Factors leading to successful island rodent eradications following initial failure

Article *in* Conservation Science and Practice · March 2021

DOI: 10.1111/csp2.404

Araceli Samaniego-Herrera
Manaaki Whenua - Landcare Research

Peter J Kappes
Western EcoSystems Technology Inc.

Keith Grant Broome
New Zealand Department of Conservation

Steve Cranwell
BirdLife International

Received: 15 December 2020 | Revised: 21 February 2021 | Accepted: 25 February 2021

DOI: 10.1111/csp2.404

REVIEW

Conservation Science and Practice
A journal of the Society for Conservation Biology
Open Access

WILEY

Factors leading to successful island rodent eradications following initial failure

Araceli Samaniego[1] | Peter Kappes[2,3] | Keith Broome[4] | Steve Cranwell[5] | Richard Griffiths[6] | Grant Harper[7] | Pete McClelland[8] | Russell Palmer[9] | Gérard Rocamora[10] | Keith Springer[11] | David Will[6] | Shane Siers[2]

[1]Manaaki Whenua—Landcare Research, Auckland, New Zealand

[2]USDA APHIS Wildlife Services, National Wildlife Research Center, Hilo, Hawaii

[3]Coastal Research and Extension Center, Mississippi State University, Biloxi, Mississippi

[4]New Zealand Department of Conservation, Wellington, New Zealand

[5]BirdLife International, Suva, Fiji

[6]Island Conservation, Santa Cruz, California

[7]Biodiversity Restoration Specialists, Murchison, New Zealand

[8]Invercargill, New Zealand

[9]Science and Conservation Division, Department of Biodiversity, Conservation and Attractions, Kensington, Western Australia, Australia

[10]Island Biodiversity & Conservation Centre, University of Seychelles, Mahé, Seychelles

[11]Canterbury, New Zealand

Correspondence
Araceli Samaniego, Manaaki Whenua—Landcare Research, 231 Morrin Road, St Johns, Auckland 1072, New Zealand.
Email: samaniegoA@landcareresearch.co.nz

Abstract

Island rodent eradications are increasingly conducted to eliminate the negative impacts of invasive rodents. The success rate in the tropics has been lower than in temperate regions, triggering research and reviews. Environmental factors unique to the tropics (e.g., land crabs and year-round rodent breeding) have been associated with eradication failure. Operational factors have also been important, but these have not been comprehensively assessed. The environmental and operational factors using global cases where rodent eradication initially failed and subsequent attempts occurred were compared. It was determined whether operational factors explained the initial failures, whether operational improvements explained subsequent successes, and whether re-attempting eradication after failure was worthwhile. About 35 eradication attempts on 17 islands, each with 1–2 species from a total of 5 species (*Mus musculus* and 4 *Rattus* spp.) were identified. On 14 islands (82%), eradication was achieved on the second (86%) or third attempt (14%). On the remaining 3 islands, eradication was not achieved. Evidence of operational faults for all failed attempts was found (e.g., poor planning, low quality bait, and gaps during bait application). In some cases, operational faults were unequivocally the cause of failure, but in others, it was impossible to discriminate from confounding, environmental factors. Nonetheless, failures appeared to be mainly the result of not exposing all rodents to a lethal dose of toxin, violating a crucial eradication principle. This can cause operational failure on any temperate or tropical island. However, there may be less tolerance for errors such as gaps in bait coverage on tropical islands, mainly due to bait consumption by land crabs. The findings on factors leading to eradication success (e.g., expert reviewed plans, realistic funding and permits, high standard baiting operations) reflect current best practice recommendations. Strict adherence to best practice is expected to increase overall rates of eradication success.

KEYWORDS

best practice, eradication principles, *Mus*, *Rattus*, rodenticide, tropical island

1 | INTRODUCTION

Invasive rodents (*Mus musculus*, *Rattus exulans*, *R. norvegicus*, *R. rattus*, and *R. tanezumi*) have been inadvertently spread around the globe by humans; their detrimental impacts on island ecosystems (Angel, Wanless, & Cooper, 2009; Kurle, Croll, & Tershy, 2008; St Clair, 2011; Towns et al., 2009; Towns, Atkinson, & Daugherty, 2006) and the benefits of their removal (e.g., Bellingham et al., 2010; Jones et al., 2016; Rocamora & Henriette, 2015; Towns, 2009; Towns, 2011) are well documented. Pioneered in New Zealand, rodent eradications were largely accidental at first (1960–1976), when rodent reduction efforts unexpectedly resulted in complete extirpation of the target species. Rodent eradications then entered an experimental phase (1977–1986) and, since the late 1980s, have become systematic operations (Towns & Broome, 2003). Likewise, the first successful trial of the aerial broadcast technique occurred in 1990 (Garden, McClelland, & Broome, 2019). Following New Zealand developments, eradications have had a similar history elsewhere (e.g., Rocamora & Henriette, 2015; Samaniego et al., 2011), with increasing success rates over time despite increasing island size (Figure 1). About 600 islands have been cleared of invasive rodents (DIISE, 2019), with many projects comprising complex multi-species eradications (e.g., Macquarie and South Georgia Islands, Springer, 2018; Martin & Richardson, 2019) or operations in challenging habitats such as mangroves (Samaniego et al., 2018). Advances in methodology (e.g., use of helicopters to spread second generation anticoagulants using GPS guidance), confidence from past successes, and positive outcomes driving funding have allowed such increases in size and complexity (Holmes et al., 2015; Howald et al., 2007; Russell & Broome, 2016).

The core eradication principles currently in use include: (a) all target animals are put at risk by the eradication technique(s); (b) target animals must be removed at a rate exceeding their rate of increase at all densities; and (c) immigration must be zero (Cromarty et al., 2002; Parkes, 1993). Best practice for meeting these principles was developed for temperate islands by the New Zealand Department of Conservation (DOC) and other agencies (Broome et al., 2011a; Broome et al., 2011b; Broome et al., 2017; Broome, Golding, Brown, Corson, & Bell, 2017; Keitt et al., 2015; Phillips, 2019; Thomas, Varnham, & Havery, 2017). The New Zealand system emerged from the advisory work of the Island Eradication Advisory Group (IEAG; Cromarty et al., 2002; Broome et al., 2011). Best practice advice was collated from this group and first labeled "best practice" in 2006, although all the recommended practices had been in use for some time by DOC (Cromarty et al., 2002; Thomas & Taylor, 2002). Once declared "best practice" it provided a benchmark for projects against which improvements could be formally adopted and promulgated in subsequent iterations. Through adaptive management and strict adherence to best practice, New Zealand has achieved an outstanding rate of success (Russell & Broome, 2016; Towns & Broome, 2003) even for invasive mice—once thought to be difficult to eradicate (Broome et al., 2019). Although house mice appear to require proportionally higher doses of anticoagulants than some rat species (Broome, Fairweather, & Fisher, 2012), and lab trials have suggested conventional bait is not as palatable as other foods (Cleghorn & Griffiths, 2002), house mice can be reliably removed, even on large islands (e.g., Antipodes Island; Broome et al., 2019; Horn, Greene, & Elliott, 2019). Indeed, all mouse eradications in the past 14 years have been successful (Figure 1). Laboratory trials are useful to assess efficacy of baits and

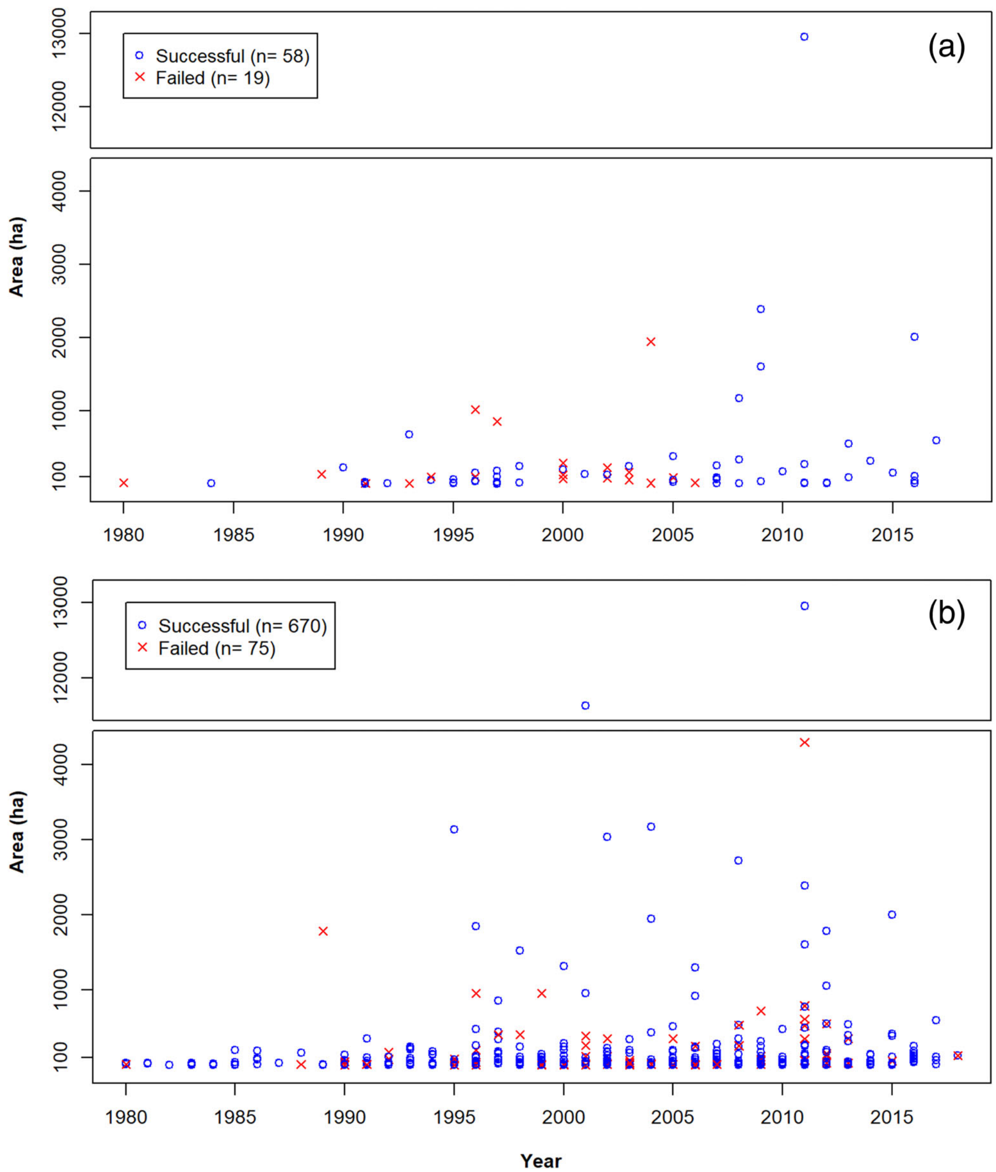

FIGURE 1 Global mouse *M. musculus* (a) and rat *Rattus* spp. (b) eradication attempts (1980–2018) and their outcomes. Source: DIISE (2019); only cases with good quality data and with confirmed outcome by 2018 are included

devices, but there is a need for follow-up trials in natural situations (e.g., Wanless et al., 2008) as well as detailed documentation during actual eradications.

The smaller number of islands and cumulative area treated in tropical regions compared with temperate regions can be partly explained by the evolution of rodent eradications. There was a delay between the pioneer work in temperate New Zealand and its application to tropical regions, where several organizations have been building capacity in addition to adapting best practices designed for temperate regions. Mexico and Seychelles are good examples of countries that have developed national capacity while adapting techniques for tropical regions (Aguirre-Muñoz et al., 2018; Rocamora, 2019). However, the overall lower eradication success rate in the tropics (Russell & Holmes, 2015) is more difficult to explain, and the causes are unresolved (Samaniego et al., 2020). Guidelines for rat eradications on tropical islands were developed to improve the success rate, acknowledging the existence of critical knowledge gaps (Keitt et al., 2015).

A statistical analysis by Holmes et al. (2015) found factors unique to the tropics, such as warm temperatures, presence of land crabs and coconut palms were clearly associated with eradication failure. A later review of a selected subset of tropical island cases (4 successful and 4 unsuccessful) using a qualitative approach (Griffiths et al., 2019) suggested that rat breeding and diet might be contributing causes of eradication failure. However, recent research on these aspects (Samaniego, Griffiths, Gronwald, Holmes, et al., 2020) concluded that eradications on tropical islands can be successful despite abundant natural food, high density of land crabs, and high density of reproductively active rats, which is consistent with other studies (Merton, 2001; Merton, Climo, Laboudallon, Robert, & Mander, 2002; Rocamora & Henriette, 2015). Crucial to eradication success is exposing all rodents to a lethal dose of highly palatable bait. There are two possible scenarios that can explain failure to achieve this: bait availability (all rats *could* not eat a lethal dose of bait) and bait palatability (all rats *would* not eat a lethal dose of bait) (Brown, Pitt, & Tershy, 2013). Reviews so far have focused on the latter (Griffiths et al., 2019; Holmes, Griffiths, et al., 2015); therefore, we focused on the former and set out to investigate the role of operational factors as causes of eradication failure.

Our review is complementary to those by Holmes, Griffiths, et al. (2015) and Griffiths et al. (2019), but approaches the topic from a different direction by studying cases where rodent eradication initially failed and subsequent attempts occurred. We compared project management, and operational and environmental factors for each attempt. We asked: (a) can operational factors explain the initial failures? (b) can improvements to operational factors explain the subsequent successes? and (c) is it worth re-attempting eradication after initial failure? Our findings are relevant for pest eradication projects in all biomes.

2 | METHODS

We focused on eradication attempts from 1990 onwards, which represents the modern era of systematic eradication operations. We used the Database of Island Invasive Species Eradications (DIISE, 2019) to identify island eradications on the basis of the following criteria: (a) target taxa: Muridae; (b) type: whole island eradications (i.e., excluding incursion response and restricted range operations); (c) primary eradication method: toxicant (i.e., excluding trapping); (d) toxicant type: known (i.e., excluding unknown); (e) year of eradication: 1990 onwards; (f) eradication status: known or "to be confirmed" (i.e., excluding unknown, reinvaded and trials; those with "to be confirmed" status were either updated to failed or successful, or discarded if unknown); and (g) quality of data: good or satisfactory, with the latter either improved to good quality with our supplemental research (1 case) or discarded if the required information was not available (4 cases).

We then identified the islands where eradication had been attempted more than once for the same target species. This approach allowed us to focus on the changes between attempts, given that other important parameters such as island size, location, topography, local environment, and human influence remained constant. On each island, 1 or 2 species of a pool of 5 invasive rodent species were the targets: house mouse (*M. musculus*), Asian house rat (*R. tanezumi*), Norway rat (*R. norvegicus*), Pacific rat (*R. exulans*) or ship rat (*R. rattus*). The resulting list included 44 eradication records on 18 islands, noting that simultaneous multi-species eradications are listed as several records (1 per target species). For 2 islands (Mokoia, New Zealand and Teuaua, French Polynesia) additional attempts before 1990 existed; we added those earlier attempts to give a complete eradication history of these islands. One island with 4 records (Matakohe, New Zealand) was excluded as it is most likely subject to continuous reinvasion given its proximity (<500 m at low tide) to the mainland. The final list included 35 eradication operations (some targeting multiple islands or rodent species) comprising 17 islands or atolls and 8 countries (Table 1).

We assessed potential causes of eradication failure, and compared management, operational and environmental factors between initial and successful operations. This included the factors identified by Holmes, Griffiths, et al. (2015) and Griffiths et al. (2019) as the main factors associated with failure on tropical islands: presence of coconut palms, land crabs, agriculture and human habitation, and year-round breeding rodent populations (Table 2). Published and unpublished literature was reviewed, and direct communication with project managers took place for some cases. Collectively, the authors of this article were involved in most reviewed projects, conducted fieldwork related to the implementation of these eradications, and have extensive experience in pest eradication worldwide. This partly alleviates the fact that written information is scarce and was difficult to obtain in several cases.

3 | RESULTS

Of the 17 islands with two or more rodent eradication attempts, success was achieved on 14 islands (82%; range 5–1,020 ha) at the second (86%) or third attempt (14%) (Table 1), despite 9 of these islands (64%) having one or more high risk environmental factors (e.g., land crabs or human settlements) (Appendices S1 and S2). On the remaining 3 islands (range 10–294 ha), rodent eradication was not achieved despite 2 or 3 attempts. However, on Kayangel, the larger, and potentially dominant, of the two rat species was removed (Table 1). On 2 of these 3 islands, one or more high risk environmental factors were present (Appendices S1 and S2).

TABLE 1 Island rodent eradications targeting the same species twice or more (1990–2018), by country and date of first attempt

Country	Island	[a]Year initial attempt(s)	[a]Year successful attempt	Target species	Notes
Temperate islands where eradication was achieved in a subsequent attempt					
New Zealand	Mokoia	1989, 1996	2001	*Rattus norvegicus*, then *Mus musculus*	First attempt targeted rats only
New Zealand	Coppermine	1992	1997	*Rattus exulans*	
Tropical and subtropical islands where eradication was achieved in a subsequent attempt					
Australia	Varanus	1994	1997	*Mus musculus*	Targeted recent introduction
Australia	Crocus	1996	1997	*Rattus rattus*	Part of Montebello
Australia	Hermite	1996, 1999	2001	*Rattus rattus*	Part of Montebello
Australia	Primrose	1996	1997	*Rattus rattus*	Part of Montebello
French Polynesia	Vahanga	2000	2015	*Rattus exulans*	
French Polynesia	Teuaua	1986, 2009	2017	*Rattus exulans*	
Mexico	Isabel	1995	2009	*Rattus rattus*	
Seychelles	Ile Denis	2000	2002	*Rattus rattus* + *Mus musculus*	Also known as Denis Island
Seychelles	Ile du Nord	2003	2005	*Rattus rattus*	Also known as North Island
The United Kingdom (Bahamas territory)	Low Cay	1999	2000	*Rattus rattus*	
The United States (Pacific territory)	Palmyra	2001	2011	*Rattus rattus*	
The United States (Puerto Rico)	Desecheo	2012	2016	*Rattus rattus*	
Tropical islands currently invaded where multiple attempts failed					
Australia	Adele	2004, 2011, 2013	N/A	*Rattus exulans*	
Palau	Kayangel	2012, 2018	N/A	*Rattus exulans* + *R. tanezumi*	Pacific rat still present
The United States (US Virgin Islands)	Congo cay	1990, 2004, 2006	N/A	*Rattus rattus*	

[a]Year of baiting.

Considering all 35 eradication attempts (Table 1), we found a higher success rate (58%) in operations that used methods comparable with today's best practice, compared with those that did not (19% successful). Examples of divergence from best practice include use of bait containing Bitrex (bittering agent intended to prevent accidental ingestion by children and pets), baiting grid too wide, or aerial application of bait without navigational guidance (GPS). We found that all failed attempts had operational issues (e.g., suboptimal bait type and gaps in bait coverage) that violated one or more of the three main eradication principles (Table 2). Importantly, some of these issues (e.g., only one bait application instead of the recommended two applications when using aerial or hand broadcast methods) were also present in successful attempts (Table 2, Appendix S2). High risk environmental factors were common in both failed (60%) and successful (40%) attempts; the most common being tropical weather and presence of land crabs (Table 2).

We found a variety of potential reasons for eradication failure (e.g., insufficient bait, land crabs, poor bait product, alternative human-sourced food, and spatial or temporal bait gaps). We categorized and broke down all reasons according to their relationship with the eradication principles, to help practitioners visualize, manage, and document these factors (Figure 2). Insufficient bait was the most common general cause of eradication failure across temperate and tropical islands, and it can be

TABLE 2 Violations of eradication principles, and environmental factors, analyzed for 35 island rodent eradication attempts

	Presence of factors			
	Failed attempts		Successful attempts	
	No.	(%)	No.	(%)
Violations of eradication principle 1				
Could not eat a lethal dose				
Insufficient bait: Coverage or density				
Poor design	11	85	2	15
Social constraints	2	100	0	0
Coverage gaps general	13	93	1[a]	7
Insufficient bait	13	93	1[a]	7
Coverage gaps: Coastal gaps	8	89	1	11
Regulatory constraints	3	75	1	25
Only 1 aerial bait application	2	67	1	33
Peer review lacking	8	67	4	33
Poor implementation	15	88	2	12
Budget constraints	5	100	0	0
Time constraints	8	100	0	0
Equipment failure	4	100	0	0
Coverage gaps general	17	94	1	6
Coverage gaps: Coastal gaps	14	93	1	7
Poor skills/capabilities	10	91	1	9
Land crabs	12	63	7	37
Multi target species	2	50	2	50
Would not eat a lethal dose				
Poor bait product				
Inefficient toxin	4	80	1	20
Bitrex present	4	80	1	20
Poor bait matrix	9	64	5	36
Alternative food				
Naturally occurring, abundant, highly attractive	9	60	6	40
Human sourced, accessible to rats	7	58	5	42
Violations of eradication principle 2				
Removal not faster than breeding				
Spatial gaps	5	100	0	0
Temporal gaps	7	88	1	13
Violations of eradication principle 3				
Reinvaded				
Human activities	5	63	3	38
Within swim range	5	63	3	38
Other environmental factors				
Agriculture/farming	5	71	2	29
Large island (>1,000 ha)	2	67	1	33
Coconut palms	7	64	4	36

TABLE 2 (Continued)

	Presence of factors			
	Failed attempts		Successful attempts	
	No.	(%)	No.	(%)
People (permanent settlement)	5	63	3	38
Tropical weather with extended wet periods	13	59	9	41
Year-round rodent breeding	5	56	4	44

Notes: Detailed results by island are available online (Appendix S2).
[a]Attempt partially successful (i.e., 1 of the 2 rat species was removed).

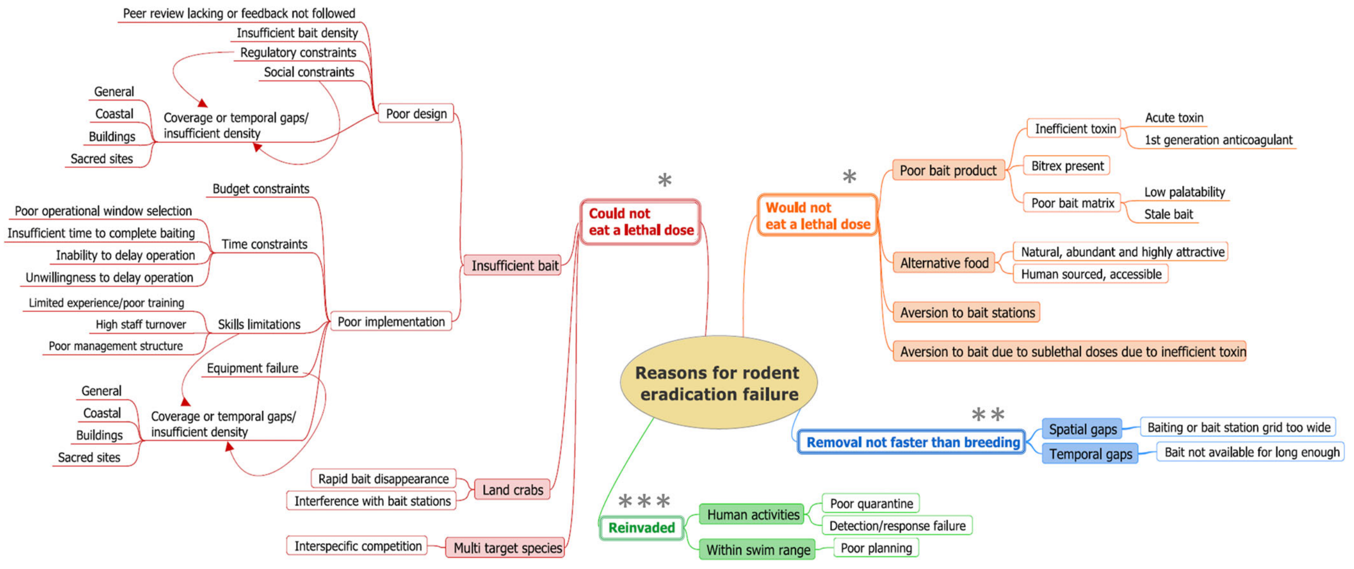

FIGURE 2 Reasons for island rodent eradication failure. Asterisks indicate relation to eradication principle 1 (*all target animals are put at risk by the eradication technique), 2 (**target animals must be removed at a rate exceeding their rate of increase at all densities), and 3 (***immigration must be zero)

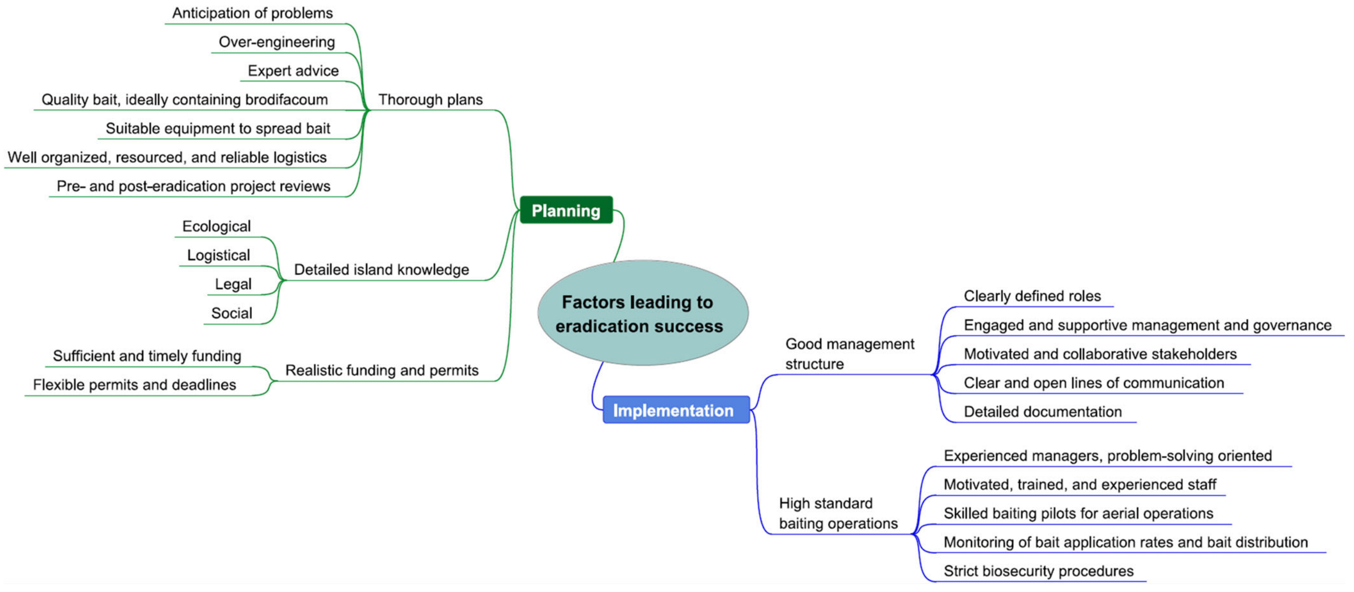

FIGURE 3 Factors leading to successful island rodent eradications

the result of gaps in bait coverage (e.g., planned because of permit restrictions, due to poor training of hand baiters, or accidental because of bait bucket failure), poor treatment of inhabited areas, insufficient general bait density (less common), or a combination of these and other factors. The significance and interconnectedness of the 33 factors analyzed (Table 2) changed considerably across islands (which included temperate, tropical, low-lying, and rugged islands) and attempts (covering all rodent eradication techniques). For example, lack of reviews or work done by inexperienced staff had different impacts depending on the complexity of the project and the novelty of the situation. Hence, island descriptions and detailed accounts per attempt are included to assist practitioners planning future rodent eradications (Appendix S1). Limited information on some factors and islands (Appendix S2), particularly for initial attempts, prevented us from performing inferential statistical analysis. Yet, we calculated percentages of failed and successful attempts in which each factor occurred (Table 2).

Finally, from the qualitative comparison of failed and successful attempts per island (Appendix S1) we identified the following factors as associated with eradication success: thorough planning, detailed island knowledge, realistic funding and permits (i.e., enabling best practice), good management structure, and high standard baiting operations. We then broke these factors into their constituent components as they relate to the eradication principles (Figure 3).

4 | DISCUSSION

Island rodent eradications are highly effective conservation interventions (Jones et al., 2016). Project managers are largely in control of such interventions via thorough planning and implementation, despite environmental factors influencing eradication strategies. Our findings indicate that many eradication failures can be attributed to human error. We believe that most eradication attempts, including those in the tropics, have similar chances of success provided the operational design meets the eradication principles, plans are independently reviewed, and plans are meticulously implemented.

Flaws within initial eradication attempts included poor planning, low quality bait, inadequate bait coverage, inexperienced pilots with no navigational guidance, inadequate baiting around human structures, insufficient treatment of infestation hotspots such as long-term accumulation of green waste (e.g., coconut piles), and deviations from operational plans. Not surprisingly, attempts preceding the development of best practice typically had more operational issues than more recent attempts. Correcting these issues in a latter operation often resulted in eradication success. This iterative process continues to refine best practice.

For some initial attempts (e.g., Teuaua and Desecheo) quality of planning was high, and potential omissions during implementation did not become apparent until the project was reviewed. There are also complex cases where operational and environmental factors were confounded, that is, the eradication strategy was refined but island conditions were also more favorable during the subsequent successful attempt. In cases such as Isabel, the timing of implementation was changed to the dry season; in others such as Desecheo, conditions were drier during the same period for the second attempt. Eradication planning requires consideration of seasonality with potential interannual deviations (Will et al., 2019). Moreover, flexibility in implementation to allow for dynamic environmental or social factors should be explicit (Harper, Pahor, & Birch, 2020). Finally, in a few cases it is likely eradications succeeded but rodents reinvaded (e.g., Congo Cay), which is still considered a project failure. Planning an eradication without appropriate biosecurity measures is poor planning (Kennedy & Broome, 2019).

In a nutshell, failed attempts did not meet the eradication principles of exposing all rodents to sufficient toxic bait, and of having zero immigration. This can cause operational failure on any island, although there appears to be less tolerance for gaps in bait distribution on tropical islands, where nontarget bait consumers can quickly enlarge bait gaps (Samaniego, Boudjelas, Harper, & Russell, 2019). Documentation, via trail cameras, of a high proportion of bait consumed by nontarget species on Desecheo is a good example (Shiels et al., 2019). Nonetheless, high risk factors have been overcome after initial eradication failure in a variety of island settings (Appendix S1). Factors leading to these successes can be summed up as thorough planning in line with best practice, and a high standard of bait application. This breakdown is useful for planning island pest eradications in general (Figure 3). Innovative thinking is required for unprecedented scenarios such as rodent eradications on mangrove islands greater than 1,000 ha.

As for our questions:

1. Can operational factors explain the failures? Mostly, yes. A variety of operational issues were identified in all initial attempts. Similarly, significant operational issues occurred during follow up attempts on the three islands where eradication was not achieved.
2. Can improvements in operational factors explain the subsequent successes? Mostly, yes. Although in some cases (e.g., Desecheo and Isabel) more favorable

environmental conditions during the second attempt may have contributed to success, there were also cases where environmental conditions were less favorable during the later successful attempt (e.g., Ile du Nord and Teuaua).

3. Is it worth re-attempting islands after initial eradication failures? Absolutely. Evidence suggests that with an experienced team for both the planning and the implementation phases, the chances of success are high, even for challenging tropical islands where environmental conditions are less favorable (e.g., mesic tropical islands) or more unpredictable.

Yet, commonly underestimated issues require more attention. In addition to land crabs interfering with bait and devices (Samaniego et al., 2019; Wegmann, 2008), cliffs require specific attention to ensure adequate coverage and intertidal areas are underestimated as potential rodent habitat and food sources (Siers, Berentsen, McAuliffe, Foster, & Rex, 2018). Mangroves, which are permanently or frequently flooded, are inhabited by rats but are challenging to treat (Harper, Dinther, & Bunbury, 2014; Samaniego et al., 2018). Accuracy of baiting grids, often un-documented, is essential to avoid gaps (Samaniego et al., 2020). Baiting of human structures and removal of alternative food sources require special care (Harper et al., 2020; Rocamora, 2019). At some sites, intensive post-baiting surveys (e.g., camera trapping, chew tags, detection dogs) can be used to aid the detection and removal of survivors, especially where complex eradication strategies are used (Harper et al., 2020).

The importance of organizational and staff management is also often under-appreciated. For example, complex management structures can create confusion and lead to conflict (Brown et al., 2013; Stringer et al., 2019). Staff must be well trained and have a professional and eradication mindset (Cromarty et al., 2002; Samaniego, Kappes, & Siers, 2020). Morrison, Faulkner, Vermeer, Lozier, and Shaw (2011) provide an excellent discussion on the nonscience components of eradication programs and propose a framework for creating resilience.

Each eradication attempt represents a unique combination of factors. Some factors are predictable, and some are situational, and need to be addressed with conservative design and capability within a team to make informed decisions. Experience with the methods, the specific island, and country regulations are essential. Aerial broadcast operations have a high success rate but they still have logistical, regulatory, and environmental challenges. Will, Howald, Holmes, Griffiths, and Gill (2019) discuss the challenges and explain why discrepancies between planned and actual bait rates are common, thus requiring flexible permits to ensure eradication principles are met.

Eradication projects must be adequately budgeted, with an appropriate contingency to respond to unexpected challenges (Kappes, Bond, Russell, & Wanless, 2019). Multispecies or multiisland eradications require extra planning, resources and flexibility (Martin & Richardson, 2019; Springer, 2016). When establishing protocols for nontarget species and environmental protection, the perceived benefits of bait application restrictions, such as bait deployment away from coastlines, should be adequately evaluated. Environmental legislation in some jurisdictions (developed in the context of mitigating harm from industrial development for which little environmental benefit is accrued) does not allow for the benefits of successful eradication to be weighed against short term contamination. Therefore, opportunities for net gains are overlooked by seeking to mitigate the contamination at the potential expense of the success of the eradication. Such policies can have a chilling effect on eradication attempts if practitioners elect not to implement projects in the face of restrictive environmental compliance or they are driven to suboptimal methods.

Practitioners are better at reporting successes than failures, and postoperation reviews are mostly not conducted (except in New Zealand) nor publicly available. In addition, there is a tendency to avoid discussion of potential human errors, which can preclude objective assessments of the significance of factors influencing operations. For this review we ameliorated the issues of scarcity and limited availability of operational reports by inviting managers involved with the projects to contribute. However, improving the quality and quantity of reports for all operations, successful or not, is a necessary step to learn from failure and clarify what is required for success. Every eradication project should include a comprehensive postoperational report as part of the overall strategy, so time and funding must be allocated in advance, and such reports should be independently reviewed to maximize learning for future projects. Keitt et al. (2015) provide a list of the main subjects that any post operational report should include; the list analyzed for this review (Table 2) is also a good guide.

Overall, our results are encouraging. In most cases successful eradication of the target species was eventually achieved, the conservation community has learned significantly from its failures, and techniques and theory are constantly improving. Comprehensive best practice documents are available, giving practitioners significant advantages over their predecessors (Broome et al., 2011a; Broome et al., 2011b; Broome, Golding, Brown, Corson, & Bell, 2017; Broome, Golding, Brown, Horn, et al., 2017;

Keitt et al., 2015; Phillips, 2019; PII, 2011; Thomas et al., 2017).

For the future, we encourage practitioners to continue planning and conducting island rodent eradications to a high standard by following a principle-based approach and adhering to best practice; ensure detailed reporting before and after operations, whether projects are successful or not; update best practice recommendations based on evidence; and continue monitoring outcomes to increase the evidence of the extensive social, economic, and ecological benefits resulting from island rodent eradications.

ACKNOWLEDGMENTS

We thank A. Burbidge, R. Clarke, T. Hall, P. Tolson, T. Withers, G. Witmer and J. Zito for providing unpublished material and comments on operational details. We also thank A. Glen, G. Norbury, B. Warburton, and all members of the New Zealand Department of Conservation's Island Eradication Advisory Group for their useful comments on previous versions, and Anne Austin for final editing.

This work was supported in part by the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Centre; reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government. Liba Pejchar and two anonymous reviewers provided useful suggestions during the submission process.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHORS CONTRIBUTION

Araceli Samaniego: Designed the review and led writing of manuscript, with important contributions from Peter Kappes and Shane Siers. All authors contributed published and unpublished documents, and comments on specific case studies. All authors provided critical feedback on several versions of the manuscript and approved the final version. Shane Siers: Provided administrative oversight.

DATA AVAILABILITY STATEMENT

All data are available either in the main manuscript or in Supporting Information.

ORCID

Araceli Samaniego https://orcid.org/0000-0001-7182-3790
Peter Kappes https://orcid.org/0000-0001-6029-5355
Shane Siers https://orcid.org/0000-0001-7961-5072

REFERENCES

Aguirre-Muñoz, A., Bedolla-Guzmán, Y., Hernández-Montoya, J., Latofski-Robles, M., Luna-Mendoza, L., Méndez-Sánchez, F., … Samaniego-Herrera, A. (2018). The conservation and restoration of the Mexican islands, a successful comprehensive and collaborative approach relevant for global biodiversity. In A. Ortega-Rubio (Ed.), *Mexican natural resources management and biodiversity conservation* (pp. 177–192). Cham: Springer.

Angel, A., Wanless, R. M., & Cooper, J. (2009). Review of impacts of the introduced house mouse on islands in the Southern Ocean: Are mice equivalent to rats? *Biological Invasions*, *11*, 1743–1754.

Bellingham, P. J., Towns, D. R., Cameron, E. K., Davis, J. J., Wardle, D. A., Wilmshurst, J. M., & Mulder, C. P. H. (2010). New Zealand Island restoration: Seabirds, predators and the importance of history. *New Zealand Journal of Ecology*, *34*, 115–136.

Broome, K., Brown, D., Brown, K., Murphy, E., Birmingham, C., Golding, C., … Griffiths, R. (2019). House mice on islands: Management and lessons from New Zealand. In C. R. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 100–107). Gland, Switzerland: IUCN.

Broome, K., Cromarty, P., Cox, A., Griffiths, R., McCelland, P., & Golding, C. (2011). The Island Eradication Advisory Group (IEAG) – A model of effective technical support for eradication project planning and management. In C. R. Veitch, M. N. Clout, & D. R. Towns (Eds.), *Island invasives: Eradication and management* (p. 524). Gland, Switzerland: IUCN.

Broome, K., Golding, C., Brown, K., Horn, S., Corson, P., & Bell, P. (2017). *Mouse eradication using aerial baiting: Current agreed best practice used in New Zealand (Version 1.0)*. Wellington, New Zealand: New Zealand Department of Conservation.

Broome, K. G., Brown, D., Cox, A., Cromarty, P., McClelland, P., Golding, C., … Bell, P. (2011a). *Current agreed best practice for rat eradication: Poison bait in bait stations (Version 1.3)*. Wellington, New Zealand: New Zealand Department of Conservation.

Broome, K. G., Brown, D., Cox, A., Cromarty, P., McClelland, P., Golding, C., … Bell, P. (2011b). *Current agreed best practice for rodent eradication: Hand broadcasting poison bait (Version 1.3)*. Wellington, New Zealand: New Zealand Department of Conservation.

Broome, K. G., Fairweather, A. A. C., & Fisher, P. (2012). *Brodifacoum pesticide information review (Version 2012/1)*. Hamilton, New Zealand: Department of Conservation.

Broome, K. G., Golding, C., Brown, K., Corson, P., & Bell, P. (2017). *Rat eradication using aerial baiting: Current agreed best practice used in New Zealand (Version 3.1)*. Wellington, New Zealand: New Zealand Department of Conservation.

Brown, D., Pitt, W., & Tershy, B. (2013). *A review of the Wake Island rat eradication project*. Honolulu, Hawaii: US Fish and Wildlife Service.

Cleghorn, M. J., & Griffiths, R. A. (2002). *Palatability and efficacy of Pestoff 20R bait on mice from Mokoia Island*. Rotorua, Wellington: New Zealand Department of Conservation.

Cromarty, P. L., Broome, K. G., Cox, A., Empson, R. A., Hutchinson, W. M., & McFadden, I. (2002). Eradication planning for invasive alien animal species on islands - the approach developed by the New Zealand Department of Conservation. In C. R. Veitch & M. N. Clout (Eds.), *Turning the tide: The eradication of invasive species* (pp. 85–91). Gland, Switzerland: IUCN.

DIISE. (2019). *The database of Island invasive species eradications*. Santa Cruz: Island Conservation, UCSC, IUCN SSC Invasive Species Specialist Group, University of Auckland and Landcare Research.

Garden, P., McClelland, P., & Broome, K. (2019). The history of the aerial application of rodenticide in New Zealand. In D. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 114–119). Gland, Switzerland: IUCN.

Griffiths, R., Brown, D., Tershy, B., Pitt, W., Cuthbert, R., Wegmann, A., … Howald, G. (2019). Successes and failures of rat eradications on tropical islands: A comparative review of eight recent projects. In C. R. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 120–130). Gland, Switzerland: IUCN.

Harper, G., Dinther, M., & Bunbury, N. (2014). Black rats in mangroves: Successful and intractable. In R. Timm & J. O'Brien (Eds.), *Proceedings of the 26th vertebrate pest conference* (pp. 125–129). Kona, Hawaii: University of California.

Harper, G. A., Pahor, S., & Birch, D. (2020). The Lord Howe Island rodent eradication: Lessons learnt from an inhabited Island. In D. M. Woods (Ed.), *Proceedings, 29th vertebrate Pest conference* (pp. 1–11). Santa Barbara, CA: University of California.

Holmes, N., Campbell, K., Keitt, B., Griffiths, R., Beek, J., Donlan, C., & Broome, K. (2015). Reporting costs for invasive vertebrate eradications. *Biological Invasions*, *17*, 2913–2925.

Holmes, N. D., Griffiths, R., Pott, M., Alifano, A., Will, D., Wegmann, A. S., & Russell, J. C. (2015). Factors associated with rodent eradication failure. *Biological Conservation*, *185*, 8–16.

Horn, S., Greene, T., & Elliott, G. (2019). Eradication of mice from Antipodes Island, New Zealand. In C. R. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 131–137). Gland, Switzerland: IUCN.

Howald, G., Donlan, C. J., Galván, J. P., Russell, J. C., Parkes, J., Samaniego, A., … Tershy, B. (2007). Invasive rodent eradication on islands. *Conservation Biology*, *21*(5), 1258–1268.

Jones, H. P., Holmes, N. D., Butchart, S. H. M., Tershy, B. R., Kappes, P. J., Corkery, I., … Croll, D. A. (2016). Invasive mammal eradication on islands results in substantial conservation gains. *Proceedings of the National Academy of Sciences*, *113*, 4033–4038.

Kappes, P. J., Bond, A. L., Russell, J. C., & Wanless, R. M. (2019). Diagnosing and responding to causes of failure to eradicate invasive rodents. *Biological Invasions*, *21*, 2247–2254.

Keitt, B., Griffiths, R., Boudjelas, S., Broome, K., Cranwell, S., Millett, J., … Samaniego, A. (2015). Best practice guidelines for rat eradication on tropical islands. *Biological Conservation*, *185*, 17–26.

Kurle, C. M., Croll, D. A., & Tershy, B. R. (2008). Introduced rats indirectly change marine rocky intertidal communities from algae- to invertebrate-dominated. *Proceedings of the National Academy of Sciences*, *105*, 3800–3804.

Martin, A., & Richardson, M. (2019). Rodent eradication scaled up: Clearing rats and mice from South Georgia. *Oryx*, *53*, 27–35.

Merton, D. (2001). *Biodiversity restoration in the Seychelles. Report on eradication of rats from Curieuse Denis & Frégate Islands and cats from Curieuse & Denis Islands*. Victoria, Seychelles: Division of Environment, Ministry of Environment and Transport.

Merton, D., Climo, G., Laboudallon, V., Robert, S., & Mander, C. (2002). Alien mammal eradication and quarantine on inhabited islands in the Seychelles. In C. R. Veitch & M. N. Clout (Eds.), *Turning the tide: The eradication of invasive species* (pp. 182–198). Gland, Switzerland: IUCN.

Morrison, S. A., Faulkner, K. R., Vermeer, L. A., Lozier, L., & Shaw, M. R. (2011). The essential non-science of eradication programmes: Creating conditions for success. In C. R. Veitch, M. N. Clout, & D. R. Towns (Eds.), *Island invasives: Eradication and management* (p. 524). Gland, Switzerland: IUCN.

Parkes, J. P. (1993). Feral goats: Designing solutions for a designer pest. *New Zealand Journal of Ecology*, *17*, 71–83.

Phillips RA. 2019. Guidelines for eradication of introduced mammals from breeding sites of ACAP-listed seabirds. British Antarctic Survey, Natural Environment Research Council, Cambridge, UK.

PII. 2011. Resource kit for rodent and cat eradication, Auckland. Retrieved from http://pacificinvasivesinitiative.org/rce/index.html

Rocamora, G. (2019). Eradication of invasive animals and other Island restoration practices in Seychelles: Achievements, challenges and scaling up perspectives. In C. R. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 588–599). Gland, Switzerland: IUCN.

Rocamora G, Henriette E 2015. Invasive alien species in Seychelles. Why and how to eliminate them? Identification and management of priority species. Island Biodiversity and Conservation centre, University of Seychelles; Biotope Editions; Muséum national d'histoire naturelle, Mèze and Paris.

Russell, J. C., & Broome, K. G. (2016). Fifty years of rodent eradications in New Zealand: Another decade of advances. *New Zealand Journal of Ecology*, *40*, 197–204.

Russell, J. C., & Holmes, N. D. (2015). Tropical Island conservation: Rat eradication for species recovery. *Biological Conservation*, *185*, 1–7.

Samaniego, A., Aguirre-Muñoz, A., Bedolla-Guzmán, Y., Cárdenas-Tapia, A., Félix-Lizárraga, M., Méndez-Sánchez, F., … Torres-García, F. (2018). Eradicating invasive rodents from wet and dry tropical islands in Mexico. *Oryx*, *52*, 559–570.

Samaniego, A., Aguirre-Muñoz, A., Rodríguez-Malagón, M., González-Gómez, R., Torres-García, F., Méndez-Sánchez, F., … Latofski-Robles, M. (2011). Rodent eradications on Mexican islands: Advances and challenges. In C. R. Veitch, M. N. Clout, & D. R. Towns (Eds.), *Island invasives: Eradication and management* (pp. 350–355). Gland, Switzerland: IUCN.

Samaniego, A., Boudjelas, S., Harper, G. A., & Russell, J. C. (2019). Assessing the critical role that land crabs play in tropical Island rodent eradications and ecological restoration. In D. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 209–222). Gland, Switzerland: IUCN.

Samaniego, A., Griffiths, R., Gronwald, M., Holmes, N. D., Oppel, S., Stevenson, B. C., & Russell, J. C. (2020). Risks posed by rat reproduction and diet to eradications on tropical islands. *Biological Invasions*, *22*, 1365–1378.

Samaniego, A., Griffiths, R., Gronwald, M., Murphy, F., Rohellec, M., Oppel, S., … Russell, J. C. (2020). A successful Pacific rat *Rattus exulans* eradication on tropical Reiono Island (Tetiaroa atoll, French Polynesia) despite low baiting rates. *Conservation Evidence*, *17*, 12–14.

Samaniego, A., Kappes, P. J., & Siers, S. R. (2020). Island rodent eradications: Little things make big things happen. In D. M. Woods (Ed.), *29th vertebrate Pest conference* (pp. 1–3). Santa Barbara, CA: UCSB.

Shiels, A., Will, D., Figuerola-Hernández, C., Swinnerton, K., Silander, S., Samra, C., & Witmer, G. (2019). Trail cameras are a key monitoring tool for determining target and non-target bait-take during rodent removal operations: Evidence from Desecheo Island rat eradication. In C. R. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (p. 223). Gland, Switzerland: IUCN.

Siers, S. R., Berentsen, A. R., McAuliffe, T. W., Foster, D. K., & Rex, K. (2018). Rodenticide application strategies for intertidal rat habitats. *Wildlife Research*, *45*, 82–91.

Springer, K. (2016). Methodology and challenges of a complex multi-species eradication in the sub-Antarctic and immediate effects of invasive species removal. *New Zealand Journal of Ecology*, *40*, 273–278.

Springer, K. (2018). Eradication of invasive species on Macquarie Island to restore the natural ecosystem. In S. Garnett, J. Woinarski, D. B. Lindenmayer, & P. Latch (Eds.), *Recovering Australian threatened species: A book of hope* (pp. 13–22). Clayton South, VIC: CSIRO Publishing.

St Clair, J. J. H. (2011). The impacts of invasive rodents on Island invertebrates. *Biological Conservation*, *144*, 68–81.

Stringer, C., Boudjelas, S., Broome, K., Cranwell, S., Hagen, E., Howald, G., … Varnham, K. (2019). Married bliss and shotgun weddings: Effective partnerships for Island restoration. In C. R. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 517–521). Gland, Switzerland: IUCN.

Thomas, B. W., & Taylor, R. H. (2002). A history of ground-based rodent eradication techniques developed in New Zealand, 1959-1993. In C. R. Veitch & M. N. Clout (Eds.), *Turning the tide: The eradication of invasive species* (pp. 301–310). Gland, Switzerland: IUCN.

Thomas S, Varnham K, Havery S. 2017. Current recommended procedures for UK (bait station) rodent eradication projects (Version 4.0). Sandy Bedfordshire, UK.

Towns, D. (2011). Eradications of vertebrate pests from islands around New Zealand: What have we delivered and what have we learned? In C. R. Veitch, M. N. Clout, & D. R. Towns (Eds.), *Island invasives: Eradication and management* (pp. 364–371). Gland, Switzerland: IUCN.

Towns, D. R. (2009). Eradications as reverse invasions: Lessons from Pacific rat (*Rattus exulans*) removals on New Zealand islands. *Biological Invasions*, *11*, 1719–1733.

Towns, D. R., Atkinson, I. A. E., & Daugherty, C. H. (2006). Have the harmful effects of introduced rats on islands been exaggerated? *Biological Invasions*, *8*, 863–891.

Towns, D. R., & Broome, K. G. (2003). From small Maria to massive Campbell: Forty years of rat eradications from New Zealand islands. *New Zealand Journal of Zoology*, *30*, 377–398.

Towns, D. R., Wardle, D. A., Mulder, C. P. H., Yeates, G. W., Fitzgerald, B. M., Parrish, G. R., … Bonner, K. I. (2009). Predation of seabirds by invasive rats: Multiple indirect consequences for invertebrate communities. *Oikos*, *118*, 420–430.

Wanless, R. M., Fisher, P., Cooper, J., Parkes, J., Ryan, P. G., & Slabber, M. (2008). Bait acceptance by house mice: An Island field trial. *Wildlife Research*, *35*, 806–811.

Wegmann, A. (2008). *Land crab interference with eradication projects: Phase I—compendium of available information*. Auckland: Pacific Invasives Initiative.

Will, D., Howald, G. R., Holmes, N., Griffiths, R., & Gill, C. (2019). Considerations and consequences when conducting aerial broadcast applications during rodent eradications. In C. R. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 71–78). Gland, Switzerland: IUCN.

Will, D., Swinnerton, K., Silander, S., Keitt, B., Griffiths, R., Howald, G. R., … Herrera-Giraldo, J. L. (2019). Applying lessons learnt from tropical rodent eradications: A second attempt to remove invasive rats from Desecheo National Wildlife Refuge, Puerto Rico. In C. R. Veitch, M. N. Clout, A. R. Martin, J. C. Russell, & C. J. West (Eds.), *Island invasives: Scaling up to meet the challenge* (pp. 154–161). Gland, Switzerland: IUCN.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Samaniego A, Kappes P, Broome K, et al. Factors leading to successful island rodent eradications following initial failure. *Conservation Science and Practice*. 2021;e404. https://doi.org/10.1111/csp2.404