Control of invasive rats on islands and priorities for future action

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Abstract: *Invasive rats are one of the world's most successful animal groups that cause native species extinctions and ecosystem change, particularly on islands. On large islands, rat eradication is often impossible and population control, defined as the local limitation of rat abundance, is now routinely performed on many of the world's islands as an alternative management tool. However, a synthesis of the motivations, techniques, costs, and outcomes of such rat-control projects is lacking. We reviewed the literature, searched relevant websites, and conducted a survey via a questionnaire to synthesize the available information on rat-control projects in island natural areas worldwide to improve rat management and native species conservation. Data were collected from 136 projects conducted over the last 40 years; most were located in Australasia (46%) and the tropical Pacific (25%) in forest ecosystems (65%) and coastal strands (22%). Most of the projects targeted* Rattus rattus *and most (82%) were aimed at protecting birds and endangered ecosystems. Poisoning (35%) and a combination of trapping and poisoning (42%) were the most common methods. Poisoning allows for treatment of larger areas, and poison projects generally last longer than trapping projects. Second-generation anticoagulants (mainly brodifacoum and bromadiolone) were used most often. The median annual cost for rat-control projects was US$17,262 or US$227/ha. Median project duration was 4 years. For 58% of the projects, rat population reduction was reported, and 51% of projects showed evidence of positive effects on biodiversity. Our data were from few countries, revealing the need to expand rat-control distribution especially in some biodiversity hotspots. Improvement in control methods is needed as is regular monitoring to assess short- and long-term effectiveness of rat-control.*

Keywords: island conservation, poison, *Rattus exulans*, *Rattus norvegicus*, *Rattus rattus*, rodent pest control, traps

Control de Ratas Invasoras en Islas y las Prioridades para la Acción a Futuro

Resumen: *Las ratas invasoras son uno de los grupos animales más exitosos a nivel mundial que ocasionan la extinción de especies nativas y cambios en los ecosistemas, particularmente en las islas. En las islas grandes, la erradicación de las ratas es generalmente imposible y el control de población, definido como la limitación local de la abundancia de ratas, hoy en día se practica rutinariamente en muchas de las islas del mundo como una herramienta alternativa de manejo. Sin embargo, se carece de una síntesis de motivaciones, técnicas, costos y resultados de dichos proyectos de control de ratas. Revisamos la literatura, buscamos sitios web relevantes, y realizamos una encuesta por medio de un cuestionario para sintetizar la información disponible sobre los proyectos de control de ratas en las áreas naturales isleñas en todo el mundo para así mejorar el manejo de ratas y la conservación de especies nativas. Se recolectaron datos de 136 proyectos que se realizaron en los últimos 40 años; la mayoría se ubicaron en Australasia (46 %) y el Pacífico tropical (25 %) en ecosistemas boscosos (65 %) y franjas costeras (22 %). La mayoría de los proyectos estaban enfocados en* Rattus rattus, *y la mayoría (82 %) estaban centrados en la protección de aves y ecosistemas en peligro de extinción. Los métodos más comunes fueron el envenenamiento (35 %) y una combinación de trampas y veneno (42 %). El envenenamiento permite tratar con áreas más grandes y generalmente dura más tiempo que el trampeo. Los anti-coagulantes de segunda generación (principalmente el brodifacoum y la briomadiolona) fueron los* *más usados. El costo medio anual de los proyectos de control de ratas fue de US$17,262 o de US$227/ha. La duración media de los proyectos fue de cuatro años. Para el 58 % de los proyectos, se reportó una reducción en la población de ratas, y el 51 % de los proyectos mostró evidencias de un efecto positivo sobre la biodiversidad. Nuestros datos provienen de pocos países, lo que revela la necesidad de expandir la distribución del control de ratas, especialmente en algunos puntos calientes de biodiversidad. Se necesita mejorar los métodos del control, así como un monitoreo regular para evaluar la efectividad del control de ratas a corto y largo plazo.*

Palabras Clave: conservación en islas, control de plagas de roedores, trampas, veneno, *Rattus exulans*, *Rattus norvegicus*, *Rattus rattus*, trampas, veneno

Introduction

Three species of rats have been introduced by humans to over 80% of the planet's island groups (Atkinson 1985), and they are now a major group of invasive species that cause native species' extinctions and ecosystem change (Towns et al. 2006). *Rattus rattus* (black rat or ship rat), *Rattus norvegicus* (Norway rat or brown rat), and *Rattus exulans* (Pacific rat, Polynesian rat, or kiore) are the most damaging rat species, particularly for insular ecosystems (Towns et al. 2006). In a recent review of global impacts of rodent pests, *R. rattus* was ranked the main rodent pest species, *R. norvegicus* was second, and *R. exulans* was fourth (Capizzi et al. 2014). These 3 omnivorous rats are opportunistic foragers that prey on and affect a broad range of plants (Pender et al. 2013; Shiels et al. 2014), birds (VanderWerf 2001; Jones et al. 2008), reptiles (Towns 1996), invertebrates (St Clair 2011; Ruscoe et al. 2012), and overall ecosystem functioning (Fukami et al. 2006; Towns et al. 2009).

The management strategy needed to slow biodiversity loss on an island due to rats depends on the time since introduction. Preventing new introductions or the prompt removal of newly introduced species is the most effective and economical strategy (Simberloff et al. 2013). However, rats have already invaded and established on many continents and islands, sometimes thousands of years ago (Ruffino et al. 2009; Capizzi et al. 2014). Thus, conservation professionals are challenged with protecting or restoring native communities and ecosystems (Howald et al. 2007; Keitt et al. 2015). Eradication of invasive rat populations is one of the most effective conservation tools on small or medium-sized islands (Howald et al. 2007). To date, 447 successful rat eradications on 416 islands have been reported (DIISE Partners 2016), and most have had positive effects on native biodiversity (Veitch & Clout 2002; Towns et al. 2013). Many factors affect whether an island-wide rat eradication is possible or can be successful, including the presence of human residents and their cooperation throughout the project, island size and latitude, and rat-removal methodology (Howald et al. 2007; Holmes et al. 2015).

Where rat eradication from islands is not possible, rat population control is largely used as an alternative (Bomford & O'Brien 1995; Armstrong et al. 2014). In this context, rat-control is best defined as the local limitation of rat abundance. Unlike eradication projects, for which best practices for successful operations are well studied (Howald et al. 2007; Keitt et al. 2015), rat-control projects in island natural areas (defined as noncrop lands with minimal human disturbance) are less recognized, and the effects of control on rat populations and biodiversity remain poorly studied (Clayton & Cowan 2010; Ruscoe et al. 2012). Despite routine performance of rat-control on many of the world's islands, the motivations, techniques, and levels of success for such projects have not been examined. We sought to partially fill this knowledge gap by analyzing rat-control projects in island natural areas worldwide. We examined the extent and duration of rat-control projects; the species most targeted; motivations for control; methods of control (e.g., poisoning, trapping, and spatial and temporal extent); nontarget species risks and mitigations; project success rates and measures to evaluate success; and the economic costs of control techniques. This analysis of completed and ongoing projects to control invasive rats should help scientists and stakeholders to prioritize research and management actions to benefit native species and ecosystems where rat eradication may not be an option.

Methods

We obtained rat-control information for our review from the literature, a questionnaire survey, and relevant websites. We compiled data from published peer-reviewed literature by searching Web of Science (1980–2015) and Google Scholar. We searched titles and abstracts for the following words and combination of words: *island*; *rodent, rat*; and *control, management, removal, poisoning, trapping.* We excluded articles with the words *eradication* and *crops*. Relevant papers published in conference proceedings such as the Vertebrate Pest Conference (1992 to 2014) and the International Conferences of Eradication of Island Invasives (2002, 2011) were also included. We distributed a questionnaire (English and French) to people involved in rat-control through the web lists Aliens-L, Pacific Invasive Initiative, and Islands-L and through our personal networks (Supporting Information). A description of the study and the

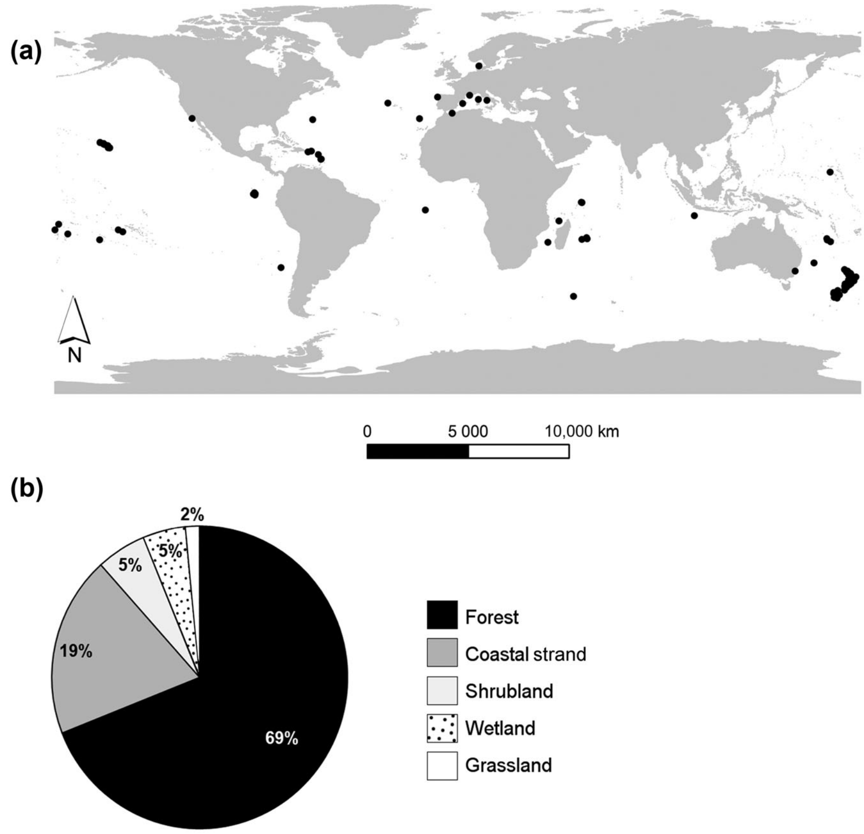

Figure 1. (a) Worldwide distribution of rat-control projects in island natural areas and (b) ecosystems in which rat-control occurs.

disclosure that information from the questionnaire would be used in a review paper accompanied the questionnaire (Supporting Information). We also searched the internet to glean information and documentation from rat-control and management websites. We believe that obtaining rat-control information through these multiple methods improved the thoroughness of our review and helped minimize the inevitable biases of such surveys and searches.

We reviewed the documents and questionnaires with the aim to synthesize the information collected on rat-control projects. Each project corresponded to one management operation in a clearly defined area. Sometimes, more than one article or questionnaire covered the same project; consequently, we compiled all the data collected for a particular project in a single entry in the data set. A Mann–Kendall test was used to determine whether the number of control projects increased significantly across years. We used Wilcoxon tests to assess whether the size of the treated area and the duration of the projects differed according to the method of control. We drew Kaplan–Meier survival curves of projects, compared their estimators among control methods with Cox proportional hazards regression models, and used Breslow χ^2 to test for significance. Then, we used a linear model to explore relationships between the cost of control (per year and per hectare) and the size of the treated area and between cost and control method (trapping, poisoning, and combined trapping and poisoning). Continuous variables were ln+1 transformed to meet normality assumptions. All statistical analyses were implemented with R version 2.15.3.

Results

Up to October 2015, we collected data on 136 different projects from 63 articles, received 50 responses to the questionnaire, and collected information from several web pages on rat-control projects on islands (Supporting Information). Almost all results reported are based on the 136 projects; when this was not the case, n is specified.

Distribution of Rat-Control

Most rat-control projects (46%) occurred in Australasia, and particularly in New Zealand (40%) (Fig. 1a). Twenty-five percent were in the tropical Pacific, most on U.S. islands, principally Hawaii (14%). Remaining projects were in the Caribbean Sea (9%), Indian Ocean (7%), North Atlantic (5%), and Mediterranean Sea (5%). Twenty-one countries (65 islands) had rat-control projects. Three countries contained 72% of the projects: New Zealand's North ($n = 41$) and South Islands ($n = 8$); Hawaii's Oahu ($n = 10$), Kauai ($n = 3$), Big

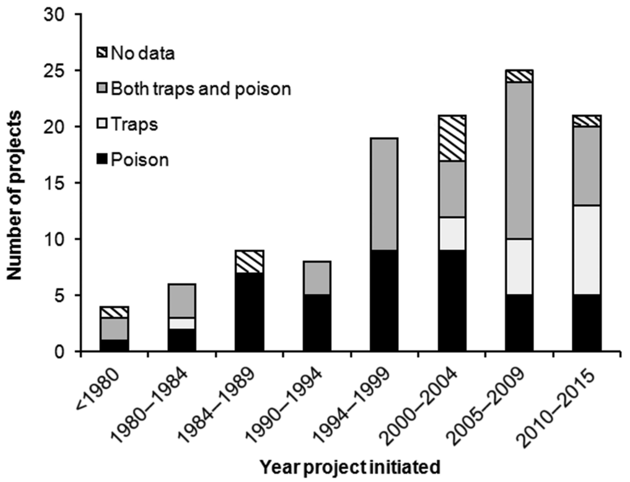

Figure 2. Number of rat-control projects by method in island natural areas worldwide.

Island ($n = 3$), and Maui ($n = 3$); and New Caledonia's Grande Terre ($n = 3$). Forty-nine percent of projects were in tropical or subtropical zones and the other half were in temperate zones. Most projects were conducted in forest ecosystems (65%) or coastal strands (22%) (Fig. 1b).

The number of projects in island natural areas increased slightly over time (Mann–Kendall test: tau = 0.815, $p = 0.008$) (Fig. 2). The earliest project was initiated in 1951 on Nonsuch Island (5.7 ha), Bermuda, to protect Bermuda Petrel (*Pterodroma cahow*) around their nesting site (Carlile et al. 2003). However, after technological advances in eradication products and methods, several rat-control operations on small islands became eradication projects (Pascal et al. 2008).

Targeted Species

Rattus rattus, *R. exulans*, and *R. norvegicus* were the species targeted for control. Eighty-one percent of the projects targeted at least *R. rattus*, 20% at least *R. exulans,* and 21% at least *R. norvegicus*. Fifty-one percent of control projects targeted only *R. rattus*, few targeted *R. exulans* alone (<1%) or *R. norvegicus* alone (1.5%), but 30% aimed to control 2 or 3 sympatric species simultaneously. The high frequency of rat-control for *R. rattus* is not surprising because it is the main rodent pest species on islands (Capizzi et al. 2014), especially forested areas of islands (Shiels et al. 2014). Of 106 projects for which there was information, 55% targeted other invasive species simultaneously. Thirty-five of these projects were in New Zealand, where possums (*Trichosurus vulpecula*), stoats (*Mustela herminea*), weasels (*Mustela nivalis*), ferrets (*Mustela furo*), and feral cats (*Felis catus*) were controlled concurrently with rats. Other species controlled concomitantly with rats included invasive plants (e.g., *Pennisetum setaceum*), mice (*Mus musculus*), hedgehogs (*Erinaceus europaeus*), mongooses (*Herpestes auropunctatus*), pigs (*Sus scrofa*), goats (*Capra hircus*), birds (*Pycnonotus cafer* and *Acridotheres tristis*), land crabs (e.g., *Gecarcinus* spp.), and hermit crabs (e.g., *Coenobita clypeatus*).

Motivations for Rat-Control

Motivations were often unclear or unspecified in the literature and thus were obtained from responses to the questionnaire ($n = 50$). For 36% of projects, the impact of the rat population on natural resources was not known or assessed before rat-control began in an area, and rat-control was conducted based on the negative impacts on natural resources in other similar areas. Thirty-eight percent of projects included a research phase before rat-control was implemented. For the remaining projects, 26% did not specify whether there was a research phase.

Most of the projects (82%) aimed to mitigate risks to species and endangered ecosystems, especially birds (71%) (Fig. 3a). Of these projects ($n = 96$), most sought to protect landbirds (56%) and seabirds (34%) (Fig. 3b). Nearly, 49% of the projects were established solely for bird conservation. For landbirds, some projects controlled rats only around trees that contained nesting birds, whereas others controlled rats in a larger area for the protection of native species other than landbirds. For seabirds, control focused mainly on breeding colonies. Fewer projects (10%) included reptile protection, and only one protected a specific reptile, the endangered giant tortoise (*Chelonoidis nigra duncanensis*) of Pinzon Island, Galápagos. Invertebrate conservation was the aim of 11% of the projects. However, only 2% were initiated solely for the purpose of invertebrate conservation (endangered snails in Hawaii, New Zealand, and New Caledonia) (Fig. 3c). Plant protection was included in 20% of projects, yet only 2% were developed specifically to save plant species. For instance, rat-control (26 ha) allowed conservation of an endangered Hawaiian lobelia tree (*Cyanea superba*) (Pender et al. 2013). Additional projects reduced rat consumption of *Apetahia raiateensis, Pouteria grayana,* and *Kadua raiateensis* in Raiatea, French Polynesia (F. Jacq, personal communication). Among the 97 projects set up to protect species and ecosystems, 21% were initiated to protect ecosystems as a whole, and most of which were forests. Nearly, 13% of the control projects had species reintroduction plans (Fig. 3a), mostly for birds. For example, the North Island Robin (*Petroica australis longipes*) was successfully reintroduced where rats were managed in 5500 ha of Puketi Forest, New Zealand (D. John and I. Wilson, personal communication). Twenty-five percent of projects were scientific experiments (Fig. 3a), 10%

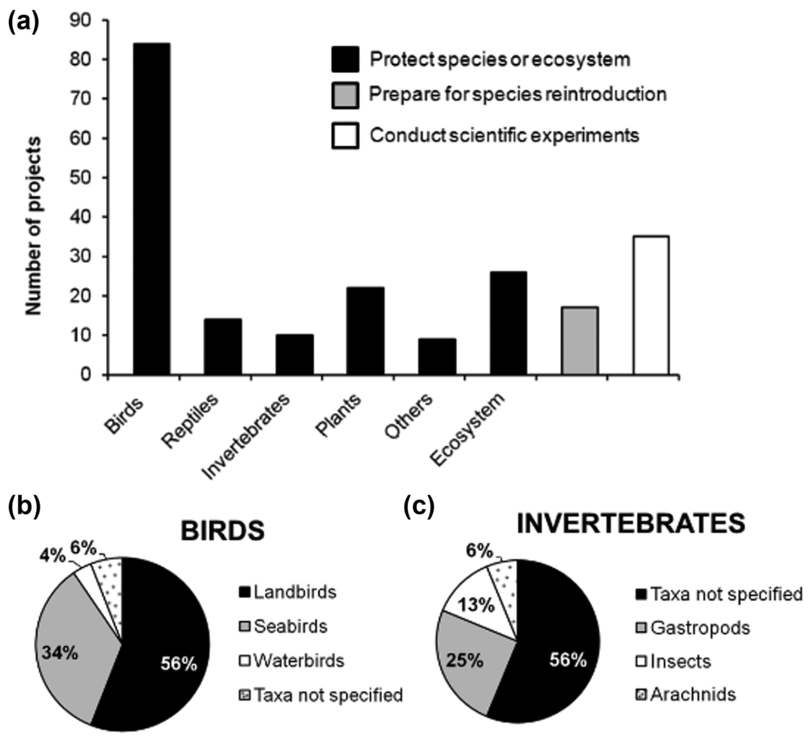

Figure 3. Motivations for rat-control projects: (a) number of projects relative to element protected or other reasons for control, (b) bird groups targeted for protection, and (c) invertebrate groups targeted for protection.

of which were planned specifically to answer scientific questions.

Control Methods

Applying poison (35%) and combining trapping and poisoning (42%) were the most common methods used to control rats in island natural areas (Fig. 2). Few projects (15%) used only trapping. No other methods (e.g., fertility control) beyond trapping and poisoning were mentioned in the literature reviewed, on websites, or in survey responses. Among trapping projects ($n = 77$), 35% used snap traps (Victor, 11%; Ka Mate, 6%; and Doc 200, 4%); 25% used live traps, and 7% used recently developed automatic self-resetting Goodnature A24 rat traps. A total of 104 projects used poison. We classified poisons into 4 groups following Howald et al. (2007): second-generation anticoagulants (i.e., brodifacoum, bromadiolone, flocoumafen, and difenacoum), first-generation anticoagulants (i.e., diphacinone, pindone, coumatetralyl, warfarin, and chlorophacinone), acute toxins (1080 [sodium monofluoroacetate]), and cholecalciferol. Anticoagulants were classified as first- or second-generation according to their potency and when they were developed (Eason et al. 2002). Second-generation anticoagulants (mainly brodifacoum and bromadiolone) were the most used poisons (51%) followed by first-generation anticoagulants (30%) (mainly diphacinone and pindone) and acute toxins (15%; mainly 1080).

Survey results (50 respondents) showed that 76% of projects assessed whether a nontarget species was at risk. Among these 38 projects, nontarget species (e.g., feral pigs, bats, birds, snails, and crabs) were at risk in 76% of projects, and in 58% of projects the nontarget species at risk were native species. For trapping ($n = 77$), only a few studies (16%) specified whether trap boxes were used to reduce incidental capture of nontarget species; trap boxes were used in 6% of projects and not used in 9%. In 5% of the projects, traps were placed in trees to limit access by nontarget species. Bait stations were used to deliver rodenticide in 82% ($n = 104$) of projects. Hand sowing of poison was used in 6% of projects, and poison bait was applied directly into seabird burrows in just one project. Aerial broadcasting of bait was used in 11% of projects, all in New Zealand.

Size of Control Area and Duration of Project

The area treated for rat-control ranged from 0.03 to 80,000 ha. The median surface area treated with trapping was 30 ha (interquartile range [IQR] = 61 ha, mean [SD] = 49.0 ha [60.4], minimum = 0.5 ha, maximum = 210 ha, $n = 17$) and was significantly smaller (Wilcoxon test: $W = 481.5$, $p < 0.001$) than areas treated by poisoning (median = 716 ha, IQR = 1934 ha, mean = 4269.4 ha [14171.5], minimum = 1 ha, maximum = 80,000 ha, $n = 32$). The largest area was in the Hauhungaroa Range (North Island, New Zealand) in August 2000, where 1080 was applied aerially to 80,000 ha (P. Sweetapple, personal communication). When trapping was the only method used, the largest area treated was about 210 ha of Halfmoon Bay on Stewart Island, New Zealand (K. Bunce, personal communication).

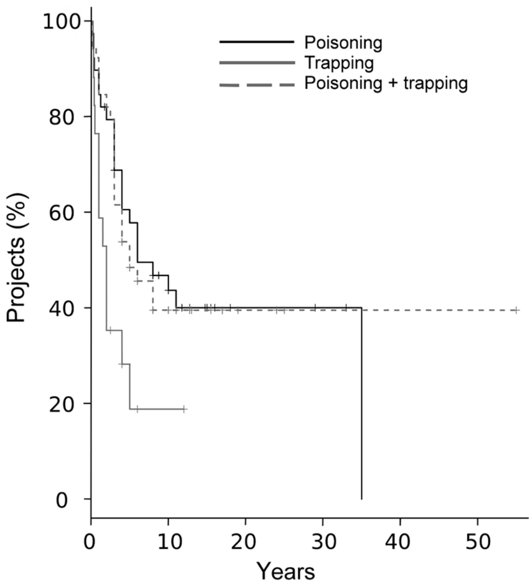

Figure 4. Duration of rat-control projects by method (short vertical lines are individual projects). The total number of projects (all methods combined) is 109.

Project duration median and mean were 4 years (IQR 9) and 7.7 years (SD 8.7), respectively, and projects varied widely from 1 day in Silver Peak, New Zealand, to 55 years in Lord Howe Island. The 1-day operation was a single application of 1080 applied aerially as part of a scientific experiment in 2011 (Schadewinkel et al. 2014). The 55-year *R. rattus* suppression at Lord Howe Island was to protect an endemic palm species (*Howea forsteriana*) (Auld et al. 2010). Project duration depended on the type of control method used (Breslow $\chi^2 = 7.0$, $p = 0.031$, df = 2, $n = 109$) and the motivation for control (Breslow $\chi^2 = 40.2$, $p < 0.001$, df = 4, $n = 112$) but did not depend on the size of control area (Breslow $\chi^2 = 3.23$, $p = 0.072$, df = 1, $n = 88$). Although suppressing rats with poison was more frequent than trapping, the duration of control projects was significantly longer for poisoning than for trapping alone (Wilcoxon test: $W = 592.5$, $p = 0.003$) (Fig. 4). Moreover, combining trapping with poisoning did not result in longer lasting projects ($W = 1105$, $p = 0.669$). Project duration was longer for projects aimed specifically at mitigating risks for endangered ecosystems and birds (Wilcoxon test: $W = 1693$, $p = 0.001$).

Rat-Control Evaluation

Rat and native-biodiversity monitoring were incorporated in 62% and 58% of the projects, respectively. Of the 84 projects incorporating rat monitoring, at least 45% included rat trapping, 36% tracking tunnels, 12% capture-mark-recapture, 8% chewing blocks, 6% bait consumption estimates, and 5% were based on other indirect methods, including monitoring of seeds for rat predation and camera observations of artificial nest predation. The types of native biodiversity monitoring (n = 70) that took place during rat-control were mainly for birds (68%), followed by invertebrates (10%), plants (8%), reptiles (1%), and bats (1%). Bird monitoring ($n = 54$) was mostly based on nesting or breeding success (48%) and on bird counts (20%). Plant monitoring included fruit and seed consumption experiments or monitoring seedlings.

Contrary to eradication, during a control operation, there is no obvious endpoint (i.e., where all rats are eliminated). Therefore, success is not easily defined and projects require constant control efforts. For 58% of the projects, rat population reduction was reported, and for 51%, positive effects on biodiversity were observed. However, 29% of projects did not provide information about whether or not rat populations were reduced, and 46% did not provide information on the effects of rat-control on biodiversity. From the questionnaire (n = 50), 6 operations were considered unsuccessful by survey respondents due to “important collateral damages” (e.g., creating trails for rat-control efforts), “inadequate planning,” a lack of cost-effectiveness, or discovery that “rats were not the principal threat.” Forty-nine percent ($n = 106$) of projects mentioned had simultaneous control of other invasive mammals, but there was no report of confounding influences from controlling other invasive mammals on the likelihood of successful rat control.

Rat-Control Costs

Twenty-six (52%) survey respondents provided information on economic costs. The cost of control per year varied widely according to the scale of the project ($500–$226,989): with a mean of $39,766 (SD 56,494) and a median of $17,262 (IQR 32,090). (All monetary units are in U.S. dollars.) The annual cost per treated hectare also fluctuated: mean $843 (SD 2086) and median $227 (IQR 503) per hectare. The larger the control area, the more cost-efficient the control operation ($p < 0.0001$, $R^2 = 0.559$) (Fig. 5). There were no differences in costs per unit area relative to the method of control ($p = 0.329$; poison vs. trapping vs. trapping+poisoning). When asked about the part of the rat-control operation that was the most expensive, most people (78%) provided answers. Of the 39 responses to questions about cost, the most expensive part of the operation was personnel (62%), followed by materials (33%), and travel (5%). The most expensive phase of the project ($n = 37$) was generally fieldwork (84%) and more rarely evaluation and data analyses (8%), preparation for fieldwork (5%), or conception of the project (3%). Of the 37 projects with information on the people involved, 35% identified the participation of volunteers in fieldwork.

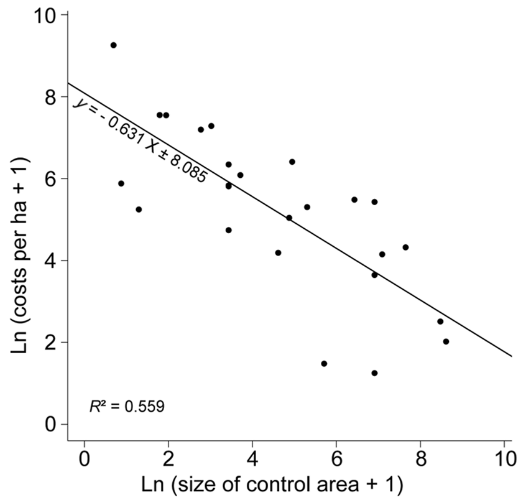

Figure 5. Annual estimated cost per hectare for rat-control projects relative to the total size of control area.

Discussion

Biodiversity and Hotspot Protection

Most island rat-control projects are concentrated in a few countries such as New Zealand, United States, or overseas territories associated with other developed countries. Nonetheless, many more islands, often in tropical areas and in developing countries, belong to biodiversity hotspots where invasive rats reside (Atkinson 1985). Considerable efforts are underway to understand rat effects and manage them in tropical ecosystems (Harper & Bunbury 2015; Keitt et al. 2015). Due to limited economic capacity and often social instability, less-developed countries cannot always effectively protect ecosystems (Fisher & Christopher 2007). The necessity to transfer knowledge, expertise, and funding to developing countries will be an essential priority for the future. As highlighted by Simberloff et al. (2013), an effort must be made to provide invasive-species research aimed at improving risk assessment and prioritizing actions. During the last decade, several people worked on prioritizing islands for eradication of a range of vertebrates (e.g., Dawson et al. 2015) or rodents specifically (Harris et al. 2011). Because current technology does not allow for many large islands to have rats eradicated, rat-control operations will continue to be common and may be prioritized over rat eradications. Benefits to species, ecosystems, and humans, and long-term sustainability of a control project, may all factor into rat-control prioritization decisions.

Ecosystem Protection

Bird conservation is currently the greatest motivation for rat-control in island natural areas. Rat-control operations are often implemented without preliminary studies at the candidate site but are often justified by an a priori understanding of rat impacts on the species of interest or similar species. Rats predominately affect native species and ecosystems negatively, yet the magnitude of such site-specific impacts can differ widely (Harper & Bunbury 2015). Thus, the level of impact must be considered before the large and often long-term commitment to control rats can be made. Benefits to entire ecosystems, rather than one to a few species, may also result from rat-control. Such ecosystem-level effects of rat-control are often more difficult to realize and study, but they are encouraged for future conservation on islands (Simberloff et al. 2013; Ruffino et al. 2015). Furthermore, considering the effects of invasive rats on the entire ecosystem prior to implementing a rat-control program helps prevent unwanted consequences such as mesopredator- or competitor-release effects (Caut et al. 2009). Because of these complex interactions, the control of other invasive species (e.g., mice, mustelids, possums, and cats) concurrently with rat-control generally enhances restoration results (Saunders & Norton 2001; Zavaleta et al. 2001). There may be problems with rat-control if native species develop dependence on invasive species. For instance, invasive rats can be crucial pollinators (Pattemore & Wilcove 2011) and seed dispersers (Shiels & Drake 2011) when native plants have lost their native pollinator or disperser.

Cost-Efficiency and Sustainability

Rat-control projects are generally not very long lasting (< 8 years), even when they show positive effects on native biodiversity. Dedication to long-term protection of species or ecosystems is necessary because rat populations reinvade the control areas. A key challenge is to determine how rat-control operations can be sustained. Project duration and cost do not depend only on the size of control area, but also on the methods used, political environment, and the reasoning for launching rat-control.

Rat-control is generally viewed as expensive due to the required field personnel, yet additional, substantial costs include materials (e.g., bait and traps) and travel to the control area. In most cases, rat-control is implemented over extended periods even though the islands are small enough to make rat eradication feasible (Pascal et al. 2008; Russell et al. 2015). As technology improves, the size of the largest rat-eradicated area also increases, and the possibility of rat eradication must now be considered on islands previously thought to be too large or complex for eradication. If eradication is not possible, an extensive plan of rat-control should be developed prior to beginning rat suppression. At minimum, a plan should include the annual cost, methods to evaluate rat suppression and benefits to native species, and a clear goal and timeline based on the monitoring results (e.g., 80% rat reduction and 50% increase in target native species in 2 years) that enables project evaluation and justifies continuation or modification (e.g., Norbury et al. 2015).

Recurrent management costs of rat-control need to be reduced. Community involvement in such conservation projects may be one solution to the cost problem (Lund 2014). Working with volunteers may allow the treatment of larger areas, reduce costs, and raise environmental awareness among citizens. Bryce et al. (2011) report reduced recolonization of 10,570 km^2 by invasive American mink (*Neovison vison*) in Scotland after they involved 186 volunteers in control of this species. In New Zealand, where conservation volunteering is frequent (Butler et al. 2014), a large control project called Ark in the Park was initiated in 2002 in the North Island. The success of this project relied on strong volunteer participation. Today, over 120 people help manage rats by trapping and poisoning 2100 ha of forest. This project showed positive effects on biodiversity and allowed for the reintroduction of native birds (Bellingham et al. 2009).

Improved Control Methods

Improving the cost-efficiency of control methods and reducing nontarget species risks are 2 key priorities for future rat-control projects. Our findings revealed that controlling rats across large areas was more cost-efficient by unit area than controlling rats across smaller areas. Although poisoning is often preferred over trapping as a more cost-effective way to remove rats from large areas (Russell et al. 2008), we found that there was no difference in total project costs between trapping and poisoning.

Second-generation anticoagulants (mainly brodifacoum) are currently the most used poisons because of their high potency. Although only a few grams of bait must be ingested before causing death, there are multiple days from first feeding before the rat dies, and this is considered inhumane by some (Hoare & Hare 2006). There are also risks to nontarget native species when rat poisons are used, although the risks vary according to the frequency of application and the way bait is applied (Hoare & Hare 2006; Pitt et al. 2015). In a recent rat eradication on Palmyra Atoll, the use of brodifacoum bait resulted in numerous deaths of birds and fishes, and brodifacoum residue was present in soil, freshwater, marine water, and in 84% of animal carcasses analyzed. However, this operation used approximately 4–8 times the amount of bait used in other studies because of high bait removal by native land crabs, and researchers did not assess overall nontarget mortality as a proportion of resident populations (Pitt et al. 2015). Similar to islandwide rat eradications, the environmental benefits of rat suppression through the use of toxic bait should outweigh the negative effects of the bait on nontarget species and soil and water contamination.

Broadcast application of poison bait by hand or aircraft for rat-control is generally uncommon, partly because the bait is readily accessible to both target and nontarget species. However, in New Zealand, aerially broadcasting poison bait by helicopter is practiced to control rodents and other pests in large or relatively inaccessible areas. Even if rat bait stations are used to reduce nontarget access to poison bait, the discrimination between rats and smaller animals, and native and non-native rats, may be difficult or even impossible (Courchamp et al. 2003). Testing for nontarget bait take in novel environments prior to setting up a control project is essential, especially for hand- or aerial-bait dispersal. Unlike rat-eradication projects that typically use poison bait applied 1–3 times over a few weeks or months (Howald et al. 2005), rat-control generally requires a regular poison bait supply for years or indefinitely. Therefore, the threats to native species from bait consumption may be much longer lasting than with rat eradications.

Rat trapping, which is a toxin-free rat-control method, may be preferred to poisoning by local human populations. When animals such as pigs are hunted, local people may be concerned about the risks of secondary poisoning (toxin accumulation in animal tissues). Rat-control through large-scale trapping effectively reduces rat populations in New Zealand (King et al. 2011) and reduces rats and protects native species in Hawaii (Pender et al. 2013). Unfortunately, covering large areas with traps is challenging; the largest area we found for controlling rats with trapping was about 210 ha. Automatic self-resetting rat traps and toxin applicators have been proposed and tested (e.g., Goodnature A24 rat traps and Spitfire Connovation). Goodnature traps have the capacity to kill 24 times, and Spitfires traps can kill up to 50–100 times, before the trap needs to be serviced. However, these devices are expensive and their effectiveness has been mixed (Campbell et al. 2015; Carter et al. 2016). Nonetheless, if proven effective and reliable, they could be a good investment for long-term rat-control and reduce labor costs (Blackie et al. 2014; Campbell et al. 2015).

Research on alternative rat-control methods is recommended to uncover more cost-effective and less dangerous ways to remove rats humanely while limiting risks to the environment and nontarget species (Meerburg et al. 2008). Littin et al. (2014) propose a decision-making process to select the control technique based on the technique's efficiency and humaneness. Campbell et al. (2015) provide a list of innovative technologies and tools that may improve future eradication methods, and some of them may also be used for continuous rat-control (e.g., norbormide poison, genetic engineering, and fertility control). With long-term rat-control, rats may develop behavioral or genetic resistance to control tools (Brunton et al. 1993; Pelz et al. 2005). Combining or alternating control methods may lessen the possibility of rat resistance to control mechanisms, but this field requires more research and experimentation to improve the efficacy of long-term control.

Project Evaluation and Adaptive Management

Around 29–45% of the projects we reviewed did not report monitoring of the rat population or biodiversity recovery following rat-control; a lack of appropriate monitoring makes the success of the project very difficult to assess by any means beyond anecdotal observations. Implementing a monitoring plan to assess the effectiveness of rat-control is essential and represents one of the biggest areas of need for current and future rat-control projects. Rat-population reduction can be monitored easily with rat trapping or rat activity measures such as tracking tunnels and chewing blocks (Blackwell et al. 2002). The confirmation of a positive effect of rat-control on biodiversity recovery can be based on increases in native species abundance or reproductive success. An additional challenge in determining the effectiveness of some rat-control projects was that other invasive mammals were concurrently being controlled, so positive effects of control were not always identifiable. To best evaluate a rat-control operation, we recommend adoption of a before-after-control-impact experimental design, where monitoring occurs on the treatment and nontreatment areas before and after the beginning of a control operation (Reddiex & Forsyth 2006). Although this approach may not be possible in all cases (e.g., resource constraints and inability to ethically abstain from rat suppression in a conservation site for sole comparison to a rat-control site), it is the most definitive way to assess rat-control efficacy. At minimum, a before-and-after monitoring approach is necessary, but typically this is only valid for assessing initial (short term) efficacy of the control implementation. These types of evaluations are important to justify the initiation and continuation of rat-control projects, including justification to financers (Ferraro & Pattanayak 2006) and local community members.

Ideally, rat-control monitoring results should be evaluated continuously and associated methods should be adapted to improve the cost-benefit ratio of the rat-control project. Evaluation will help determine how much suppression effort is needed to reduce the rat population to a point that benefits native biodiversity. This adaptive-management approach is highly favored for managing biological systems in the presence of uncertainty (Westgate et al. 2013). Adaptive management is a trial-and-error process that requires learning constantly about control effects on rat populations and on native biodiversity. Adaptive management may include the type of control method used (e.g., type of poison and trap), frequency of control sessions, and grid arrangement and size. Considering the complexity and the costs of such rat-control, monitoring the operation to decide to continue, adjust methods, or cease the operation seems essential.

Conclusions

Based on the 136 operations to control invasive rats on islands we reviewed, we identified actions for improving the effectiveness of rat management and native species conservation. We highlighted some priorities such as enlarging the worldwide distribution of invasive rat-control, targeting control efforts to protect entire ecosystems, increasing project cost-efficiency and sustainability, improving control methods, and evaluating the control operations to enhance adaptive management. Improving accessibility to data from rat-control projects worldwide will help transfer knowledge, expertise, and funding opportunities among projects and may help determine the causes of project successes and failures. We encourage researchers and stakeholders to monitor the effects of their rat-control operations and to make their methods and results accessible so that rat-control management can be improved.

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Supporting Information

The emails and questionnaire sent to people involved in rat-control projects (Appendix S1) and the list of the 136 rat-control projects collected for this review (Appendix S2) are available online. The authors are solely 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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