PART THREE

Restoration of Seabird Islands

10

Eradication of Invasive Predators on Seabird Islands

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Introduction

In 1750, Russian fur traders began introductions of Arctic foxes (*Vulpes lagopus*) into the Aleutian Islands, a practice that continued into the twentieth century. By 1936, an estimated 99% of the total area of the Aleutians was used for fox farming. The industry was based on unsustainable use of native ground-dwelling birds, especially seabirds, by an introduced predator. Inevitably, the local Aleuts reported: "foxes come, seabirds go" (Williams et al. 2003). One severely affected species was the whiskered auklet (*Aethia pygmaea*), which is endemic to the Kurile Islands between Russia and Japan, and the Aleutian Islands between Russia and Alaska (Williams et al. 2003). Whiskered auklets were regarded as quite abundant by naturalists in the late nineteenth century, but by 1911 were almost impossible to find. The declines in whiskered auklets and other native birds also affected the foxes, which began to die out on some of the islands. The U.S. conservation agencies also eradicated many populations of invasive foxes from the Aleutians. Subsequently, many species of native birds then began to recover (Bailey 1993), and by the mid 1970s, counts of whiskered auklets estimated 25,000 birds in the Aleutian archipelago (Byrd and Gibson 1980). By 2003, a single flock of 30,000–40,000 birds was reported adjacent to an island from which foxes had been removed in 1996, and total population estimates for the archipelago increased to 116,000 (Williams et al. 2003).

The Aleutian example demonstrates how declines of native species of seabirds can be reversed on islands if introduced predators are removed. Five groups of introduced mammals, identified in Chapter 3 as particularly widespread or damaging on seabird islands, form the focus of this chapter. In order of distributional range, these include three species of rats (*Rattus rattus*, *R. norvegicus*, *R. exulans*), house mice (*Mus musculus*), cats (*Felis catus*), pigs (*Sus scrofa*), mongooses (*Herpestes* spp.), and at least two species of foxes (*Alopex lagopus* and *Vulpes vulpes*). Most of these species have now been eradicated from some islands. However, some members of the public, the scientific community, and government organizations still struggle to comprehend that every individual of an introduced species can or even should be removed, especially when such claims include rats and mice (Simberloff 2002, Lorvelec and Pascal 2005, Towns et al. 2006, Ogden and Gilbert 2009). Here we respond to such skepticism by outlining how the most widespread seabird predators are now routinely eradicated from islands, constraints on these eradications, the possibilities for more complex and ambitious projects, and the way public perceptions might influence these projects. We will frequently use examples from Alaska and New Zealand because of the long histories and high frequency of predator removal in these areas (Ebbert and Byrd 2002, Genovesi 2007, Howald et al. 2007). We also emphasize issues around the removal of rodents because they are particularly widespread, they are the most frequently targeted, and their eradication is technically demanding. We conclude that regardless of the invasive species involved, extraordinarily ambitious projects can be successful if there is a multidisciplinary approach, and the inclusion of specialists at each level of planning and implementation.

Success with Eradications of Introduced Seabird Predators

Despite centuries of the spread of introduced species of predatory vertebrates, their effects only became documented around the turn of the twentieth century. For example, Richard Henry quickly witnessed the impacts of government sanctioned releases of mustelids to control rabbits (*Oryctolagus cuniculus*) in New Zealand. From 1894–1900 he moved hundreds of forest birds to islands, only to see his efforts destroyed when the mustelids swam from the mainland in 1900 (Hill and Hill 1987). Similarly, the detrimental effects of introduced rats on bird life of southern New Zealand islands were already apparent by 1913 (Guthrie-Smith 1925). Furthermore, the effects of cats became apparent to the New Zealand government when lighthouse keepers on Stephens Island became indirectly responsible for extinction of a flightless wren (*Traversia lyalli*), destroyed by cats in 1895 (Galbreath and Brown 2004). In a belated attempt to avoid further damage to huge populations of seabirds, and reptiles including tuatara (*Sphenodon punctatus*), eradication of the cats from the island by shooting started in 1899 (Tennyson and Martinson 2006). Although Stephens Island is only 150 ha, the campaign, which was based on bonuses paid by the government to the lighthouse keepers for each cat killed, provided them with additional income for 26 years. The island was finally free of cats by 1925 (Veitch and Bell 1990).

The eradication of many other introduced predators stemmed from these early attempts and gathered pace from about the middle of the twentieth century. For example, pigs were removed by government hunters from Aorangi Island (110 ha), New Zealand, by shooting in 1936 (Veitch and Bell 1990). In the Aleutian Islands, the removal of Arctic foxes released for fur began with leghold trapping in 1949 (Bailey 1993). The first fox eradications in the Aleutians by the U.S. Fish and Wildlife Service included the use of toxicants, but the most recent fox eradications on the largest islands were by shooting and trapping (Ebbert 2000).

To date, foxes have been removed from more than 40 islands comprising an area of over 500,000 ha (Ebbert and Byrd 2002).

The first recorded eradication of rats was in 1951, when Norway rats (*Rattus norvegicus*) were eliminated from the French island of Rouzic (3.3. ha) in the Sept Îles using strychnine (Lorvelec and Pascal 2005). In New Zealand, Norway rats were inadvertently eradicated from Maria Island (1 ha) and David Rocks (1 ha) in 1960, during attempts to control rats in a seabird colony using the anticoagulant rodenticide, warfarin (Towns and Broome 2003).

By the end of the twentieth century, seabird predators were routinely being removed from islands throughout the world (Table 10.1). A view of the global extent of successful eradications can be obtained from publications in Veitch and Clout (2002). This one volume recorded the eradication of 138 populations of seabird predators in 10 countries (Figure 10.1). With increasing frequency of eradications, there have also been orders of magnitude increases in the size of islands where eradications have succeeded. These include mice and ship rats (*Rattus rattus*) on Rangitoto-Motutapu, New Zealand (3,880 ha); Pacific rats (*Rattus exulans*) on Little Barrier Island (Hautaru), New Zealand (3,083 ha); Norway rats on Campbell, New Zealand (11,300 ha); cats on Marion, South Africa (29,000 ha); foxes on Attu, United States (90,574 ha); and pigs on Santiago, Ecuador (58,465 ha; see Ebbert 2000, Clout and Russell 2006, Donlan and Wilcox 2008). Additional details of the distribution and history of these eradications are provided by Towns and Broome (2003) and Howald et al. (2007) for rats, Nogales et al. (2004) for cats, Ebbert and Byrd (2002) for foxes and Cruz et al. (2005) for pigs (see also Parkes and Panetta, 2009, for additional species).

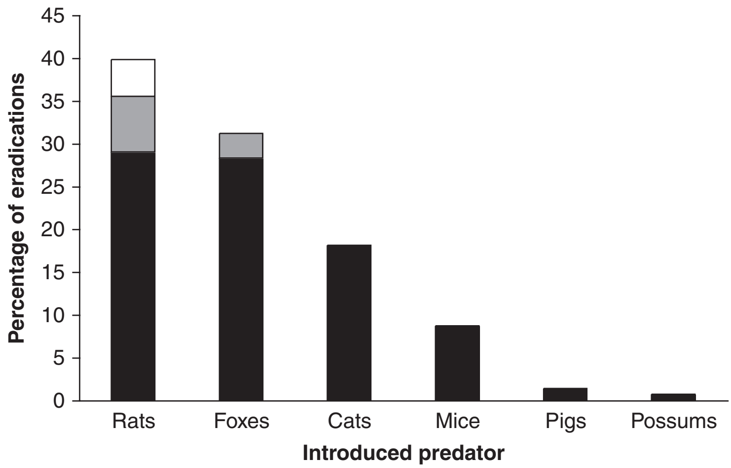

FIGURE 10.1 Frequency composition of 138 global eradications of seabird predators based on published accounts in Veitch and Clout (2002), with ship or black rats (*Rattus rattus*) in column 1 (black), Norway rats (*Rattus norvegicus*) (gray) and Pacific rats (*Rattus exulans*) (white); and Arctic foxes (*Alopex lagopus*) in column 2 (black) and red foxes (*Vulpes vulpes*) (gray).

TABLE 10.1.
Responses of Native Species to the Removal of Introduced Predators from Selected Seabird Islands.

Country/Region	Predator Species	Methods	Response	References
Alaska	Arctic foxes (some red foxes) and Norway rats	Toxins, mostly traps and shooting (foxes), aerial spread toxins (rats)	Terrestrial birds and at least 9 species of seabirds	Bailey (1993), Byrd et al. (1994), Williams et al. (2003)
French territories and offshore islands	Ship and Norway rats	Trapping and toxins	Terrestrial birds, mammals and at least 5 species of seabirds	Micol and Jouventin (2002), Lorvelec and Pascal (2005), Pascal et al. (2008)
Indian Ocean	Cats, mice, ship and Norway rats	Trapping (cats); baits in bait stations or broadcast by hand	Reptiles and at least four species of seabirds	Bell (2002), Merton et al. (2002)
Mexico	Cats, mice, ship and Norway rats	Shooting and trapping (cats); toxic baits in bait stations (rats and mice)	At least 78 taxa of vertebrates (reptiles, birds and mammals) and 227 breeding colonies of seabirds protected	Tershy et al. (2002), A. Aguirre-Muñoz (pers comm.)
New Zealand	Pigs, cats, stoats, possums, mice, Pacific, ship, and Norway rats	Shooting (pigs); shooting, trapping and toxic baits (cats, stoats, possums); toxic baits in bait stations (rats and mice); aerial spread of baits (all except pigs)	At least 73 species of vertebrates (reptiles and birds) including 16 species of seabirds	Bellingham et al. (2010)
US tropical Pacific	Cats, Pacific and ship rats	Traps and shooting (cats); traps, toxic baits in bait stations (rats)	At least 12 species of seabirds	Smith et al. (2006), Rauzon (2007), Rauzon et al. (2008)
Western Australia	Red foxes, cats, ship rats, and mice	Toxic baits (red fox, cats, rats and mice); traps (cats); aerial spread of baits (cats, rats)	Terrestrial mammals and unspecified species of seabirds	Algar et al. (2002), Burbidge and Morris (2002)
United Kingdom	Norway rats	Toxic baits in bait stations	Terrestrial mammals and at least 6 species of seabirds	Zonfrillo (2001)

Positive responses were determined from increased breeding success, increased colony size and natural recolonization.

These eradications have had significant benefits for native species (Table 10.1). For example, after eradications of 115 populations of 13 species of invasive vertebrates on 89 New Zealand islands (31,000 ha), there has been effective protection and range extension for 16 taxa of seabirds (includes subspecies), and 57 other species of vertebrates. Similarly, 12 species of invasive mammals have been eradicated from 31 islands in western Mexico (51,000 ha), which protects at least 227 colonies of seabirds (Aguirre-Muñoz et al. 2008). These responses of selected species of seabirds to predator removals (Chapter 3) are almost certainly an underestimate of the total response possible. In part, this is because most eradications are relatively recent (within the last 20 years), and the response time for natural recovery of species such as seabirds may take decades to reach completion (see Chapter 11).

The Keys to Success

Increases in the size of islands cleared of introduced predators, and the range of species attempted, have resulted from a combination of attitudinal shifts with planning, monitoring results (which enabled learning from experience), technological advances, stakeholder support, and improved knowledge of the biology of target animals for biosecurity and prevention of reinvasions.

PLANNING

Essentially, early eradications used everything available, all at once, for as long as necessary to get the job done. There may have been little long-term planning, and the people given the job may have had no experience and little time to devote to the task. This was the case on Stephens Island, New Zealand, where the bonuses paid to lighthouse keepers for killing cats were little more than an income supplement to be indulged as time allowed and finances required. It worked well for the lighthouse keepers for a quarter of a century. There are numerous other examples where eradications failed or were impeded by poor planning, insufficient training, inappropriate equipment, or a lack of committed professional staff (e.g., Parkes 1990). For example, the campaign against pigs on Santiago Island, Ecuador, was one of sustained intermittent control for 20 years. Yet, once there was commitment to a well planned and executed eradication, the entire pig population was eliminated in 5 years (Cruz et al. 2005).

Today, eradication planning involves a process for minimizing the risk of failure. The development of methods for invasive predator eradication on islands has been attained through a systematic approach guided by the scientific method, and differs little from mammal pest control on the mainland (e.g., Parkes and Murphy 2003). An attitudinal shift is also required, with a clearly understood distinction between control and eradication. Under control regimes, populations are reduced or contained, and if control is eased, the population recovers through reproduction by survivors or rapid reinvasion from neighboring unmanaged populations. In contrast, eradication removes all potentially reproductive individuals of a population, there is no potential for recovery, and the probability of reinvasion is greatly reduced by physical barriers such as expanses of water. Unlike control, eradications may thus require particularly heavy investment when populations are low, because the aim is to locate and remove the last individuals.

Once the above constraints are understood, an eradication plan can be developed, which ideally contains four elements: (1) a proposal aimed at decision-makers and stakeholders that justifies why the campaign is necessary; (2) a feasibility study that assesses the technical issues involved, and their risks, constraints, and costs; (3) an operational plan developed by those actually conducting the project; and (4) a biosecurity plan that outlines quarantine during and after eradication, and defines how risks of reinvasion or future invasive species introductions will be managed.

The feasibility study needs to consider three essential biological rules (Parkes 1990) and three additional tenets, which help with evaluating whether the eradication should then be attempted (Bomford and O'Brien 1995, Broome et al. 2005). Parkes and Murphy (2003) call these *obligate* and *desirable* rules. The obligate rules are:

1) All potentially reproductive animals within a target population are at risk of mortality by the removal methods employed.
2) All target animals can be removed at a rate exceeding their reproduction. Though apparently obvious, it is important to remember that population reductions result in higher reproduction and survival rates due to the increased resources available below carrying capacity.
3) Reinvasion must be prevented or managed to near zero probability. The benefits of eradication only accrue in the absence of the invasive species, and are nullified by reintroduction.

The desirable rules are:

1) Animals can be detected at low densities. Furthermore, funds can still be allocated when there is high effort for low return.
2) Benefits associated with the project outweigh costs. Eradication decisions should be made using detailed cost-benefit analyses, as control may be more cost effective. Comparison between the costs of control and eradication can be difficult where quantitative measures of damage are not available, and less measurable conservation values, such as reduced risk of extinction, are considered. Eradication can be very costly, and any attempt should assess the potential for failure in decision making.
3) There is political, social, and cultural support. Even when all other criteria can be met, weak or little stakeholder support is likely to transform into strong resistance if eradication methods are viewed as unpalatable to the public, or there are negative impacts on nontarget species or the environment.

Operational plans need to detail regulatory compliance (e.g., Table 10.2), public communication, eradication methods, team member responsibilities, safety, and logistics. Projects involving toxicants also need plans for monitoring nontarget

TABLE 10.2.
Regulatory Framework for the Use of Toxins against Rodents in the USA based on Legislation Administered by the US Environmental Protection Agency.

Function	Regulations and Purpose
Use of rodenticides for research control or eradication	*Federal Insecticide, Fungicide and Rodenticide Act*
Registration of new rodenticides	Specifications of the amount, frequency, timing of use, storage and disposal for pesticide label (Section 3)
State-specific registrations	Allows for registration in a state or for a demonstrated local need for specified products (Section 24(c))
Emergency exemptions	Use of unregistered products in emergencies (Section 18)
Experimental use	Experimental Use Permits for pesticides under development (Section 5)
Decision-making over the use of pesticides	*National Environmental Policy Act*
Compliance across environmental laws and regulations	Procedural law to provide informed decision-making with regard to: Endangered Species Act, Marine Mammal Protection Act, Coastal Zone Management Act, Magnusen-Stevens Act, Wilderness Act and the Migratory Bird Treaty Act
Environmental assessment	Preparation of Environmental Impact Statement that summarizes policies and scientific studies, identifies challenges to success, provides understanding of rodenticide to be used and its potential adverse effects (e.g., on water, soil and non-target species), demonstrates compliance with relevant regulations and conducts impact analysis with actions to minimize adverse effects
State and federal local approvals	Pesticide use proposals for applications on federal land and state permits to use toxins or take wildlife
Operational requirements	Pesticide Applicator certifications, Animal Care and Use Committee approvals for any animals held in captivity, certification of pilots and aircraft used in aerial operations

impacts and efficacy. Some organizations encourage independent critical review of the plans before they are approved. In New Zealand, the Department of Conservation convenes an Island Eradication Advisory Group to review proposals, using other project managers and experts (Cromarty et al. 2002). Project review can also be beneficial when non-experts are included, because this forces the project manager to break down the operation plan to its basic elements.

MONITORING

Monitoring is an expensive component of eradication projects, but necessary to determine project efficacy and impacts on target and non-target species. A multi-tiered approach may be required, which should include frequent reviews of the eradication planning while it is in progress, as well as assessing effects on species, habitats, and stakeholders. There can also be considerable benefit from designing complementary projects, each with specific information targets. For example, the development of aerial broadcast methods against rats used a form of adaptive management, or "learning by doing" that involved the evaluation of each project alongside incremental increases in island size, and more effective targeting of bait. As a result, there were also progressively increased ecological benefits (Towns and Broome 2003). Refinements of ground-based bait station methods followed a similar process (Thomas and Taylor 2002). The value of regular monitoring has been emphasized by many authors (e.g., Atkinson 1994, Courchamp et al. 2003, Smit 2003) and can be divided into four levels:

1) Outcomes: the ecological effects of predator removal on specific populations of plants and animals, but ultimately overall biodiversity and ecosystem function. This assures stakeholders that they are indeed receiving value for money.
2) Nontarget: adverse impacts to nontarget species and other resources. This provides valuable information on hazards and risks that can be applied to other projects, but also tests whether preoperational risk assessments were accurate.
3) Toxicity: environmental fate of any toxicants used through the analysis of bioaccumulation in nontarget organisms, the rate of bait disappearance, and its persistence in soil and water. This assures stakeholders that there are no risks to health and safety and, if there are restrictions on access, how long they need to be applied.
4) Efficacy and biosecurity: ensuring the absence of target predators after the operation to remove them has reached its planned conclusion.

The results of these assessments also provide valuable information for other organizations intending similar projects. Detailed reviews of successful approaches to monitoring and planning are provided by Parkes and Murphy (2003), Genovesi (2007), Broome (2009) and Parkes and Panetta (2009).

STAKEHOLDER SUPPORT

The research and development approach to predator eradications has not only led to enormous expansions of the size of islands cleared of predatory mammals, it has also led to projects on islands in full public view (Box 10.1), or on islands with residents (see also Chapter 12). Increasingly, such advances have led to public debate over whether the financial and environmental costs will be outweighed by biological, social, or economic benefits. A small group of antagonistic residents can effectively derail projects even when the majority is in support. Such a situation appears to have developed on Great Barrier Island, New Zealand, where plans to eradicate introduced predators are on hold due to localized opposition (Ogden and Gilbert 2009).

Such situations might be avoided if there is appropriate capacity for stakeholder education and involvement. Furthermore, stakeholders need to be convinced that eradications will be of benefit to species and ecosystems, no unnecessary negative effects will harm nontarget species, and introduced species are not being removed

BOX 10.1

When Natural Events and Eradications Coincide: "The Attack of the Killer Slugs"

Location: Rangitoto-Motutapu Islands, northeast New Zealand
Climate type: warm temperate

Rangitoto-Motutapu (3881 ha) are neighboring islands, connected at low tide at the entrance to the Waitemata Harbor, and are dominant features in the Auckland city landscape. Rangitoto Island is a young (650-year-old) volcano in the process of colonization by early successional forest, dominated by two species of *Metrosideros* and hybrids between them (Haines et al. 2007). In contrast, Motutapu Island is largely of sedimentary material, with most of its original coastal forest converted to pasture that is now maintained to protect archeological and historic sites. By 1990, nine species of mammals had become established as a result of farming, hunting, by accident, as attempts at controlling pests, and as curiosities. They included Australian marsupials (brush-tailed rock wallabies *Petrogale penicillata*) and brushtail possums), rabbits, feral cats, hedgehogs, stoats, two species of rats (*Rattus rattus* and *R. norvegicus*), and mice (Wilcox 2007). The two species of marsupials devastated the developing forests on Rangitoto, so eradication of these species on both islands was undertaken by the Department of Conservation (DOC) beginning in 1990. The campaign began with an initial knockdown using aerial spread of Compound 1080 from helicopters on Rangitoto, and was completed by 1997 using manual baiting, traps, shooting, and trained dogs (Mowbray 2002).

Subsequently on Motutapu, some pasture was retired and replanted with successional native species in order to increase the extent of coastal forest. Restoration activities and interpretation of historic sites are now coordinated and funded by a citizen volunteer group, the Motutapu Restoration Trust (www.motutapu.org.nz) in partnership with DOC. Early studies indicated that recovery of birdlife and the regeneration of forest would be either impossible or severely hampered by the remaining introduced mammals (Miller et al. 1994), and the restoration trust sought political support for the removal of all remaining pest mammals. The proposal was approved and announced publically by the prime minister and minister of conservation in 2006, with instructions for DOC to undertake the eradication as soon as practicable (R. Griffiths personal communication). In 2008, the project was notified under the Resource Management Act, an Assessment of Environmental Effects released for public scrutiny, the case for and against argued before independent commissioners, and legal processes completed.

The campaign against all seven species of mammals began in June 2009 with the aerial spread of rodenticide (brodifacoum) against the three species of rodents. Shortly before the third and final spread of bait, deaths were reported for unusually large numbers of pilchards (*Sardinops sagax*), and little blue penguins (*Eudyptula minor*), as well as eight common dolphins (*Delphinus* sp.). At least six dogs also became sick, suffered convulsions and died after being exercised on Auckland beaches. Speculation immediately began in the media that the dogs had died of 1080 poisoning, with the island eradication identified as the source. Once it became clear that 1080 had not been used since 1990, brodifacoum was then claimed as responsible, even though none of the dogs or dead marine life showed any signs of the internal hemorrhages associated with the toxicant. Extensive tests indicated that brodifacoum could not have been involved in the deaths of pilchards, penguins, dolphins, or dogs, and only minute traces were found in three penguins (www.doc.govt.nz/about-doc/news/

(*Continued*)

BOX 10.1 (*Contd.*)

issues/archive). The cause of the fish, penguin, and dolphin deaths remains unknown, but academics, government agencies and vets agreed that they were probably unrelated. The dog deaths were linked to tetrodotoxin (TTX), a highly toxic substance found in a range of marine organisms. A previously unknown accumulator of TTX was found to be the marine slug *Pleurobranchaea maculata*. Two months after completion of the bait drop on Rangitoto-Motutapu, dead slugs washed onto the beaches were finally identified as the cause of dog mortality, ending a sequence of events sufficiently bizarre to be labeled "the attack of the killer slugs" (Morton 2009). However, the demonstrated link to marine slugs was not enough to convince some members of the public, and a coalition of antitoxin organizations formed with the aim of banning the spread of toxins from the air.

In this example, the project to eradicate pests was initiated by stakeholder groups, had political support at the highest levels, and passed rigorous project design and public scrutiny. It may have suffered the disadvantage of being visible to a million residents of Auckland, but it also demonstrated that some citizen groups refuse to accept evidence based on science (Koubaridis 2009).

simply because it is possible. In early planning stages, stakeholders should be involved in the development of criteria to prioritize potential eradications. Open discussion and debate can produce broadly accepted criteria, as well as reasons for eliminating alternative approaches. If multiple islands are involved within fixed budgets, some form of priority-setting system will need to be applied within a conservation unit or region. Such systems are also likely to be accepted if there is wide agreement over the most appropriate criteria. Models for stakeholder participation in such processes are discussed in Chapter 12.

Preconditions and Limitations on Eradications

Among the obligate and desirable rules that govern the feasibility of eradications, two require particular attention. First, regardless of political and social support for the proposal, what regulatory constraints need consideration? Second, can the risk of reinvasion be managed, because this will be an ongoing maintenance cost against the project (Broome 2009)?

REGULATORY CONSTRAINTS

Regulations that govern the use of any method to eradicate populations of introduced animals vary by country. The regulations may include laws pertaining to animal welfare, humaneness of methods used to dispose of animals (see "Ethical Considerations" below), and the discharge of toxicants into the environment, as well as legal procedures to evaluate hazards and risks. In most countries, the complete eradication of an entire vertebrate population is one of the most controversial tasks an agency can attempt. In New Zealand, the Department of

Conservation has opted to take proposed eradications of pests using toxicants on large islands to public appeal through the Resource Management Act of 1991 (Broome 2009). This process requires submitters to prepare an Assessment of Environmental Effects, which is available to the public and through which objections can be raised to independent commissioners. There are also options for appeal of judgments by the commissioners through the courts. This provides a transparent process by which stakeholders can air their concerns, and risks are publicly debated to ensure accepted limits will be placed on the way the activities are conducted.

A similar process is used in the United States. The federal National Environmental Policy Act (NEPA 1969) is used to guide public officials to ensure notification of the public and other agencies, and to ensure that the environment is protected, restored, and enhanced as a result of actions proposed. In the case of eradications, the scale and methods used determine whether an environmental review or environmental assessment is required. If significant impact is likely, a detailed Environmental Impact Statement (EIS) is required. The EIS should discuss impacts, and alternatives that would avoid or minimize adverse impacts or enhance the quality of the human environments.

In the United States, toxicants are regulated by at least fourteen different federal acts. Many of the regulations associated with the registration and application of pesticides used in eradication projects are under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA 1972), which is administered by the Environmental Protection Agency. This agency determines how a pesticide, such as a rodenticide, can be applied, where it can be applied, and for what purposes. Registration of a new pesticide may take nine years, following which, periodical reviews of existing uses may result in a label changes. Currently, environmental fate and movement of pesticides is more scrutinized than in the past. Other acts, such as the Endangered Species Act and Clean Water Act, have additional monitoring requirements relative to the use of pesticides. Both NEPA and FIFRA provide the most significant regulatory framework in the design of eradication projects using pesticides in the United States.

Conservation biologists are often asked to assist with the approvals, but must rely on the well-documented results of past eradications as an essential tool to inform the public. Furthermore, as explained above, projects are likely to be seen as less controversial if stakeholder groups are involved in prioritizing and planning eradications, and broader-scale policies on invasive species management. Nonetheless, even with all of these components covered, unexpected problems can arise, as we show in Box 10.1 for the eradication of predators on Rangitoto-Motutapu Islands.

BIOSECURITY

Biosecurity involves risk assessment and the application of measures to protect natural resources from the arrival of unwanted organisms. Successful eradication of predators from islands can be undone if a new invasive species colonizes due to poorly designed or funded biosecurity. At least 40 species of introduced predators have invaded seabird islands (Chapter 3), and once introduced, they can often spread further by self-dispersal. Furthermore, the four species of rodents are adept stowaways and colonizers. Biosecurity measures against introductions of invasive species to islands rely heavily on education about the damage caused by introduced predators, because preventative measures are difficult to apply against unforeseeable problems. For stowaway species, educational programs must also focus on the risks of people as vectors for invasions in vessels or cargo. For example, the U.S. Fish and Wildlife Service joined with native groups to reduce the risk of invasions by rats into the Pribilof Islands (Box 10.2) and expanded the effort to other islands in a promotion called "Keep Alaskan Islands Rat Free" (www.stoprats.org). Regardless of invasion pathway, biosecurity against invasions requires networks of interception devices and educational material at departure and arrival locations. The tools used for biosecurity are similar to those used for eradication. However, their performance may differ greatly among

BOX 10.2

Biosecurity against Infestation of Islands from Invasive Species

Location: Pribilof Islands, southwest Alaska, USA
Climate type: cold temperate

The Pribilof Islands, sometimes referred to as "The Galapagos of the North," are a special case where human communities live close to large numbers of important wildlife resources, such as 2.5 million seabirds, nearly 750,000 fur seals (*Callorhinus ursinus*), and endangered Steller sea lions (*Eumetopias jubatus*). The villages on St. George and St. Paul islands were settled in the late 1700s, and although house mice became established in St. Paul village during the 1800s, rats have never become established on either island. A breeding population of rats in the Pribilof Islands would devastate the significant seabird colonies now present. A single pregnant female rat could infest an island, because of their dispersal abilities (Box 10.3) and high reproductive potential.

Faced with the threat of rodent invasion from increased commercial fishing activity, the communities of St. Paul and St. George, working with partners and stakeholders, started an aggressive rodent prevention program. Ecosystem Conservation Offices of the tribal governments were created on both islands. The primary goal was stopping any rat that jumped ship. The communities, commercial processors, and the U.S. Fish and Wildlife Service partnered to create a network of rodent prevention and detection stations throughout the town's harbors and dumps. To date, the 15-year-old program has captured six rats that were transported to St. Paul by vessels.

Additionally, St. George and St. Paul created city ordinances banning any ships with a rat aboard from city waters and the city dock (www.stoprats.org/stpaulordinance.htm). City authorities inspect vessels, and have ejected ships from their harbors that were known to contain rats. Local commercial fish processors are required to have rodent prevention programs, and the tribes offer rat prevention kits to boats (www.stoprats.org/kits.htm). The shore-based rodent prevention program in the Pribilof Islands is a long-term investment aimed at protecting natural biodiversity, and local community and industry participation are essential for its success.

species and locations. Tools effective after historic invasions, when predators have reached carrying capacity of the environment, may be much less effective when the same species has recently arrived and densities are low.

New Developments and Possibilities

The basic tools used for detecting and eradicating introduced predators differ little from those used in the fur industry 200 years ago. They still involve traps, guns, baits, and assistance from well-trained dogs (see also Courchamp et al. 2003). Until recently, the way these tools were used often relied on improvising with whatever products were locally available. For example, bait stations used in New Zealand during the 1980s against rats were made by hand from plastic drainage pipe, and baited with rat poisons available from supermarkets (Thomas and Taylor 2002). More recent successes have used technologies from other fields, and applied them with great effect against introduced mammals on islands. Foremost among these has been the use of helicopters to spread bait, move large quantities of equipment, and provide rapid access to inaccessible sites; more appropriate toxicants for use against rodents, including some subsequently developed for medicinal use; computerized mapping of bait broadcast using Global Positioning Systems, a development from satellite navigation systems; and DNA tracking of populations of invading species, effectively modeled on the DNA fingerprinting developed for forensic science.

Other advances have largely concentrated around increasing the efficiency of the products used. For example, laboratory trials with rats have indicated the characteristics of bait stations most likely to be entered (Spurr et al. 2006, 2007). Similar trials with mice and rats have tested the acceptance of various bait formulations (Morriss et al. 2008). In addition, animal welfare concerns about the efficiency of some traps, previously used for predators such as mustelids, has led to the design of more effective and humane traps (Poutu and Warburton 2005). These improvements were not accidental, but have been the result of coordinated scientific effort, substantial government funding, and international collaborations. For example, research institutions in New Zealand and Australia collaborate through Cooperative Research Centres (CRCs), with the Invasive Animal CRC established to improve the effectiveness of pest control (E. Murphy personal communication).

Of the key innovations listed below, five provide for the evaluation of the other devices and techniques used. They are of particular value against rodents, either in planning eradications or securing borders against reinvasion. Some of the remaining innovations have helped increase the scope and scale of eradications that have been achieved. However, the first of them, biological control, has been the most persistently applied solution to invasive species such as predators of seabirds, but has also been the one to most frequently create additional problems.

BIOLOGICAL CONTROL

Biological control is the use of natural predators, competitors, parasites, or diseases to suppress an established invasive population. Pest control with a biological agent rests on the assumption that one invasive species can be reduced or eliminated by the introduction of another, without irreversible impacts on native species or communities. Biological control has been successful in suppressing some agricultural pests, such as insects and weeds (Murphy and Evans 2009). However, when attempted on islands using such diverse vertebrates as feral pigs, several species of *Mustela* and *Herpestes*, cats, and foxes, it has generated some of the most difficult conservation problems we now face (Courchamp et al. 2003). In one particularly ill-conceived attempt, sugarcane growers in Jamaica introduced ants (*Formica omnivora*) as a way of suppressing introduced rodents, but the ants themselves became a problem. The growers then introduced cane toads (*Bufo marinus*) in an attempt to control ants and rodents together. When this also failed, and the cane toads became a pest, the growers' solution was to introduce the small Indian mongoose (*Herpestes javanicus*). The mongooses then preyed on native birds (Lever 1994), including the Jamaica petrel (*Pterodroma caribbaea*), which was last collected in 1879, seven years after the introduction of mongooses. The petrel is now presumed extinct (Brooke 2004).

Introduction of diseases has been attempted, and may temporarily reduce numbers, but on its own has yet to eliminate any population. Problems with the control of vertebrates using disease involve transmission, virulence, and short-term indirect issues such as prey-switching by other members of introduced predator guilds, and increased collateral damage to native populations. Even if effectiveness can be increased, unlike other approaches using traps or toxicants, biological control is a method that cannot be switched on and off in response to local conditions (Parkes and Murphy 2003). Furthermore, there is often strong public resistance to the use of viral disease control for vertebrates (Murphy and Evans 2009). The introduction of mammalian disease may provide an initial knockdown before the application of other methods, but we know of no examples where this was effective against seabird predators other than assisting with the removal of cats on Marion Island (van Rensburg et al. 1987, Courchamp et al. 2003).

Biological control using an infertile predator/competitor was accomplished on two islands (63 ha and 939 ha) on the Alaska Maritime National Wildlife Refuge. Sterilized red foxes were released onto the islands, which were inhabited by Arctic foxes (Bailey 1992). After several years, all Arctic foxes disappeared, probably through a combination of predation and competition by red foxes of the smaller Arctic fox. The upper size limit for islands where this might be effective is unknown. The method has potential on other islands, but has not been tried again.

Laboratory trials indicate that the fertility of vertebrates can be reduced using a genetically modified organism (GMO) such as a species-specific virus, bacterium, or parasite, to vector a vaccine that blocks reproduction. Known as virus-vectored immunocontraception, this technology may be a future tool for eradications, but must satisfy public concerns about the use of GMOs (Courchamp et al. 2003, Parkes and Murphy 2003).

DNA TRACKING

The DNA fingerprints of individuals can be used to monitor population structure and link individual animals to the wider population. For example, DNA tracking is now being used before eradications to identify the genetic composition of rat metapopulations and to determine the likely source of original invaders, whether groups of islands should be treated as one eradication unit, and the extent to which animals might swim between them (Robertson and Gemmell 2004, Abdelkrim et al. 2005). The same analyses can be used after eradications by assigning newly detected individuals to their source populations, and determining the likelihood of reinvasion from adjacent populations that cannot be eradicated (Russell et al. 2009). Furthermore, new individuals detected after an attempted eradication can be fingerprinted to determine whether they are survivors, which would indicate a failed eradication, or they represent a new invasion, which would indicate failed biosecurity (Abdelkrim et al. 2007, Russell et al. 2010b). Assigning genetic identity usually requires samples of 20 or more individuals from each of the most likely source populations. Where the data are for assessments of the efficacy of eradications, samples must be collected prior to eradication. Of course, genetic resources of introduced mammals on islands can be important in their own right for scientific study (e.g., Garkavenko et al. 2001).

TELEMETRY AND INTENTIONAL RELEASES

Telemetry has recently been used for island eradications and biosecurity. Sophisticated transmitters contain mortality sensors, can be linked to satellite navigation systems, and may be tracked online. They have been used in eradications to test the nontarget effects of the application of toxic bait, and to assist in the social attraction of residual animals at very low densities. Telemetry has also proved valuable for species as small as mice, to assess their behavior on islands and susceptibility to interception on arrival at a new location.

On Tuhua Island, New Zealand, secondary nontarget effects of the rodenticide brodifacoum were studied by fitting transmitters on feral cats before bait was broadcast by helicopter, targeting two species of rats. All cats with transmitters died after the baiting, suggesting that they probably ingested the bait through poisoned rats (Towns and Broome 2003, Broome 2009). Similar nontarget effects were investigated using radio transmitter ear tags with a mortality function on pigs, when eradication was attempted by aerial broadcast using brodifacoum at Maugatautari, New Zealand. All of the tagged pigs died, and no other pigs were subsequently detected (Speedy et al. 2007). Elsewhere, transmitters have been used on pest mammals to locate small groups or individuals at low densities. For example, during late stages of the eradication of pigs from Santa Cruz Island, California, transmitters were fitted to boars, and sterilized sows in estrus, as a means of locating any remaining animals (Ramsey et al. 2009). This use of telemetry cannot provide a statistical confidence in the likelihood of eradication success, but it can inform managers about the fate of individuals of a species during an eradication project. As we demonstrate below, telemetry can also provide important information on the population biology of animals at low density, simulating the survivors of target species during eradication projects, as well as new invaders (Russell et al. 2010a).

The effectiveness of biosecurity is difficult to assess when invasion rates are unknown. The absence of invaders may be a true reflection of low risk, but alternatively it may reflect frequent failed attempts to invade. Very often, the rate of island invasion cannot accurately be known until after eradication has taken place, such as on islands around New Zealand where invasion rates are not strictly a function of distance offshore (Russell and Clout 2005).

The intentional release of predators carrying transmitters onto islands can provide unique information on their population biology, community interactions, and detectability (Nellis 1979, Schoener and Spiller 1996, Russell et al. 2010a). Releases of invasive animals onto an island may at first seem counterintuitive, but this method can provide island-specific tests of biosecurity systems (Box 10.3), rather than relying on systems developed on other islands. Eradication planning could include a post-operation biosecurity system test by releasing sterilized individuals immediately following an eradication attempt. These individuals might also help to locate any survivors of the eradication as "Judas" individuals (Ramsey et al. 2009).

BOX 10.3

Intentional Incursions as Tests of Responses to Biosecurity: Razza the Amazing Rat

Location: Noises Islands, northeast New Zealand
Climate type: warm temperate

The Noises had a long history of rat reinvasion. Norway rats first colonized the Noises in 1956, probably as a result of garbage dumping in the harbor providing a raft for rats to follow the tidal current out past the relatively isolated islands. The first rat eradications in New Zealand were achieved on Maria Island and the David Rocks from 1960–1964. In 1978–1979, Norway rats were probably eradicated on the main Noises Islands (Otata and Motuhoropapa) during trials of rat eradication methods (trapping and poisoning) by Phil Moors and coworkers of the New Zealand Wildlife Service. Over the next 25 years, rats were eradicated from the Noises six more times using existing best-practice methods (Russell et al. 2008b). Given the large 2.2km distance from the nearest source population on Rakino Island, it was assumed that the eradication campaigns were failing. Only when Norway rats were finally eradicated from Rakino Island in 2002 did reinvasion of the Noises Islands stop. Rats were likely swimming the 2.2 km distance from Rakino Island to recolonize the Noises, although genetic samples are not available to confirm this hypothesis.

Due to its long history of rat reinvasion, Motuhoropapa was chosen as the focal site for a study of reinvading rat behavior, and the efficiency of rodent detection methods. Because rats had only recently been eradicated from the Noises for the final time, the flora and fauna were still marginalized from a 45-year history of rat invasion. Five male Norway rats were intentionally released on Motuhoropapa from 2004–2006, and monitored for approximately one month after release with nightly radio tracking (weeks one and three). The three rats that survived the entire three weeks showed ranging behavior much larger

(*Continued*)

BOX 10.3 (*Contd.*)

than usual for within interacting populations of Norway rats, and movement patterns that effectively did not differ from a random movement model, although rats did focus their activities around den sites (Russell et al. 2010a). Following monitoring, rats were removed in a test of island biosecurity systems. The most efficient system for removing rats was one that combined multiple strategies (such as traps, poisons, and rodent dogs), and used complete island coverage (Russell et al. 2008a). Hand-spread bait was particularly efficient at removing invading rats, which could be neophobic of devices such as traps and bait stations, particularly when bait stations were made of unnatural materials such as plastics (Spurr et al. 2006).

The first rat released on Motuhoropapa evaded capture for a total of 18 weeks, following radio-collar failure, and swimming over 400m to neighboring Otata Island. On both islands, this rat ranged widely, presumably searching for other rats. With abundant natural food resources in the recovering habitat, the rat avoided artificial devices set to capture him. Only when a rodent dog located the rat's home range on Otata, and a single trap was set, baited with highly attractive natural food (dead penguin), was the rat caught (Russell et al. 2005). The account was fictionalized into a New Zealand children's story book by Witi Ihimaera: *The Amazing Adventures of Razza the Rat*, about a rat that captured the world's attention by demonstrating its remarkable ability to swim and evade detection.

TRAINED DOGS

Dogs have been used for millennia as tools for tracking and holding other animals, and for at least 100 years to locate threatened species of ground dwelling birds in countries such as New Zealand. Historically, their efficiency with finding species of birds such as kiwi (*Apteryx* spp.) was such that they have since been specifically trained to detect a range of invasive predators, including cats, mustelids, hedgehogs (*Erinaceus europaeus*), and rodents. The effectiveness of dogs for detecting newly arrived predators was demonstrated in New Zealand when two rat-free islands were reached by individual Norway rats in 2008. On Motuora Island (80 ha), no dogs were available after rat footprints were seen, so destruction of the rat was attempted using traps. This required 14 person-days of effort, and the use of 400 traps at a direct cost of NZ $18,000 (R. Renwick personal communication). On Motuihe Island (195 ha), after rat footprints were detected, a rodent dog was employed from the outset. The rat was detected and destroyed within 24 hours at a cost of less than NZ $ 5,000 (F. Buchanan personal communication). Trained dogs with hunters were responsible for detecting 60% of the last 63 pigs on Santa Cruz Island (Parkes et al. 2010), but were surprisingly ineffective against cats on Hauturu in New Zealand (Veitch 2001). A range of specially trained dogs is being used to detect the presence of stoats (*Mustela erminea*), rabbits, cats, and hedgehogs on Rangitoto-Motutapu Islands (R. Griffiths personal communication; Box 10.1). Field trials suggest that properly trained rodent dogs can have a success rate of over 80% (Gsell et al. 2010), and are an important tool for rodent biosecurity (Russell et al. 2008a). Confidence in the use of dogs could be further enhanced if a modeling approach to detection probabilities was applied (see below).

MODELING

Modeling techniques can give managers more confidence in the decision-making process during pre-eradication cost-benefit and risk analysis (Leung et al. 2002, Baxter et al. 2008), as well as in post-eradication survivor and biosecurity monitoring (Regan et al. 2006, Hauser and McCarthy 2009). The Bayesian approach has been particularly powerful, allowing models to incorporate prior information based on species biology and expert advice (Low Choy et al. 2009).

Cost-benefit analysis models for invasive species can be optimized for the time of intervention, and to determine whether control or eradication is the better approach. A cost-benefit model applied on Lavezzu Island indicated that eradication of rats for seabird conservation was more cost effective than six years of control by untrained staff (Pascal et al. 2008), although biosecurity costs were not included. Models can also formalize the prediction of confidence with which a species has been eradicated. Detection models accurately predicted the failed eradication of musk shrews (*Suncus murinus*) from Île aux Aigrettes due to early termination of the trapping program (Solow et al. 2008), while the eradication of pigs from Santa Cruz Island was declared successful when the probability of survivors dropped below 5% (Ramsey et al. 2009).

Biosecurity systems can be strengthened when a rigorous statistical approach is applied that incorporates the unique behavior of individuals and detection devices at low density. Intentionally released Norway rats on islands off the coast of New Zealand allowed the random behavior of individuals to be modeled (Russell et al. 2010a), while simultaneously testing the efficacy of a range of rodent detection devices (Russell et al. 2008a). Such data allowed a statistically rigorous and defendable biosecurity system to be implemented on Barrow Island off Western Australia (Jarrad et al. in press). The Bayesian approach further allowed expert opinion to be weighted and incorporated into the Barrow Island system.

CURRENT AND PROPOSED TOXICANTS

A decisive breakthrough for the eradication of seabird predators on islands was the development of anticoagulant toxicants for use against rodents (Towns and Broome 2003). As the name suggests, the most effective rodenticides were those that impede blood coagulation, resulting in death from hemorrhage and hypovolemic shock. All anticoagulants now commonly used have the benefit of delayed toxicosis. Symptoms are separated from the time of ingestion by a prolonged period, usually 4–10 days, making it impossible for rodents to associate the bait with any ill effects. This ensures rodents continue to feed on the poison, often long after a lethal dose has been consumed. All anticoagulants are multiple feeding compounds, which is why they are referred to as chronic rodenticides. The first-generation products, such as warfarin, are widely used in urban and agricultural settings; however, rodents began to develop resistance in some large cities from improper use. The second generation of compounds was specifically designed to kill resistant animals, and is far more toxic and persistent, as well as less species-specific. Details of the derivation and mode of action of these toxicants are provided by Erickson and Urban (2004) and Eason and Ogilvie (2009).

The most potent of the anticoagulants is brodifacoum. Because brodifacoum is slow to be metabolized from animals, in some island systems it has produced extensive nontarget mortalities (Erickson and Urban 2004). The nontarget effects have nonetheless provided unexpected benefits in complex multipredator systems in New Zealand, although intentional use in this way is not approved in the United States. On the other hand, slow metabolic and environmental breakdown, accumulation in the food chain, and secondary poisoning probably contributed to the more than 400 bird carcasses found on Rat Island, Aleutians (2777 ha) 8 to 10 months after an aerial broadcast of brodifacoum against Norway rats (*Rattus norvegicus*) in 2008. Most birds found were glaucous-winged gulls (*Larus glaucescens*) and bald eagles (*Haliaeetus leucocephalus*), but included twelve other species. All gulls and eagles tested were positive for brodifacoum. Liver tissue from one rock sandpiper *(Calidris ptilocnemis*) and one peregrine falcon (*Falco peregrinus*) was tested, and also confirmed exposure to brodifacoum. Some risk to gulls was predicted, but bald eagle mortality was unexpected since only seven eagles were observed on the island during the broadcast. Eagles may have scavenged dead and dying gulls or rats. Some dead birds had the highest brodifacoum residues ever recorded for birds after an eradication operation (S. Ebbert unpublished data).

Recent research on toxicants is concentrating on three areas: reduced nontarget mortality, improved efficacy of existing products, and creation of new products that are effective but specific to particular pest species (Tobin 1994, Fisher 2005, Eason and Ogilvie 2009). Nontarget mortality can be reduced through the use of more specific and less persistent anticoagulants, some of which are currently being used in Hawaii. Another approach is to combine two toxicants in the same bait, which can increase potency on the target species by synergistic effects (Eason and Ogilvie 2009). Species-specific toxicants are now in development that may be applied against pigs (Thomas and Young 1999), mustelids, foxes, dogs, and cats (Eason and Ogilvie 2009). One of these is the toxicant para-aminopropiophenone (PAPP), which was originally studied as a protection from radiation. PAPP is highly effective against carnivores, and less toxic to birds and humans (Savarie et al. 1983). The toxicant is being developed to target stoats, cats, dogs, and foxes, and its effectiveness against rodents is under investigation (Eason and Ogilvie 2009). Because of the rapid onset of impaired oxygen fixing ability leading to unconsciousness, PAPP is likely to be considered more humane than products such as brodifacoum (Mason and Littin 2003, Eason and Ogilivie 2009).

In sum, the aerial broadcast of toxicants has been pivotal for large-scale and topographically challenging eradications of introduced predators of seabirds on islands, especially those without endemic mammals. Furthermore, despite nontarget impacts and slow mode of action, brodifacoum is still used most frequently for eradication projects against rodents on islands (Howald et al. 2007), especially in New Zealand (Clout and Russell 2006). The development of new ways to use safer products for eradication is currently in the later stages of development. However, the use of new products, or revised techniques for fast acting compounds, will still require the same process of careful field trials as those applied to other toxicants (e.g., Towns and Broome 2003, Broome 2009).

MULTIPLE PEST ERADICATIONS

As the size of islands increase, so too does the likelihood that past or present human use has left more than one species of introduced predators. For example, fur trappers in Alaska and Russia quickly learned that the foxes might not survive once seabirds were depleted. To ensure an adequate food supply for newly stocked fox populations, sometimes trappers introduced smaller mammals such as voles (*Microtus* spp.) and arctic ground squirrels (*Spermophilus parryii*; Bailey 1993), which are also predators of seabirds or their eggs (see Chapter 3). Similarly, once islands became permanently inhabited, rodents frequently arrived by accident and cats were sometimes introduced to control them (see biological control above). Historically, these legacies of invasion have tended to be treated piecemeal; if eradications were attempted, they could only be carried out against those species that technology allowed at the time. For example, 11 species of mammals were introduced to Kapiti Island (1965 ha), New Zealand, five of which are known or likely predators of seabirds. The first eradication (pigs) was completed by shooting in 1902, and the last (rats) was completed using aerial broadcast of rodenticide bait from helicopters, 94 years later in 1996 (Towns and Broome 2003, Fuller 2004). These separate operations raise the risk that the removal of one invasive species may lead to the proliferation of another, and perhaps even greater damage to native species through indirect interactions (see also Chapter 9).

Earlier in this chapter, we gave examples of the very large size of islands from which introduced seabird predators have been removed. We have also identified where improved planning can reduce the time required for eradications to succeed. Some eradications are now being undertaken that combine an understanding of food webs, the relationships between introduced species, the mode of activity of toxicants, and all of the components of good planning (e.g., Zavaleta 2002). For example, cats and rats have been eradicated simultaneously on islands in Mauritius (Bell 2002), the Seychelles (Merton et al. 2002) and New Zealand (Towns and Broome 2003, Broome 2009). Here, the nonspecificity and persistence of brodifacoum was documented in the field, rodents (rats or mice) were targeted as the basal predator, and the effects of a trophic cascade were assessed through the food chain to apex predators (cats). In effect, toxic rodents were the bait for their predators. A similar approach was applied to a more complex predator guild on Motutapu-Rangitoto Islands (Box 10.1) in 2009 (Broome 2009). Such operations usually still require additional methods to eliminate the last surviving predators. For example, over 1000 traps for stoats and mice were set permanently on Rangitoto-Motutapu Island, and specially trained dogs were used to search for the remaining hedgehogs and cats and any sign of rodents and stoats. To date, there has been no sign of stoats or rodents, with dogs and traps only required for residual cats and hedgehogs (R. Griffiths personal communication).

Problems and Impediments

POOR DISTRIBUTIONAL DATA

Eradication campaigns cannot be designed or implemented if the identity of target species is unclear. The lack of accurate data on the distribution of invasive species within archipelagos is almost global. For example, within-archipelago distributions of seabird predators provided in Chapter 3 were selected from those few where data are available. The number of islands where data were complete determined the sample sizes within archipelagos. Even within this modest sample, large numbers of islands were excluded because the identity of some predators (especially rodents) had not been determined (D.R. Towns unpublished data). Without accurate distributional data, it is difficult to determine the range and intensity of the effects of introduced predators on seabird populations. Furthermore, the rate of new invasions is also unclear.

Atkinson (1985) used historical data to estimate rates of invasion by rats onto islands from 1840–1980, and found a spike in the frequency of invasions from 1941–1960, which coincides with very large amounts of equipment moved between islands during World War II. The average invasion rate was approximately 7 invasions per 20-year period. By comparison, Howald et al. (2007) identified 332 successful rodent eradications, almost all over the previous 20 years. They also provided data on the rate of failures (9.5%), which is probably an underestimate because most failures remain unreported. Whether the rate of eradication of introduced predators exceeds the frequency of invasion remains unclear, due to the lack of recent data on invasions (but, see Clout and Russell 2008). Nonetheless, with numerous successful eradications of rats, cats, foxes, and pigs, there are now parts of the world where the rate of removal of pests exceeds the rate of invasion (Russell et al. 2008a).

REGIONAL ISSUES

Eradications of the larger, widespread vertebrates, such as pigs and cats, have been equally successful in temperate and tropical environments (Parkes and Panetta 2009). However, technology for the eradication of rodents was developed in temperate areas and based upon seasonal variations in the food supply. This is especially the case for aerial broadcast of toxicants, which are usually conducted in winter when rodent populations are stressed by seasonally low natural food supplies. In tropical environments, the population dynamics of rodents are less well understood, and may vary according to weather and when sites are wet or dry. So far, successful eradications of rats from tropical islands have rarely been achieved on islands >100 ha, but are regularly achieved in temperate areas (mainly New Zealand) on islands over 10 times this size (Howald et al. 2007). Tropical islands have the complicating effects of more rapid decomposition of bait in warm, humid environments, and potential competition for bait by native species such as land crabs. Considerable work is now being undertaken in the tropical Pacific to assess the extent of these problems (S. Boudjelas personal communication).

However, not all seabird predators are widespread, so there is little incentive for a global approach to their removal. For example, across the 10 archipelagos analyzed in Chapter 3, 26 species of introduced predators of seabirds were identified, half of which were found only in one archipelago. Included among these were Australian brush-tailed possums (*Trichosurus vulpecula*) and stoats in New Zealand; Argentine grey fox (*Pseudalopex griseus*) in the Falkland Islands; Arctic foxes, ground squirrels (e.g., *Spermophilus paryii*), voles, and deer mice (*Peromyscus* spp.) in the Aleutian Islands; several species of monkey in Cuba; and barn owls (*Tyto alba*) in Hawaii. For some species, such as foxes, the technologies for control may be exportable between archipelagos. However, for others, such as possums, monkeys, and barn owls, local solutions may need development.

PATCHY DATA ON BENEFITS

A crucial requirement for extending the effects and effectiveness of invasive predator removal is support from the public, politicians, and funders. Widespread support is vital when sectors of the public question the methods and ethics of eradication (see Chapter 12). The key to this support is using the techniques with the least possible negative impacts on nontarget species and the environment, and effective and accurate reporting of how eradications benefited native biodiversity, especially when the eradications are controversial (e.g., Box 10.1). However, such data have tended to be scattered, buried in the reports of government agencies, or not reported at all (Simberloff 2002). This is an acknowledged problem for eradications in New Zealand, where the outcomes of eradications have only been measured for selected species on eight large projects completed since 1996, despite operational costs of $NZ 6 million (Broome 2009). This apparently reflects a mindset among managers that removal of invasive species is a necessity, but monitoring the recovery of native species after the event is an optional luxury (K. Broome personal communication). Failure to measure and communicate the costs and benefits of eradications can have wide repercussions. First, despite claimed benefits to biodiversity, funders may become reluctant to support new initiatives if the outcomes of previous financial outlays are not clear. Second, those opposing the removal of introduced predators can use the absence of data, or the presence of inconclusive results, to cogently argue that the costs of methods used outweigh their risks. The danger is that the most effective methods for predator removal will then be withdrawn due to political pressure. These risks should be greatly reduced if a program of targeted monitoring is identified and included within the design of each project.

Public Perceptions of Eradications

ETHICAL CONSIDERATIONS

Decisions about management of the eradication of introduced predators on islands reflect those required for any introduced organism. Like many conservation activities, these decisions are based on value judgments and links with legal requirements within the planning processes described earlier. Value judgments are a reflection of how people view introduced species within the political and cultural landscape of individual countries (see also Chapter 12). Therefore, *whether* an action should be undertaken is a reflection of local value systems. *How* that action is undertaken requires another set of decisions, including assessments of the suffering incurred by target species.

Conservation managers face a philosophical dilemma that weighs animal ethics (e.g., Littin et al. 2004) against environmental ethics (e.g., Marks 1996). In many countries, actions that cause unnecessary suffering to individual animals are regarded as abhorrent, with legislation enacted to protect the animals from abuse (e.g., USDA Animal Welfare Act, as amended). On the other hand, introduced animals (in particular), can inflict harm to native species and ecosystems. Conflicts arise when species, communities, or ecosystems protected by environmental regulation, such as the U.S. Endangered Species Act, are seemingly at odds with introduced animals, which are protected to differing degrees by animal welfare regulations (Perry and Perry 2008). For example, the number of seabirds that a single introduced predatory cat or fox can kill (see Chapter 3) gives utilitarian weight to removing the introduced predator. Thus, where there are obligations or regulations to protect systems subjected to a human disturbance, we must take actions to mitigate the impacts of introduced species. However, the actions should be taken within the overarching goal of community and species restoration. Killing introduced vertebrates just because they are present is not acceptable—unless, of course, it is to thwart the establishment of a newly arrived invasive species.

Acknowledgement of this point has resulted in a shift to evidence-based conservation, where the removal of introduced predators has been shown to have significant benefits in the recovery of native species (Green 2002, Miskelly and Roberston 2002, Sinclair et al. 2005, Whitworth et al. 2005, Smith et al. 2006, Bellingham et al. 2010), as long as the removal itself does not cause lasting harm to nontarget species or the environment. Given an established need for remedial action against introduced species, whether specific actions are appropriate may fall within an assessment of environmental impacts or animal welfare. The objective of animal welfare is to minimize the suffering of the individual, and judgment within this criterion requires an understanding of neurophysiology. Those animals capable of detecting pain are referred to as "sentient" (having sense). Since most predators of seabirds are vertebrates (see Chapter 3), they are sentient and are directly affected by welfare considerations.

The most humane methods for pest control may not be the most cost-efficient or suitable for complete eradication. For example, labor intensive ground-based methods can achieve the same objectives, but sometimes at a greater economic cost than aerial broadcast projects (Thomson 1986, Towns and Broome 2003), and may limit the size of islands from which eradication can be achieved. In these circumstances, alternative methods may be justified, especially when ongoing ecosystem decline is well documented and no alternatives can be found. Sometimes, methods that at first appear humane can in fact lead to greater suffering. For example, hedgehogs introduced to the Uist Islands in Scotland became a major pest of breeding shorebirds (see Chapter 12). The solution preferred by the public was live capture and translocation of hedgehogs back to their “native” range on the mainland U.K. However, subsequent studies revealed that the live capture, long-term holding for disease monitoring, and subsequent reintroduction into high-density populations with resident hedgehogs, in fact led to greater suffering of individual hedgehogs (Uist Wader Project 2002).

Ethical standards fluctuate (Eggleston et al. 2003), and absolute distinctions between what is right and wrong will differ among regions, and even among projects. Most importantly, conservation managers must seek a middle ground that fairly balances stakeholders’ environmental goals of ecosystem restoration with appropriate environmental assessment and animal welfare standards. The dilemmas faced by conservation managers can be addressed if they subscribe to ethical obligations for wild animal management (Litten et al. 2004). These are that: (1) the most humane of all available methods should be used; (2) active attempts should be made to improve the humaneness of available methods, thereby reducing harmful effects over the medium term; and (3) active attempts should be made to develop new and more humane methods, thereby reducing harmful effects over the long term. This approach enables practitioners to retain ethical credibility by committing to an ideal: methods for the control or eradication of sentient species that are effective, affordable, humane, specific to nominated target species, and safe for operators and in the environment. Even if this ideal solution becomes available, the most locally appropriate management methods will still need to be pursued and applied to protect native species from threats to their existence.

CITIZEN-BASED INITIATIVES

Issues over ethics and public perception may seem complex, or even overwhelming. However, the fundamental point is that the public often needs to have a role in setting priorities for eradication of invasive predators and the restoration of seabird islands (Chapter 11). The changing public attitude to invasive species is now reflected in numerous citizen-led restoration projects underway in many countries (see Chapter 12). In some areas, this has also involved introduced predator eradication projects that have been initiated, or even conducted, by citizen groups. One such example was on Mokolii Island off the coast of Oahu in Hawaii, when a flotilla of unlikely craft (including surfboards) ferried 10 volunteers and a state conservation worker to set traps and bait stations to remove ship rats. At only 1.6 ha, this eradication was on a very small scale. Nonetheless, it was followed by increases in survival of wedge-tailed shearwaters, and demonstrated how communities could make a difference (Smith et al. 2006). The direct involvement of volunteers in larger projects is problematic because of potential health and safety issues and the need for specialized training. However, there have been attempts at village-based eradication of rats in Fiji (Chapter 12). Increasingly, large projects have involved community groups that either apply for the funds, or form partnerships with government agencies. For example, the eradication initiative on

Rangitoto-Motutapu Island was a citizen-sponsored project (Box 10.1). Similarly, an attempt to eradicate two species of rats and stoats from 20 islands and islets off northeastern New Zealand in 2009 was largely conceived by a citizen group, the Guardians of the Bay of Islands. This group integrated interested locals, Māori groups, private landowners on the islands, and government agencies into a management partnership over an entire archipelago (www.boiguardians.co.nz).

Conclusions

Any attempt to remove species that have been introduced into new environments can be extremely challenging (Myers et al. 2000), and to some may still seem impossible (Simberloff 2002). The counter to such attitudes can be found in the numerous examples where this challenge has been met; some of the most inspirational of these are from islands where reinvasion is unlikely (Simberloff 2002). They include almost all of the most widespread seabird predators, have become increasingly large and complex operations, and are succeeding in many countries. Historically, the most intensive activity has been in Alaska, New Zealand, and Western Australia, with a wide scattering of examples in French Territories and the tropical Pacific and Indian oceans. More recently, introduced predators of seabirds have been cleared from numerous islands off Mexico, and there have also been successes in such widespread locations as the United Kingdom and the Galápagos. These successes have been supported by technological advances, but are also tempered by some impediments. First, some introduced species are confined to specific climatic regions that may require the development of local solutions. The success of this can be seen in the Aleutian Islands, where a range of effective techniques have been applied against introduced Arctic foxes. Whereas, at the other end of the climate scale, on tropical islands, there have been few removals of mongooses, although they have been widely released. Furthermore, technologies for the large-scale removal of rodents developed in temperate areas such as New Zealand have yet to be applied on a similar scale in the tropics. Nonetheless, there are now island archipelagos in the Aleutians, Mexico, New Zealand, and the tropical Pacific, where populations of seabirds that once experienced catastrophic declines are now flourishing for the first time in centuries (see also Chapter 3).

Despite some caveats, technological advances have enabled increasingly large and complex projects to be attempted. Until recently, successful eradications have relied on improvisation around existing technology. For example, eradications of rats used rodenticides designed for urban use and in farm buildings. These products were then broadcast from the air using methods borrowed from agriculture. Today's eradications are now effectively supported by a unique blend of specialized disciplines. These include new developments in invasion ecology, which combines behavioral science, community ecology, genetics, and modeling; the use of specially trained dogs to detect new incursions and locate the last survivors of eradication projects; the use of telemetry to test the effectiveness of eradication methods, locate the last few animals, and test biosecurity systems through intentional incursions; and the development and testing of new toxicants. Instead of borrowing from other fields, a new scientific approach to eradication is not only creating its own momentum, but may provide new methods for pest management and biosecurity.

Even without new developments, the upper size of areas possible for eradications of predators of seabirds using existing technology is unknown (Towns and Broome 2003). However, as the size of islands where eradications are attempted increases, so too does exposure to the public. Increased public interest brings increasing potential for conflict between those who advocate for the removal of problem species for the restoration of island ecosystems, and those who dislike the methods used. One solution is to better inform the public of responses of seabird species affected by introduced predators. But for this to happen, two other issues need resolution. First, the methods used for successful eradications need to be reported in high quality international journals (Simberloff 2002). Second, the outcomes for biodiversity need to be measured and documented, since the justification given for eradications is based on such benefits. This is a particular failing, even in New Zealand with its long history of pest removals (Broome 2009), and as a result, opportunities to identify the effects of some invasive species have sometimes been lost. For example, failure to comprehensively document responses of resident species to the removal of pigs in 1936 from Aorangi Island, New Zealand, has been at the cost of informed debate about the effects of pigs elsewhere. Furthermore, the benefits of the eradications are central to ethical debates about the reason for removing introduced species, and the methods used.

These debates require decisions that are political (whether to proceed) and regulatory (how to proceed). In effect, there are layers of value judgments, complicated by a range of philosophical and ethical issues. Animal rights activists are only willing to go partway with this debate if they assert that all wild animals have a right to life regardless of their origins or effects. Conservation biologists argue that such a stand ignores the effects of the introduced species, and can doom native species to local extirpation or total extinction. These views have been debated by ethicists, who concede that if harm to native species and ecosystems can be demonstrated, the removal of introduced species is justified as long as the methods used are the most humane available, and negative impacts on nontarget species and the environment are reduced to the lowest possible level while still being effective.

Science has a crucial role in this debate. For example, since justification for the eradication of introduced predators may be potential harm to species such as seabirds, there need to be robust data on these effects. Agencies need information on the efficacy and negative impacts of the methods available and the potential development of new ones. The public needs information on environmental safety, and the way species and ecosystems respond after the eradications are completed. This information should form a feedback loop that assists with further regulatory development. Of course, the most important of these components is the public. If the evidence can be delivered in a scientifically defensible form that is useful and understandable to the public, and the outcome of eradications are there for people to see, pest removals should attain growing public support. The evidence of such support can be seen where citizens have chosen to undertake eradications, or volunteered their time to assist with them (see also Chapter 12). This may only be possible on a relatively small scale, such as Mokolii Island in Hawaii but, as has been found in New Zealand, it can lead to public pressure for governments to undertake much larger and more complex attempts. Furthermore, there are now increasing examples of extraordinarily ambitious projects undertaken against introduced predators through a multidisciplinary approach, including the application of specialists at each level of planning and implementation (Broome 2009). The extent to which this can improve prospects for whole ecosystems, rather than individual species of seabirds, is only now being investigated and forms much of the content of the next chapter.

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