning for weka (Empson & Miskelly 1999). The financial cost of the campaign was estimated as approximately $500,000 excluding DOC staff time, i.e., at least $254/ha. At least half of this cost was for monitoring the effects of the operation on potential non-target species (R. Empson pers. comm.).

There was no evidence of a food chain effect such as poisoning of insectivorous birds feeding on insects that had ingested bait (R. Empson pers. comm.). Such an effect would have resulted in bird deaths continuing for some time after the bait was laid. There was also no evidence of reduced fecundity of birds such as robins and saddlebacks that might have ingested sub-lethal doses of brodifacoum. On the contrary, nesting success was particularly high for robins directly after the spread of baits, and the number of nests per female over the 2 years after the campaign was the highest ever recorded on Kapiti Island. Similarly, by 1998, the number of pairs of saddlebacks (previously predicted to decline to extinction on the island) had increased by 120%—the first natural increase since translocation to the island began in the 1980s. The endangered hihi (*Notiomystis cincta*) also had significantly higher survival rates after the removal of rats than in the previous 5 years. Furthermore, the surviving weka and those returned to the island bred prolifically, spread throughout (Empson & Miskelly 1999) and achieved pre-1996 encounter rates within 3 years (Miskelly & Robertson 2002).

4. Tuhua/Mayor Island

The final island eradication campaign we discuss is important for three reasons. First, this project targeted two trophic layers of introduced predators: Norway rats and kiore as intermediate predators and cats as top predators. Second, it was conducted in collaboration with local iwi, Te Whanau A Tauwhao ki Tuhua, through their Trust Board. The Board administers the island as the majority shareholder, with the Crown as a minority shareholder. The campaign was conducted after agreement on future management of the island, and completion of a restoration plan and a co-operative conservation management agreement. The iwi removed a population of feral pigs (*Sus scrofa*) before the cat and rat eradication project began (Hunt & Williams 2000). Third, the project was undertaken as a model for Raoul Island (2938 ha) in the Kermadec Islands north-east of mainland New Zealand. At the time, Raoul Island had the same combination of introduced mammals as Tuhua, and was topographically similar, but because of its larger size and remoteness, presented greater logistical challenges than Tuhua.

Tuhua Island is a volcanic caldera with precipitous cliffs rising to over 200 m around the caldera walls and on the coast (Table 3). The base of the caldera also has two lakes joined by wetlands and a tholoid dome of fractured lava across which access is extremely difficult. The restoration plan proposed the removal of cats and rats in order to enable recovery of seabird colonies that had been drastically reduced, and the restoration of other species that had been lost from the island. For example, the removal of cats would enable recovery of resident populations of both fruit pigeons/kereru (*Hemiphaga* *novaeseelandiae*) and kaka. The removal of rats would also make possible reintroduction of birds such as New Zealand robins and whitehead (*Mohoua albicilla*).

Although slightly smaller than Kapiti Island, Tuhua Island had a much smaller fauna of terrestrial birds and therefore fewer species at risk of accidental poisoning. There were no weka, and robins had disappeared. This small fauna reflected the combined effects of predation by cats and rats, the 26 km distance from the mainland that restricted recolonisation, habitat destruction during historic occupation by Maori and failed attempts at farming, and the volcanic history of the island. The latter included a massive eruption about 6340 years ago during which the present caldera was formed (Houghton et al. 1992).

The eradication campaign proposed to use the same methods for aerial spread of baits as had been successfully applied against rats on Kapiti Island. However, the additional question was whether the cats would also succumb as an indirect result of the rat poisoning. This might happen by cats feeding on rats carrying toxic loads of brodifacoum, or by cats becoming more vulnerable to traps or other poison baits due to the loss of rats as an easily accessible supply of terrestrial prey. Unlike the Kapiti Island operation, the Bay of Plenty Regional Council resource consent was non-notified under the RMA. However, consultation with all affected parties raised no public objections to the Tuhua proposal (D. Hunt pers. comm.).

In order to test how the campaign against rats affected resident cats, six cats were live trapped on the island, fitted with transmitters on collars and released. Baits were spread twice, 10 days apart, in September 2000. The first distribution of bait was at 8 kg/ha and the second at 4 kg/ha, with the helicopter flying at right angles to the original flight path on the second spread. The transmitters on cats were monitored throughout the operation. Two transmitters were not functioning by the time the poison baits were laid. Within 10 days of the spread of baits the four remaining cats carrying transmitters had died (D. Williams; A. Jones pers. comms). There has been no sign of cats or rats since the campaign despite some intensive monitoring in 2002 (D. Williams pers. comm.).

The total cost of the campaign was estimated as $146,000 excluding staff time; i.e., a cost of $114/ha (D. Williams; A. Jones pers. comms.). This relatively low cost reflected the application of knowledge gained on Kapiti Island about species at risk plus the relatively depauperate fauna on Tuhua, which required few mitigation measures.

DISCUSSION

Technology employed

Over the last 20 years, there has been a reversal of attitude to the perceived impossibility of removing *long established* rat populations from islands around New Zealand. There is now justified confidence that such populations can be removed using technology that has undergone rigorous testing and proved highly effective. In fact, now that the 2001 eradication attempt on Campbell Island (11 300 ha) has been declared successful by DOC, the upper limit of island size from which rats can be eradicated using current techniques is unknown. On the other hand, the risks of rodents reaching islands presumably remains the same, and there have been so few field trials of detecting and eradicating *newly-established* populations that there are as yet fewer grounds for confidence that new populations are eradicable.

The products used for rat eradications on islands have not changed greatly over the last two decades. At present, the most effective toxins are the second generation anticoagulant rodenticides such as brodifacoum which replaced less potent toxicants when rodent resistance to first generation anticoagulants such as warfarin became problematic for agriculturalists (Eason 1999). No new rodenticides are likely to be developed in the foreseeable future (C. O'Connor & C. Eason pers. comm. in Dilks & Towns 2002).

The products and the methods now used to eradicate rats from islands were mostly developed for pest control in agricultural areas and modified in innovative ways. For example, Talon 50 WB™ is a commercially available product which has been used against rats on islands around New Zealand since at least 1980 (Moors 1985). The cereal pellets Talon 20 P™, used over the last 12 years against rats on islands >50 ha, were originally developed for use against rabbits and have been reformulated as Talon 7–20™ or Pestoff 20 R™ for more effective use on islands (e.g., Empson & Miskelly 1999). Indeed, the use of Talon 20 P™ pellets by helicopters with bait spreaders against rabbits in 1985 on Moutohora (Whale) Island differed little from the method used today against rats. The eradication of Norway rats from Moutohora Island was an unexpected by-product of this campaign against rabbits (Jansen 1993).

The most significant technical advance recently was not in the baits or the means of spreading them, but the availability of satellite navigational guidance systems (GPS). The capacity to precisely identify helicopter flight paths has enabled the elimination of refuge (unbaited) areas in which a few target animals could survive and allowed coordinated approaches to the rapid spreading of baits over very large areas.

These large projects also required meticulous planning and implementation and enlightened project appraisal (Cromarty et al. 2002). The result of these planning and technical improvements has been successful eradication of two species of rats simultaneously from Kapiti Island and two species of rats plus cats from Tuhua Island. Both forms of improvement were essential precursors to the most ambitious campaign yet attempted on Campbell Island, where up to four helicopters were used during the campaign against Norway rats (McClelland & Tyree 2002).

Economic, ethical, and legal requirements

Funding the earlier eradication attempts was not easy (Thomas & Taylor 2002), largely because the long-term implications of what they might achieve were not clear. Also, the technical aspects were seen as research rather than management issues (Towns & Stephens 1997). This attitude has changed with continuing successful eradications. Economically, it is far more cost-effective to remove rats from islands where the risks of reinvasion are low, than it is to control rats (and other predators) on the mainland where reinvasion is inevitable. Furthermore, the long-term benefits to entire island ecosystems following rat removal may be profound, whereas the benefits to mainland systems from predator control are limited to selected species for which the costs of pest control are sustainable. For these reasons, the most spectacular gains from pest removal on the mainland are likely to be within fenced sites such as the Karori Sanctuary (Campbell-Hunt 2002). Nonetheless, building and maintaining an effective predator-proof fence is probably more expensive than keeping pests off islands.

Ethical issues raised by the public have mainly concerned the actual or potential deaths of non-target organisms in the course of campaigns against rats (see also Biological problems below). Most campaigns have resulted in the loss of small numbers of native and introduced birds. The species likely to be vulnerable are now well known as a result of risk analyses (Empson & Miskelly 1999). For example, these analyses predicted a high mortality of weka during the campaign on Kapiti Island, and this certainly raised public objections. During several campaigns, species perceived at the time to be at risk from the baits have been confined or temporarily removed. Populations of tuatara were removed from the Mercury Islands, weka and robins were removed from Kapiti Island, fernbirds (*Bowdleria punctata*) and almost the entire population of kakapo (*Strigops habroptilus*) were removed from Whenua Hou (Codfish) Island, and short-tailed bats were confined in captivity on Whenua Hou (McClelland 2002). Of these, only weka have proved consistently susceptible to rat baits.

There are strict legal constraints on the use of toxicants to eradicate rats. Only two products are licensed for aerial spread against rodents in New Zealand. These are 0.08% compound 1080 (sodium monofluoroacetate) and three formulations of cereal baits carrying 0.002% brodifacoum. Compound 1080 has not been used against rodents on islands since early studies showed that it was not effective against entire rat populations (Moors 1985; McFadden & Towns 1991). This leaves brodifacoum as the only product that fills the practical and legal criteria for effective use in large scale aerial campaigns. Furthermore, the license is only for "Restricted Use", which limits aerial spread to Department of Conservation use on islands that lack livestock. All other rodenticides, including those that are commercially available, are restricted to ground-based operations using bait stations. In addition, aerial campaigns are usually subject to the Resource Management Act (RMA) because they involve the discharge of contaminants. As part of this process, rat eradication campaigns may therefore be advertised for public comment.

Biological problems

Knowledge of the biology of both target and non-target species has been vital to the success of eradication projects on islands. The minimum home range size of the target rat species is particularly important for campaigns using bait stations, because each rat must encounter at least one bait station. It is also useful in aerial operations in order to ensure that gaps left in bait coverage are never large enough to risk a rat not finding fresh (palatable) bait.

The timing of aerial operations, usually winter to early spring, takes into account other biological factors. For kiore this timing coincides with seasonal lows in the natural population dynamics (Moors 1985; Moller & Craig 1987) which is helpful in ensuring enough bait for all rats on the island and has proven successful for bait acceptance to kiore. The success of kiore eradications in other seasons has not been tested, because there is no need to take the risk (Andy Cox pers. comm.). Timing operations for periods of relatively low kiore breeding reduces the risk of young in the nest not eating bait, as does applying bait in a second drop some days after the first to expose emerging survivors (among other more operational reasons). Lower winter temperatures in New Zealand reduce activity for many invertebrate and lizard species, which may contribute to the relatively low occurrence of non-target deaths observed so far.

Minimal biological knowledge has been sufficient to ensure the eradication of many invasive species (Simberloff 2003). On the other hand, prevention of invasion, or reinvasion, or successful early interception of invaders, may require considerable knowledge about invasion behaviour. The invasion biology of rats is virtually unknown in New Zealand. There are good reasons to be concerned about our ability to detect invasions by rats. Despite an earlier successful eradication, Norway rats twice reinvaded Moturemu Island in Kaipara Harbour, and on the second occasion did not touch bait in bait stations left specifically to intercept such arrivals (T. Wilson pers. comm.). In the Seychelles Islands, an invasion of Norway rats was detected in 1995. Although bait was laid, the rats showed extreme neophobia, baits were removed by non-target species and all attempts at stemming the invasion failed (Thorsen et al. 2000).

The biological effects of toxicant use are not always clear. One concern with persistent toxicants is that they will move through the food chain at non-lethal doses to accumulate and cause unexpected mortality of top predators. This was identified as a potential risk to insectivorous species such as fernbirds and short-tailed bats on Whenua Hou Island by McClelland (2002). Brodifacoum is not toxic to insects such as weta (Morgan et al. 1996) since estimates by Lloyd (in McClelland 2002) suggest that the toxin is passed through weta in 12 days. Fernbirds showed surprisingly high susceptibility to bait containing brodifacoum when it was aerially spread, but not when baits were used in open-ended bait stations on the ground (A. Roberts pers. comm.). Since both forms of bait delivery are equally available to insects, it seems likely that the fernbirds were vulnerable to primary poisoning by being attracted to the cereal baits on the ground. In contrast, bats in captivity showed no interest in non-toxic baits, and there were no observable losses of bats from the wild population in the course of the campaign on Whenua Hou (McClelland 2002). Primary poisoning through ingestion of bait, and secondary poisoning of predators or scavengers feeding on dead rats, therefore remain the only demonstrated effects of one-off aerial campaigns against rats.

Results for target species and ecosystems

Broad ecosystem effects of rat removals

Rats have now been removed from 37% of offshore islands >5 ha that they had previously occupied around New Zealand (island data from Atkinson & Taylor 1992). If smaller islands are included, eradication campaigns have been conducted on at least 90 islands (C. R. Veitch pers. comm. in Towns et al. 2001). Of these, at least 22% are wildlife refuges or nature reserves, which are islands with strict limits on access. Given reasonable precautions, it is therefore likely that almost all of these should remain free of rodents in the long term. In total, the successful rat eradication campaigns conducted so far have re-created almost 19 000 ha of pest-free habitat (assuming the success of Campbell Island has not been called prematurely). Furthermore, the outcome of the Raoul Island project has yet to be determined. If successful, it will add another 2900 ha to the total already achieved.

The presence of newly available large pest-free islands has intriguing implications for offshore terrestrial ecosystems. Two processes are likely to induce fundamental changes in these systems, even if there is no action to restore species that have been lost. The first is recolonisation by seabirds, and the second is a shift in plant succession.

Historically, island systems (and many on the mainland) were dominated by huge populations of seabirds (Procellariiformes), especially shearwaters, petrels, and prions (Daugherty et al. 1990; Markwell 1999). For example, in the Snares Islands alone, an estimated 2.75 million pairs of sooty shearwaters occupy a land area of just 328 ha in the summer breeding season (Warham & Wilson 1982). In time, seabirds are likely to recolonise many of the islands from which rats have been removed, or greatly increase in numbers where residual populations have survived. Dense seabird populations modify soil chemistry and structure, and may also affect forest regeneration (Hawke et al. 1999; Mulder & Keall

2001). This process has implications for the density and diversity of invertebrates and reptiles and, on large islands, also for terrestrial birds.

Second, patterns of regeneration on islands after kiore have been removed, and comparisons of seed and seedling viability on islands where kiore are still present (Campbell 1978; Campbell & Atkinson 1999, 2002), indicate that rats have influenced forest composition. On some islands, kiore have apparently been responsible for the local extinction of species such as milktree (*Streblus banksii*) and coastal maire (*Nestegis apetala*). The species most affected by rats often have large fruit and seeds, and are particularly attractive to kereru that distribute the seeds after feeding on the fruit. Campbell & Atkinson (2002) describe an indirect negative interaction between kiore and kereru: progressive declines of large-fruited species due to seed predation by kiore lead to reduced visitation rates by kereru. Fewer visits by kereru further reduce recruitment of large-fruited plants and other forest species. Consequently, once rats are removed, forest structure on some islands may change to form plant communities rarely seen on these islands in historic times. The results of vegetation monitoring on islands where kiore have been removed indicate that such a change is already underway (Campbell & Atkinson 1999).

There are also subtle indirect interactions between kiore and plants that have implications for other species further along the food chain. For example, Towns (2002) described how suppression of the coastal plant karo (*Pittosporum crassifolium*) by kiore (see also Atkinson 1986) appears to have effectively removed the hosts of honeydew scale insects. When present, honeydew produced by the scale insects is highly attractive to geckos and to terrestrial honey eating birds such as tui (*Prosthemadera novaeseelandia*) and bellbirds (*Anthornis melanura*). Infestations of honeydew scale are now spreading on some islands, but on others the scale has disappeared and may be reintroduced to meet island restoration goals.

The benefits of the campaigns at the ecosystem level may take many years to become clear because of the inherently slow rate of recovery of some island species. For example, on Korapuki Island, Towns & Ferreira (2001) could not determine the long-term prospects of the skink (*Cyclodina alani*) 7 years after release. Twelve years of fieldwork were required to demonstrate that *C. whitakeri* was successfully established. Despite regular monitoring for large native weevil species on Hawea Island, flax weevils (*Anagotus fairburni*) were not recorded until 5 years after eradication of Norway rats and it was at least 10 years before two other species were found (B. Thomas pers. comm.).

Benefits for indigenous species

Since 1985, eradications of rats from islands have been undertaken to protect remaining island species under direct threat from the rats present, to reduce or remove the risk of rats spreading within island archipelagos, or for restoring threatened species translocated from nearby islands. For example, kiore have been removed from six islands off northern New Zealand where they threatened populations of tuatara through predation of eggs or juveniles. In a review of the benefits to reptiles from rat eradications around New Zealand, Towns et al. (2001) concluded that 7 species of geckos and 10 species of skinks are likely to increase in abundance as a result of eradications already completed. Furthermore, 1 species of frog, 4 species of geckos, and 8 species of skinks have already been translocated to islands from which mice and rats have been removed (Tocher & Newman 1997; Towns et al. 2001). These include species such as *Cyclodina whitakeri*, *C. alani*, and *C. macgregori* which are confined to tiny fragments of their former range (Towns 1999). An estimated 40% of the New Zealand frog and reptile fauna is largely or totally confined to islands (Daugherty et al. 1994), so the removal of rats, and a capacity to intercept invasions, should have positive outcomes for up to 26 rare species belonging to this fauna alone.

The benefits of rat removals for invertebrates have only recently been explored. For example, two species of large insects were released onto Breaksea Island in 1991, and the large flightless Mahoenui weta (*Deinacrida* sp.) was released on Mahurangi Island in 1993 (Sherley 1998). Tree weta (*Hemideina thoracica*) were successfully established on Korapuki Island in 1997 as part of an ecosystem restoration project (C. Green pers. comm.), and attempts are underway to establish the extremely rare Mercury Island tusked weta (*Motuweta isolata*) on other islands in the Mercury Group from which kiore have been removed (I. Stringer pers. comm.).

The response of some resident bird species following rat removal has also been measured. Increased encounter rates have been recorded for saddlebacks on Red Mercury Island (Robertson et al. 1993), Kapiti Island (Empson & Miskelly 1999), and Tiritiri Matangi Island (Graham & Veitch 2002). Similarly, encounters of red-crowned kakariki (*Cyanoramphus novaezelandiae*) increased after the removal of kiore from Tiritiri Matangi Island (Graham & Veitch 2002) and kiore and Norway rats from Kapiti Island (Miskelly & Robertson 2002). In the Marotere Islands, Pycroft's petrel (*Pterodroma pycrofti*) and little shearwater (*Puffinus assimilis haurakiensis*) both increased their productivity once kiore were removed. For example, on Coppermine Island, the percent breeding success (survival to late fledging) of little shearwaters was less than 10% before removal of kiore, but attained over 80% afterwards (Pierce 2002). Similarly, Imber et al. (in press) found that breeding success of Cook's petrels (*Pterodroma cookii*) at a site where kiore were formerly abundant on Whenua Hou Island significantly increased after kiore were removed.

Recent campaigns against rats have implications for many species, partly because of the large size of the islands involved, but also because of the improved survival prospects for endemic species. For example, the success of the Campbell Island campaign will enable the reintroduction of endemic flightless teal (*Anas nesiotis*) and at least eight species of endangered invertebrates. There are also likely to be natural recolonisations by other subantarctic species such as a recently discovered subspecies of snipe (*Coenocorypha aucklandica*), the pipit (*Anthus novaeseelandiae*), and at least six species of burrowing seabirds (McClelland & Tyree 2002; G. Elliott pers. comm.). If the attempted eradication of cats, Norway rats, and kiore from Raoul Island in the Kermadec Islands in 2002 is successful, it could enable the recolonisation of up to 16 species of marine and terrestrial birds, and remove eight species from the threatened species lists (Anon. 1995).

Costs

The relative costs of various types of campaign are difficult to compare because they cover at least 20 years of changes in currency value, and component costs may be difficult to trace. Nonetheless, even if inflation is ignored, when actual costs (excluding preparation costs) are compared, there has been an order of magnitude decline in financial costs since 1985. For example, Moors (1985) estimated that the Noises Islands campaign against Norway rats cost \$760/ha, and McFadden & Towns (1991) estimated that the Rurima Island campaign against kiore cost \$1,131/ha. Using the same criteria, this compared with \$1,073/ha calculated for the campaign against Norway rats on Hawea Island (Taylor & Thomas 1989). Costs had declined to \$198/ha when the Korapuki Island campaign was completed in 1986.

The costs of aerial spread operations reached \$366/ha in the early phases of the Mercury Islands campaigns, but had declined to \$114/ha by the Tuhua Island campaign, despite it involving cats and two species of rats. With larger islands, there are increasing economies of scale. However, these economies can be offset by high monitoring and mitigation costs on large islands with a wide range of susceptible species, such as those encountered on Kapiti Island.

All factors being equal, the declining cost per hectare is reflected also in declining risks to non-target organisms, because the quantity of bait distributed per hectare has been progressively reduced (Towns & Stephens 1997). For example, the first general broadcast of bait attempted in the Mercury Islands used a rate of 18.5 kg/ha, but baits were successfully applied from the air on Tuhua Island at 12 kg/ha. However, this is complicated by the higher diversity of species on large islands and therefore an increased range of potential non-target effects.

None of the eradication campaigns have included planning time in the costs. With the larger and more complex campaigns the planning component alone may be considerable (Cromarty et al. 2002). There are also compliance costs for campaigns conducted by air. The preparation of a Resource Consent application, and its defence at a hearing can take many weeks and involve legal, planning, and specialist staff from DOC, and the regional and local councils. These compliance costs are not usually a feature of ground-based operations using bait stations, but this approach is not a viable option on many large, topographically difficult islands. For example, a ground-based operation against kiore on Little Barrier/Hauturu Island would require 13 552 bait stations on a 50 × 50 m grid for which 670 km of track would need to be cut through extremely rugged country while destroying at least 27 ha of forest (R. Griffiths pers. comm.). In contrast, the successful Langara Island campaign targeted Norway rats with a 100 × 100 m grid using nearly 4000 bait stations. Although a servicing track was cut around the island, the grid itself was a "… simple flagged route which did not require much cutting of undergrowth …." (Kaiser et al. 1997, p. 19).

Public response and cultural issues

There has been no analysis of public attitudes before and after an eradication campaign against rats on islands. Furthermore, many of the campaigns conducted since 1985 have been to remove rats from nature reserves that are more than 1500 m offshore and to which public access is strictly limited. However, where the campaigns have been publicly notified and stakeholders consulted, the submissions in support of Resource Consent applications have so far out-numbered those against. Other examples of support are the Supporters of Tiritiri Matangi Island, an incorporated society that in 1993 provided its own funds to assist DOC with removing kiore from the island, and the Te Whanau A Tauwhao ki Tuhua Trust Board, which actively supported the Tuhua Island project and has taken responsibility for the ongoing prevention of future rodent introductions.

Permission for the public to visit a selection of islands from which rats have been removed is therefore important in two respects. It enables first-hand experience of the recovery of systems where rats have been present. Secondly, it reinforces the need for vigilance to ensure that an educated public is alert to the problem of reinvasions. Open-sanctuary islands include Matiu and Kapiti near Wellington, Moutohora off Whakatane, and Tiritiri Matangi near Auckland. Pest-free islands act as benchmarks against which the effects of modification or management of mainland ecosystems can be measured. Nonetheless, there is still a need to study carefully the short- and long-term responses of island systems to rat removal, particularly species such as ship rats which are as yet little studied. With the right information, models of species recovery and biotic succession can be applied to other islands and to the mainland. This information can also be made available to interested groups.

Objections to the eradication of rats on cultural grounds have concerned the role of kiore as taonga (treasures) to some iwi (Beston 2002), who see kiore as providing links to their past and to songs, proverbs, and legends (Haami 1992). This debate over the role of kiore has varied in intensity. For example, the removal of kiore from Whenua Hou, Kapiti, and Tuhua Islands was supported by iwi, who in the latter case, were the majority owners of the island. As Dickison (1992) pointed out, the debate really becomes one of priorities since one taonga (kiore) may be detrimentally affecting many other species also regarded as taonga. On the other hand, DOC has also been heavily criticised for not acting decisively against kiore on Little Barrier Island while attempting to resolve the conflict between cultural concerns for kiore and the threats the kiore pose to threatened invertebrates (Gibbs 1999). This illustrates the problem that introduced animals considered pests by some New Zealanders are valued differently by others. Island reserve managers are faced with reconciling such competing human values with likely extinctions of vulnerable native species. Kiore especially can demonstrate cultural and natural heritage values in collision.

Successes and failures

The aerial spread of rodenticides against rats on offshore islands has been remarkably successful. None of the campaigns has yet failed to eradicate rats on the first attempt, although there have been problems with mice. Indeed, a ground-based campaign on Coppermine Island in 1992 designed to test the maximum spacing of bait stations failed to remove kiore (Thomas & Taylor 2002), but a second attempt using aerially spread baits in 1997 was successful (Towns et al. in press). Furthermore, regardless of the eradication methods used, there have been no successful reinvasions of islands from which rats have been removed as long as the islands are well outside the known swimming range of each rat species.

There have been some potential new invasions, however. In August 1988 a female ship rat was caught in a rat trap on Korapuki Island on monitoring trap lines set up following the removal of kiore in 1986 (McFadden & Towns 1991). Ship rats had never been encountered on the island before, and the nearest source, Great Mercury Island, was 2.5 km away. It is therefore most likely that the rat escaped from a boat, possibly during an illegal landing.

The Korapuki Island example is one of least 80 recorded rodent incursions to islands including at least five reinvasions of inshore islands after rats have been removed (A. Roberts pers. comm.). For example, there have been repeated reinvasions of Norway rats onto the Noises Islands, and Norway rats have also been intercepted at least three times both in the water and after landing on Ulva Island in Paterson Inlet, Stewart Island (A. Roberts pers. comm.). All of these reinvasions have been to islands within the swimming range of rats or within a tidal stream that would bring rats from adjacent areas such as from Stewart Island to Ulva Island and from Rakino Island to the Noises. At least some of the invasions of Ulva Island have been from rats hiding on vessels (A. Roberts pers. comm.).

Implications and future needs

So far, all reinvasions of Ulva Island have been intercepted and rats have not established. However, such vigilance is not available everywhere.

The lack of information on invasion behaviour and an absence of tools for effectively intercepting invasions is now the most significant impediment to further advances in island conservation. Much of the New Zealand rodent eradication experience has been directed to long established populations of kiore and to a lesser extent Norway rats. In contrast, the most significant rodent invasion threats from the mainland are mice and ship rats. The small size and strongly commensal behaviour of mice means they have a high *likelihood* of being stowaways in the equipment of island visitors. The arboreal, predatory behaviour of ship rats means that the *consequences* of an invasion would be potentially more serious than other rodent species due to a wider range of native species being vulnerable.

There are two categories of islands awaiting effective protection from rodent invasion. The first group includes islands now free of rodents and where the risk of accidental reinvasion is low, but the cost of eradicating an incursion may be high. The second group includes inshore islands where the risk of reinvasion by natural means is high, but there would be benefits to species and ecosystems if reinvasions could be reliably prevented. For example, large near-shore islands such as Anchor (1525 ha), Long (1878 ha), Secretary (8140 ha), and Resolution (20 860 ha) in the southern fiords of New Zealand, would eventually be available for restoration and protection of species threatened on the mainland if rats and other mobile predators could be intercepted. Similarly, if the risk of reinvasion on the connected inner Hauraki Gulf islands of Rangitoto and Motutapu (3881 ha) could be overcome, a major restoration initiative could completed within easy access of Auckland, New Zealand's largest city (Towns & Ballantine 1993; Miller et al. 1994).

These initiatives require the development of long-life baits, remote sensing devices, and lures and bait stations attractive to rats (Dilks & Towns 2002). They will also need new approaches to community involvement and invasion risk management. The limit of existing eradication technology is yet to be found in terms of island size. However, the associated increased risk of reinvasion, both likelihood and consequences, means that further advances are required to make projects attempting eradication on large near-shore or inhabited islands viable socially and economically.

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