Invasive Rodent Eradication on Islands

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Abstract: *Invasive mammals are the greatest threat to island biodiversity and invasive rodents are likely responsible for the greatest number of extinctions and ecosystem changes. Techniques for eradicating rodents from islands were developed over 2 decades ago. Since that time there has been a significant development and application of this conservation tool. We reviewed the literature on invasive rodent eradications to assess its current state and identify actions to make it more effective. Worldwide, 332 successful rodent eradications have been undertaken; we identified 35 failed eradications and 20 campaigns of unknown result. Invasive rodents have been eradicated from 284 islands (47,628 ha). With the exception of two small islands, rodenticides were used in all eradication campaigns. Brodifacoum was used in 71% of campaigns and 91% of the total area treated. The most frequent rodenticide distribution methods (from most to least) are bait stations, hand broadcasting, and aerial broadcasting. Nevertheless, campaigns using aerial broadcast made up 76% of the total area treated. Mortality of native vertebrates due to nontarget poisoning has been documented, but affected species quickly recover to pre-eradication population levels or higher. A variety of methods have been developed to mitigate nontarget impacts, and applied research can further aid in minimizing impacts. Land managers should routinely remove invasive rodents from islands <100 ha that lack vertebrates susceptible to nontarget poisoning. For larger islands and those that require nontarget mitigation, expert consultation and greater planning effort are needed. With the exception of house mice (*Mus musculus*), island size may no longer be the limiting factor for rodent eradications; rather, social acceptance and funding may be the main challenges. To be successful, large-scale rodent campaigns should be integrated with programs to improve the livelihoods of residents, island biosecurity, and reinvasion response programs.*

Keywords: eradication, invasive species, island conservation, *Mus musculus*, *Rattus rattus*, *Rattus norvegicus*, *Rattus exulans*

Erradicación de Roedores Invasores de Islas

Resumen: *Los mamíferos invasores son la mayor amenaza a la biodiversidad insular, y los roedores invasores son probables responsables de la mayoría de las extinciones y cambios en los ecosistemas. Las técnicas para la erradicación de roedores de las islas fueron desarrolladas hace 2 décadas. Desde entonces ha habido*

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un desarrollo y aplicación significativa de esta herramienta de conservación. Revisamos la literatura sobre erradicaciones de roedores invasores para evaluar su estado actual e identificar acciones para hacerlo más efectivo. Mundialmente, se han efectuado 332 erradicaciones de roedores exitosas, identificamos 35 erradicaciones fracasadas y 20 campañas con resultados desconocidos. Los roedores Invasivos ha sido erradicados de 284 islas (47,628 ha). Con la excepción de dos islas pequeñas, se utilizaron rodenticidas en todas las erradicaciones. Se utilizó Brodifacoum en 71% de las campañas y en 91% de la superficie tratada. Los métodos más frecuentes de distribución de rodenticida (de más a menos) son estaciones de cebo, aplicación manual y aplicación aérea. Sin embargo, las campañas de aplicación aérea abarcaron 76% de la superficie tratada. Se ha documentado la mortalidad de vertebrados nativos debido a envenenamiento accidental, pero las especies afectadas recuperan, o superan, rápidamente los niveles poblacionales previos a la erradicación. Se ha desarrollado una variedad de métodos para mitigar los impactos no deseados, y la investigación aplicada puede ayudar a minimizar los impactos aun más. Los gestores de recursos deben remover rutinariamente a roedores invasores de islas <100 ha que carezcan de vertebrados susceptibles de envenenamiento no deseado. Para islas más extensas y para las que requieren de mitigación de envenenamientos no deseados, se requiere de la consulta de expertos y de mayores esfuerzos de planificación. Con la excepción de Mus musculus*, es posible que el tamaño de la isla ya no sea el factor limitante para la erradicación de roedores, más bien, la aceptación social y el financiamiento pueden ser los retos principales. Para ser exitosas, las campañas a gran escala deben estar integradas por programas para mejorar las condiciones de vida de los residentes, de bioseguridad insular y de respuesta a reinvasiones.*

Palabras Clave: conservación de islas, erradicación, especies invasoras, *Mus musculus*, *Rattus exulans*, *Rattus norvegicus*, *Rattus rattus*

Introduction

Extinctions over the past thousand years have been dominated by insular species, and invasive mammals have caused the majority of these extinctions (Atkinson 1989; Groombridge et al. 1992). Invasive rodents (rats and house mice [*Mus musculus*]) are likely responsible for the greatest number of extinctions and ecosystem changes on islands (Towns et al. 2006). Because they are omnivorous, they can affect plants, invertebrates, reptiles, mammals, and birds (Atkinson 1985; Cuthbert & Hilton 2004; Towns et al. 2006). Invasive rodents occur on over 80% of the world's major islands, and they continue to be introduced onto islands (Atkinson 1985; Pitman et al. 2005).

In response to the negative impacts of invasive rodents on island species and their ecosystems, systematic techniques for eradicating rodents from islands were developed in New Zealand over 2 decades ago (Moors 1985; Taylor & Thomas 1989, 1993). Since then, conservation practitioners have been improving these techniques and leveraging new technologies. As a result, rodents can now be eradicated from larger and biologically complex islands, and eradication has become a powerful tool to prevent extinctions and restore ecosystems (Donlan et al. 2003*b*; Towns & Broome 2003). Unfortunately, many invasive rodent eradications remain unpublished or inaccessible, creating the perception among land managers and conservation biologists that successful rodent eradications are rare events (Simberloff 2001; Donlan et al. 2003*b*). We reviewed invasive rat and house mice eradication campaigns on islands throughout the world. We assessed the approaches, successes, and challenges of these conservation actions to facilitate the conservation of island ecosystems.

Methods

We compiled data from published and gray literature and personal communications on rodent eradications. We judged an eradication campaign a failure or a success based on the outcome reported by the group that conducted the eradication. Because rodents are difficult to detect at low densities (Russell et al. 2005), a widely accepted indicator of eradication success is no detection of rodents after 2 years of intensive monitoring following the eradication effort. Unfortunately, without genetic sampling of rodents on the target island and from potential source populations, it is not possible to distinguish between failure and reinvasion in the first 2–4 years following the eradication effort (Abdelkrim et al. 2007). We did not include secondary eradication efforts of small rodent populations that reinvaded islands following a previous, successful eradication campaign. This is common on islands located close to a mainland source population (Russell & Clout 2005).

All statistical analyses were performed in SPSS, with an α level of 0.05 (SPSS 1999). We used a general linear model to explore relationships of economic costs of eradication campaigns to area, method of baiting, and eradication year. The area covered in an eradication and the cost of the eradication (adjusted to US$2005) were

$\log_{10}$ transformed to meet normality assumptions. We considered the method of baiting as a categorical fixed effect and modeled the rest of the variables as covariates.

History and Impact of Rodent Introductions

The first rodent (e.g., black rat [*Rattus. rattus*]) introductions to islands may have occurred in the Mediterranean between 5500 and 8000 years ago (Vigne 1992). The kiore (*R. exulans*) was introduced to the islands of the Pacific from Indo-Malaysia some 3000 years ago by the seafaring Lapita people (Atkinson 1985). By approximately 950 years ago, kiore occurred on most of the islands in the Pacific, including New Zealand and likely the Hawaiian and Easter islands (Atkinson 1985; Wilmshurst & Higham 2004). Although exploration by Eurasians may have dispersed black rats to some islands, prior to AD 1500, most islands outside the Pacific were likely free of rats (Atkinson 1985). Between the sixteenth and seventeenth centuries, European explorers spread rats to islands throughout the Indian and Atlantic oceans.

Sometime in the early 1700s, Norway rats (*R. norvegicus*) colonized western Europe, displacing black rats, and subsequently became the dominant species in European and eastern North American ports (Atkinson 1985). Consequently, Norway rats became the dominant rodent on ships and thus the most-introduced rat species on islands throughout the seventeenth and eighteenth centuries. Inexplicably, after the 1850s ship records show that black rats became more common than Norway rats. The presence of both Norway and black rats aboard ships meant that many islands in the Atlantic and Indian oceans had both species and that many Pacific islands had three species.

The distribution of black and Norway rats and kiore on islands worldwide has had devastating effects on island biodiversity. They have negatively affected at least 170 taxa of plants and animals on over 40 islands or archipelagoes and have led to at least 50 extinctions (Towns et al. 2006). Significant indirect and synergistic community- and ecosystem-level effects have also been documented, both in terrestrial and marine environs (Navarrete & Castilla 1993; Imber et al. 2000; Towns 2002; Fukami et al. 2006). Towns et al. (2006) review in detail the biodiversity and ecosystem impacts of *Rattus* spp. in insular environments (for further reference, see Atkinson 1985; Burger & Gochfield 1994).

House mice have had a variety of negative impacts on island ecosystems, including some caused by their predation on reptiles, invertebrates, and the nests of terrestrial birds (Copson 1986; Rowe-Rowe et al. 1989; Newman 1994; Cole et al. 2000; Ruscoe & Murphy 2005). In New Zealand they may have caused the extinction of two invertebrate species on Antipodes Island (Marris 2000). The effects of house mice on seabird populations are likely underestimated; for example, on Gough Island, house mice prey on Tristan Albatross (*Diomedea dabbenena*) and have significantly reduced the breeding success of colonies (Cuthbert & Hilton 2004). Indirect impacts, such as hyperpredation, of house mice are also probable. They often serve as alternative prey to invasive predators, which in turn can elevate predation levels on native fauna (Bloomer & Bester 1990; Alterio & Moller 1997; Courchamp et al. 2000).

Recovery of insular species following the eradication of invasive rodents is commonplace. Recoveries of terrestrial invertebrates, lizards, and forest birds after eradication have occurred on New Zealand islands (Towns et al. 2006). Seabird populations have responded positively to rat eradications (Jones et al. 2005; Whitworth et al. 2005; Smith et al. 2006; Towns et al. 2006).

Island Rodent Eradications

The first successful rodent eradication was of Norway rats in 1951 on Rouzic Island, France (3.3 ha; Lorvelec & Pascal 2005). Rouzic and early eradications in New Zealand were unintentional byproducts of rodent control efforts (Towns & Broome 2003; see Supplementary Material). Starting in the 1960s and continuing through the mid 1980s, New Zealand conservationists conducted research on bait station approaches and other systematic rodent eradication techniques that resulted in a number of successful intentional eradications on small islands (Moors 1985; Thomas & Taylor 2002). Building on these successes, Norway rats were eradicated from Breaksea Island (170 ha) in 1987, which demonstrated that rodent eradication on larger islands was possible (Taylor & Thomas 1993). The approach used in the Breaksea campaign centered on dispensing a bait containing a proven rodenticide into the territory of every rat with a method that would minimize nontarget poisoning while actively monitoring the progress of the campaign (Taylor & Thomas 1989). Concurrent with the Breaksea and other New Zealand eradication campaigns, black rats were being eradicated on islands in western Australia, including Bodie Island (170 ha; Morris 2002). These research programs and subsequent successful eradications in New Zealand and Australia have spurred hundreds of rodent eradication programs worldwide over the past two decades.

Rodents have been eradicated from at least 284 islands worldwide, totaling over 47,628 ha (Fig. 1; Supplementary Material). Of the known eradication attempts where the result has been documented, 90% have been successful. We documented 387 invasive rodent eradication campaigns, of which 332 were reported successful, 35 failed, and 20 were of unknown outcome. Because successes are more likely to be reported than failures, the success rate may be inflated. On some islands there were

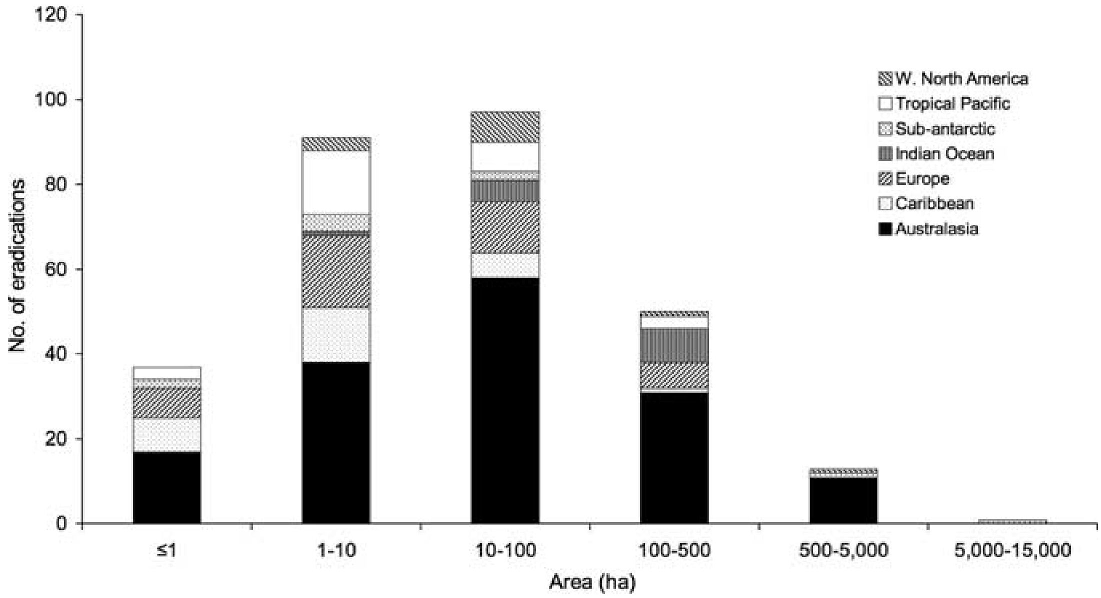

Figure 1. Location and size of islands where successful eradications of invasive rodents have been carried out.

multiple eradication campaigns that either targeted different rodent species or the same species that reinvaded and reestablished after a successful eradication. Most rodent eradications took place in Australasia (155), especially New Zealand (Fig. 1). The majority of rodent eradications have been on islands of <100 ha (78%; Fig. 1). Rats have been removed from 14 islands of over 500 ha. Black rats have been eradicated from most islands worldwide, followed by Norway rats, kiore, and house mice (Table 1). Neither black rats nor house mice have been eradicated from an island larger than 1,000 ha, whereas Norway rats have been removed from Campbell Island, New Zealand, the largest island on which rodent eradication has been successful to date (11,300 ha; Table 1).

Rodenticides

A rodenticide contained in a cereal-based bait was used in all but two small (<14 ha) eradication campaigns (Fig. 2, Supplementary Material). Rodenticide choice and bait depend on a number of factors. The ideal bait is one that is (1) palatable and lethal to the target species after a single feeding event, (2) persistent in the environment long enough for the target species to be exposed but short enough to minimize nontarget species exposure, (3) has a low probability of engendering bait shyness in target organisms, and (4) is nontoxic or unpalatable to nontarget species. Anticoagulant rodenticides are the most widely used toxin for control of small mammals worldwide (Eason et al. 2002; Hoare & Hare 2006). They act by inhibiting the synthesis of vitamin-K-dependent clotting factors in the liver, which ultimately results in death by internal hemorrhaging, typically within 3–10 days (Hadler & Sahdbolt 1975). Anticoagulants are classified as first- or second-generation according to their potency and when they were developed (Eason et al. 2002). Brodifacoum (3-[3-(4′–bromobiphenyl-4-yl)-1,2,3,4-tetrahydro-1-naphthy]-4 hydroxycoumarin), and other second-generation anticoagulants are more potent with lower LD_{50} (median lethal dose) values; a single feeding of a few grams of bait can be lethal (Eason et al. 2002). First-generation anticoagulants are less toxic and require multiple feedings over several days to illicit a toxic effect. The higher toxicity and persistence of second-generation anticoagulants is an advantage in eradicating target species; however, that same toxicity and persistence can be a concern when nontarget species are at risk (Hoare & Hare 2006).

Table 1. Invasive rodent eradications: successes, failures, and the largest successful campaign to date.

Species	*Successful eradications*	*Failures (%)*	*Largest island (ha)**	*Method(s)*	*Reference*
Rattus rattus	159	15 (8)	Hermite, AUS (1,022)	aerial broadcast brodifacoum	Burbidge 2004
Rattus norvegicus	104	5 (5)	Campbell, NZL (11,300)	aerial broadcast brodifacoum	McClelland & Tyree 2002
Rattus exulans	55	6 (10)	Hauturu (Little Barrier), NZL (3,083)	aerial broadcast brodifacoum	R. Griffiths, personal communication
Mus musculus	30	7 (19)	Enderby, NZL (710)	aerial broadcast brodifacoum	Torr 2002

**Abbreviations: AUS, Australia; NZL, New Zealand.*

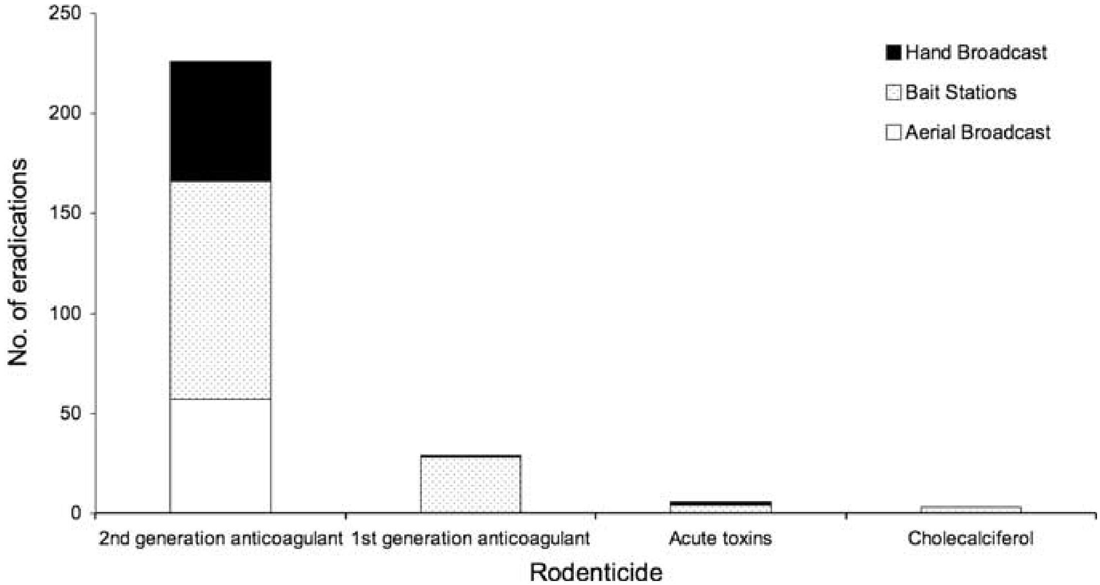

*Figure 2. Number of successful invasive rodent eradication campaigns by type of rodenticide and method of bait delivery (*n *= 264 islands).*

First-generation anticoagulants (i.e., chlorophacinone, diphacinone, pindone, and warfarin) were used in 29 eradication campaigns as the primary rodenticide, and second-generation anticoagulants were used in 226 campaigns (i.e., brodifacoum, bromadiolone, difenacoum, and flocoumafen; Fig. 2). Acute toxins (i.e., 1080 and strychnine) and cholecalciferol were used in six and three campaigns, respectively, as the primary rodenticide (Fig. 2). These nine islands were small (<22 ha), and all but three were supplemented with second-generation anticoagulants (Supplementary Material). Trapping was used to supplement poisoning efforts on 40 islands. Although a number of campaigns used multiple toxins ($n = 33$), this is likely unnecessary unless there are issues with inheritable resistance or high LD_{50} variation (Quy et al. 1995). In 71% of successful campaigns and on 91% of the total area of islands eradicated of invasive rodents, brodifacoum had been applied, making it the most widely used rodenticide.

Bait Delivery

In general the best method for the delivery of a rodenticide depends on island topography, habitat, economics, and vulnerability of nontarget species. The delivery methods currently available are bait stations and hand and aerial broadcasting.

Bait stations, containing rodenticide and distributed on a grid, are the oldest technique used in planned rodent eradication campaigns. Grid sizes vary from 25 to 100 m, depending on the home range of the rodent targeted. Bait stations are monitored and kept filled with rodenticide bait for 1–2 years (Thomas & Taylor 2002). The bait stations have a number of advantages: they (1) minimize primary exposure to potential nontarget species (e.g., granivorous birds), (2) reduce the amount of toxin delivered to the environment, (3) act as a self-monitoring program with respect to rodenticide uptake, and (4) can be used in combination with nontoxic baits or tracking boards as detection devices after the last rodent supposedly has been killed, which enables managers to kill survivors or immigrants (Thomas & Taylor 2002). Nevertheless, the approach is labor intensive and thus potentially expensive at large scales (e.g., trails might need to be cut), and regular visits to bait stations can result in disturbance of sensitive species, such as breeding seabirds. Furthermore, a bait station approach is impossible with islands that have steep cliffs.

The effectiveness of hand broadcasting was first compared with the bait station technique in 1989 during the eradication of *R. exulans* from Double Island, New Zealand (27 ha). Hand broadcasting proved more cost-effective and led to the development of aerial broadcasting with helicopters (McFadden 1992). Eradication campaigns began using helicopters for aerial broadcast of rodenticides in the early 1990s. Following this, aerial broadcasting was used on larger islands, and hand broadcasting was used on smaller islands (Fig. 3).

Aerial broadcast by helicopter is becoming the most common method of rodenticide delivery (Towns & Broome 2003). Rodenticides can be broadcast on islands with steep and inaccessible cliffs, and aerial or hand broadcasting is often more cost-effective than bait stations. The advent and adoption of geographic positioning systems and geographic information systems technologies have increased the effectiveness and efficiency of

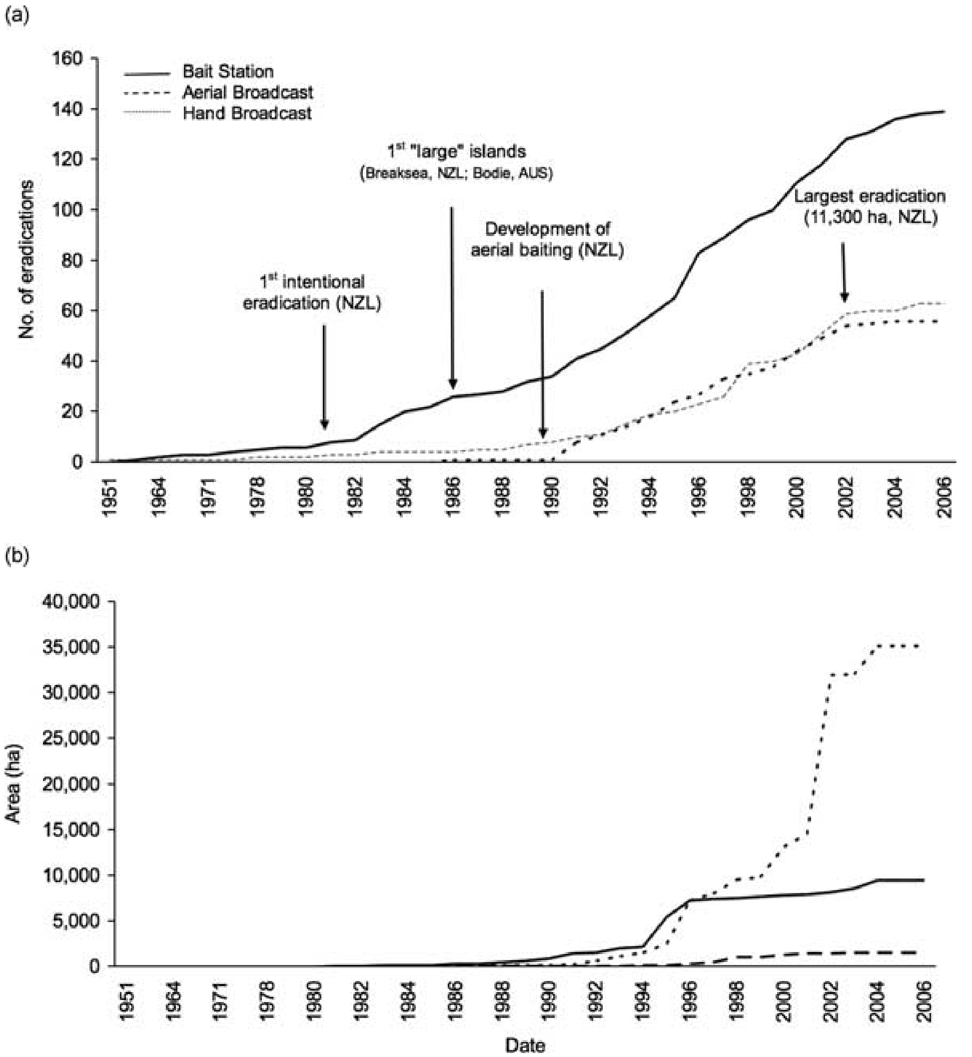

*Figure 3. (a) Number of campaigns to eradicate invasive rodents and (b) total area of islands from which rodents have been eradicated with three different methods of bait delivery (percentage of successful campaigns and area of eradication, respectively: bait stations, 54%, 20%; aerial broadcast, 22%, 76%; hand broadcast, 24%, 4% [*n *= 269 islands; large islands >150 ha]).*

invasive mammal eradications, including aerial-based rodent eradications (Lavoie et al. 2007). Because broadcasting entails a single or double bait-application event, usually 10–14 days apart, and bait station campaigns last up to 2 years, broadcasting significantly shortens the eradication campaign (and thus the period of risk to nontarget species). Broadcasting bait in a single application also avoids the issue of cohort selection and interspecific dominance (i.e., where more than one species of target rodent is present), which is likely to arise with the bait stations. In some cases multiple delivery methods may work best. For example, on a small island with steep, accessible cliffs, combining bait stations and hand broadcasting may be the most cost-effective and safest approach. In the end the decision of whether to use bait stations or broadcasting should be one based on experience, consultation, and the constraints of the system (e.g., topography, nontarget species, economics).

The timing of bait delivery also plays a role in eradication planning. Although empirical evidence is scarce (Sweetapple et al. 2002), timing the bait delivery to when rodents are in decline or during lows in their annual food-dependent population cycle may improve probability of eradication by increasing competition for bait. Timing of bait delivery may also minimize possible nontarget impacts caused by the rodenticide application (e.g., migratory birds) or by the physical nature of the campaign (e.g., disturbing nesting seabirds). With a bait station approach, timing of bait delivery is less of a risk in terms of probability of failure as long as bait remains available throughout food-dependent population declines and long enough for all rodents to gain access to the stations.

The most frequent way of distributing rodenticides was bait stations ($n = 144$) followed by hand broadcasting ($n = 64$) and then aerial broadcasting ($n = 57$; Fig. 2). Nevertheless, aerial broadcast was responsible for 76% of the total area treated. Although bait stations are the most common technique, they have been used on islands of medium size, whereas aerial broadcast has been used on large islands (mean island area of single method campaigns [SE, n], traps = 7.4 ha [$n = 2$], hand broadcast = 20.8 ha [7.3, 37], bait station = 66.2 ha [28.3, 114], aerial broadcast = 876.4 ha [319.5, 38]). Sixty-seven campaigns used multiple methods (Supplementary Material). Details of hand or aerial broadcast techniques were reported for only 16 campaigns. Of those, rodenticide was delivered in 1–3 applications (mean = 1.56, SE = 0.18, $n = 16$), with a mean application rate of 17.6 kg/ha (median = 15.0, range: 10–35, SE = 2.0, $n = 16$).

Nontarget Species

The risk to nontarget species during an eradication campaign is a function of species present on the island and their behavior; toxicological properties, composition, and delivery method of bait; the susceptibility of those species to the toxin; and the probability of exposure to the toxin either directly by bait consumption or indirectly by feeding on animals that have consumed baits. Although nontarget impacts on vertebrates by primary and secondary poisoning have been documented for eradication campaigns, the affected species have recovered quickly to pre-eradication population levels or higher (Empson & Miskelly 1999; Howald et al. 1999; Davidson & Armstrong 2002; Howald et al. 2005). Invertebrates are less susceptible to anticoagulant toxins. Toxic effects have been elicited in the laboratory, but impacts have not been observed in natural settings, and population-level impacts are unlikely (Booth et al. 2001). Nonetheless, decisions on the choice and delivery of rodenticides, as well as mitigation actions, should be made strategically to minimize any lethal or sublethal impacts on nontarget wildlife (Eason et al. 2002).

Mitigation techniques for vertebrates include live capturing and temporary holding, which has been done successfully for raptors, landbirds, reptiles, and rodents; the use of bait stations in conjunction with an aerial broadcast to provide a selected area as a refuge where rodenticide is not widely available to nontarget species; and the modification of bait stations to limit access to baits by certain species (Towns et al. 1993; Towns et al. 1994; Empson & Miskelly 1999; Pergams et al. 2000; Moro 2001; Merton et al. 2002; Morris 2002; Howald et al. 2005). The need to reduce short-term nontarget impacts should be balanced with maximizing the probability of eradication and economic realities (e.g., the lack of funds for a second campaign if an attempt with an alternative toxin fails). Within a holistic framework, a variety of methods are available to mitigate possible nontarget impacts.

Eradication Failures

Eradication failure rates range from 5% for Norway rats to 19% for house mice and depend on the species of rodent, but are only marginally significant ($\chi = 7.32$, df = 3, $p = 0.06$, $n = 381$, Table 1). These differences in failure rates highlight the need for more research on house mice eradications, which lag behind in terms of number of successes and largest island successfully targeted. The cause of these failures is unclear, but they may be related to inadequate bait density in a broadcast application. The home range of house mice is smaller than that of *Rattus*. In general a smaller home range decreases the probability of a target species being exposed to bait that is broadcast at a fixed density over a large area. Additionally, differences in foraging behavior between house mice and *Rattus* could play a role in the dynamics of bait consumption (Macdonald & Fenn 1994).

Managers reported or speculated on causes that contributed to campaign failure in 18 cases (51%). These possible causes included technical issues (e.g., inadequate or insufficient bait deployment), failure to follow established protocols, observed or suspected nontarget poisoning issues that halted the campaign, lack of funding and public support, and bait competition by terrestrial invertebrates.

Economics

We obtained economic costs for only 12% ($n = 47$) of eradication campaigns. Total costs varied widely (US$123–$1,615,2000, adjusted to 2005 prices), as did cost per hectare ($3–$20,000). Not surprisingly, island area and cost of eradication campaign were correlated in log-log space ($F_{1,45} = 76.1$, $p < 0.001$, R^2 [adjusted] = 0.62). A full model, including method of bait delivery (aerial broadcast, hand broadcast, and bait station) and eradication date, did not result in additional significant relationships (method: $F_{3,41} = 0.205$, $p = 0.552$; date: $F_{1,41} = 1.81$, $p = 0.186$; log[area]: $F_{1,41} = 59.9$, $p < 0.001$, R^2 [adjusted] = 0.62). With raw data, area and cost were significantly correlated (Spearman rank correlation: $r_s = 0.746$, $p < 0.01$, $n = 47$).

Martins et al. (2006) claim that eradication costs can be estimated based on limited information, such as area, species, date of eradication, and remoteness. This claim, based on a limited sample size ($n = 41$ for all invasive mammals), is disconnected from the many realities of the costs of eradications (Donlan & Wilcox 2007). In addition to area, remoteness, and target species, the costs of eradication campaigns can differ drastically depending on a suite of fixed and nonfixed costs, including mitigation for potential nontarget species, techniques used, local capacity and bureaucracy, and the environmental compliance required (Donlan & Wilcox 2007).

Challenges and Recommendations

The eradication of invasive rodents from islands, like other invasive mammals, is no longer a rare event (Nogales et al. 2004; Campbell & Donlan 2005). Rather, it is a powerful tool to prevent further extinctions and to restore ecosystems (Hutton et al. 2007), often with high conservation returns from a cost-benefit perspective. For example, 201 seabird colonies and 88 endemic terrestrial vertebrates have been protected on the islands of western Mexico through invasive mammal eradications at a cost of US$21,000 and US$49,000 per colony or taxon, respectively (Aguirre-Muñoz et al. 2007). In addition to negative biodiversity impacts, rodents also affect people living on islands through their degradation of food crops and their role as disease vectors (Hood et al. 1971; Chanteau et al. 1998). Thus, rodent eradications can also result in social and economic benefits. For example, the residents of Lord Howe Island, Australia, have proposed eradicating rodents to reduce the economic impacts on agriculture (A.S., personal observation).

With proper preparation (Cromarty et al. 2002), land managers should routinely remove invasive rodents from islands <100 ha that lack native vertebrates susceptible to nontarget poisoning. For larger islands and islands with potential nontarget poisoning issues, land managers should seek expert consultation from experienced practitioners. Additional planning focused on the type, timing, and delivery method of rodenticide and on mitigating potential nontarget impacts is needed. Whenever possible the negative effects of the eradication process and the benefits of the island being rodent-free should be documented in a monitoring program. Furthermore, invasive mammal eradications offer unique opportunities for large-scale ecological experiments (Donlan et al. 2002; Croll et al. 2005). At the least, eradication campaigns should report success or failure and economic costs. A public database is available for reporting on eradication campaigns (http://www.issg.org). Development of global and regional prioritization models to elucidate where to invest in rodents and other invasive species eradications to maximize biodiversity gained on the investment should be a high priority.

Eradication campaigns can face opposition from individuals or organizations concerned about animal rights or toxicity issues (Towns et al. 2006). For example, on Anacapa Island (California, U.S.A.), an animal rights organization filed an unsuccessful legal injunction to halt a rat eradication (Howald et al. 2005). As larger islands, many of them with human populations, are targeted for eradication, incorporating human dimensions into eradication planning will be increasingly important (Genovesi 2007).

Conservationists must also work with regulatory agencies on a nuanced set of laws that protect people and wildlife in continental settings, but maintain the use of a suite of useful rodenticides. For example, in the United States and United Kingdom there are serious concerns and issues with nontarget rodenticide poisoning of birds and mammals due to the widespread availability, chronic use, and misuse of brodifacoum. These concerns have resulted in calls for wholesale restrictions (Stone et al. 1999; Fournier-Chambrillon et al. 2004; Brakes & Smith 2005). This level of use of brodifacoum is vastly different than a one-time, restricted rodenticide application on an island for conservation purposes. Although increased regulation on certain rodenticides may be justified, brodifacoum is currently the most important rodenticide for invasive rodent eradications on islands and should remain available to practitioners to use responsibly.

Applied research can help eradication campaigns minimize potential nontarget impacts of native wildlife while maximizing probability of eradication success. Collaborative research is underway to explore the possibilities of a toxin specific to *Rattus*. Invasive and native rodents are equally susceptible to available rodenticides. To date, invasive rodents have been eradicated from only two islands with an endemic terrestrial mammal (Morris 1989; Howald et al. 2005). Both *Rattus*- and *Mus*-specific toxins would have substantial global conservation implications, particularly on islands with endemic terrestrial rodents and endemic birds susceptible to nontarget poisoning. Research is also needed to test the field efficacy of alternative toxins and lower application rates that could minimize potential nontarget impacts and reduce the amount of toxin released into the environment. Small islands are the ideal testing grounds for this research. Encouragingly, diphacinone and cholecalciferol, which are less toxic to birds, have been used successfully in four rodent campaigns on small islands (Donlan et al. 2003*a*; Smith et al. 2006; Witmer et al. 2007). Finally, more research is needed on house mice eradications and invasive rodent eradications in tropical environments, where bait competition with terrestrial invertebrates (e.g., land crabs) presents unique challenges (Rodríguez et al. 2006).

A significant risk that has yet to be addressed adequately in aerial baiting strategies is the inability to detect, locate, and address potential survivors of eradication campaigns. Current practice is to plan carefully and hope the campaign kills 100% of the rodents. Failure is assessed by waiting until such time as survivors could have produced enough offspring for the population to become easily detectable. This approach assumes that it would cost more to detect and locate potential survivors than to repeat the entire eradication campaign. Tactical research is needed to shift this cost-benefit differential toward timely posteradication detection (e.g., highly trained dogs) and response. Such response is required for rabbit eradications, where 100% of the population is never killed during initial aerial baiting campaigns and for other species for which eradication is achieved via repeated harvesting (Parkes 2006). Additionally, managers need decision tools to determine when it is cost-effective to switch management schemes from active eradication to monitoring (Cacho et al. 2006; Regan et al. 2006).

Conservation practitioners are now eradicating invasive rodents from larger and more biologically complex islands. As larger islands are targeted, a number of factors will become increasingly important: rodenticide choice and the development of new rodenticides, minimizing nontarget and secondary poisoning events, and leveraging technology to allow techniques to scale from smaller to larger islands. With the exception of house mice, island size may no longer be the most limiting factor with respect to the ability to remove invasive rodents; rather, nontarget impacts, sociology, and funding will be the main challenges. Because of the presence of humans on many larger islands, future rodent eradications will require integrated environmental education, island biosecurity, and reinvasion response programs. Failure to maintain adequate island biosecurity regimes can lead to reinvasions, which can be difficult to detect and to mount a response against. Increasing the efficiency of eradications, including bioeconomic analyses, will also be important because absolute costs, probability of failure, and conservation benefits will all increase with the size of the island (e.g., Choquenot & Parkes 2001; Choquenot 2006). A large percentage of the world's threatened biodiversity resides on islands where invasive species are the major threat. Because it is possible to safely eradicate invasive rodents from islands and because there is a high return in biodiversity gains following eradication, invasive rodents should be routinely removed from islands.

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Supplementary Material

Characteristics of islands where invasive rodent eradication failed or was successful or of unknown outcome (Appendix S1) are available as part of the on-line article from http://www.blackwell-synergy.com/. The author is responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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