Lessons Learned from Failed Island Rodent Eradications Redone Successfully:Implications for the Second Rat Eradication Attempt on Wake Atoll

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September 20, 2020

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Suggested Citation:
Samaniego, A., P. Kappes, K. Broome, S. Cranwell, R. Griffiths, G. Harper, P. McClelland, R. Palmer, G. Rocamora, K. Springer, D. Will and S. Siers. 2020. Lessons learned from failed island rodent eradications redone successfully: implications for the second rat eradication attempt on Wake Atoll. Unpublished Final

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Report QA-3179. USDA APHIS Wildlife Services National Wildlife Research Center. Hilo, HI.

Background

Island rodent eradications are increasingly conducted to counteract the negative impacts of invasive rodents. From early accidental eradications on tiny islands in the 1960s to systematic projects on massive islands (>10,000 ha) since 2000, the global achievements to date are remarkable. Over the past two decades, eradication theory has advanced commensurately with methodology. Through adaptive management and strict adherence to best practice , temperate New Zealand achieved an outstanding rate of success even for invasive mice once thought to be 'difficult to eradicate'.

Conversely, the lower eradication success rate in tropical regions has triggered reviews, research and the development of guidelines for rat eradications on tropical islands. A statistical analysis on factors associated with rodent eradication failure (Holmes et al. 2015b) found factors unique to the tropics, such as warm temperatures, presence of land crabs and coconut palms, to be clearly associated with eradication failure. Other factors associated with failure relate to the eradication method, aerial broadcast projects having the highest success rate. A later review of a subset of eight cases using a qualitative approach (Griffiths et al. 2019) suggested that rat breeding and dietary characteristics pertaining to tropical climates could be contributing causes of eradication failure. However, recent research studying these aspects 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 project results from several countries. Therefore, we set out to investigate the role of operational factors as potential causes of failure.

Our qualitative review is complementary to those by Holmes et al. (2015b) and Griffiths et al. (2019), also aiming to shed light on how to maximize our chances of eradication success, but approaching the topic from a different direction. We examined cases where rodent eradication initially failed but was eventually achieved in a later attempt. We compared project management, operational and environmental factors for both the initial and successful attempts. We asked: i) can faults in operational factors explain the initial failures? ii) can improvements in operational factors explain the subsequent successes? and iii) is it worth re-attempting more islands after initial failures? We also present recommendations for Wake Atoll, where a second eradication attempt is currently being planned. Finally, a brief assessment of unsuccessful projects that have not been attempted again is provided, with suggestions for follow-up research.

Case studies and target species

We used the Database of Island Invasive Species Eradications (DIISE) to identify islands where eradication had been attempted more than once for the same target species . We focused on operations conducted from 1990 onwards for the first attempt, thus reviewing systematic rather than early (experimental) eradications. Forty-two rodent eradication attempts on 17 islands scattered around 8 countries were analyzed. In all cases, one or two species of a pool of five invasive rodent species were the targets: house mouse (*Mus musculus*), Asian house rat (*Rattus tanezumi*), Norway rat (*R. norvegicus*), Pacific rat (*R. exulans*), or ship rat (*R. rattus*).

Factors analyzed

Results are presented by island, grouped by country. For each case, a summary table and a narrative of each eradication attempt is provided. We compared management, operational and environmental factors across attempts. Published and grey literature was reviewed, and direct communication with project managers took place. Collectively, the authors of this report were involved in most reviewed projects. Yet, inconsistent and limited reporting continue to be major issues preventing learning from failure.

Results

Out of 17 islands, on 14 (82%; ranging 5-1020 ha) eradication was achieved on the second (86%) or third attempt (14%). On the remaining three islands (10-217 ha) eradication was not achieved despite two (on Kayangel) or three attempts (on Adele and Congo Cay), noting that on Kayangel one of the two rat species was removed during the second attempt. The 14 islands where eradication was subsequently achieved can be grouped into two categories according to the level of change in the eradication strategy between the initial and successful attempt (Table 1).

Discussion

We found evidence of major operational faults for all first attempts (e.g. poor planning, low quality bait, inadequate bait coverage across the island, helicopters with no GPS, insufficient baiting around human structures, or poor management of alternative foods), which once corrected in a later operation often lead to eradication success (e.g. Mokoia and Low Cay). However, there are complex cases where operational and environmental factors are confounded, i.e. the eradication strategy improved but the island conditions were also more favorable for eradication, either because a better operational window was identified (e.g. Isabel) or local conditions were monitored to avoid unpredictable rain (e.g. Desecheo). Simply put, most failed attempts may not have met the first eradication principle of exposing all rodents to a lethal dose of a highly palatable bait. This can cause operational failure on any type of temperate or tropical island, although the latter appear to have less room for error given the high abundance of bait competitors. In some cases, improved biosecurity standards and appropriate removal and treatment of infestation hotspots in human-made areas may explain the success of the second attempts (e.g. Ile du Nord).

The main contributing factors leading to successful rodent eradications, often acting in concert, are:

- thorough and meticulous planning
- anticipating problems and overengineering (e.g. removing artificial food sources)
- deep island knowledge
- expert advice
- sufficient funding
- clearly defined management structure
- high standard baiting operations involving motivated, trained and experienced staff
- highly motivated and collaborative local stakeholders (e.g. resident communities and hotels)
- project managers with exceptional problemsolving and decision-making skills
- quality bait, ideally containing brodifacoum (for example from Bell Labs or from Orillion)

Table 1: Islands where rodent eradication attempts succeeded after initial failure, according to the level of change in the eradication strategy.

Major changes (bait, technique and team changed)	**Moderate changes** (bait quantity and/or spatial coverage and/or team changed)
Mokoia Island, New Zealand	Teuaua Island, French Polynesia
Coppermine Island, New Zealand	Ile du Nord, Seychelles
Varanus Island, Australia	Low Cay, United Kingdom
Montebello Islands, Australia	Desecheo Island, United States
Vahanga Island, French Polynesia	
Isabel Island, Mexico	
Ile Denis, Seychelles	
Palmyra Atoll, United States	

- suitable equipment (e.g. helicopters with GPS and specialized spreader bucket or bait stations adapted to function under local conditions)
- well organized, resourced and reliable operational logistics, especially when operating on remote islands
- experienced baiting pilots to apply the bait for aerial operations • realistic and flexible permits and deadlines
- strict biosecurity procedures
- pre- and post-eradication project reviews

Issues that we repeatedly found being underestimated include: land crab interference with bait and devices, cliffs and intertidal areas as potential rodent habitat and food sources, presence of mangroves, accuracy of baiting grid, baiting of human structures, removal or adequate treatment of infestation hotspots, training and mindset of staff, confusion caused by complex management structures, multi-species or multi-island eradications, permitting constraints, reporting, and biosecurity. Most of these factors and issues are discussed across the several available best practice and guidelines documents, which contain management recommendations and research suggestions. One factor requiring more evidencebased discussion is permitting constraints, which may result either from government policies or community concerns. Requiring non-flying zones as a way to avoid bait entering the ocean, for example, can create gaps in bait coverage that may not be possible to cover by hand, and also adds pressure to the already complex aerial work. The observations compiled by hundreds of eradication operations around the globe suggest the risk for marine species is lower than expected a few decades ago. A comprehensive review assessing all the species and ecosystems that have been monitored during eradication operations would be valuable for future operations.

As for our questions:

1. *Can faults in operational factors explain the failures?* Mostly, yes. Particularly for older cases, the faults are evident and the solutions clear, as managers worked on the subsequent attempt under similar environmental conditions. Even for the cases where confounding factors occurred, operational improvements were implemented after the initial attempt, largely as a result of independent reviews. Likewise, all operations, both initial and follow up, on the three islands where eradication was not ultimately achieved, appear to have experienced major operational issues.
2. *Can improvements in operational factors explain the subsequent successes?* Mostly, yes. Although in some cases (e.g. Desecheo and Isabel) the more favorable environmental conditions during the successful attempt most likely contributed, there are also cases where environmental conditions were less favorable for eradication during the later successful attempt (e.g. Ile du Nord and Teuaua).
3. *Is it worth re-attempting more islands with initial failures?* Yes. The evidence suggests that with proper planning, adequate resources and an experienced team for both the planning and the implementation phases, the chances of success are high even for the challenging tropical islands where environmental conditions are never highly favorable (e.g. Wake Island)

   or are difficult to predict (e.g. Kayangel Island). Independent project reviews of unsuccessful attempts have played a key role, increasing awareness among stakeholders and making subsequent operational plans more robust. Improving the review rate for both successful and unsuccessful attempts would maximize the learning after each operation.

Environmental factors inherent to tropical islands (e.g. land crabs, year-round rodent breeding) indeed pose extra risk that must be studied and managed. Nevertheless, recognizing that steering groups are largely in control of the result is important to encourage stakeholder support, and contributes to thorough planning and implementation of eradication projects to a high standard.

Conclusions

As a result of the overall mix of failures and successes in rodent eradications, best practices and guidelines have been established and have evolved, additional research has been conducted, and project reviews have been commissioned. We still have knowledge gaps and expect some projects to fail moving forward, but it is important that we keep learning from each attempt. Every eradication project, successful or not, should include a comprehensive post operational report as part of the overall strategy and such reports should be independently reviewed to maximize learning for future projects.

The role of operational factors as a contributor to eradication failure is frequently underestimated, despite best practice calling for high standards. High standard operations have higher probabilities of success regardless of the type of island, although it appears that tropical islands have less room for errors such as gaps in bait coverage – partly due to the diversity and abundance of bait competitors and alternative food, and higher relative rodent population densities. In addition to adherence to best practice, we encourage project teams to adopt a principle-based approach while writing or reviewing rodent eradication documents so that the logic behind a specific baiting strategy demonstrates why it maximizes the chances of success for that particular island, and risks can be identified and accepted by all stakeholders.

We identified faults in a variety of management and/or operational factors in most failed attempts reviewed, but rodent eradications are complex operations. In some cases, operational faults were unarguably the cause of eradication failure. In other cases, the significance of such faults was impossible to tease out in the presence of other confounding, and possibly associated, environmental factors. We do not deny the importance of managing environmental factors (e.g. alternative foods) but emphasize the implications of errors in operational factors. In any case, conservation managers have more control over operational than environmental factors overall, so the best chance for a successful eradication outcome is to strive for excellence at each attempt. Recommendations for all aspects of eradication, from planning to implementation to reporting, are already available. It is our choice to take them seriously and our responsibility to improve them as we learn by doing.

Follow-up research

There were only three islands (Adele, Kayangel and Congo Cay) where subsequent attempts did not achieve eradication, and one of them (Congo Cay) is at high risk of reinvasion. The risk of reinvasion is nowadays an important factor while assessing feasibility of a project; reinvasion, rather than operation failure, may be the reason why some of these islands are rodent infested at present. Hence, future research evaluating the importance of certain operational factors as causes of eradication failure should be conducted on islands with low risk of reinvasion.

For the same period than as our main analysis (1990-2018) we identified 45 rodent eradications on islands that have not been repeated after initial failure. Of these, 35 (77.8%) are probably under constant reinvasion pressure: 27 (60%) are within 500 m of another rodent population source (e.g. an inhabited or rodent infested island) and eight more (17.8%) appear to have high visitation rates. In these cases, it is possible that the eradication operation went well but rodents reinvaded, i.e. the projects may have failed due to biosecurity breaches or failure to recognize the ability of rodents to swim and reinvade, rather than operational failure. Some projects were conducted before the swimming capabilities of invasive rodents were understood; however, for other projects it appears that a lack of, or poor, feasibility planning was the lead cause for the oversight of such significant risks. Future eradication projects on these islands may require extending the eradication unit (e.g. archipelago wide) and applying strict biosecurity protocols.

The remaining ten islands (22.2%) appear to be at low risk of rodent reinvasion and are scattered across a variety of climatic zones with varied landforms, vegetative cover, non-target species and tenure. Thus, this island group represents a good opportunity to conduct second eradication attempts in a systematic way to maximize learning. We suggest this work is undertaken as a joint conservation and research project. With strict adherence to eradication principles and detailed monitoring of environmental factors, important lessons can be learnt by clearing these islands of rodents in the future.

Applying the lessons learned: Planning the second attempt for Wake Atoll

Wake Atoll (US territory in the tropical Pacific) is a small coral atoll consisting of three islands, namely Wake (526 ha), Peale (95 ha) and Wilkes (76 ha). Peale is separated from Wake Iisland by ~100 m and at low tide Wilkes and Wake are essentially connected. The climate is tropical maritime, dominated by northeast trade winds. Temperature variation is minimal, with monthly averages of 24.4°C to 28.3°C. Rainfall is light, averaging only about 890 mm per year, with rain showers occurring most often between midnight and sunrise, and heaviest rainfalls during the July to October Pacific typhoon season. The distance to the closest source of invasive rodents, another atoll, is 850 km.

Current vegetative cover on unimproved grounds comprises three natural plant associations. The driest plant association is xeric forest dominated by *Tournefortia*, with shrub-like expression at 1-2 m along beaches and inland stands reaching as high as 6 m. Cordia forest occurs in mesic conditions and grows to an average of 7-10 m. Pemphis habitat is found on sandy and saturated coastal substrates. Other vegetation communities include casuarina forest, ruderal vegetation, and mowed/maintained vegetation. The atoll supports a large and diverse assemblage of migratory seabirds and shorebirds, with the largest colonies (e.g. >100,000 breeding pairs of sooty terns *Onychoprion fuscatus*) on Wilkes and the northern tip of Peale.

Rats on Wake are known to prey on seabird eggs and chicks, native plants, and invertebrates.
Chewing by rats on Wake causes damage to military infrastructure, contaminates food stores, and constitutes a potential health threat to the island community of military personnel and base operations contractors.

Diagnosis

The 2012 eradication targeted both Asian house rats and Pacific rats. The Asian house rat was successfully eradicated from the entire atoll. The Pacific rat was eradicated from Peale but a few individuals survived on Wake and/or Wilkes and have repopulated both islands (Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019). At the time, this was considered one of the most complicated rat eradications attempted, particularly because of the permanent human settlement and the number of restrictions placed on the implementers by the USAF. Given the complexity, it is difficult to identify one single factor responsible for the failure, but likely there were several overlapping issues including:

- bait gaps or localized shortages due to inadequately designed baiting methodology in commensal and intertidal (Pemphis) habitats and complicated combinations and integration of various baiting methodologies, all of which were exacerbated by known application errors or difficulties.
- low overall bait rates with insufficient buffer (Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019).
- bait preference/aversion issues coupled with availability of alternative natural or commensal foods (Brown et al. 2013, Hanson et al. 2019), but lack of observed commensal foods and the success on Peale and Wilkes indicate this might not be an issue (Griffiths et al. 2014).
- rat breeding during the operation causing temporal or spatial unavailability of bait to juveniles emerging from natal nests; (or, speculatively, behavioral avoidance of bait by some breeding females (Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019), although there is conflicting evidence (Samaniego et al. 2018, Samaniego et al. 2020a).
- poor understanding of habitats that are underground and/or abandoned structures.

- insufficient understanding of interactions between the two species resulting in inadequate bait accessibility for Pacific rats (Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019).

One of the known application errors is pilot error, which is rarely talked about during project reviews. There is evidence of the pilot sowing lines but with no bait in the bucket. Although this may not have resulted in a physical gap, bait would have been at a lower density in these locations. Furthermore, the lack of a single operation manager diffused responsibilities. Divisions in roles between agencies led to shortfalls and lack of integration in planning, miscommunications between individuals and agencies, and lack of "ownership" of the project (Brown et al. 2013). Additionally, there is doubt about the comprehensiveness of coverage within buildings; commensal waste management did not go according to plan, which may have resulted in availability of alternative food sources for rats; and it is possible there was competitive exclusion of Pacific rats from bait stations by Asian house rats (Hanson et al. 2019). The project was also understaffed and staffed with inexperienced practitioners, which may have also contributed to the failure by elevating the likelihood of errors (Wegmann & Hanson 2012). Finally, outreach to build Wake Island community buy-in and support could have been improved (Hanson et al. 2019).

Table 2: Comparison of operational and environmental factors across eradication attempts and recommendations for next attempt on Wake Atoll.

Factor	Initial attempt	Recommendations for next attempt
Year	2012	As soon as the operational plan is approved, and funding is secured
Target species	Asian house rat (eradicated) + Pacific rat (survived)	Conduct extensive trapping to make sure Pacific rat is the only species present. Survey Peale to ensure it remains rat free
Season + month	Dry season (May)	Dry season (driest month); Avoid the main nesting seabird season
Environmental conditions	Normal	Avoid abnormally wet conditions
Land crabs present	Yes (primarily Coenobita spp.)	Monitor diversity and abundance
Coconut palms present	Yes	Remove big piles of coconuts or leaves on the ground
Agriculture present	Yes (Thai gardens)	Remove edible parts (e.g. fruits) and apply supplementary bait. Monitor closely
Human habitations	Yes	Bait every room of every building, inside, outside, underneath, and any roof spaces; including service ducts and sub-surface spaces
Method	Combination of aerial baiting (18 + 9 kg/ha, 2 applications, total of 27 kg/ha), hand broadcast, and bait stations (until Nov 2012)	Ideally bait 100% of island aerially. Use ground methods to apply extra bait in and around human structures, applying bait at higher rates in problem areas (e.g. waste facility); Appoint an experienced practitioner as eradication manager, with a support team familiar with country regulations and local conditions
Bait	Conservation 25-W	Use the same bait as it has been trialed on Wake, has a proven track record and is already registered in the United States

Active ingredient	Brodifacoum 25 ppm	Brodifacoum ≥20 ppm
Organization	USAF 15th Airlift Wing, Pacific Air Forces, USFWS, IC	Include key people involved with the first attempt as well as new experienced practitioners so the experience is retained but new ways of thinking are also incorporated
Notes	Aerial broadcast (590 ha), bait stations (commensal areas; 4.2 ha), & hand broadcast (Pemphis habitat/coastal areas, bunkers, underground, cantonment areas, and overlap areas; 32 ha), combined aerial & hand broadcasting (~11 ha); 59.5 ha not baited (runway and bunded fuel storage areas) ; No sightings of Asian house rat on any of the islands since May 2012; Pacific rats removed from Peale but survived on Wake. Monitoring is ongoing	A new operational plan is being developed. It should ensure that application rates are not compromised by permitting constraints and that USAF prioritizes the operation during implementation; Fuel storage areas should also be baited
Risk of reinvasion	Low	Develop/ refine/ enforce biosecurity plan
Best practice (BP) followed	Overall, yes	Strictly follow best practice, from planning to implementation to biosecurity
References	Wegmann & Hanson 2012, Brown et al. 2013, Griffiths et al. 2014, PACAF 2017, Hanson et al. 2019	Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019, this review

Table 3: Risk factors identified in the review process that could have caused failure because rats could not eat enough bait, recommendations and research conducted to address those concerns or knowledge gaps, and reference(s) addressing recommendation or indication if work has been completed to address recommendation. All bait trials used Bell Labs Conservation 25-W bait (hard) as the rodenticide. Soft bait in 2019 trials was Bell Labs FINAL Soft Bait with Lumitrack®.

Risk Factor	**Recommendation**	**Reference or technical or methodological advance**
Insufficient Bait	Supplemental label(s) to increase bait application above maximum, to the rate determined by onsite trials	Keitt et al. 2015
	Supplemental label to increase 2nd application to be as robust as initial application	Keitt et al. 2015
	Supplemental label to increase number of applications	Keitt et al. 2015
	Extend interval between applications to increase period of availability of palatable bait on the ground (e.g. for breeding behaviors)	Keitt et al. 2015
	Stratify application rates to specific areas only if necessary:	Samaniego et al. 2020a,b
	• Focus on comprehensive bait coverage	• Niebuhr et al. 2018:
	• Describe treatment locations	• Keitt et al. 2015
	• Accurately identify boundaries	• Keitt et al. 2015
	• Determine appropriate bait application rates based on onsite trials	• Keitt et al. 2015

	• Ensure minimum desired rates are applied in all habitats, i.e. extra care at buffers	• Keitt et al. 2015
	• Solid waste aggregation area study	• Keitt et al. 2015
Gaps in coverage: complex baiting strategy	Pre-determine and verify application technique for each zone	Hanson et al. 2019
	Minimize the number of exclusion zones for aerial baiting, e.g. also treat fuel storage areas	Hanson et al. 2019
	Lift restrictions that reduce baiting efficiency , e.g. c coastal baiting, aerial baiting over commensal areas, bunded fuel areas etc.	Hanson et al. 2019
Gaps in coverage: tidally inundated habitat	Tested variety of delivery methods and proposed bait application strategies	Siers et al. 2018
Gaps in coverage: structures poorly known	Detailed update of structure data base with all above and below ground structures	Completed 2019 (NWRC unpubl. data)
	Geo-reference all above and below ground structures into digital database	Completed 2019 (NWRC unpubl. data)
	Assess if bait can be delivered for rodents utilizing subterranean habitat	Completed 2019 (NWRC unpubl. data)

Table 4: Risk factors identified in the review process that could have caused failure because rats would not eat enough bait, research conducted to address those concerns or knowledge gaps, reference(s) addressing recommendation or indication if work has been completed to address recommendation.

Risk Factor	Research	Outcome	Research/Reference
Aversion/palatability issues: Preference for natural food items	2-choice trial between toxic bait and natural food items	Preferred bait	Shiels et al. 2015
Aversion/palatability issues: Localized dietary preferences	2-choice trial between soft and hard formulations of toxic bait with rats from commensal, bush, and solid waste aggregation locations	No soft bait consumed; 27% of rats (mostly from commensal and bush locations) consumed no bait	Completed 2019 (NWRC unpubl. data)
Tolerance to bait	No-choice efficacy trial	100% mortality	Shiels et al. 2015
	No-choice efficacy trial	Hard bait: 100% mortality Soft bait: 80% mortality	Completed 2019 (NWRC unpubl. data)

Remedial activities

Subsequent to the review by Brown et al. (2013) the USAF embarked on sponsoring a course of literature review, research, and planning efforts to identify and resolve all knowledge gaps and methodological shortcomings in anticipation of a future successful eradication of Pacific rats from Wake Atoll. Below we summarize the activities associated with addressing causes of eradication failure causes associated with the possibility that rats could not eat enough bait (Table 19) or would not eat enough bait (Table 20).

As part of these efforts, USAF also funded a supplemental review (Hanson et al. 2019) to identify all remaining knowledge gaps and to make recommendations for their resolution prior to a second eradication attempt. They have identified several risk factors that still need to be addressed, which are summarized in the remainder of this section.

Both Brown et al. (2013) and Hanson et al. (2019) have noted that community understanding and buy-in during the previous attempt was not sufficient. Prior to another eradication attempt, a robust community outreach program will need to be developed. Emphasis should include educating the Wake community about eradication fundamentals and facilitating community buy-in by involving them in the planning process and implementation of a zero waste program. The zero waste program addresses the risk factor that rats could have access to alternative anthropogenic food sources and will require community participation and commitment to be successful. While the majority of previous eradication projects have been conducted on uninhabited islands, community buy-in has been an essential component of eradications on inhabited islands. Lessons learned from eradications on other inhabited islands, such as the Lord Howe Island Rodent Eradication Project (Harper et al. In press) and Ascension Island (Ratcliffe et al. 2009), include the development of a robust outreach program. To be most effective these programs should be administered by a professional social scientist, and have proven to require a substantial commitment of time and resources that are easy to underestimate (Harper et al. In press). Importantly, Wake is a special case where everyone is employed by the military, either directly or indirectly, to be there.

Future efforts will continue to resolve areas of uncertainty, particularly regarding how aspects presenting a risk to eradication efficacy are addressed. For example, rather than estimating appropriate bait rates for Wake Island's solid waste aggregation area (SWAA), it would be ideal to remove the condition which necessitates an adjustment. Previous studies have been unable to meet best practice guidelines for bait persistence outlined in Pott et al. (2015) due to rapid and complete consumption by a hyperabundance of rats in this area. Practitioners undertaking a future effort on Wake Atoll should also strive for continuity of staff within key roles and avoid including a high proportion of inexperienced participants (Brown et al. 2013, Hanson et al. 2019, Samaniego et al. In press). In particular, it will be important to ensure that the operation is managed by an experienced project leader who has spent substantial time working with the island residents and has a thorough understanding of the environmental and on-island social conditions under which the eradication will occur. The continuity of having this individual in place, with well-established relationships to both the island and military command structure, will allow them to minimize compromises to best practices and give them the authority to postpone the project if substantial concerns are raised throughout the planning process and/or if critical pre-operational conditions are not met (Brown et al. 2013). Every effort is being made to incorporate these recommendations into the operational planning for a future eradication attempt on Wake.

Conclusion

The failed 2012 eradication attempt was an extremely complex project, but what appear to be the most important factors that played a role in the failure were gaps in baiting from known malfunctions, poor bait application methodologies and integration of different methodologies, overly complex operational command structure with understaffed and inexperienced practitioners in key positions, poor outreach and buy-in from the local Wake community and lack of understanding and documentation of abandoned structures and subterranean habitat/structures leading into the eradication.

As emphasized throughout this review, factors leading to initial failure can be remedied and subsequent eradication attempts can be successful. The operational plan for a future eradication on Wake Atoll should incorporate the lessons learned while resolving existing knowledge gaps particular to Wake Atoll, and reflect explicit consideration of the factors leading to successful subsequent eradications highlighted throughout this broader review. With proper permitting, preparation and implementation, Wake Atoll may be added to the list of successful island rodent eradications following initial failure.

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The contents of this Appendix comprise a draft in preparation for submission to a peer-reviewed journal. This report is for internal use only and does not constitute publication, nor does it represent any official U.S. Department of Agriculture finding or policy. This work was supported in part by the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center.

QA-3179 Final Report Appendix 1

Draft date: September 21, 2020

Factors leading to successful island rodent eradications following initial failure

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1 Executive summary

1.1 Background

Island rodent eradications are increasingly conducted to counteract the negative impacts of invasive rodents. From early accidental eradications on tiny islands in the 1960s to systematic projects on massive islands (>10,000 ha) since 2000, the global achievements to date are remarkable. Over the past two decades, eradication theory has advanced commensurately with methodology. Through adaptive management and strict adherence to best practice, temperate New Zealand achieved an outstanding rate of success even for invasive mice once thought to be 'difficult to eradicate'.

Conversely, the lower eradication success rate in tropical regions has triggered reviews, research and the development of guidelines for rat eradications on tropical islands. A statistical analysis on factors associated with rodent eradication failure (Holmes et al. 2015b) found factors unique to the tropics, such as warm temperatures, presence of land crabs and coconut palms, to be clearly associated with eradication failure. Other factors associated with failure relate to the eradication method, aerial broadcast projects having the highest success rate. A later review of a subset of eight cases using a qualitative approach (Griffiths et al. 2019) suggested that rat breeding and dietary characteristics pertaining to tropical climates could be contributing causes of eradication failure. However, recent research studying these aspects 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 project results from several countries. Therefore, we set out to investigate the role of operational factors as potential causes of failure.

Our qualitative review is complementary to those by Holmes et al. (2015b) and Griffiths et al. (2019), also aiming to shed light on how to maximize our chances of eradication success, but approaching the topic from a different direction. We examined cases where rodent eradication initially failed but was eventually achieved in a later attempt. We compared project management, operational and environmental factors for both the initial and successful attempts. We asked: i) can faults in operational factors explain the initial failures? ii) can improvements in operational factors explain the subsequent successes? and iii) is it worth re-attempting more islands after initial failures? We also present recommendations for Wake Atoll, where a second eradication attempt is currently being planned. Finally, a brief assessment of unsuccessful projects that have not been attempted again is provided, with suggestions for follow-up research.

1.2 Case studies and target species

We used the Database of Island Invasive Species Eradications (DIISE) to identify islands where eradication had been attempted more than once for the same target species. We focused on operations conducted from 1990 onwards for the first attempt, thus reviewing systematic rather than early (experimental) eradications. Forty-two rodent eradication attempts on 17 islands scattered around 8 countries were analyzed. In all cases, one or two species of a pool of five invasive rodent species were the targets: house mouse (*Mus musculus*), Asian house rat (*Rattus tanezumi*), Norway rat (*R. norvegicus*), Pacific rat (*R. exulans*), or ship rat (*R. rattus*).

1.3 Factors analyzed

Results are presented by island, grouped by country. For each case, a summary table and a narrative of each eradication attempt is provided. We compared management, operational and environmental factors across attempts. Published and grey literature was reviewed, and direct communication with project managers took place. Collectively, the authors of this report were involved in most reviewed projects. Yet, inconsistent and limited reporting continue to be major issues preventing learning from failure.

1.4 Results

Out of 17 islands, on 14 (82%; ranging 5-1020 ha) eradication was achieved on the second (86%) or third attempt (14%). On the remaining three islands (10-217 ha) eradication was not achieved despite two (on Kayangel) or three attempts (on Adele and Congo Cay), noting that on Kayangel one of the two rat species was removed during the second attempt.

The 14 islands where eradication was subsequently achieved can be grouped into two categories according to the level of change in the eradication strategy between the initial and successful attempt (Table 1).

Table 1. Islands where rodent eradication attempts succeeded after initial failure, according to the level of change in the eradication strategy.

Major changes (bait, technique and team changed)	**Moderate changes** (bait quantity and/or spatial coverage and/or team changed)
Mokoia Island, New Zealand	Teuaua Island, French Polynesia
Coppermine Island, New Zealand	Ile du Nord, Seychelles
Varanus Island, Australia	Low Cay, United Kingdom
Montebello Islands, Australia	Desecheo Island, United States
Vahanga Island, French Polynesia	
Isabel Island, Mexico	
Ile Denis, Seychelles	
Palmyra Atoll, United States	

1.5 Discussion

We found evidence of major operational faults for all first attempts (e.g. poor planning, low quality bait, inadequate bait coverage across the island, helicopters with no GPS, insufficient baiting around human structures, or poor management of alternative foods), which once corrected in a later operation often lead to eradication success (e.g. Mokoia and Low Cay). However, there are complex cases where operational and environmental factors are confounded, i.e. the eradication strategy improved but the island conditions were also more favorable for eradication, either because a better operational window was identified (e.g. Isabel) or local conditions were monitored to avoid unpredictable rain (e.g. Desecheo). Simply put, most failed attempts may not have met the first eradication principle of exposing all rodents to a lethal dose of a highly palatable bait. This can cause operational failure on any type of temperate or tropical island, although the latter appear to have less room for error given the high abundance of bait competitors. In some cases, improved biosecurity standards and appropriate removal and treatment of infestation hotspots in human-made areas may explain the success of the second attempts (e.g. Ile du Nord).

The main contributing factors leading to successful rodent eradications, often acting in concert, are:

- thorough and meticulous planning

- anticipating problems and overengineering (e.g. removing artificial food sources)
- deep island knowledge
- expert advice
- sufficient funding
- clearly defined management structure
- high standard baiting operations involving motivated, trained and experienced staff
- highly motivated and collaborative local stakeholders (e.g. resident communities and hotels)
- project managers with exceptional problem-solving and decision-making skills
- quality bait, ideally containing brodifacoum (for example from Bell Labs or from Orillion)
- suitable equipment (e.g. helicopters with GPS and specialized spreader bucket or bait stations adapted to function under local conditions)
- well organized, resourced and reliable operational logistics, especially when operating on remote islands
- experienced baiting pilots to apply the bait for aerial operations
- realistic and flexible permits and deadlines
- strict biosecurity procedures
- pre- and post-eradication project reviews

Issues that we repeatedly found being underestimated include: land crab interference with bait and devices, cliffs and intertidal areas as potential rodent habitat and food sources, presence of mangroves, accuracy of baiting grid, baiting of human structures, removal or adequate treatment of infestation hotspots, training and mindset of staff, confusion caused by complex management structures, multi-species or multi-island eradications, permitting constraints, reporting, and biosecurity. Most of these factors and issues are discussed across the several available best practice and guidelines documents, which contain management recommendations and research suggestions. One factor requiring more evidence-based discussion is permitting constraints, which may result either from government policies or community concerns. Requiring non-flying zones as a way to avoid bait entering the ocean, for example, can create gaps in bait coverage that may not be possible to cover by hand, and also adds pressure to the already complex aerial work. The observations compiled by hundreds of eradication operations around the globe suggest the risk for marine species is lower than expected a few decades ago. A comprehensive review assessing all the species and ecosystems that have been monitored during eradication operations would be valuable for future operations.

As for our questions:

Can faults in operational factors explain the failures? Mostly, yes. Particularly for older cases, the faults are evident and the solutions clear, as managers worked on the subsequent attempt under similar environmental conditions. Even for the cases where confounding factors occurred, operational improvements were implemented after the initial attempt, largely as a result of independent reviews. Likewise, all operations, both initial and follow up, on the three islands where eradication was not ultimately achieved, appear to have experienced major operational issues.

Can improvements in operational factors explain the subsequent successes? Mostly, yes. Although in some cases (e.g. Desecheo and Isabel) the more favorable environmental conditions during the successful attempt most likely contributed, there are also cases where environmental conditions were less favorable for eradication during the later successful attempt (e.g. Ile du Nord and Teuaua).

Is it worth re-attempting more islands with initial failures? Yes. The evidence suggests that with proper planning, adequate resources and an experienced team for both the planning and the implementation phases, the chances of success are high even for the challenging tropical islands where environmental conditions are never highly favorable (e.g. Wake Island) or are difficult to predict (e.g. Kayangel Island). Independent project reviews of unsuccessful attempts have played a key role, increasing awareness among stakeholders and making subsequent operational plans more robust. Improving the review rate for both successful and unsuccessful attempts would maximize the learning after each operation.

Environmental factors inherent to tropical islands (e.g. land crabs, year-round rodent breeding) indeed pose extra risk that must be studied and managed. Nevertheless, recognizing that steering groups are largely in control of the result is important to encourage stakeholder support, and contributes to thorough planning and implementation of eradication projects to a high standard.

1.6 Conclusions

As a result of the overall mix of failures and successes in rodent eradications, best practices and guidelines have been established and have evolved, additional research has been conducted, and project reviews have been commissioned. We still have knowledge gaps and expect some projects to fail moving forward, but it is important that we keep learning from each attempt. Every eradication project, successful or not, should include a comprehensive post operational report as part of the overall strategy and such reports should be independently reviewed to maximize learning for future projects.

The role of operational factors as a contributor to eradication failure is frequently underestimated, despite best practice calling for high standards. High standard operations have higher probabilities of success regardless of the type of island, although it appears that tropical islands have less room for errors such as gaps in bait coverage – partly due to the diversity and abundance of bait competitors and alternative food, and higher relative rodent population densities. In addition to adherence to best practice, we encourage project teams to adopt a principle-based approach while writing or reviewing rodent eradication documents so that the logic behind a specific baiting strategy demonstrates why it maximizes the chances of success for that particular island, and risks can be identified and accepted by all stakeholders.

We identified faults in a variety of management and/or operational factors in most failed attempts reviewed, but rodent eradications are complex operations. In some cases, operational faults were unarguably the cause of eradication failure. In other cases, the significance of such faults was impossible to tease out in the presence of other confounding, and possibly associated, environmental factors. We do not deny the importance of managing environmental factors (e.g. alternative foods) but emphasize the implications of errors in operational factors. In any case, conservation managers have more control over operational than environmental factors overall, so the best chance for a successful eradication outcome is to strive for excellence at each attempt. Recommendations for all aspects of eradication, from planning to implementation to reporting, are already available. It is our choice to take them seriously and our responsibility to improve them as we learn by doing.

1.7 Follow-up research

There were only three islands (Adele, Kayangel and Congo Cay) where subsequent attempts did not achieve eradication, and one of them (Congo Cay) is at high risk of reinvasion. The risk of reinvasion is nowadays an important factor while assessing feasibility of a project; reinvasion, rather than operation failure, may be the reason why some of these islands are rodent infested at present. Hence, future research evaluating the importance of certain operational factors as causes of eradication failure should be conducted on islands with low risk of reinvasion.

For the same period as our main analysis (1990-2018) we identified 45 rodent eradications on islands that have not been repeated after initial failure. Of these, 35 (77.8%) are probably under constant reinvasion pressure: 27 (60%) are within 500 m of another rodent population source (e.g. an inhabited or rodent infested island) and eight more (17.8%) appear to have high visitation rates. In these cases, it is possible that the eradication operation went well but rodents reinvaded, i.e. the projects may have failed due to biosecurity breaches or failure to recognize the ability of rodents to swim and reinvade, rather than operational failure. Some projects were conducted before the swimming capabilities of invasive rodents were understood; however, for other projects it appears that a lack of, or poor, feasibility planning was the lead cause for the oversight of such significant risks. Future eradication projects on these islands may require extending the eradication unit (e.g. archipelago wide) and applying strict biosecurity protocols.

The remaining ten islands (22.2%) appear to be at low risk of rodent reinvasion and are scattered across a variety of climatic zones with varied landforms, vegetative cover, non-target species and tenure. Thus, this island group represents a good opportunity to conduct second eradication attempts in a systematic way to maximize learning. We suggest this work is undertaken as a joint conservation and research project. With strict adherence to eradication principles and detailed monitoring of environmental factors, important lessons can be learnt by clearing these islands of rodents in the future.

2 Introduction

Four species of invasive rodents (*Mus musculus, Rattus exulans, R. norvegicus* and *R. rattus*) have been inadvertently spread around the globe by humans; the detrimental impacts on island ecosystems (e.g. Towns et al. 2006, Kurle et al. 2008, Angel et al. 2009, Towns et al. 2009, St Clair 2011) as well as the benefits of their removal (e.g. Towns 2009, Bellingham et al. 2010, Towns 2011, Rocamora & Henriette 2015, Jones et al. 2016) are well documented. From early accidental eradications on tiny islands in the 1960s to systematic projects on massive islands (>10,000 ha) since 2000, the global achievements and conservation gains are remarkable (Howald et al. 2007, Veitch et al. 2019). Over 500 islands have been cleared of invasive rodents (DIISE 2018), with many projects comprising complex multi-species eradications (e.g. Macquarie Island, Springer 2018) or operations in challenging habitats (e.g. 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 outstanding outcomes driving funding has allowed such increases in size and complexity (Howald et al. 2007, Holmes et al. 2015a, Russell & Broome 2016).

The core eradication principles currently in use include: i) all target animals are put at risk by the eradication technique(s), ii) target animals must be removed at a rate exceeding their rate of increase at all densities and iii) immigration must be zero (Parkes 1993, Cromarty et al. 2002). Best practice recommendations facilitating the meeting of these principles were developed by the New Zealand Department of Conservation (DOC) and other agencies (Broome et al. 2011c, Broome et al. 2011b, Keitt et al. 2015, Broome et al. 2017a, Broome et al. 2017b, Thomas et al. 2017, Phillips 2019). The New Zealand system emerged from the advisory work of the Island Eradication Advisory Group (IEAG; Cromarty et al. 2002, Broome et al. 2011a). Best practice advice was collated from this group and first labelled '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 (Towns & Broome 2003, Russell & Broome 2016) even for invasive mice – once thought to be 'difficult to eradicate' (Broome et al. 2019).

Comparing temperate versus tropical regions, the smaller number of islands and cumulative area treated in tropical 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 (AguirreMuñoz et al. 2018, Rocamora 2019). However, the lower eradication success rate in the tropics (Russell & Holmes 2015) is more complicated to explain and the potential reasons are unresolved (Samaniego et al. 2020a). Guidelines for rat eradications on tropical islands were developed aiming to improve the success rate, acknowledging the existence of critical knowledge gaps (Keitt et al. 2015). Similarly, the resource kit for cat and rat eradications (PII 2011) is a valuable planning tool.

A statistical analysis on factors associated with rodent eradication failure (Holmes et al. 2015b) found factors unique to the tropics, such as warm temperatures, presence of land crabs and coconut palms to be clearly associated with eradication failure. A later review of a selected subset of tropical island cases (four successful, four 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 studying these aspects (Samaniego et al. 2020a) 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 reports (Merton 2001, Merton et al. 2002, Rocamora & Henriette 2015). A key component of any successful eradication is ensuring the first eradication principle of comprehensive bait coverage, that all animals are put at risk, is met. There are two possible scenarios that can explain failure to achieve this principle: 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 et al. (2013). Reviews so far have focused on the latter (Holmes et al. 2015b, Griffiths et al. 2019); therefore, we focused on the former (i.e. operational factors) and set out to investigate the role of these factors as causes of failure.

Our qualitative review is complementary to those by Holmes et al. (2015b) and Griffiths et al. (2019), also aiming to shed light on how to maximize the chances of eradication success, but approaching the topic from a different direction by studying cases where rodent eradication initially failed but was eventually achieved in a later attempt. We compare project management, operational and environmental factors for both the initial and successful attempts on each island. We also assess the potential causes of initial failure and identify the key factors leading to subsequent eradication success. Our three main questions were: i) can faults in operational factors explain the initial failures? ii) can improvements in operational factors explain the subsequent successes? and iii) is it worth re-attempting more islands after initial failures? We also present recommendations for Wake Island, an atoll where a second eradication attempt is currently being planned, which encouraged this review. Finally, and pointing towards future research, a brief assessment of the failed eradications that have not been attempted again is provided in the last section. Our findings are useful for island rodent eradication projects in any temperate or tropical environment.

3 Methods

3.1 Case studies (1990 - 2018)

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). The later phase commenced with the Breaksea Island (170 ha) eradication, implemented in 1988 and confirmed successful in 1990 (Thomas & Taylor 2002). Likewise, the first successful trial of the aerial broadcast technique occurred in 1990 (Towns & Broome 2003). Following New Zealand developments, eradications have had a similar history elsewhere (e.g. Samaniego et al. 2011, Rocamora & Henriette 2015), with increasing success rates over time despite increasing island size (Figure 1). Given the nascent nature of early eradications, we chose to focus on first eradication attempts from 1990 onward as representative of the modern era of systematic eradication operations.

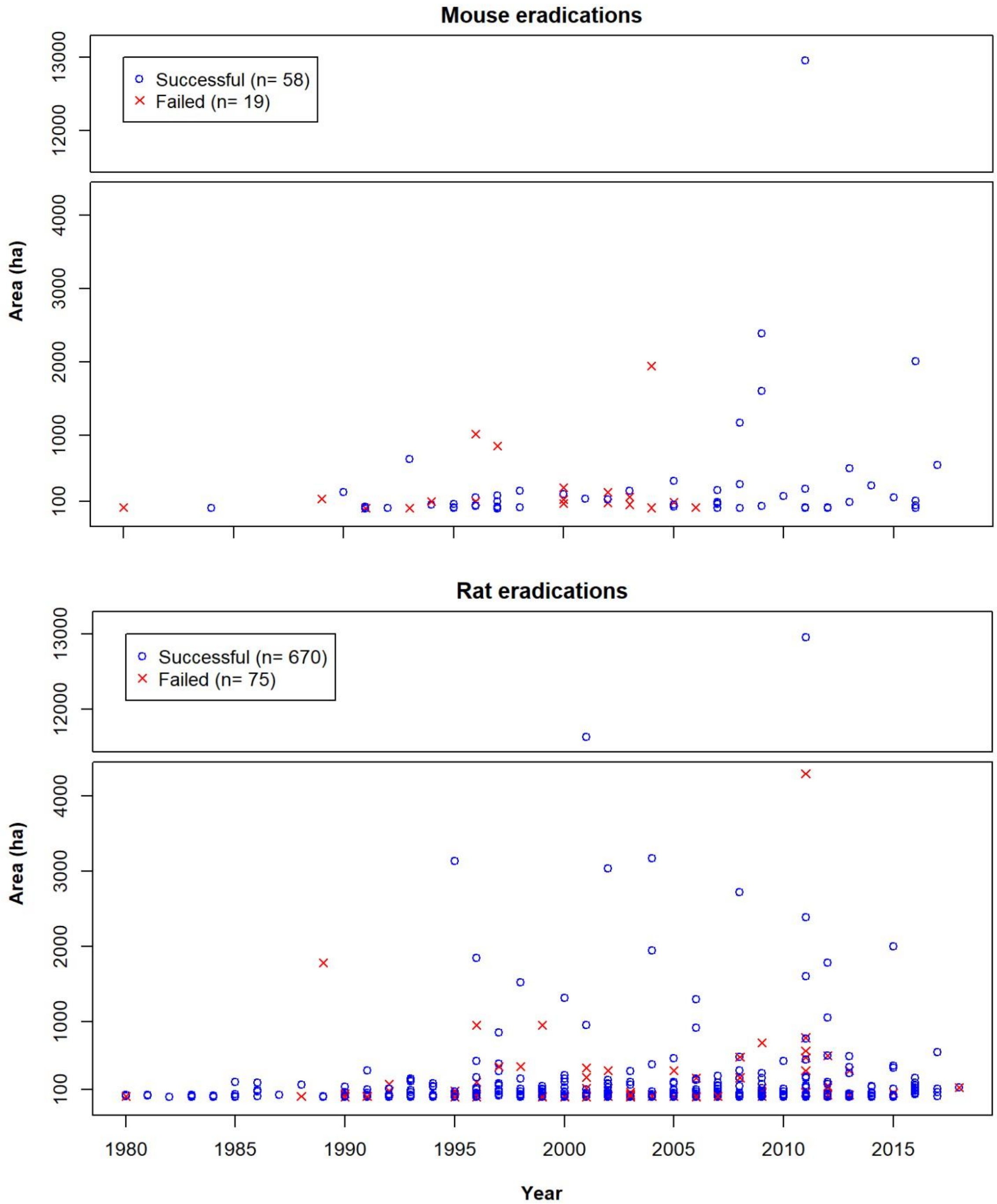

Figure 1. Global mouse (*M. musculus*) and rat (*Rattus* spp.) eradication attempts (1980-2018) and their outcomes. Data source: DIISE (2018); only cases with good quality data and with confirmed outcome by 2018 are included.

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We used the Database of Island Invasive Species Eradications (DIISE 2018) to identify island eradications based on the following criteria: 1) target taxa: *Muridae*, 2) type: whole island eradications (i.e. excluding incursion response and restricted range operations), 3) primary eradication method: toxicant (i.e. excluding trapping), 4) toxicant type:

known (i.e. excluding unknown), 5) year of eradication: 1990 onwards, 6) 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 7) quality of data: good or satisfactory, with the latter either improved to good quality with our supplemental research (one case) or discarded if the required information was not available (four cases).

We then identified the islands where eradication had been attempted more than once for the same target species. On each island, one or two species of a pool of five 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*). Indications on the status of rodent populations (level of abundance and breeding activity) are either based on local data or data from similar ecosystems. The resulting list included 44 eradication operations on 18 islands. For two islands (Mokoia and Teuaua) additional attempts prior to 1990 existed; we added those earlier attempts to give a complete eradication history of these islands. Of the 18 islands, 14 constituted cases where rodent eradication was eventually achieved whereas the remaining four referred to cases where eradication was never achieved despite several attempts. We grouped and reviewed the latter separately. One case from this category (Matakohe, New Zealand) was excluded as most likely it is subject to continuous reinvasion given its proximity (500 m) to the mainland. The final list included 42 operations comprising 17 islands and eight countries (Table 2).

Table 2. Island rodent eradications targeting the same species twice or more (1990-2018), by country and date of first attempt.

Country	**Island**	***Year initial attempt(s)**	***Year successful attempt**	**Target species**	**Notes**
Temperate islands where eradication was achieved					
New Zealand	Mokoia	1989, 1996	2001	*Rattus norvegicus*, then *Mus musculus*	First attempt targeted rats only
New Zealand	Coppermine	1992	1997	*Rattus exulans*	
Tropical & subtropical islands where eradication was achieved					
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

Country	Island	*Year initial attempt(s)	*Year successful attempt	Target species	Notes
United Kingdom (Bahamas)	Low Cay	1999	2000	*Rattus rattus*	
United States (Tropical Pacific)	Palmyra	2001	2011	*Rattus rattus*	
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
USA	Congo Cay	1990, 2004, 2006	N/A	*Rattus rattus*	

*Year of baiting (as opposed to year of confirmation, usually 1-2 years after baiting).

3.2 Factors analyzed

Results are presented by country and island in the order shown in Table 2. A brief island description is provided to give context for the summary table and narrative of each eradication attempt. We compared management, operational and environmental factors across attempts, including those identified by Holmes et al. (2015b) 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. The operational factors in the summary tables include those that we could get reliable information for across all islands. Risk of rodent reinvasion was categorized as:

- **High**: the island is <1,000 m from either the mainland or another infested island, so reinvasion can occur by rodents swimming the gap or floating on vegetation or other debris. However, the swimming capabilities of rodents are different for each species. In general, larger species can swim longer distances and vice-versa.
- **Moderate**: the island is >1,000 m from a potential source of reinvasion but there is regular movement of people and goods.
- **Low**: the island is remote, uninhabited, and human activities are limited.
- Published and grey literature was reviewed, and direct communication with project managers took place for some cases. Collectively, the authors of this report 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 for several cases. Lack of, inconsistency and inaccessibility of reporting continues to be a major issue preventing learning from failure (see discussion).

3.3 Acronyms and glossary

ATV: All-Terrain Vehicle

CALM: Department of Conservation and Land Management – Australia (Western Australia), now Department of Biodiversity, Conservation and Attractions (DBCA)

CI: Conservation International

DBCA: Department of Biodiversity, Conservation and Attractions – Australia (Western Australia), formerly Department of Conservation and Land Management (CALM)

DEC: Department of Environment and Conservation – Australia (Western Australia), a predecessor of the Department of Biodiversity, Conservation and Attractions (DBCA)

DGPS: Differential GPS

DPAW: Department of Parks and Wildlife – Australia (Western Australia), a predecessor of the Department of Biodiversity, Conservation and Attractions (DBCA)

DIISE: Database of Island Invasive Species Eradications

DOC: Department of Conservation – New Zealand

DTF: Dutch Trust Fund

FFEM: French Facility for Global Environment/Fonds Français pour l'Environnement Mondial

GECI: Grupo de Ecología y Conservación de Islas – Mexico

GPS: Global Positioning System

IBA: Important Bird Area

IC: Island Conservation

ICS: Island Conservation Society – Seychelles

IEAG: Island Eradication Advisory Group

ILM: Institute Louis Malardé – French Polynesia

MET: Ministry of Environment and Transport – Seychelles

NGO: Non Governmental Organization

NWRC: USDA Wildlife Services National Wildlife Research Center

OCT: Overseas Country and Territory

PCS: Palau Conservation Society

PII: Pacific Invasives Initiative

SOP-Manu: Polynesian Ornithological Society/Société d'Ornithologie de Polynésie – French Polynesia

TNC: The Nature Conservancy – USA

UNAM: National Autonomous University of Mexico/Universidad Nacional Autónoma de México

UNESCO: United Nations Educational, Scientific and Cultural Organization

USAF: US Air Force

USDA: United States Department of Agriculture

USFWS: United States Fish and Wildlife Service

USVI: United States Virgin Islands

Adaptive management is a systematic approach for improving resource management by learning from management outcomes. It involves exploring alternative ways to meet management objectives, predicting the outcomes of alternatives based on the current state of knowledge, implementing one or more of these alternatives, monitoring to learn about the impacts of management actions, and then using the results to update knowledge and adjust management actions (e.g. Allan & Stankey 2009). This approach is useful when there is substantial uncertainty regarding the most appropriate strategy for managing resources.

Alternative food is any potential rodent food other than bait, which can be naturally occurring or human produced. See also commensal food and commensal waste.

Bitrex® (denatonium benzoate) is a bittering agent intended to prevent accidental ingestion of toxic bait by children and pets. There is evidence suggesting the inclusion of Bitrex may adversely affect palatability of baits to rodents; therefore, while the risk may be acceptable for control operations it is not an acceptable risk for eradication operations (Cromarty et al. 2002). The most common bait products used for eradications at present (see below) do not contain Bitrex.

Commensal food is all the food brought or grown for consumption by humans and their animals; this may provide alternative food for rodents.

Commensal waste is the food and human waste generated by human presence and activities; this may provide alternative food for rodents.

Copra is the dried meat or kernel of the coconut, from which coconut oil is extracted.

Interspecific competition is a form of competition in which individuals of different species compete for the same resources in an ecosystem.

Iwi are the largest social units in Aotearoa Māori society. The word is usually translated as 'tribe'.

Land crabs comprise over a hundred species but for the purpose of eradication planning they can be categorized into three broad groups: burrowing crabs, hermit crabs and coconut crabs; although the latter single species (*Birgus latro*) is technically a hermit crab (Samaniego et al. 2019). Land crabs show significant behavioral, morphological, physiological, or biochemical adaptations permitting extended activity out of water; this includes a few families of the diverse infraorders Anomura (hermit crabs) and Brachyura (burrowing crabs) (Burggren & McMahon 1988).

Māori are the indigenous Polynesian people of New Zealand.

Rodenticides are classified into two categories: non-anticoagulant acute poisons and anticoagulants, the latter separated into first-generation (multi-feed) and second-generation (single-feed) chemicals.

The active (toxic) ingredients (Eason & Ogilvie 2009) mentioned in this document are:

- **Brodifacoum and bromadiolone** are a second generation (single-feed) anticoagulants. Like other anticoagulant toxicants (first and second generation), they act by interfering with the synthesis of vitamin K-dependent clotting factors. This increases the clotting time of blood and leads to death from hemorrhaging. The persistence of second generation anticoagulants in the environment is higher than that of first generation anticoagulants.
- **Bromethalin** is a neurotoxicant. It is a single-feed rodenticide that is registered for use in the USA; however, its use is restricted to bait stations in and around buildings.
- **Diphacinone and chlorophacinone** are first generation (multi-feed) anticoagulants. They are most effective against rodents when ingested as multiple consecutive doses over several days. First generation are less toxic than

second generation anticoagulants, which can benefit non-target species but also increase the risk of not killing all rodents.

- **Pindone** is another first generation anticoagulant commonly used in the management of rodent and rabbit populations.
- **1080 (sodium fluoroacetate)** is the 'salt' form of the naturally-occurring toxin, fluoroacetate, found in several poisonous plants around the world. 1080 bait is highly water soluble and naturally breaks down in the environment into harmless substances through the process of biodegradation and dilution. It does not accumulate or leave permanent residues in soil, plants, in water or in animals.

The bait products used for the reviewed projects are:

a) Mainly for both aerial and hand broadcast operations

- **Conservation 25-D**: Brodifacoum Conservation 25-D are 2 g pellets made by Bell Labs (Madison, WI, USA). This formulation is designed for dry climatic conditions and it does not contain Bitrex.
- **Conservation 25-W:** Brodifacoum Conservation 25-W are 2 g pellets also made by Bell Labs. This formulation is designed for wet climatic conditions and it does not contain Bitrex.
- **Pestoff 20R**: Pestoff Rodent Bait 20R are pellets with brodifacoum made by Orillion (Whanganui, New Zealand) and are available in different sizes. This bait is designed for a wide range of climatic conditions and it does not contain Bitrex.
- **Whanganui No.7**: cereal pellets with Bitrex and cinnamon lure made by Orillion.

b) Mainly for bait stations and sometimes directly on the ground under floors or in roof cavities

- **Final**: FINAL Soft Bait with Lumitrack is a soft bait packed in 15 g sachets with an extruded hole in the center to secure them in bait stations. This bait incorporates Lumitrack, a dye that causes rodent droppings to brightly glow under UV or black light.
- **Talon (G, WB, XT), Contrac Blox, FASTRAC All-Weather BLOX (Fastrac)**: weather resistant blocks made by Syngenta (Talon) or Bell Labs (Contract Blox and Fastrac) and come in several presentations and concentrations (i.e. different shapes, sizes and colors). This bait is designed to withstand harsh climatic conditions for months as it contains wax. All of these products contain Bitrex as they are available to the general public.

4 Results

Out of 17 islands with two or more attempts, eradication was achieved on 14 (82%; ranging 5-1020 ha) at the second (86%) or third attempt (14%). On the remaining three islands (10-217 ha) complete eradication was not achieved despite two or three attempts, noting that on Kayangel one of the two rat species was removed. Detailed results by island, grouped by country, are shown below.

4.1 New Zealand

New Zealand is internationally recognized as both the pioneer and the leader of pest eradications on islands (Russell & Broome 2016). Its long history of removing invasive vertebrates from islands has been greatly assisted by several factors, including efforts largely being concentrated within one organization, DOC, which has implemented incremental approaches toward the development of technology and has a legal mandate to conduct the work (Towns et al. 2013). To date, about 117 New Zealand islands have been cleared of invasive rodents including notable records such as the rat eradication on Campbell (McClelland & Tyree 2002), the mouse eradication on Antipodes (Horn et al. 2019) and the multi-species eradication on Rangitoto-Motutapu (Griffiths et al. 2015). Winter has always been the target season for implementation given the significant decreases in rodent abundance and reproduction due to low temperatures and scarcity of food.

4.1.1 **Mokoia** (135 ha, 156 m maximum elevation)

Island description (mainly from Perrott & Armstrong 2000): Mokoia is in Lake Rotorua in the North Island. The climate is temperate with an annual temperature of 12.8°C. The rain falls on 117 days and averages 1,341 mm of precipitation per year. It has secondary forest, which has been regenerating for about 50 years. Mokoia has a long history of Māori occupation. Māori grew crops in the fertile soil for hundreds of years, and most of the island was burned, cleared and terraced until about 1950. Māori also modified Mokoia by introducing many native trees probably not present before. Europeans planted exotic tree species like pines and a variety of fruit trees from 1830. Goats were introduced in 1985 to control blackberry but they began browsing the regenerating forest, so they were eradicated during 1989-90 by DOC. The island's vegetation is now composed largely of understory species such as five-finger (*Pseudopanax arboreus*), kawakawa (*Macropiper excelsum*), mahoe (*Melicytus ramiflorus*) and rangiora (*Brachyglottis repanda*). The vegetation is low and scrubby on the ridges, particularly near the summit, but there is a closed canopy with an open forest floor in gullies and near the lake shore. Several species of native birds have either been reintroduced or have recolonized the island. The distance to the closest source of invasive rodents, the mainland, is 2 km.

Conservation/ownership status: wildlife refuge, community (iwi) owned. The island is sacred to Māori of the Te Arawa iwi. Access is only allowed to certified operators.

Figure 2. Mokoia Island, New Zealand (Photo: Mokoia Island Wai Ora Experiences).

Table 3. Comparison of operational and environmental factors across eradication attempts on Mokoia Island, New Zealand.

Factor	Initial attempts	Successful attempt
Year	1989 & 1996	2001
Target species	1989: Norway rat (successful) 1996: house mouse (failed)	House mouse
Season + month	Winter	Winter
Environmental conditions	Normal	Normal
Land crabs present	No	No
Coconut palms present	No	No
Agriculture present	No	No

Human habitation	No (but there is a research hut)	No (but there is a research hut)
Factor	**Initial attempts**	**Successful attempt**
Rodent ecology	Not assessed; most likely at low density and not breeding at the time of eradication	Not assessed; most likely at low density and not breeding at the time of eradication
Method	1989: bait stations, 50 × 50 m grid 1996: aerial and hand broadcast, 1 aerial application of 10 kg/ha + hand broadcast along the coast	Aerial broadcast, 2 applications: 8 kg/ha + 4 kg/ha; total of 12 kg/ha. Swath overlap: 50% for first application and 25% for second application
Bait	1989: Talon WB 1996: Whanganui No.7	Pestoff 20R
Active ingredient	1989: brodifacoum 50 ppm 1996: brodifacoum 20 ppm	Brodifacoum 20 ppm
Organization	DOC	DOC
Notes	1989: only Norway rat targeted and eradicated; mice only detected afterwards 1996: only one aerial application with manual coastal baiting, which was difficult in some areas	Adaptive management applied
Risk of reinvasion	High	High
Best practice (BP) followed	N/A (pre-BP)	N/A (pre-BP)
References	Owen 1998, Cleghorn & Griffiths 2002, Broome et al. 2019	MacKay et al. 2007, Broome et al. 2019

4.1.1.1 Diagnosis

The first attempt (1989) using bait stations was designed around the home range of Norway rats, which were eradicated. This operation did not explicitly target mice, which survived and became detectable after the rat population was eradicated (Broome et al. 2019). Hence, this attempt should be treated as a successful rat eradication only and not as a failed mouse eradication.

The second baiting operation (1996) targeted mice for the first time. Bait was aerially applied once, and coastal areas were treated manually as authorities were concerned about bait spillage into the lake. The application of bait reduced mice to extremely low levels; however, the mouse population slowly built up in the months after the drop and appeared to reach pre-poison levels within 12 months (Armstrong et al. 2001). It is possible that some mice were not exposed to bait due to gaps in bait coverage. In particular, Cleghorn & Griffiths (2002) reported that '*Areas of dense blackberry on the eastern side of the island made spreading bait by hand difficult in some areas'.* Given the year it is likely the team had limited experience in hand baiting, and overlapping areas with different types of treatments to avoid gaps in bait coverage was not practiced back then. In addition, the bait used included Bitrex.

The third baiting operation, the second attempt for mice (2001), was successful. This time the island was completely treated aerially, two bait applications took place, a bait with a proven track record of successful mouse eradications was used, and the overall operation was explicitly set to implement higher standards in the helicopter operation (Broome et al. 2019).

4.1.1.2 Conclusion

The first attempt was ground based and targeted Norway rats only, and was successful.

The second attempt employed aerial bait application on the bulk of the island and hand broadcast along the coast, and targeted mice. Several operational faults occurred. The main potential causes of failure were identified by the operators as gaps in bait coverage and type of bait.

The third attempt, this time 100% aerial, included two applications with overlapping swaths and achieved mouse eradication by correcting faults and raising overall implementation standards.

4.1.2 **Coppermine** (80 ha, 184 m maximum elevation)

Island description (mainly from Cameron 1984): the climate is temperate with rainfall most of the year. The island measures ~1.7 × 0.5 km. The coastline is rugged with steep cliffs except for the western end. The forest was extensively modified by Māori. The vegetation has not only suffered from fire, in both Māori and European times, but also mining. In 1849 and 1896 attempts were made to mine copper, but it was found to be uneconomic. During this period vegetation was burnt, though the western end of the island escaped this and was probably last burnt in the early 1900s. The vegetation today includes varied coastal broadleaf forest such as pohutukawa, kohekohe, karaka, taraire, tawa, puka and areas of kanuka. The distance to the closest source of invasive rodents, the mainland, is 2 km.

Conservation/ownership status: nature reserve. Evidence of past Māori occupation is still present.

Figure 3. Coppermine Island, New Zealand (Photo: NZ).

Table 4. Comparison of operational and environmental factors across eradication attempts on Coppermine Island, New Zealand.

Factor	Initial attempt	Successful attempt
Year	1992	1997
Target species	Pacific rat	Pacific rat

Season + month	Winter	Winter
Environmental conditions	Normal	Normal
Factor	**Initial attempt**	**Successful attempt**
Land crabs present	No	No
Coconut palms present	No	No
Agriculture present	No	No
Human habitation	No	No
Rodent ecology	Not assessed; most likely at low density and not breeding at the time of eradication	Not assessed; most likely at low density and not breeding at the time of eradication
Method	Bait stations, 100 × 100 m grid	Aerial broadcast, 1 application of 10 kg/ha
Bait	Talon WB	Whanganui No.7
Active ingredient	Brodifacoum 50 ppm	Brodifacoum 20 ppm
Organization	DOC	DOC
Notes	The grid spacing was intentionally wider than usual, as a trial	No GPS used
Risk of reinvasion	Low	Low
Best practice (BP) followed	N/A (pre-BP)	N/A (pre-BP)
References	McFadden 1997, Thomas & Taylor 2002	McFadden 1997, Thomas & Taylor 2002

4.1.2.1 Diagnosis

The first attempt in 1992 occurred at a time when practitioners had become confident with the bait station technique, but they were still testing the efficacy of various spacings for different target species. To test the efficacy of a 100 × 100 m grid to eradicate Pacific rats, an experimental eradication took place on Coppermine Island (Thomas & Taylor 2002). Today we know that using 100 m spacing is a risky approach for targeting any invasive rat (but see Kaiser et al. 1997) and particularly the Pacific rat – the smallest of the invasive rats in both body size and home range (King 1990). Current best practice recommends a spacing of 25 × 25 m when bait stations are used against Pacific rats in New Zealand (Broome et al. 2011b). Thus, most likely the grid used in the first attempt on Coppermine simply did not expose all rats to the bait, as suggested by Clapperton (2006). Furthermore, and equally important, the project was not sustained but *'stopped due to a management decision before the planned work was completed'* (Clout & Russell 2006).

The second attempt five years later (1997) was conducted by helicopter, although before formal best practice was well established. It succeeded despite conducting only one bait application and using no GPS in the helicopter. The small size of the island, the New Zealand winter and the skills of the pilot might have all been contributing factors to the success. At present, two bait applications and GPS guidance for all helicopters used are recommended for aerial broadcast operations.

4.1.2.2 Conclusion

The first attempt was ground based and was essentially an experiment testing whether a wide grid is effective for Pacific rats. The operation failed, suggesting tighter spacings should be used, as is recommended at present. Failure to maintain continuity of operations was also likely a contributing factor.

The second attempt, an aerial operation, was successful. The eradication technique, allowing better bait distribution, was the main change.

4.2 Australia

Australia has a long history of eradications of non-indigenous species, particularly on Western Australian islands (e.g. Burbidge & Morris 2002, Priddel et al. 2011). Invasive rodents have been eradicated from numerous small islands, although the focus remains on cats and foxes as these introduced species are implicated in most mammal extinctions on Australian islands (Burbidge & Abbott 2017). Yet, three remarkable achievements concerning rodents deserve to be highlighted. The first one is the multi-island project on the Montebello Islands (see details below); the second is the multi-species (house mouse, ship rat and European rabbit) project on Macquarie Island (12,800 ha), at the time the largest mouse eradication and second largest ship rat eradication in the world (Springer 2018); and the third one is the recent (2019) mouse and ship rat eradication on Lord Howe (1,455 ha), the largest inhabited island attempted (Harper et al. In press), which is yet to be confirmed. Several other rodent eradications, including islands in the northern wet tropical regions of Australia, are being planned.

4.2.1 **Varanus** (80 ha, 18 m maximum elevation)

Island description (from Apache 2012): Varanus Island is the largest of the Lowendal Islands, an archipelago off the northwest coast of Western Australia. The climate of the region is arid subtropical with hot summer temperatures and low and unpredictable rainfall, high evaporation, occasional cyclones and associated summer rainfall. The annual average rainfall of the Lowendal Islands is approximately 300 mm, mostly as a result of tropical cyclones. The topography of Varanus Island is flat to undulating low dunes. The vegetation is low, from open shrubland of *Scaevola spinscens, Rhagodia preissii* and *Sarcostemma viminale* on limestone plains and ridges to closed mixed grassland/herbland of *Setaria dielsii* and *Amaranthus pallidiflorus* on the deeper orange sands of inland plains. The distance to the closest source of invasive rodents, another island, is 11 km.

Conservation/ownership status: the island is part of the Lowendal Islands Important Bird Area (IBA). There is an oil and gas base, which at the time of the eradication was operated by Apache Energy and at present is operated by Santos Limited.

Figure 4. Varanus Island, Australia (Photo: Google Earth).

Table 5. Comparison of operational and environmental factors across eradication attempts on Varanus Island, Australia.

Factor	Failed attempt	Successful attempt
Year	1994	1997
Target species	House mouse	House mouse
Season + month	Dry season	Dry season
Environmental conditions	Normal	Normal
Land crabs present	No	No
Coconut palms present	No	No
Agriculture present	No	No
Human habitation	Yes	Yes
Rodent ecology	Not assessed; most likely at low density and breeding at the time of eradication	Not assessed; most likely at low density and breeding at the time of eradication
Method	Bait stations at irregular intervals	Bait stations, 20 × 20 m grid
Bait	Wheat	Wheat vacuum-impregnated with pindone and Talon WB
Active ingredient	1080	Pindone and brodifacoum 50 ppm
Organization	Apache Energy (staff)	Apache Energy

Notes	Mice accidentally introduced in 1993 The company tried mouse control around the base, then expanded to whole-island treatment	The island users consulted with experts and a systematic baiting strategy was implemented
Risk of reinvasion	Moderate	Moderate
Best practice (BP) followed	N/A (pre-BP)	N/A (pre-BP)
References	Burbidge & Morris 2002	Burbidge & Morris 2002

4.2.1.1 Diagnosis

This simple case is summarized by Burbidge & Morris (2002): '*In May 1993, the house mouse was introduced to Varanus Island in food containers supplied to an oil and gas base operated by Apache Energy. From there it spread naturally to nearby Bridled (22 ha) and Beacon (1.2 ha) Islands. Initial attempts by the company to eradicate near their facilities and then across all of Varanus Island using wheat with I080 failed, probably due to insufficient bait being laid in bait stations that were too far apart and lack of follow up. After consultation with experts and better planning, eradication was achieved using wheat vacuum-impregnated with pindone and wax blocks with brodifacoum laid in bait stations on a 20 m grid and maintained over a period of months. Eradication was achieved in 1997 (I. Stejskal, Apache Energy and John Angus, CALM, pers. comm.).'*

The bait used in the first attempt is currently not recommended for mice. Pindone was tested in the early years but it is currently not used for island eradications. Brodifacoum is the toxicant used in the vast majority of successful eradications to date. No detailed reports of the ground work are available but it is clear that the second attempt was improved by better planning, including systematic implementation of more effective baits in more densely spaced stations, for a longer period.

4.2.1.2 Conclusion

Initial attempts of managing an accidental mouse introduction failed due to poor planning; the attempt after expert consultation succeeded, when more effective bait and a systematic approach were used.

4.2.2 **Montebello** (1-1020 ha, 1-28 m maximum elevation)

Island description (from Burbidge et al. 2000): the Montebello Islands is an archipelago of about 180 islands, islets and rocks totaling >2000 ha, located in Western Australia. The islands covered in this section are Hermite (1020 ha), Crocus (33.6 ha) and Primrose (35.4 ha). There are moderately high cliffs on the west coast of Hermite Island. Most islands are composed of limestone with low coastal cliffs and white sand beaches. The islands have a tropical arid climate. The hottest months are February and March and the coolest is July. Most rain comes from summer tropical cyclones and thunderstorms and autumn and early winter middle level disturbances. The mean annual rainfall is 320.3 mm; the wettest months are June (mean 64.6 mm), March (60.8 mm), February (55.0 mm) and April (48.5 mm). Limestone areas are dominated by *Triodia* hummock grassland with scattered low shrubs, while sandy areas have grasses and sedges with low shrubs (mainly *Acacia* spp.). There are three small areas of mangrove (~13 ha in total) on Hermite Island, mainly *Avicennia marina* with some *Rhizophora stylosa*. Current human usage of the islands is restricted to short visits by tourists. Several charter boats bring visitors to the islands, mainly for fishing. Montebello Islands Safaris maintains a houseboat in a bay at the southern end of Hermite Island. The distance to the closest source of invasive rodents, another archipelago, is 22 km.

Conservation/ownership status: all islands are within Class A Reserve No. 42196, Conservation Park, while the land between high and low water is Class C Reserve 42197, Conservation Park. Both reserves are vested in the Western Australian Conservation and Parks Commission and managed by the Department of Biodiversity, Conservation and Attractions (DBCA).

Figure 5. Montebello Islands, Australia (Photo: australianorthwest.com).

Table 6. Comparison of operational and environmental factors across eradication attempts on Montebello Islands, Australia.

Factor	Failed attempt	Successful attempt
Year	1996 (whole archipelago treated) & 1999 (only Hermite treated)	2001
Target species	Ship rat	Ship rat
Season + month	1996: dry/cool season (May-September) 1999: dry/cool season (October)	Dry/cool season (September)
Environmental conditions	Normal	Normal
Land crabs present	No	No
Coconut palms present	No	No
Agriculture present	No	No
Human habitation	No	No
Rodent ecology	Density was high on some small islands where the rats were apparently feeding on the intertidal zone	Not assessed; most likely at low density and breeding at the time of eradication

Factor	**Failed attempt**	**Successful attempt**
Method	1996: bait stations, 50 × 50 m grid 1999: aerial broadcast, 1 application of 6 kg/ha No GPS, pilot attempted 50% swath overlap flying by eye	Aerial broadcast, 2 applications 10 days apart: 8 kg/ha + 4 kg/ha; total of 12 kg/ha DGPS and 50% swath overlap
Bait	1996: Talon G pellets with Bitrex 1999: Pestoff 20R	Pestoff 20R
Active ingredient	1996: brodifacoum 50 ppm 1999: brodifacoum 20 ppm	Brodifacoum 20 ppm
Organization	DOC and CALM Threatened Species and Communities Unit and Pilbara Region	DOC and CALM Threatened Species and Communities Unit and Pilbara Region
Notes	Multi-island project (~180 Montebello Islands) Most personnel were CALM staff who volunteered; 8 people spent 14 weeks in the field In 1997, Crocus and Primrose were rebaited as rat tracks were found In May 1999, rats were detected on Hermite. An aerial attempt shortly followed (October 1999); however, the helicopter ended up not having a GPS	The helicopter was fitted with a DGPS Swath width for flight lines was 100 m
Risk of reinvasion	Low	Low
Best practice (BP) followed	N/A (pre-BP)	N/A (pre-BP)
References	Burbidge & Morris 2002, Burbidge 2004, A. Burbidge pers. comm.	Burbidge & Morris 2002, Burbidge 2004

4.2.2.1 Diagnosis

The first attempt (1996) was strategically conceived after a series of successful small eradications in the region. Despite being early days in Australia's eradication history, this project was remarkably well planned. The Montebello Islands project was an ambitious complex project targeting the entire archipelago (~2000 ha pooling ~180 islands). Burbidge & Morris (2002) summarize the approach: '*The presence of two granivorous birds (bar-shouldered dove Geopelia humeralis and brown quail Coturnix ypsilophora) required the development of a bait station that excluded these species and allowed access by rats. Experimentation on one island in 1995 showed that a bait station comprising a* *plastic bottle with two 43 mm holes cut in its sides provided a suitable method and in 1996 over 12,000 bait stations were installed and serviced on a 50 m grid on all islands.'* Many small islets and rocks were hand baited by throwing, from a small boat, plastic bags containing bait onto the islet/rock. This occurred twice 10 days apart and was successful. One 4 ha long, narrow island was baited by dropping numerous plastic bags full of bait and they were all consumed within a day or two. Two follow ups were necessary given the remarkably high rat density on some small islands, where rats appeared to be feeding on the intertidal zone (A. Burbidge, pers. comm). Eradication was achieved on all islands except the largest (Hermite) and two adjacent smaller islands, where rats were not detected until 1999.

The following facts are based on the detailed report by Burbidge (2004) with additional details from A. Burbidge (pers. comm.). The original eradication plan had a monitoring component built in. In March 1997, monitoring revealed limited rat sign only on Primrose and Crocus, which were rebaited using the existing stations. Therefore, we consider this action an extension of the first attempt rather than a second attempt on Crocus and Primrose (as currently listed on the DIISE). The response was successful; in July 1997 no rat sign was detected. During this visit most bait stations were examined, as empty bait stations might reveal inadequate baiting during 1996. No empty bait stations were detected except on Primrose and Crocus, which suggests gaps in bait coverage may have occurred during the initial attempt. The extensive monitoring in 1998 revealed no rat sign, but in May 1999 rats were detected in low numbers on Hermite and two small adjacent islands. Being Hermite the largest island (1020 ha), the resources available were insufficient for an immediate ground response —the baiting in 1996 required eight people for 14 weeks in the field. Yet, a decision was made to promptly rebait Hermite and adjacent islands (in case rats had swum there) by helicopter.

For the second attempt on Hermite (October 1999), an aerial operation was undertaken after consultation with New Zealand DOC, noting that the 1996 operation had demonstrated no effect on the granivorous birds or via secondary poisoning to raptors or large carnivorous reptiles such as *Varanus gouldii*. The bait and bait bucket were sourced from New Zealand, and an experienced pilot and manager were contracted. However, a helicopter without GPS had to be used given the unit originally considered was not suitable without a base station, and there was not enough time to source one. In addition, there were problems with the motor on the bucket, which had been dowsed with sea water while being transported to the islands on a barge. This meant the spinner of the bucket kept stopping while the bucket was in use at least once per trip, so the pilot had to return to base for the motor to be restarted or land and restart the motor himself. Some small peninsulas were hand baited (from a low flying helicopter) to minimise spread into the ocean. A visit in August 2000 revealed low level tracks on Hermite Island. No tracks or other sign were located on any other island. It was believed that the above logistical problems had prevented a fully comprehensive baiting in 1999 and it was decided to rebait in 2001. A visit in June 2001 revealed rat racks on Alpha and Bluebell Islands, which had been considered rat free since 1996, showing the ability of rats to readily swim between the islands. Rat tracks were still present on Hermite.

The third attempt (2001) on Hermite was carried out successfully in September 2001. This time a DGPS was fitted to the helicopter and two bait applications were conducted, which greatly reduces the risk of bait gaps during bait application (Broome et al. 2017b). Given the potential risk of rat reinvasion on nearby islands, 'a*ll islands from Ah Chong northward to Primrose were baited… Inspections covering all of the larger and many small islands in September 2002 and May 2003 did not reveal any rat activity on any island'* (Burbidge 2004). Frequent visits since associated with translocations of native mammals and birds from Barrow Island have confirmed eradication (A. Burbidge, pers. comm.). During both aerial attempts (1999 and 2001) the areas with mangroves did not receive any treatment other than the aerially applied bait. At present, mangrove dominated areas are considered high risk areas and in some cases it is recommended to apply extra bait (Keitt et al. 2015).

4.2.2.2 Conclusion

The first attempt was ground based. It was an ambitious and thoroughly planned project. Both aspects are remarkable given this occurred before the development of best practice. The project covered a large archipelago of ~180 islands; all were cleared of rats except for Hermite, the largest of the Montebello Islands and also the largest island attempted at the time. It is not clear why it failed but, as discovered during the monitoring in 1997, some stations were missed during the original baiting and remained unbaited for some time.

The second attempt was aerial and focused on Hermite and a few adjacent islands. It was planned based on expert advice, used bait with a better track record, and an expert helicopter pilot was contracted. However, due to complications shortly prior to and during implementation only one bait application took place, no GPS was fitted to the helicopter and there were problems with the bait bucket. Gaps in bait coverage are therefore the most likely cause of failure.

For the third attempt, also aerial, the helicopter was guided by a DGPS and two bait applications were conducted. Hermite and several nearby islands were treated to counteract the risk of rat reinvasion by swimming; all islands remain rat-free.

4.3 French Polynesia

French Polynesia is a European Overseas Country and Territory (OCT) located in the South Pacific, formed by 120 tropical and subtropical oceanic islands (76 being inhabited) dispersed over a marine area as wide as Europe, and divided into five archipelagos: Austral, Marquesas, Society, Tuamotu, and Gambier Islands. A total of 46 species including 35 plants and 11 animals have been legally declared "a threat to biodiversity" in French Polynesia; invasive vertebrates in particular are widely considered the most significant threat to French Polynesia's avifauna (Meyer & Fourdrigniez 2019). However, investment for the management of invasive vertebrate species is limited and most of the eradication efforts are recent and have been executed by international partnerships implementing multi-island projects (e.g. Dérand et al. 2017).

4.3.1 **Vahanga** (380 ha, 3 m maximum elevation)

Island description (from Griffiths et al. 2011): mesic (wet) tropical without pronounced seasons. Vahanga is a typical coral atoll with an outer coral reef platform and beach c.10 km in circumference, succeeded by a shrubland and forest belt 200-400 m wide (broadleaf forest and coconut plantation), beyond which is a large lagoon. Channels dissect the atoll dividing it into discrete motu (two main motu and ten smaller). The distance to the closest source of invasive rodents, another island, is 6.5 km.

Conservation/ownership status: Important Bird Area (IBA). Tenararo-Vahanga is a key biodiversity area in Conservation International's (CI) critical ecosystem partnership fund ecosystem profile for the Polynesia/Micronesia Hotspot (#127). Vahanga is owned by the Catholic Church and managed by the Tureia Commune.

Figure 6. Vahanga Atoll, French Polynesia (Photo: Google Earth).

Table 7. Comparison of operational and environmental factors across eradication attempts on Vahanga Island, French Polynesia.

The contents of this Appendix comprise a draft in preparation for submission to a peer-reviewed journal. This report is for internal use only and does not constitute publication, nor does it represent any official U.S. Department of Agriculture finding or policy. This work was supported in part by the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center.

Factor	Initial attempt	Successful attempt
Year	2000	2015
Target species	Pacific rat	Pacific rat
Season + month	Dry season	Dry season
Environmental conditions	Normal	Normal
Land Crabs present	Yes	Yes
Coconut palms present	Yes	Yes
Agriculture present	No	No
Human habitation	No (one old church remains)	No (one old church remains)
Rodent ecology	Not assessed; most likely at high density and breeding at the time of eradication	Not assessed; most likely at high density and breeding at the time of eradication
Method	Bait stations, 50 × 50 m grid	Aerial broadcast, 2 applications 18 days apart: 30 kg/ha + 43 kg/ha; total of 73 kg/ha
Bait	Commercial bait locally manufactured (Tahiti)	Conservation 25-W
Active ingredient	Intended to be brodifacoum, but believed to have included chlorophacinone and bromadiolone (unknown ppm)	Brodifacoum 25 ppm
Organization	BirdLife, SOP-Manu	BirdLife, SOP-Manu, IC
Notes	Major issues with the bait, the baiting grid and the staff were acknowledged post-operation	The operation ran smoothly despite the multi-island approach of the wider project
Risk of reinvasion	Moderate: copra production was ongoing	Low: copra production has ceased as a protection measure
Best practice (BP) followed	No	Yes
References	Blanvillain 2001, Gouni et al. 2011.	Gouni et al. 2011, Dérand et al. 2015, Dérand et al. 2017, Griffiths et al. 2019.

4.3.1.1 Diagnosis

Gouni et al. (2011) reviewed the first attempt (2000) and concluded that the failure '*was mainly due to a lack of suitable management and planning - some of the factors that may have contributed to the failure include:*

- uncertain bait specifications as it was not possible to test the toxin provided by a poison bait manufacturer on Tahiti – originally intended to be brodifacoum, but believed to include chlorophacinone and bromadiolone,
- insufficient bait for the size of the atoll (island size underestimated and bait quantity was less than ordered),
- too few, untrained workers with little or no interest in the outcome, leading to poor quality of operation (e.g. some bait being dumped in the sea),
- insufficient time for set-up, poisoning and follow-up,
- gaps in coverage (intervals between lines up to c.100 m),
- rapid loss of baits from some stations (crabs),
- no supervision during follow-up period,
- some rats may not have been prepared to climb to some higher bait stations set on young palm fronds.'

Most of these issues are significant enough to cause eradication failure on their own, and combined, they would likely ensure an unsuccessful operation on any type of island. Indeed, even in the area that received better treatment the rat population never decreased significantly.

The second attempt (2015) took place 15 years later and benefited from a more experienced team, recent international guidelines and a larger partnership. The baiting strategy changed completely, correcting all past issues, and Vahanga was included in an ambitious multi-island, multi-species project (Dérand et al. 2015, Griffiths et al. 2019). All islands were treated aerially, following best practice; all but one were successful (Dérand et al. 2017). Rats were eradicated from Vahanga without major issues reported.

4.3.1.2 Conclusion

The first attempt was ground based; both the management and the implementation were sub-optimal. A range of operational issues, from low quality bait to gaps in bait coverage were identified.

The second attempt was an aerial operation implemented to high standard by an experienced team. In addition, Vahanga was a priority site during this multi-island project.

4.3.2 **Teuaua** (5 ha, 20 m maximum elevation)

Island description (from Withers et al. 2017): Teuaua is an offshore island of Ua Huka Island, which is the driest area of the Marquesas Islands, French Polynesia. The climate is dry tropical; the limited rain usually falls in MarchApril and again around June. The topography of Teuaua is a flat plateau surrounded by cliffs 10-20 m height. Access is only possible at high tide from one point where the cliff can be climbed with the assistance of a fixed rope. Vegetation is dominated by *Amaranthus* bushes, which can form a thick mat after rainfall. The distance to the closest source of invasive rodents, the mainland, is 2.5 km.

Conservation/ownership status: the area is collectively an Important Bird Area (IBA); Teuaua is an important colony of sooty terns (*Onychoprion fuscatus*). The community at Ua Huka uses Teuaua for traditional egg harvesting, so community engagement was crucial.

Figure 7. Teuaua Island, French Polynesia (Photo: Island Conservation).

Table 8. Comparison of operational and environmental factors across eradication attempts on Teuaua Island, French Polynesia.

Factor	Initial attempts	Successful attempt
Year	1986-1987 & 2009	2017
Target species	1986-1987: ship rat and Pacific rat (successful for ship rat, but not for Pacific rat) 2009: Pacific rat	Pacific rat
Season + month	Aseasonal (dry year-round) 1986-1987: 2 pulses, November and May 2009: July	Aseasonal (dry year-round) June
Environmental conditions	Normal	Atypical with high vegetative growth in lead up to the operation and an associated abundance of food during the baiting
Land crabs present	No	No
Coconut palms present	No	No
Agriculture present	No	No
Human habitation	No	No
Rodent ecology	Breeding at the time of eradication	At low density and breeding at the time of eradication

Factor	Initial attempts	Successful attempt
Method	1986-1987: trapping, fumigation (butane) and limited hand laid bait 2009: trapping and hand broadcast, 2 applications of 15 kg/ha on a 10 m × 10 m grid; total of 30 kg/ha	Hand broadcast, 2 applications of 23.6 kg/ha 18 days apart, 20 m × 20 m grid (153 bait points); total of 47.2 kg/ha The above was decided shortly before baiting; the original plan was for 3 applications of 15 kg/ha each, 15 days apart, for a total of 45 kg/ha
Bait	1986-1987: Talon WB 2009: Pestoff 20R	Conservation 25-D
Active ingredient	1986-1987: brodifacoum 50 ppm 2009: brodifacoum 20 ppm	Brodifacoum 25 ppm
Organization	1986-1987: ILM 2009: SOP-Manu, BirdLife	IC, SOP-Manu, BirdLife
Notes	1986-1987: the experimental nature of the project was acknowledged. Using multiple techniques was considered advantageous; none was applied systematically 2009: ~20,000 pairs of sooty terns were breeding on the plateau at the time of baiting	Arrived to implement in January 2017 but delayed to June due to abundant sooty terns In June, sooty terns were fewer but still abundant and breeding. After significant rainfall the island was comparatively lush, with high invertebrate activity. Physical conditions were not favorable, but further delays would have impacted the relationship with the community. Implementation took place to high standard
Risk of reinvasion	Low	Low
Best practice (BP) followed	1986-1987: N/A (pre-BP) 2009: overall, yes, but trapping is not a recommended eradication technique	Yes
References	1986-1987: Séchan et al. 1987 2009: Faulquier 2008, Faulquier et al. 2009a,b, Faulquier 2011	Withers et al. 2017, Zito & Withers 2017, Withers pers. comm.

4.3.2.1 Diagnosis

The first attempt (1986-1987) took place around the time variations of the ground eradication methods were being explored. Séchan et al. (1987) describes how a plan to remove invasive rats was developed by researchers to increase the breeding success of the seabirds on Teuaua, particularly sooty terns. The operation considered the ecology of the island and even the distribution of both rat species was studied, with ship rats dominating the plateau and Pacific rats mainly inhabiting the cliff areas. They tried trapping and poisoning in 1986 and gas fumigation in 1987. However, it appears none of the methods were applied systematically nor covered 100% of the island. As many rats were evidently killed, this was considered a successful project (i.e. it gave the seabirds a period without significant predation). Ship rats were eradicated but Pacific rats, inhabiting the cliff areas, survived.

The second attempt (2009) was implemented 22 years later by a different team and with a more systematic approach, taking advantage of the advances in the field (Howald et al. 2007). An operational plan (Faulquier 2008), based on recent fieldwork conducted by the team, was produced. In addition to trapping and to the 10 × 10 m grid on the plateau to be treated by hand broadcast at a rate of 15 kg/ha, the operational plan included a baiting prescription for the cliffs: '*5 kg of poison will be dispersed on the cliffs from the plateau during each bait application. The perimeter of the island is about 1000 meters (930 m based on Google Earth); the dispersion will be made from 20 different points distributed every 50 meters. A quantity of 125 g must therefore be dispersed from each of these points'* [translated from French]. However, the post-operational reports (Faulquier et al. 2009a, Faulquier et al. 2009b) do not mention any treatment of the cliffs. Therefore, it appears that a good effort was put in on the plateau but not along the cliffs, although there is limited rat habitat and food there. Interestingly, the internal review of the second attempt (Faulquier 2011) mentioned '*An extra small amount of bait was spread on the cliffs (by hand from the plateau) as they were too vertical and steep and at many points the bait would have fallen into the water*' and concluded that the most likely reasons explaining the failure were: a) the abundant alternative food resources for rodents given the ~20,000 pairs of sooty terns breeding on the Teuaua plateau at the time of baiting and b) the numerous cavities found on the islet which provide shelter and probably additional food for rats. However, as explained below, both conditions were still present in the subsequent attempt.

The third attempt (2017) was a follow-up project of the second attempt. It was implemented eight years later by the same organization, although with greater support from international experts including on the ground collaborations. The new operational plan (Withers et al. 2017) was informed by the accumulated work on Teuaua, recent field surveys, and international experience. The baiting strategy remained similar; the main differences were: a) stop rules (if sooty terns are found to be breeding at the time of implementation, the project will be postponed), b) baiting interval (increased to 15 days between applications), c) bait quantity (sufficient bait for a third application, in case of rain or increased consumption, was ordered) and d) cliff treatment ('*Cliff areas were audited to ensure that all potential rat habitats were found. The potential for rat habitat on these cliffs is low (too steep, not enough plant species or birds nesting). The cliffs do not need to be audited again, thus, an amount of bait will be either spread from the top of the island or via boat'*). On arrival for eradication implementation in January 2017, the team decided to postpone due to the high abundance of nesting sooty terns (i.e. the stop rule). Next May, pictures of Teuaua provided by the local partners showed low numbers of birds so the operation restarted. However, when the baiting team came back in June, the sooty terns were fewer than in January but still abundant and breeding, and after significant rainfall the island was comparatively lush with high invertebrate activity. Physical conditions were not highly favorable for eradication, but further delays would have impacted the relationship with the community, so the team proceeded, acknowledging they were breaking their stop rule (Withers pers. comm.). As planned, and to counteract the island conditions, the team baited the island thoroughly. The details of the high standard operation are described by Zito & Withers (2017), including the careful treatment of the cliffs. Given the conditions the baiting rate was increased to 23.6 kg/ha in two applications (totaling 47.2 kg/ha), rather than the 15 kg/ha in three applications (totaling 45 kg/ha) that was originally planned. The monitoring showed bait was available for several weeks. The rat population was finally eradicated.

4.3.2.2 Conclusion

The first attempt in 1986-7 was ground based. It was experimental in nature, as little was known about the principles of eradication at the time. The team used a variety of methods but the approach and topography made it difficult to achieve complete coverage. Still, ship rats were eradicated and Pacific rats, reportedly living around the cliffs, survived.

The second attempt 22 years later was also ground based but planned mostly following best practice, although trapping is not a recommended eradication technique. The tight baiting grid and good quality bait appear to have resulted in good bait coverage, so the operational issues resulting in failure, if any, are not clear. A potential weak point was the absence of experienced practitioners among the ground team. The environmental issues suggested by the operators may not have been significant given than even less favorable conditions were encountered during the subsequent successful attempt.

The third and final attempt was planned and implemented in a similar way to the second one, although no trapping was conducted and the need to raise the standard was recognized and executed (e.g. proper treatment of cliffs and cavities). Importantly, the eradication succeeded despite the unfavorable conditions of a lush green cover, abundant nesting seabirds and high invertebrate activity.

4.4 Mexico

Mexico has a good international standing in the field of vertebrate pest eradications. To date, 60 mammal eradications on 39 islands have been successfully completed, and several more are ongoing projects (Aguirre-Muñoz et al. 2018). Invasive rodents have been eradicated from 15 islands ranging 3-539 ha and all but one of these eradications have been successful at first attempt. As in New Zealand, most operations have been led by one organization –Grupo de Ecología y Conservación de Islas (GECI)– allowing for adaptive management, innovation (Samaniego et al. 2011) and ground-breaking projects for tropical islands such as the largest mangrove archipelago cleared of invasive rats (Samaniego et al. 2018).

4.4.1 **Isabel** (82 ha, 85 m maximum elevation)

Island description (from CONANP 2005): Isabel is located in the mouth of the Gulf of California, Mexico. It is of volcanic origin, topographically complex with cliffs and rocky beaches, and the main crater is now a hyper-saline lake. The climate is tropical with two distinctive seasons: dry (December-May) and wet (June-November). Average temperatures range from 22.6°C (in January) to 30.3°C (in September). There are four offshore islets and several rock stacks. The main island is covered with tropical deciduous forest dominated by *Crataeva tapia* and *Euphorbia schlechtendalii*. Isabel was declared a National Park given it is a nesting refuge for nine species of marine birds and six species of reptiles. It appears ship rats and domestic cats were introduced by fishermen in 1930, and in the following decades several crops were planted across the island. The distance to the closest source of invasive rodents, the mainland, is 29 km.

Conservation/ownership status: National Park since 1980; part of the UNESCO World Heritage Site Gulf of California Islands. Isabel is internationally recognized as an important breeding site for seabirds.

Figure 8. Isabel Island, Mexico (Photo: GECI).

Table 9. Comparison of operational and environmental factors across eradication attempts on Isabel Island, Mexico.

Factor	Initial attempt	Successful attempt
Year	1995	2009
Target species	Ship rat	Ship rat
Season + month	Rainy season (October-November)	Dry season (May)
Environmental conditions	Normal (lush green canopy and understory)	Normal (no canopy as the island is dry ‘brown’ with open understory during the dry season)
Land crabs present	Yes, small hermit crabs and large burrowing crabs, all active during the rainy season	Same species present but mainly inactive during the dry season. Interference was negligible
Coconut palms present	Yes, patchy distribution	No, all were removed months before the rat eradication
Agriculture present	Yes, limited and semi-abandoned due to rat damage	No, all crops were removed along with the coconut palms
Human habitation	Yes, fishermen and research camps of up to 100 people in total	Yes, although human presence was kept at a minimum during the eradication operation
Rodent ecology	Not assessed; most likely at high density and breeding at the time of eradication	At high density and breeding at the time of eradication
Method	Bait stations, ~20 × 20 m grid (1,227 marked points; 247 of those with bait stations)	Aerial broadcast, 2 applications 7 days apart: 13 kg/ha + 7.6 kg/ha; total of 20.6 kg/ha
Bait	Talon-Klerat (5 g scented wax and cereal cubes)	Conservation 25-D
Active ingredient	Brodifacoum 50 ppm	Brodifacoum 25 ppm
Organization	UNAM	GECI

Factor	**Initial attempt**	**Successful attempt**
Notes	Only a fifth of the grid points had bait stations, so bait was placed on the ground on most points Rat removal done simultaneously with cat removal, which used several baits including fish Land crab interference, although not evaluated, must have been substantial given the season	All crops (e.g. sugarcane, bananas, coconuts and pineapples) were removed before the rat eradication Land crab interference was minimal as most crabs are inactive in their underground burrows during the dry season
Risk of reinvasion	Low	Low
Best practice (BP) followed	N/A (pre-BP)	Yes
References	Rodríguez et al. 2006	Samaniego et al. 2014, A. Samaniego pers. comm.

4.4.1.1 Diagnosis

At the time of the first attempt on Isabel (1995), there was very little experience of rodent eradications on tropical islands globally. Island eradications in Mexico had just started on small desert islands and Isabel was the first tropical forested island with a multi-species eradication targeting ship rats and feral cats. The project managers (seabird biologists working on the island) sought advice from New Zealand experts during the planning phase; however, during the implementation phase important deviations occurred. This, along with novel challenges inherent to the tropics that compounded and exacerbated the mistakes, can explain the failed rat eradication (the cat eradication was eventually successful). The main issues, in chronological order, were:

- The ecology of the target species and potential non-target bait consumers were not studied, despite the lack of information on Isabel and tropical islands in general. Had the rat population been observed, aspects such as the season of eradication and bait rates around inhabited areas, particularly the crops, may have been planned better. Likewise, had basic bait and bait station trials been performed, two critical aspects would have become evident: large land crabs move and eat significant amounts of bait, and their level of activity is highly seasonal with the high peak at the end of the wet season (i.e. the time of the first eradication attempt) and the low peak at the end of the dry season (i.e. the time of the second eradication attempt).
- Operational timing relied solely on non-target species considerations. Although impacts on non-targets species must always be considered, it is recommended to identify and aim for the season when the target species is most likely to consume bait. On Isabel, timing the first attempt during the wet season was far from ideal. Resources like water, green vegetation, invertebrates, fruits and nesting habitat for rats are only plentiful during the wet season. In addition, field work is much more challenging as vegetation is very dense, humidity is high and mosquitoes are super abundant. Conditions in the dry season are the opposite as Isabel is dominated by deciduous forest. Nine species of seabirds nest asynchronously on Isabel so there is no month of the year with zero seabird nesting activity.
- The size of the island was never confirmed. The eradication plan was based on a 194 ha surface (Rodríguez et al. 2006) whereas the island is actually 82 ha (CONANP 2005). While the opposite (i.e. underestimation of island

area) can be operationally worse (e.g. not enough bait is purchased), the discrepancy between island area and grid points established (see below) suggests poor planning and sub-optimal implementation.

- The baiting operation severely deviated from planning. The baiting was planned to be along a 20 × 20 m grid of bait stations; however, only 1,227 grid points were marked and only 247 of those points had a bait station (Rodríguez et al. 2006). At 20 m spacing, 1,227 grid points would cover 49 ha which is 60% of the island. There is an inland lake (not treated; Figure 7) but it represents 5% of the island. The most parsimonious explanation is that the actual grid was wider than 20 × 20 m and was not systematic. Further, only a fifth of the grid points had bait stations meaning on 80% of the points the bait was placed on the ground. On Isabel and the tropics in general, this is an issue because the numerous invertebrates, mainly land crabs, can quickly consume most of the bait. Rodríguez et al. (2006) reported no decrease in bait consumption during the six weeks of baiting but failed to monitor and detect which species were removing the bait. Whether the few bait stations used (PVC tubes) were effectively excluding non-target species is not clear; even if they were, the number of bait stations was insufficient to achieve eradication. In addition, three days after rat baiting commenced cat baiting also commenced. Some cat baits were toxic (contained 1080) but others were just attractants to traps, which most likely represented alternative foods for rats.
- High-risk areas did not receive special treatment. Apart from some baits thrown down the cliffs, no systematic identification or treatment of high-risk areas was done. Areas such as the fishermen and research camps, the large abandoned house, the dense patches of crops, the shore of the inland lake, and all of the cliffs and adjacent islets should have been mapped in advance and treated and monitored carefully over the operation. Even with a perfect grid on the bulk of the island, gaps in bait coverage around these food-rich and complex (3-D) environments can lead to eradication failure.

The second attempt (2009) was planned and implemented by another team with a completely different approach. Given the 14 years between attempts, the advances in the field and the development of a highly specialized national team, the project included overlapping management, research and social objectives. First, it was recognized that local ecological information needed to be collected. On the social front, the previous failure meant that some authorities and community members considered the rat eradication impossible, which delayed permitting and complicated logistics. Moreover, the researchers in charge of the failed attempt, still monitoring seabirds on the island, opposed and fought the new eradication proposal on the grounds that the use of a helicopter would have catastrophic impacts on the seabird colonies – which did not happen. Such opposition resulted in having to treat a small portion of the island (5%) by hand as a permit condition, a deviation from the plan that was considered risky but was carefully managed (Samaniego et al. 2014). Fortunately, the local rangers and government managers were extremely supportive and helpful. In summary, for the second attempt the team:

- Conducted ecological studies of the target and non-target species over the two years prior to the eradication
- Acquired a 60 cm per pixel resolution QuickBird satellite multilayer image
- Planned an eradication operation based on best practice
- Conducted trials on bait uptake, palatability and persistence in the environment
- Organized workshops with the local community
- Trained all personnel involved so they were familiar with both the island and the eradication procedures
- Removed all crops (sugar cane, pineapple, banana, coconut palm and oil palm) and resulting organic waste off the island before the eradication
- Mapped out and developed specific baiting strategies for all high-risk areas
- Secured access to every human structure, removed junk and managed organic waste
- Used rodent bait designed for conservation projects
- Implemented a high standard aerial operation on the main island and adjacent islets
- Helped the island managers to develop a biosecurity plan

4.4.1.2 Conclusion

The first attempt was ground based and was implemented by people familiar with the island's seabirds but without experience of invasive species management and in a time when little was known about the challenges of working on tropical islands (e.g. land crab interference). Understanding the local environment is most important when managers face novel situations; indeed, the unfilled knowledge gaps on Isabel contributed to eradication failure. One of the main faults was operating in the most favorable season for rats and least favorable for field work. In addition, serious deviations from the original planning occurred (e.g. not setting bait stations in every grid point) and there was no management of high-risk areas such as crops, buildings and inhabited areas. Baiting was abandoned after six weeks without sign of decrease in bait consumption. Most likely land crabs, which are not susceptible to anticoagulants, were the main culprits of the sustained bait consumption.

The second attempt was an aerial operation that benefited from the international and national experience accumulated over 14 years. With best practice now developed and with experienced GECI staff in charge of the operation, virtually every aspect (e.g. eradication technique, bait, season, management of high-risk areas and social engagement) improved. Yet, it was still experimental in the tropical island context and many lessons were learned. For example, the significant bait consumption by land crabs during the wet season was effectively avoided by operating during the driest month (see Samaniego et al. 2019 for more on land crabs). In fact, based on bait monitoring it appears that lower bait rates would have been enough for all rats to consume a lethal dose, but land crab inactivity in the presence of abundant food was unclear. A fraction of the island (5%) was done by hand due to a permit requirement, but this should be avoided as it can reduce the chances of success by introducing variability into bait distribution compared to aerially distributed bait. The rigorous planning and confirmation procedures gave funders and authorities confidence of success, overcoming the "can't-be-done" feeling left by the 1995 failed attempt.

4.5 Seychelles

The Seychelles archipelago in the Indian Ocean comprises 115 main granite and coral islands spread over 1350 km. The Seychelles was one of the first tropical island nations to implement island restoration projects resulting in biodiversity gain, and by 2017 a total of 50 invasive vertebrate populations (33 mammal, 16 bird and one reptile) had been eradicated with a success rate of 33% for house mouse, 56% for common myna, 57% for feral goat, 75% for ship rat and Norway rat and 100% for other species (Rocamora 2019). Rocamora & Henriette (2015) provide a rich history and detailed species accounts for the main invasive plants and animals in Seychelles and how to manage them.

4.5.1 **Ile Denis** (143 ha, 4 m maximum elevation)

Island description (from Hill 2002, Bristol 2014): Seasonal tropical, flat coralline island. It is the second north easternmost island in the Seychelles. The original vegetation included open grassy areas and tall forest; extensive guano deposits indicate the historical presence of seabirds. The island was changed significantly through coconut plantations and guano mining between the end of the 19th century and the mid-20th century. In 1975 an airstrip and a small hotel were built, and the coconut plantation was abandoned. In 1998 the island changed ownership and today it is managed as a luxury tourist resort with active ecological restoration. The current area of native-dominated woodland is approximately 40 ha, comprising 29% of the island's total surface area. The distance to the closest source of invasive rodents, the mainland, is 50 km.

Conservation/ownership status: privately owned; managed partly as a nature reserve with the local NGO Green Island Foundation.

Figure 9. Ile Denis, Seychelles (Photo: Scott Dunn).

Table 10. Comparison of operational and environmental factors across eradication attempts on Ile Denis, Seychelles.

Factor	Failed attempt	Successful attempt
Year	2000	2002
Target species	Ship rat. House mouse was present but not targeted	Ship rat & house mouse
Season + month	Dry season (early June), although timing was dictated by the seasonal low in tourism rather than biological factors	Dry season (June-July)
Environmental conditions	Normal	Normal
Land crabs present	Yes	Yes
Coconut palms present	Yes	Yes
Agriculture present	Yes	Yes
Human habitation	Yes	Yes
Rodent ecology	Rats at moderate density (24.5/100 trap-nights); presence of reproductively active females at the time of eradication	Information not available; most likely at high density and breeding at the time of eradication

Factor	**Failed attempt**	**Successful attempt**
Method	Aerial broadcast, 2 applications 9 days apart: 13 kg/ha + 10 kg/ha; total of 23 kg/ha 80 m swath with 50% overlap; DGPS used for all drops Protocols put in place to prevent rats accessing human foods and refuse Permanent bait stations installed in/under buildings and 'hotspots', loaded after each drop and regularly refilled Hand baiting in/around all buildings	Hand broadcast: 25 × 25 m grid, 3 applications: 12 kg/ha + 9 kg/ha (8 days later) + 4.4 kg/ha (12 days later); total of 25.4 kg/ha Protocols put in place to prevent rats accessing human foods and refuse Permanent rat bait stations installed in/under buildings and 'hotspots' and regularly refilled Hand baiting in/around buildings repeated beyond the whole-island drops targeting survivors, mainly around farm buildings where mice survived up to two months
Bait	Pestoff 20R	Pestoff 20R
Active ingredient	Brodifacoum 20 ppm	Brodifacoum 20 ppm
Organization	The wider project (3 islands) was coordinated by the Seychelles MET, funded by island owners and management, together with a grant from the DTF, and organized by Don Merton (DOC), who led the eradication team comprised of New Zealanders and Seychellois	Funded entirely by island owners
Notes	Feasibility study produced (1999) Multi-island (3) and multi-species (rats and cats) project Mice were known to be present but were not explicitly targeted Protocols for hand baiting around human structures are unknown Pregnant and lactating females recorded just prior to baiting Risk of reinvasion from rats swimming ashore from fishing boats moored close in-shore overnight estimated as high	Biosecurity protocols were revised Adaptive management was applied Adherence to the new operational plan was stricter

Risk of reinvasion	Moderate	Moderate
Best practice (BP) followed	N/A (pre-BP)	N/A (pre-BP)
References	Merton 2001, Merton et al. 2002, Beaver & Mougal 2009, Rocamora & Henriette 2015, Millett et al. 2019	Beaver & Mougal 2009, Rocamora & Henriette 2015, Millett et al. 2019

4.5.1.1 Diagnosis

The first attempt, which targeted cats and rats only despite the presence of mice (Merton et al. 2002, Millett et al. 2019), was motivated by both conservation and business gains, as the owners run a luxury resort. Denis was one of three islands targeted for simultaneous mammal eradications in 1999 (Merton et al. 2002). Few eradications on tropical and inhabited islands had been conducted by then, so the planning was mainly informed by experiences from temperate regions and before best practice was developed, although local surveys and a feasibility study were carried out. The aerial applications were complemented with hand baiting around buildings and gardens, but the thoroughness and effectiveness of this crucial activity is unclear. Indeed, Merton et al. (2002) describe the aerial operation in detail but fail to describe how the human settlement was treated. The cat eradication began one week after the second brodifacoum application. Although we do not believe that this second sequential eradication had a significant negative effect on the rat eradication, it meant that the team had less time to conduct survey trapping to detect possible survivors or train local managers and staff to implement biosecurity. Merton et al. (2002) considered this failed attempt to be a reinvasion due to inadequate maintenance of biosecurity protocols, as initial reports indicated a small and relatively localized population. Rats were discovered more than a year after the eradication attempt but it is unclear if survey trapping had been conducted before. Moreover, Millett et al. (2019) explained that '*on the same day the last cat was killed, black (ship) rats were confirmed as being present again and breeding. It was not possible to conclude if the population arose from survivors or reintroduction* (no DNA samples were collected). *However, given the short time duration between eradication and discovery and better understanding of factors influencing tropical island rodent eradications, eradication survival is likely.'* We agree there was room for operational failure, particularly around the human settlement.

Shortly after, the owners decided to conduct a second attempt, this time (2002) targeting both ship rats and house mice. Presumably because of the difference in cost (the advantages of a multi-island project were not there anymore), this time the eradication was undertaken using the hand broadcast technique, but at a similar baiting rate. The cats had been eliminated, so the team could focus on the rodents. Team members were also more familiar with the island and the necessity of thorough treatment of all human structures. '*Monitoring indicated that rats were killed quickly, but mice persisted for several weeks around the livestock farm where alternative food sources were available (G. Climo, pers. comm., 2002). Both species were eradicated successfully within two months'* (Millett et al. 2019).

4.5.1.2 Conclusion

The first attempt was an aerial operation that faced the complexities of working on tropical and inhabited islands before the development of best practices. In addition, the team had divided attention given that they were conducting cat and rat eradications on Denis and two other islands during a two-month period (four when including preparations and follow-up) with limited resources. Multi-island/species eradications can and have been successfully conducted, but appropriate planning and resourcing are needed for such demanding projects. The main weaknesses on Denis were probably the (hand) treatment of the inhabited and farm areas, and the limited capacity to implement biosecurity measures to prevent reinvasion. Ship rats were targeted but not mice; both species were detected months after aerial baiting, probably survivors but could also be reinvaders. No genetic samples to help discern this were collected.

The second attempt was ground based (presumably due to financial limitations) and occurred two years after the first one, once the cat eradication was completed. Therefore, this time the team was focused on the rats, had more experience with the island and the complexities of treating human structures, and the capacity of the island managers to implement effective biosecurity protocols improved. All of these factors may have contributed to the success of this attempt.

4.5.2 **Ile du Nord** (201 ha, 180 m maximum elevation)

Island description: seasonal tropical, granitic. The native vegetation had been almost entirely burned down or logged by the end of the 18th century; agriculture was developed and in the late 19th century or early 20th century extensive plantations of coconut and fruit trees were established and guano was exploited (Hill 2002). The coconut plantation and farming were abandoned in the 1970s, and guano excavation left pits that are still present today. The island was privately purchased in 1997 by an eco-tourism company, which opened an exclusive resort to fund the rehabilitation of the island (Millett et al. 2019). The hotel facility completed in 2003 includes 11 guest villas, a restaurant, a spa, a gym, plus a staff village with restaurant, a workshop and a lodge. A native plant nursery established in 2000 has been producing tens of thousands of trees for large scale re-planting, resulting in the replanting or rehabilitation of c.50 ha of vegetation (Rocamora 2019). The distance to the closest source of invasive rodents, another island, is 7 km.

Conservation/ownership status: privately owned as a luxury resort.

Figure 10. Ile du Nord, Seychelles (Photo: North Island Ltd).

Table 11. Comparison of operational and environmental factors across eradication attempts on Ile du Nord, Seychelles.

Factor	**Failed attempt**	**Successful attempt**
Year	2003	2005
Target species	Ship rat	Ship rat
Season + month	Dry season (August)	Dry season (August-September)
Environmental conditions	Normal	Normal
Land crabs present	Yes	Yes
Coconut palms present	Yes	Yes
Agriculture present	Yes	Yes
Human habitation	Yes	Yes

Rodent ecology	At high density and breeding at the time of eradication	At high density and breeding at the time of eradication
Method	Aerial broadcast, 3 applications: 15 kg/ha + 8 kg/ha (5 days later) + 8.6 kg/ha (16 days later); total of 31.6 kg/ha Hand broadcast around the hotel complex and other areas using uneven baiting rates	Aerial broadcast, 4 applications: 14 kg/ha + 10 kg/ha (8 days later) + 8.4 kg/ha (16 days later) + 7.5 kg/ha (19 days later); total of 39.9 kg/ha Hand broadcast around the hotel complex and other areas using uneven baiting rates
Bait	Pestoff 20R	Pestoff 20R
Active ingredient	Brodifacoum	Brodifacoum
Organization	North Island (Ltd) Management	ICS, North Island (Ltd) Management

Factor	**Failed attempt**	**Successful attempt**
Notes	Feasibility study in 2003 A large-scale clean-up of rubbish and construction material was undertaken prior to baiting However, the large main green waste dumping site, a rat infestation hotspot, could not be removed and adequately treated, and biosecurity was deficient Multispecies project (rats and cats). Cat eradication was successful Swath overlap was only 20% GPS used for the first two drops. Last drop flown by a local pilot, most likely without GPS as it was brought by the New Zealand pilot and he had gone back by then No breeding females reported	Rats were the only target. A rat-proof trailer was built (to avoid building a pest-proof room on each of the two landing beaches), food waste management improved, a huge green waste/coconut pile (having grown larger than in 2003) was eliminated (dug, flattened and compacted; less composted material buried under 1-2m of soil; branches and rotten coconuts mulched). Sensitization and training of the island's personnel took place Swath overlap was 50%, although the GPS (brought by the New Zealand pilot) was only available for the third drop due to a fault early in the project. Using natural landmarks and compass bearings, pilots followed equally spaced parallel transect lines plotted on A3 aerial orthophotos for other drops. Last drop flown by a local pilot without GPS. Rat monitoring confirmed rat breeding during operation; rat density was higher than in 2003
Risk of reinvasion	Moderate	Moderate
Best practice (BP) followed	N/A (pre-BP)	N/A (pre-BP)

References	Climo 2004, Climo & Rocamora 2006, Beaver & Mougal 2009, Rocamora & Henriette 2015, Millett et al. 2019	Rocamora & Climo 2005, Climo & Rocamora 2006, Beaver & Mougal 2009, Rocamora & Henriette 2015, Millett et al. 2019

4.5.2.1 Diagnosis

The first attempt in 2003, targeting rats and cats simultaneously, was funded by the island owners, the North Island Ltd island resort, and involved New Zealand experts (consultant and pilot), although it was implemented before the development of any published best practice, particularly for tropical islands. It appears that considerable effort went into the planning (e.g. a feasibility study was produced) and crucial ground preparation work was undertaken (e.g. a large-scale clean-up of rubbish and construction material) prior to baiting. The eradication used high quality bait spread aerially in three separate drops, combined with hand baiting around the hotel complex and green waste sites.

However, weak points of the baiting strategy include the limited overlap between swathes (20% as opposed to the recommended 50%) and probably most importantly a large and deep green waste pile that could not be dealt with as it was in 2005. The treatment for inside the buildings (which should include treatment of roof spaces) is unclear but we do not believe this could be one of the reasons for failure as any rats in there would have had to rely on outside food. Climo & Rocamora (2006) explained that '*All major dumpsites from hotel construction had been cleaned up satisfactorily during the 2003 campaign and a "preliminary" rubbish disposal system was in use before eradication began (clean up continued during the eradication period) but many smaller sites including the green waste still needed attention*.' Climo (2004) concluded that the eradication had been successful but rat prevention protocols were probably not followed sufficiently strictly, leading to reinvasion. For example, a barge was offloaded at night without respecting any of the recommended biosecurity protocols and abatement measures only a few days and a few hundred meters from the first rat sightings.

However, rats were detected less than 4 months after the last baiting and confirmed breeding 2.5 months after that (Beaver & Mougal 2009). The fact that the large green waste dumpsite could not be removed and adequately treated may also have led to the survival of some rats. This green waste pile was confirmed in 2005 as a high density infestation hotspot, where rats had access to an accumulation of several meters of green waste including huge numbers of decaying coconuts (a favorite source of food for rats in the tropics, and the most attractive bait for trapping). Given the deficiencies in terms of biosecurity and of the treatment of green waste and small rubbish disposal sites around the inhabited areas, and the rate of rat recovery observed after other failed attempts, this suggests eradication failure rather than reinvasion. As on Denis, the operational team were targeting cats and rats at the same time. Although this is unlikely to have been a major factor to explain the failed outcome of the eradication, it also means less time was available to concentrate on intensive survey trapping to look for survivors or to train the North Island team to implement effective biosecurity. Unfortunately, the lack of pre-eradication DNA samples prevented the definitive identification of rats as survivors or new arrivals, but the possibility of eradication failure (i.e. rats surviving) was conceded by Rocamora & Climo (2005).

A couple of years later (2005), as part of a Fonds Français pour l'Environnement Mondial (FFEM) funded island restoration program (Rehabilitation of Island Ecosystems), a second aerial attempt was undertaken, led by the Island Conservation Society (ICS). There were changes in leadership and personnel, but the 2003 rat eradication expert from New Zealand was retained as his know-how and experience with the island and Seychelles was essential; a new protocol and eradication plan was written (Rocamora & Climo 2005). Since rats may have endured the 2003 attempt by either surviving or reinvading, the new strategy focused on stricter biosecurity protocols, enhanced bait application protocols, and pre-eradication preparations including adequate treatment of rubbish and green dumpsites – the large green waste pile having further grown since 2003. These key pre-eradication aspects were agreed through a memorandum of understanding between ICS and North Island Ltd, the island and hotel managers. The baiting strategy was similar (see Table 11) but explicitly implemented to higher standard, although a GPS could only be used during one out of the four aerial applications. In addition, a 50 m grid of 162 bait stations refilled periodically with blocks ensured availability of bait for an additional 7 months in much of the low-lying area, that included inhabited and manmade habitats, rubbish sites and green waste piles, all of which were known as infestation hotspots. According to (Beaver & Mougal 2009) '*several months of intensive preparation were required and included the refurbishment of the rat-proof room, the building of a rat-proof trailer, proper management of food waste, the elimination of a huge green waste/coconut pile, sensitisation and training of the island's personnel, setting up permanent bait stations along the coast to prevent reinvasion and around buildings, plus a 50m central grid of bait stations covering much of the plateau area*.' Climo & Rocamora (2006) provide a detailed account of the operation, including useful insight of several operational issues encountered during the second attempt and the confirmation of rat breeding at the time of baiting.

4.5.2.2 Conclusion

The first attempt was an aerial operation that included good planning and used modern techniques. However, weak points both in the aerial and clean-up preparation procedures such as not removing a large green waste pile, as well as poor biosecurity compliance could explain eradication failure.

The second attempt was also aerial, followed similar protocols and was partly implemented by the same team. The main difference was that the standards were explicitly raised, including increased aerial swath overlap, detailed intensive clean-up during the pre-eradication phase including the huge green waste pile and baiting of the inhabited area and green waste piles. Rat eradication was achieved despite rat density and breeding activity being higher than during the first attempt.

4.6 United Kingdom

Rat eradications have been undertaken on islands in the United Kingdom (UK) for the past 50 years. Although during this time many countries have moved from ground-based operations to the aerial application of rodenticides as the preferred option, this is not the case for the UK due to legislative limitations upon the outdoor use of rodenticides and application methods. Overseas territories may have more flexibility. Bell (2019) describes the history and development of ground-based rat eradications using bait stations in the UK, giving examples of operations and covering lessons learnt and how local communities have been involved. Ground-based eradications have been completed on UK islands ranging in size from <1 ha to 3,100 ha. The distance to the closest source of invasive rodents, another island, is 1 km.

4.6.1 **Low Cay** (Bahamas) (10.8 ha, 7 m maximum elevation)

Island description (from Correll 1979): temperatures in summer range from 22 to 32°C whereas in winter range from 17 to 27 °C due to the moderating effect of the Antilles Current flowing past San Salvador. Annual rainfall for San Salvador averages 1000 mm. Cold fronts from the north bring winter rains, and summer rains result from convection. The major rainy season is from September to November, caused by tropical depressions, tropical storms, and hurricanes. Low Cay is a small island with minimal vegetation, rolling topography and barren habitat with residual (<30 cm) cacti; dominant plants are *Ambrosia, Coccoloba, Ipomoea, Sesuvium.* **Conservation/ownership status**: private island.

Figure 11. Low Cay, Bahamas (Photo: Vladi).

Table 12. Comparison of operational and environmental factors across eradication attempts on Low Cay, United Kingdom (Bahamas).

Factor	Initial attempt	Successful attempt
Year	1999	2000
Target species	Ship rat	Ship rat
Season + month	Summer	Summer
Factor	**Initial attempt**	**Successful attempt**
Physical conditions	Normal	Normal
Land crabs present	Yes	Yes
Coconut palms present	No	No
Agriculture present	No	No
Human habitation	No	No
Rodent ecology	Not assessed; most likely at low density and breeding at the time of eradication	Not assessed; most likely at low density and breeding at the time of eradication
Method	Bait stations on the ground, 20 × 20 m grid	Bait stations elevated on PVC tubes, 20 × 20 m grid
Bait	Talon WB XT	Talon WB XT
Active ingredient	Brodifacoum 50 ppm	Brodifacoum 50 ppm
Organization	Loma Linda University*	Loma Linda University*

Notes	Hermit crabs swarmed the bait and clogged the bait stations	The PVC elevated system allowed access to rats but not crabs Initial bait take was high but decreased by end of the first week. No rats were captured 3 weeks later
Risk of reinvasion	High. The island is close (~1 km) to San Salvador (with rats) and other cays (some with rats)	High. The island is close (~1 km) to San Salvador (with rats) and other cays (some with rats)
Best practice (BP) followed	N/A (pre-BP)	N/A (pre-BP)
References	Hayes et al. 2004, Hayes & Carter 2005	Hayes et al. 2004, Hayes & Carter 2005

* With support from Bahamas Ministry of Agriculture, Chicago Zoological Society, Denver Zoological Society, Disney Foundation, Insular Species Conservation Society, and International Iguana Foundation.

4.6.1.1 Diagnosis

The first attempt (1999) seems to be a simple case of poor planning. A strategy applied on other similar islands was replicated on Low Cay but without conducting trials. As the eradication was a graduate student's project, time and resources were limited. The attempt clearly failed because the bait stations were not elevated off the ground and became clogged with hermit crabs (Hayes et al. 2004, Hayes & Carter 2005), who presumably also consumed most of the bait. Land crabs had not been a significant issue for the team before, so they were unaware of the potential issue until the operation. Trials prior to the eradication implementation would have helped with identification of risks.

For the second attempt (2000) the following year, the baiting strategy remained the same, including personnel, except for elevating the bait stations on PVC piping that allowed rats to access the bait but not the crabs. It was successful (Hayes et al. 2004, Hayes & Carter 2005).

4.6.1.2 Conclusion

The first attempt using bait stations most likely failed due to land crab interference.

On the second attempt the same bait stations were elevated to prevent crabs from clogging the stations and competing for bait, and the rats were eradicated.

4.7 United States

Rodent eradications on islands and territories of the United States commenced in the early 1990s, and since then several federal and state agencies, along with conservation organizations, have been investigating, implementing and advancing rodent management methods (Witmer & Shiels 2018). Out of 40 island rodent eradication attempts, 22 (55%) have succeeded (DIISE 2018), the largest island being Hawadax Island (2,900 ha), formerly known as Rat Island. As Witmer et al. (2011) note, additional experimental eradications (e.g. in Bay of Islands, Alaska) perhaps should not be included in the list of more concerted eradication efforts as eradication methods were being investigated.

4.7.1 **Palmyra** (250 ha, 2 m maximum elevation)

Island description (from Howald et al. 2004): the tropical climate of Palmyra is characterized by high humidity (>90%) and warm temperatures (23.8°C – 29.4°C) with almost daily copious rainfall events associated with thunderstorms. Mean annual rainfall is 4,060 mm. Palmyra is an atoll comprising 54 islets, which are not connected but can be reached by wading or swimming across narrow channels, or by boat. The aseasonal climate on Palmyra supports dense vegetation of native and non-native trees and shrubs. A large portion of the atoll lies under a canopy of non-native coconut palm. Other habitats include broadleaf forest composed of *Terminalia catappa*, *Pisonia grandis*, and the shrub-like *S. sericea* and *Tournefortia argenatea*. The distance to the closest source of invasive rodents, another island, is 325 km.

Conservation/ownership status: national wildlife refuge co-managed by the USFWS and TNC.

Figure 12. Palmyra Atoll, tropical Pacific (Photo: Island Conservation).

Table 13. Comparison of operational and environmental factors across eradication attempts on Palmyra Atoll, United States.

Factor	Initial attempt	Successful attempt
Year	2001-2003	2011
Target species	Ship rat	Ship rat
Season + month	Aseasonal (year-round fieldwork)	Aseasonal (June)
Factor	**Initial attempt**	**Successful attempt**
Environmental conditions	Normal	Normal
Land crabs present	Yes, active all year round due to the high humidity	Yes, probably at the highest abundance and diversity recorded during an eradication
Coconut palms present	Yes, widespread	Yes, widespread
Agriculture present	No	No
Human habitation	Limited to a small research station	Limited to a small research station
Rodent ecology	Not assessed; most likely at high density and breeding at the time of eradication	At high density and breeding at the time of eradication

Method	Bait stations, 50 × 50 m grid. About 1,800 kg of Talon XT and 30 kg of Fastrac were used	Aerial broadcast, 2 applications 6-10 days apart (varied across islets): 82 kg/ha + 82 kg/ha; total of 164 kg/ha
Bait	Talon XT and Fastrac	Conservation 25-W
Active ingredient	Brodifacoum 50 ppm and Bromethalin 100 ppm	Brodifacoum 25 ppm
Organization	USFWS, TNC, USDA	IC, USFWS, TNC
Notes	Significant and constant land crab interference Bait station design changed several times during the operation	Land crab interference was managed by increasing bait rate and using the aerial technique Sooty tern breeding is aseasonal and while it had been hoped to avoid it, there were tens of thousands of birds present at the time of the operation, hence additional hand baiting around the colonies was undertaken
Risk of reinvasion	Low	Low
Best practice (BP) followed	N/A (pre-BP)	Yes
References	Howald et al. 2004	Wegmann et al. 2012

4.7.1.1 Diagnosis

Howald et al. (2004) reviewed the first eradication attempt on Palmyra and reported: '*The project in 2001-2003 violated the first two rules for eradication: all individuals were not at risk from the eradication technique, and the rats were repopulating the island at least as quickly as they were removed from the ecosystem in the latter stages of the baiting operation. There were problems with the planning, communication, and funding that were complicated by the local biological conditions, especially the competition from land crabs and the small ranging territories of rats on the island. There was an assumption that the same management and eradication techniques applied successfully elsewhere could be applied on Palmyra without any background research or trials. A small-scale trial would have revealed that the eradication technique would not have been successful and could have allowed for research into new techniques, such as the effective bucket bait station that was ultimately designed and used. However, the bait bucket model designed to exclude crabs could have excluded rats, the spacing of the bait stations physically excluded some rats from gaining access to the bait, the presence of Bitrex in the bait likely caused bait shyness in some individual rats, and the chronic baiting apparently resulted in slight brodifacoum resistance. Cumulatively, these problems presented insurmountable challenges to the eradication because there was no research/monitoring program built in to identify and then rectify problems. Had a project manager with expertise in rat eradication been involved with the project throughout, these problems could have been identified early, saving money, time, effort and frustration. Unfortunately, it is unclear to what extent each of these problems alone or in combination caused the failure of the eradication.'*

We agree with the conclusions of the review although we want to expand on the baiting team. A project manager with some experience in rodent eradication was involved for part of the project but not all, which emphasizes the importance of staff continuity. Another important issue was the lack of training and support of the ground team, who were volunteers and reported having cohesion issues resulting in substandard labor quality. Having worked on Palmyra and many other tropical islands, we also want to highlight that land crab interference, particularly on wet islands where crab diversity and abundance is highest, is a major challenge regardless of the eradication technique (Wegmann 2008, Samaniego et al. 2019).

The second attempt was planned and implemented using a different approach, after 10 years of accumulated experience in the tropics worldwide. The institutions managing Palmyra were this time assisted by rat eradication experts throughout each phase of the project. In fact, the second attempt was informed by a 7-year investigation of Palmyra's eradication environment. Wegmann et al. (2011) describe the pre-eradication research and Wegmann et al. (2012) discuss the challenges faced by the second eradication team, and the methods that were employed to overcome these challenges. In summary, the local challenges were identified, and solutions were proposed, tested and refined before the eradication. In addition, the eradication operation was implemented to high standard by experts in both rodent eradications and Palmyra's environment. As most operational components changed (e.g. eradication technique, bait, personnel), it is difficult to evaluate the significance of each one; however, it was probably the combination of improvements that ultimately resulted in the success of this benchmark operation.

4.7.1.2 Conclusion

The first attempt was ground based and lacked detailed planning and qualified staff, leading to the use of techniques that proved inadequate to eradicate rats from Palmyra. Despite the lengthy operation, the problems were never solved due to turnover of staff, lack of expertise and of clear management structure, and limited funding.

The second attempt was an aerial operation and is probably the most intensively researched project to date, both pre- and post-eradication. The combination of research, expertise, use of technology, adequate funds and strong partnerships led to a rigorous implementation of best practice and a successful eradication on Palmyra's wet aseasonal environment.

4.7.2 **Desecheo** (117 ha, 200 m maximum elevation)

Island description (mainly from Will et al. 2019b): Desecheo is a small hilly island situated in the Mona Passage about 17 km offshore of the west coast of Puerto Rico. It is composed of a peak of volcanic calcareous rock with a mosaic of grassy patches, shrublands, woodlands with candelabra cacti, and semideciduous forests dominated by *Bursera simaruba*. The climate is tropical; temperatures range between 18°C and 32°C and annual rainfall between 750 mm and 1,039 mm. The driest period is from January to March. The distance to the closest source of invasive rodents, the mainland, is 20 km.

Conservation/ownership status: national wildlife refuge.

Figure 13. Desecheo Island, Puerto Rico (Photo: Island Conservation).

Table 14. Comparison of operational and environmental factors across eradication attempts on Desecheo Island, United States.

Factor	Initial attempt	Successful attempt
Year	2012	2016
Target species	Ship rat	Ship rat
Season + month	Dry season	Dry season
Environmental conditions	Abnormally green (4603 mm total rain in 6 months prior)	Normal (772 mm total rain in 6 months prior)
Land crabs present	Yes, abundant hermit crabs present. Highly active during the operation	Yes, abundant hermit crabs present. Highly active during the operation
Coconut palms present	No	No
Agriculture present	No	No
Human habitation	No	No
Rodent ecology	At high density and breeding at the time of eradication	At high density and breeding at the time of eradication
Method	Aerial broadcast, 2 applications 9 days apart: 17.1 kg/ha + 9.1 kg/ha; total of 26.2 kg/ha GPS on helicopter and 50% overlap was used Bait stations (107), at 25 m intervals along two ridgelines	Aerial broadcast, 2 applications 22 days apart: 40.3 kg/ha + 39.9 kg/ha; total of 80.2 kg/ha GPS on helicopter and 50% overlap was used Bait stations (100), 25 × 25 m grid in valleys during second application
Bait	Conservation 25-D	Conservation 25-D
Active ingredient	Brodifacoum 25 ppm	Brodifacoum 25 ppm
Organization	IC, USFWS	IC, USFWS
Notes	Rat observed 12 days after 2nd application Wetter than normal conditions Rodent breeding detected Some areas received lower than prescribed bait rates	Bait stations placed in valleys after higher than anticipated bait disappearance observed
Risk of reinvasion	Low	Low
Best practice (BP) followed	Yes	Yes

References	Brown & Tershy 2013, Will et al. 2019	Will et al. 2019

4.7.2.1 Diagnosis

Brown & Tershy (2013) reviewed the first eradication attempt on Desecheo and reported: '*The project failure could have derived from a single factor or a "perfect storm" of several overlapping issues. The most likely causes of failure include inadequate overall or localised bait rates and/or bait availability, accentuated by known non-uniformity of bait distribution particularly in the critical first bait application; unusually wet weather patterns promoting an abundance of alternative natural foods during bait application; or rat breeding during the operation causing either temporal and/or spatial unavailability of bait to juveniles emerging from natal nests, or more speculatively behaviourrelated bait avoidance by some breeding females*.' However, recent research (Samaniego et al. 2020a) suggests that natural food availability, rat breeding, and diet of reproductive females are all issues that can be overcome if comprehensive bait applications of good quality bait are conducted. We agree the bait used is one of the best available options; therefore, a potential explanation is problems with overall or localized bait rates, which essentially refers to potential gaps in bait coverage, especially along the coast due to permit restrictions.

Brown & Tershy (2013) also examined the planning, design and implementation of the first attempt: '*Bait rate evaluations did not allow sufficient margin for possible temporal or spatial variances over the island and did not focus on the "extreme" results which needed to be catered for in eradication design. Data collected in previous years with different weather patterns could have been misleading on rodent density and breeding cycles and on bait competitor activity or abundance. Implementation strategy was significantly affected by maximum permissible bait rates and other regulatory requirements and was clearly less than ideal as a result, with identifiable concerns with both the comprehensiveness of the coverage and the bait rates. Critical review of some plans was insufficient, and where advice was received it was not always addressed. A more experienced project manager, and less diffused responsibilities within the project, may have increased the level of "ownership" of the project's technical aspects. GIS analysis of the first application should have identified areas for re-treatment, and this information should have been acted upon.'* We agree that it was most likely a combination of planning and implementation issues that led to the unsuccessful result, and that US regulatory restrictions on maximum bait rates and coastal baiting prevented what should have been a standard procedure in eradications (i.e. re-treating areas where baiting rates are suspected to be lower than the target rates).

The second, successful attempt was implemented by the same team using a similar, yet improved, eradication approach four years later (2016). The accumulated experience regarding the island's particular environment was clearly an advantage, and together with a revised baiting strategy it allowed for higher implementation standards. Will et al. (2019b) describe the project in detail, concluding '*the following to be key to the success of the second attempt: 1) monitoring environmental conditions prior to the operation, and proceeding only if conditions were conducive to success, 2) reinterpretation of bait availability data using the lower 99% confidence interval to inform application rates and ensure sufficient coverage across the entire island, 3) treating the two applications as independent, 4) increasing the interval between applications, 5) seeking regulatory approval to give the operational team sufficient flexibility to ensure a minimum application rate at every point on the island, and 6) being responsive to operational monitoring and making any necessary adjustments.'* Whether increasing the baiting rate to the extent that was done (>3 times the first attempt) was necessary is debatable, as a high percentage (>75%) of the bait was not consumed by rats (Shiels et al. 2019), but it probably contributed to the later success as higher bait rates may increase bait coverage. Another development was the greater understanding of pilot error when bait in the bucket runs out, which could have also contributed to a greater risk of bait gaps in 2012. It is also possible that a combination of relatively minor improvements across factors, both operational (e.g. better bait coverage) and environmental (e.g. normal dry conditions) made the difference.

4.7.2.2 Conclusion

The first attempt was conducted by helicopter and was planned by experts and implemented to a high standard in most regards. However, several issues, including potential gaps in bait coverage along the coast due to permit restrictions, were identified during the project review.

The second attempt was also aerial and benefited from having the same operational team, the post-operation review, the recent guidelines for eradications on tropical islands (Keitt et al. 2015), the continuous fieldwork and the cooperation of the authorities by redefining permit conditions. The analysis and comparison of both attempts by Will et al. (2019b) is an excellent platform and source of information.

4.8 Tropical islands currently invaded where multiple attempts failed

4.8.1 **Adele**, Australia (294 ha, 4 m maximum elevation)

Island description (mainly from Coate 1997): Adele Island is a low-lying vegetated sand cay situated on Adele Reef on the northwest shelf, approximately 85 km from the Australian mainland. The island is ~3 km by 1.6 km, with a wide base to the south and has a total land area of 294 ha. An inlet opens to a tidal lagoon on the eastern shore. Adele Island has a dense cover of coastal grasses, herbs and, to a lesser extent, shrubs. Dense beach spinifex (*Spinifex longifolius*) is the dominant vegetative cover: over much of the island it forms a continuous tangled thicket of cover that is knee to waist high. Shrubby thickets of Indian lantern flower (*Abutilon indicum*) occur to the south of the lagoon. The climate is semi-arid and monsoonal, with a 'wet' season (November-April) and 'dry' season (MayOctober). Annual rainfall averages between 800 mm and 1,500 mm. The dry season is characterized by warm to hot temperatures and low humidity, the wet season is characterized by warm to hot temperatures and high humidity. The region is cyclone-influenced and has semidiurnal tides with a maximum range of ~10 m. Adele Island is surrounded by extensive mud flats, sand flats and fringing reefs that extend up to 12 km out from the island at low tide. Despite the presence of an abundant *Rattus exulans* population, at least 12 species of seabird and two species of coastal waterbird breed on the island with counts documenting as many as 33,000 individuals (Clarke et al. 2012b, Clarke et al. 2012a, Clarke et al. 2013). Adele Island is also an internationally important site for migratory shorebirds with between 17,000 and 24,000 individuals being present in the austral summer (Rogers et al. 2011). There is no infrastructure on the island other than an automated weather station and light tower and its remote location (an ~18hour boat crossing from the nearest major port of Broome, WA) necessitates a live-aboard vessel for the duration of all island work. The presence of saltwater crocodiles prevents overnight stays. Access and work programs therefore require significant financial resources and careful planning to ensure contingencies are provided for. The distance to the closest source of invasive rodents, the mainland, is 75 km.

Conservation/ownership status: Class A nature reserve (Western Australian Government).

Figure 14. Adele Island, Australia (Photo: Kevin Coate).

Table 15. Comparison of operational and environmental factors across eradication attempts and recommendations for next attempt on Adele Island, Australia.

Factor	Initial ground-based attempts	Aerial attempt	Recommendations for next attempt
Year	2004 & 2011	2013	
Target species	Pacific rat	Pacific rat	
Season + month	2004: 19-26 November (late dry season – ~50 mm rain fell in a storm during attempt) 2011: 20 May-2 June (mid-dry season, cooler)	20-31 October (late dry season – no rain)	Target the late dry season during the change-over between the seabird breeding season and the arrival of migratory shorebirds. Food resources for rats should also be more limited at this time
Physical conditions	Normal	Normal	Monitor conditions
Land crabs present	No. Shoreline species including ghost crabs were present at the island perimeter	No. Only species foraging on the sand beaches and the fringes of the tidal lagoon	
Coconut palms present	No	No	
Agriculture present	No	No	
Human habitation	No	No	
Rodent ecology	Not assessed for 2004	Rat densities were high. Snap trap grids in dense beach spinifex returned	Determine rat densities and breeding activity, along with bait uptake rates

Factor	Initial ground-based attempts	Aerial attempt	Recommendations for next attempt

	Limited trapping in 2011 indicated high rat densities	estimates of 51 rats/ha from a single night of trapping in April 2012. Over two nights in April 2013 it was 100 rats/ha. Consumption rates of pinned non-toxic Pestoff block baits were between 5.5 and 8.3 kg/ha/night in April 2013	leading into program. However, an eradication could still proceed without this, using previous rat density data and best practice application rates for tropical islands
Method	2004: program was instigated with hand baiting on a 12.5 m grid, but this was modified to a 25 m grid after it was determined there was insufficient bait on hand to cover the island 2011: ~800 kg bait applied on a 25 m x 25 m grid (~5,250 bait stations - 6 bait blocks pinned per station). Some bait was also hand broadcast into impenetrable thickets (amount not recorded). Second application from Day 7 involved hand broadcasting of bait along every second line (50 m), ~400 kg of bait applied	Aerial broadcast, 2 applications: 37.0 kg/ha + 7.2 kg/ha (10 days later); total of 44.2 kg/ha. A gap identified after the first drop along a curved section of the western coastline was hand baited twice before the second drop commenced (details below). Small vegetated islets surrounded by lagoon flats were hand baited prior to the second drop	Aerial baiting following contemporary best practice. Two bait applications 7-14 days apart. Ensure thorough coverage of coastal margin
Bait	2004: Contrac Blox 2010: X-Verminator (rebranded Pestoff)	Pestoff 20R	Pestoff 20R or Conservation 25-D are likely to be the preferred toxicants
Active ingredient	2004: bromadiolone 50 ppm 2011: brodifacoum 50 ppm	Brodifacoum 20 ppm	Brodifacoum 20/25 ppm (depending on product)
Organization	DBCA and predecessor agencies (DPAW, DEC, CALM) for all	DBCA	

Factor	Initial ground-based attempts	Aerial attempt	Recommendations for next attempt
Notes	2004: size of island underestimated by ~60 ha, meaning they had 10,000 bait blocks (280 kg) for 294 ha island, <1 kg/ha in single application 2011: two applications of bait, 4.1 kg/ha in total	Issues with bait spreader engine stalling in flight, meaning some lines needed repeating, leading to ~1500 kg extra bait used during first drop. Limited bait available for second drop. A beach inspection on an ATV following first application identified bait was lacking along a section on the west coast; a gap up to 20 m by 2.6 km long in the coastal swath was found in the adjacent vegetation. Bait (old wax blocks from previous projects ~16 months past use-by date) was hand broadcasted from ATV into the gap (35 kg) and then 9 days later (65 kg; one day before the second drop), with irregular dispersal	
Risk of reinvasion	None naturally	None naturally	
Best practice (BP) followed	2004: N/A (pre-BP) 2011: no	Yes	Use of experienced baiting pilot. Prior testing of all equipment Sufficient budget to conduct operation to best practice standards including equipment backup and contingency bait amounts Negotiate permit conditions impacting coastal margin baiting

References	Unpublished Departmental reports (Morris & Johnson 2010, Johnson 2011), R.	Unpublished Departmental reports (Palmer 2013a, b, 2014), R. Palmer and K. Springer pers. comm.	
Factor	**Initial ground-based attempts**	**Aerial attempt**	**Recommendations for next attempt**
	Palmer and K. Springer pers. comm.		

4.8.1.1 Diagnosis

The 2004 hand baiting attempt was undertaken by a team of local conservation staff members and ten volunteers with no rodent eradication experience. Ground baiting was used due to concerns that aerial baiting would disrupt seabird nesting and pose a significant bird-strike risk to the helicopter. The team hand spread 10,000 Contrac Blox baits (~280 kg) in a single application over what they believed was a ~220 ha island. The total vegetated area of Adele Island was found to be larger during the second day of their baiting program, at 294 ha. With this new knowledge team leaders decreased the bait application density by shifting from a 12.5 m grid to a 25 m grid. Given the remoteness of the island this was required to ensure island-wide coverage (albeit at a reduced rate) was achieved. The overall bait application rate was extremely low (<1 kg/ha). This attempt failed.

In the planning stage for the second attempt, aerial baiting was again not considered an option due to perceived issues associated with bird strike and logistical difficulties (Morris & Johnson 2010). The first failure was put down to a range of possible reasons including: no monitoring of bait uptake rates, lack of a second bait application, presence of Bitrex in the bait and reductions in bait application rates mid-baiting program. During the 2011 ground baiting program, the team used fixed stations to facilitate monitoring of bait uptake rates. At each station, six bait blocks were threaded onto a survey marker pin that was then pinned to the ground on a 25 m grid across the island (so no traditional box-like bait stations were used). Baiting was undertaken by a team of eight people each with a hand-held GPS. Approximately 5,250 stations were established over ~6 days with a baiting rate of ~2.7 kg/ha. A second application of bait commenced on Day 7 of the program, along every second bait line (50 m intervals; 1.4 kg/ha). Baits were hand broadcast along the line and on either side out to ~10 m. Bait take rates from the first application were ~100% in areas of dense beach spinifex. Lower rates of bait uptake were documented in more sparsely grassed areas. The bait did not contain Bitrex (Johnson 2011).

The 2011 program also failed. Less than one year later, rat densities were found to be extremely high. Kill rates from snap trap grids set for a single night in dense beach spinifex in April 2012 returned estimated densities of 51 rats/ha (Palmer 2013b). Camera trap monitoring of pinned bait blocks (same type used in second attempt but non-toxic) also revealed that large male rats were able to monopolize the baits for long periods of time. This led to a portion of the rat population being excluded from accessing bait during the first bait application in May 2011. During the second application, baits were broadcast more widely by hand along transects spaced at 50 m intervals, but the application rate was low (1.4 kg/ha).

Bait application rates for both ground baiting attempts (2004 and 2011) were inadequate for a *Rattus exulans* population that occupied a tropical island with a dense cover of thicket-like beach spinifex. Productivity on Adele Island is also likely to be high given it receives high nutrient input from significant seabird colonies. Team leaders did not consider best practice aerial baiting options due to concerns surrounding disturbance to breeding birds and/or bird strike on helicopters. The physical demands of carrying and spreading adequate quantities of bait by hand over a densely vegetated tropical island of this size was simply not feasible. This was especially so during the 2004 attempt that was conducted in mid-November when temperatures can exceed 35°C and humidity is high.

Prior to a further attempt, a full review of bird survey data was undertaken (Palmer 2013a). Further surveys of birds were undertaken in April and November 2012, and April 2013 (Clarke et al. 2012b, Clarke et al. 2012a, Clarke et al. 2013). Rat densities and bait uptake rates were also investigated during the April 2013 visit (Palmer 2013b). In areas of dense beach spinifex, kill rates of rats in 10 m snap trap grids over two nights indicated that rat densities may exceed 100 rats/ha and they consumed up to 8.3 kg/ha/night of non-toxic block baits from bait stations. As camera trap monitoring showed large male rats were monopolizing bait stations, this was considered an underestimate. The broadcasting of significant quantities of bait from the air was therefore considered the only viable means of eliminating such a high density of rats from this relatively large island. At this late stage of this externally funded project, funds were limited, but it was decided to press ahead.

As the project manager had no experience in aerial baiting, an operational advisor was brought in as a consultant for the baiting program. Thirteen tons of Pestoff 20R was imported from New Zealand, with a planned application rate of ~32 kg/ha for the first drop and ~12 kg/ha on the second drop after 10 days. A new bait spreader bucket was also purchased. Testing of this spreader bucket on the mainland prior to steaming to the island was relatively limited but calibration trials were conducted at an airstrip in Derby, after a delay caused by a mechanical malfunction on the helicopter. The spreader motor did cut-out during a test flight, but this was possibly due to damage to the throttle mechanism sustained during shipping from New Zealand. A mechanic in Broome undertook repairs and serviced the motor and an engineer milled discs more suitable to prescribed application rates, prior to departure. To conserve limited funds, a spare bucket to provide redundancy during the baiting operation had not been freighted from across the country for the job.

During the first application of bait on Adele Island in 2013, the spreader bucket engine cut out intermittently and the bucket was also throwing the belts. The pilot was not always confident that he could identify exactly when the engine stopped each time and thus where bait coverage wasn't achieved. This meant that some bait lines had to be repeated following an engine stoppage and additional bait was used to achieve this and ensure that lines were covered (an extra 1,470 kg or 5 kg/ha). As there was limited contingency bait available, the trade-off from this action was a reduction in available bait for the second application (Palmer 2014).

The morning following the first drop, the upper beach was inspected from an ATV for presence of bait, as the operating permit (Australian Pesticides and Veterinary Medicines Authority) did not allow for bait to be spread on sand beyond the shoreline vegetation margin. Lack of visible bait along a 2.6 km length of the west coast prompted further inspection of the adjacent vegetation. A gap up to 20 m wide was found in the coastal swath along this section. This gap, which was not reflected in the flight path data, was not discovered until the following morning, after the helicopter had returned to the mainland the previous evening. An attempt was made to provide some bait in this gap by handbroadcasting 35 kg of old Pestoff wax blocks from the adjacent shoreline (~6.7 kg/ha). Due to the lack of funding to remain at the island, the vessel and baiting team were then diverted to undertake surveys of inshore islands for another project. There were no opportunities to continue monitoring on Adele Island, although eight camera traps were deployed before departing (Palmer 2014).

The baiting team returned to the island nine days later. A further 65 kg Pestoff wax blocks were applied to the gap on the west (~12.5 kg/ha), although aerially broadcast bait did target this area in particular during the second drop. Significant problems with the spreader bucket engine were encountered once the second application was commenced. The problem appeared to derive from direct airflow around the motor once in flight, causing the engine to cut out. This may have been due to carburetor freezing or airflow into the exhaust. At the time, attempted on-site adjustments (attaching a plastic shield over the front of the motor and replacing some parts) failed to address the issue so the problem persisted and some baiting lines were not treated with a high degree of confidence. The average application rate for the island for the second drop was 7.2 kg/ha. However, the repeating of sections of lines used available contingency bait and some remaining allocated bait, resulting in a further reduced application rate over part of the island. The issue was subsequently addressed by fitting a baffle in front of the engine to deflect direct airflow around the motor.

The timing of the baiting operation to coincide with the change-over from the breeding season of mostly large seabird species and the arrival of migratory shorebirds for the austral summer meant that bird numbers were lower on Adele Island during the baiting operation (Palmer 2014). Hence the probability of bird strike to the helicopter was reduced and in the event no bird strike incidents occurred.

Camera trap monitoring demonstrated a rapid collapse in the rat population following the first bait application. The last live rat was detected on day 10/11 following the first bait drop. No further rats were detected on the seven operating cameras collected on 22 November 2013 (day 32 from first drop; Palmer 2014). Further camera trap monitoring occurred from 28 April to 20 August 2014, with seven camera traps spaced around the perimeter of the island. A rat was detected by a camera trap on the 26 May 2014, which was approximately seven months post-baiting. Several more rats were detected by the cameras in June and July at different locations (opposite ends of the island). The team collecting the camera traps also sighted rats on 19 August 2014 in one location (pers. comm. Jarrod Hodgson). In the absence of funding no further actions were possible.

4.8.1.2 Future attempt

A future attempt at eradication of *R. exulans* from Adele Island is considered entirely feasible, and the errors contributing to failure of the 2013 attempt can be corrected with appropriate planning and resourcing. Resourcing of an operation in remote locations needs to be at a level where project managers are not forced to cut corners in planning. In other words, the budget needs to fit the project needs, not the project being attempted within an arbitrary budget amount. With sufficient resourcing, spare equipment; costs for the required time on island; and a suitable amount of contingency bait are all included in planning. If the primary causes contributing to the 2013 failure were the likely gaps in coverage on one or both bait drops due partly to equipment malfunction, then rectifying this by use of suitablytested equipment, using an experienced baiting pilot, and having the helicopter remain on site until ground checks are completed can be mandated.

Nor should it be forgotten that regulatory conditions can reduce the chance of successfully completing an eradication. Bureaucratic decisions made by regulatory staff lacking practical knowledge and without an eradication goal are nonetheless binding, and strict compliance may reduce the likelihood of eradication. In this instance, a permit condition precluded allowing any bait to be spread beyond the vegetation margin on the shoreline, and any bait that was incidentally spread on sand had to be removed. But the staff resources required to search and remove bait would be extensive (compared to waiting for one tidal cycle), so every attempt was made to prevent bait going across the shore. It is possibly this aspect that lead to the gap in coastal coverage on the first bait drop. Yet standard eradication practice is to overfly the coast to prevent exactly this situation (risk of insufficient bait coverage) from occurring. In this instance, there is no reason to expect that some bait going beyond the coastal margin would have made any material difference to non-target impacts. The extremely high tidal range at Adele Island would have removed most bait pellets that would fall on the shoreline or estuary within a tidal cycle, so bait on sand would not be exposed for more than 12 hours. Conducting coastal swathes at or near high tide would also help remove any bait from the littoral zone.

4.8.1.3 Conclusion

Adele Island is a remote tropical island that is difficult to access due to a fringing reef and the large tides. For the first two attempts there were no lead-up surveys due to the cost of visiting this island and the baiting teams had limited to no experience. Lack of knowledge of rat densities led to the failure of these ground baiting attempts in 2004 and 2011 due to inadequate bait application rates. Hand spreading of bait on a hot tropical island with a tangled mat of knee to waist high beach spinifex means there were also likely gaps in the bait coverage in the 2004 attempt and the second application during the 2011 attempt. Large male rats may have monopolized access to the bait stations (pinned bait blocks) that were used in the first application in 2011.

Over 10 times the amount of bait was then applied during an aerial baiting program in 2013 (44.2 kg/ha). The failure of this eradication attempt was likely due to a number of factors. For this third attempt, funding was limited so corners were cut in the planning process. The newly purchased bait spreader bucket was calibrated but not fully tested prior to being transported to the island and a second spreader bucket, which would have ensured a degree of equipment redundancy, was not taken. Spreader bucket motor problems resulted in the use of excess bait in the first drop. Plus, a gap in the coastal swath (up to 20 m wide and 2.6 km long) was discovered after the helicopter had departed at the conclusion of the first drop. This gap was hand baited with block bait but this coverage was poor. The second aerial bait application was besieged with problems with the bait spreader motor cutting out mid-flight. There was insufficient contingency bait to complete bait application according to plan and gaps in the second application were possible. It emphasized the need to have a baffle fitted to the motor to prevent carburetor freezing, even in tropical conditions. Operational problems identified in the 2013 attempt should be rectified easily in a future attempt assuming commensurate resources are available, but regulatory constraints, if unchanged, may continue to challenge eradication success.

4.8.2 **Kayangel**, Palau (112.3 ha, 3 m maximum elevation)

Island description (from Holm et al. 2006): Kayangel is the largest and only permanently inhabited island of the four islets that form Kayangel Atoll. It's 2,570 m long north-south, with a width between 270 m in the south and 700 m in the north. The island is low lying, sandy and largely forested with numerous freshwater wetlands, the largest of which are used for growing taro. Approximately 60 people live permanently on the island. There is temporary or permanent horticulture of bananas, taro and corn, and domestic animals include low numbers of pigs, cats and dogs. There are two sacred areas with restricted access: no person is allowed into the smaller area and only a small group of people from a family clan is allowed into the larger area. The size of each area does not have defined boundaries and might change over time. The distance to the closest source of invasive rodents, another island, is 38 km.

Conservation/ownership status: the islands are privately owned.

Figure 15. Kayangel Island (in front) at Kayangel Atoll, Palau (Photo: Island Conservation).

Table 16. Comparison of operational and environmental factors across eradication attempts and recommendations for next attempt on Kayangel Island, Palau.

Factor	Initial attempt	Second attempt (one of two rat species successfully removed)	Recommendations for next attempt
Year	2012	2018	

Target species	Asian house rat + Pacific rat (both survived)	Asian house rat (eradicated) + Pacific rat (survived)	Pacific rat

Factor	**Initial attempt**	**Second attempt** **(one of two rat species successfully removed)**	**Recommendations for next attempt**
Season + month	Mostly aseasonal (August, second dry period of the year)	Mostly aseasonal (April, usually drier)	April
Environmental conditions	Normal (green, wet)	Abnormal (drier than usual)	Delay if conditions are wetter than anticipated
Land crabs present	Yes	Yes	Monitor activity
Coconut palms present	Yes	Yes	Record fruiting
Agriculture present	Yes + livestock	Yes (livestock removed or contained)	Remove (preferably) or contain livestock
Human habitation	Yes	Yes	Engage the community
Rodent ecology	Likely breeding at the time of eradication	Likely breeding at the time of eradication	Monitor to assess breeding and relative abundance
Method	Hand broadcast, 2 applications 7 days apart: 15 kg/ha + 10 kg/ha on a 20 m × 20 m grid; total of 25 kg/ha + bait stations throughout inhabited area and in gardens	Hand broadcast, 2 applications 24 days apart: 21 kg/ha + 28 kg/ha on a 25 m × 25 m grid; total of 49 kg/ha	Aerial application by drone or helicopter so that sacred areas are treated to the same standard
Bait	Pestoff 20R	Pestoff 20R	Pestoff 20R or Conservation 25-W
Active ingredient	Brodifacoum 20 ppm	Brodifacoum 20 ppm	Brodifacoum 20-25 ppm
Organization	PCS, BirdLife	IC, PCS, BirdLife, Kayangel State Government	

Factor	Initial attempt	Second attempt (one of two rat species successfully removed)	Recommendations for next attempt
Notes	Grid established and checked but not GPS'd Sacred areas (~9 ha), baited by guardians, may not have been treated thoroughly. Bait spread largely by the community and State personnel Food waste partly discarded into forest or at island land fill Livestock (2 pigs) tethered outdoors and fed from containers	Grid GPS'd and coverage audited everywhere except for within sacred areas (~4 ha), baited by locals Bait spread largely by community members although with more experienced staff on the ground. Additional applications of bait around wetlands and the coastline Food waste management improved but didn't eliminate the risk Livestock removed or contained (fences were not rat proof) Bait disappeared quickly from some areas with high density of burrowing land crabs	As per 2018 but aerial vs. ground based application
Risk of reinvasion	Moderate	Biosecurity plan established but risk still moderate	
Best practice (BP) followed	Yes, except for sacred areas	Yes, except for sacred areas	
References	Gupta 2011, Holm et al. 2006, Griffiths & Hall 2017	Hall & Zito 2019	

4.8.2.1 Diagnosis

The feasibility study produced in 2006 concluded that two rat species, probably ship rat and Norway rat based on indirect evidence, were present on all four islands and that their eradication was possible (Holm et al. 2006) despite the largest island being inhabited and livestock and commensal animals (cats and dogs) being present. The presence of mice could not be determined in 2006 but it was recommended to plan as if they were present. The other main recommendation was to undertake studies to address the information gaps identified (e.g. risks to non-target species).

Some issues were investigated (e.g. palatability of bait to native species) but others (e.g. land crab density and bait uptake rate) were not, as noted in the Operational Plan (Gupta 2011). Interestingly, the same plan mentions that the potential causes of eradication failure on Fanna (400 km from Kayangel) include '*coconut crabs and land crabs ate much of the bait. There had been no quantitative study to determine the expected crab uptake rate of bait…'*.

The decision to operate in Kayangel in August rather than April (usually the driest month, originally planned for the operation) was driven by pressures within the lead organization to complete the operation, compounded by donor timeframes; August is typically the second lowest rainfall month. The chosen eradication method for the first attempt was two hand broadcast applications of brodifacoum bait across the entire island, with bait stations at all homes and structures, among crops and in swamps. Although the operational plan is reasonably detailed in some aspects, it does not identify the selection of team members, the training needed and who would provide it. These aspects were dealt with separately by the project manager and operational training needs were provided by the operation technical advisor. Expert advice was given throughout the project but no experienced managers were present during baiting. The smaller sacred area (~10 × 10 m or 0.01 ha) was baited from the outside and the larger one (~300 × 300 m or 9 ha) was baited inside by the guardians but without systematic bait lines.

The project did not succeed in removing rats from the main island of Kayangel, but it was successful on the three other islets (Gupta et al. 2013). Griffiths & Hall (2017) reviewed the project and, through DNA analysis, confirmed the presence of Pacific rat and identified Asian house rat as the second species, previously thought to be ship rat. The review concluded that '*the greatest risks to the project and the most likely reason why rats survived on Kayangel was a bait application rate that was too low to ensure a reasonable period of bait availability, a short (8 day) interval between applications and the possibility that some rat territories* (e.g. inside the sacred areas and dwellings) *were missed during bait application. Any one or a combination of these factors could have created a spatial or temporal gap in bait availability and resulted in survivors.'*

The review and recommendations by Griffiths & Hall (2017) set the basis for the second attempt (2018) on Kayangel. Key differences during the 2018 attempt are described by Hall & Zito (2019) and included tighter management of food waste, with the island landfill closed for the operation and all food waste taken offshore for the duration of the operation. The availability of alternative food sources from horticulture such as bananas and wax apples was minimized. Bait was applied at a higher rate and over a longer interval. Bait stations were established inside (including roof spaces) and bait spread underneath all structures across the island. The baiting grid was GPS'd allowing its accuracy to be evaluated and gaps filled ahead of bait application. However, the two sacred areas were difficult to bait evenly. The smaller of the two sites was ~0.08 ha and no one was permitted to enter. A perimeter of extra baiting points was established around this site; bait pellets and paper bags with bait were thrown from the perimeter into the site. Training and oversight were provided to family members who applied bait within the larger sacred area (3.8 ha), although due to the project leadership's inability to audit bait availability this remained a significant concern. The number of transects cut and the number of baiting points reported were acceptable. Yet, a portion of this sacred area was covered by a sprawling hibiscus tree over an area mixed with limestone and portions of standing water. There are other areas like this on the island and it is extremely difficult to move around and cut trails. In addition, sacred trees could not be cut for cultural reasons, which probably resulted in an uneven baiting grid, and uneven baiting, in the sacred area. Baiting gaps as small as 10 × 10 m while targeting Pacific rats on tropical islands may pose a risk of not all juveniles being exposed to bait (Samaniego et al. 2020a).

The availability of bait was monitored on 30 transects spread across the island, with bait remaining in all transects for a minimum of four nights after the first application. Bait disappeared more quickly after the second application with one transect falling to zero after three nights and for others after four. Bait disappeared most quickly in areas of higher crab density. Baiting took most of April 2018 given the interval between bait applications. During the next few months, a series of unconfirmed rat sightings were reported by the community, always followed by localized trapping and baiting by the local team. A rat was finally trapped on 22 January 2019 by one of the local ranger and a rapid response was also implemented. The formal confirmation survey conducted in July 2019 (15 months after the eradication) corroborated that rats were present on Kayangel at low density. Rats were found to be widely distributed across the island therefore localized treatments stopped (Hall & Zito 2019). It appears that the larger Asian house rat was eradicated whereas the smaller Pacific rat survived the attempt.

4.8.2.2 Conclusion

The first attempt was ground based and was not successful for the main island of Kayangel although a concurrent operation with a different baiting strategy was successful for the three other islets. Insufficient bait availability appears to be the primary reason for failure on the inhabited island. Potential issues contributing to this include a significant area (~9 ha) was not treated systematically with marked bait lines and points due to being sacred, not all dwellings were treated inside, and alternative foods may have meant individual rats did not access sufficient bait within the period it was available.

The second attempt on Kayangel, also ground based, eradicated the dominant Asian house rat but not the Pacific rat, an outcome also seen on Wake Island. Reasons why Pacific rats persisted are not clear but likely relate to interspecific competition and some individuals not having access to bait. Bait distribution may not have been sufficiently comprehensive in all areas, particularly in the sacred areas, to overcome competitive exclusion and/or the smaller foraging ranges for some subdominant individuals.

4.8.3 **Congo Cay**, US Virgin Islands (10.6 ha, 52 m maximum elevation)

Island description (from Dammann & Nellis 1992): the climate is dry tropical with an average temperature of 27.5° C (24°C – 31°C) and an annual rainfall of 838 mm. The vegetation is open dry deciduous forest, sometimes with a dense understory of cactus, thorny shrubs, vines and grasses. The distance to the closest source of invasive rodents, another island, is 0.24 km.

Conservation/ownership status: managed by Department of Planning and Natural Resources, Division of USFWS as nesting habitat for seabirds, particularly brown pelicans (*Pelecanus occidentalis*).

Figure 16. Congo Cay, US Virgin Islands (Photo: Christian Wheatley).

Table 17. Comparison of operational and environmental factors across eradication attempts and recommendations for next attempt on Congo Cay, US Virgin Islands.

Factor	Initial attempts	Recommendations for next attempt
Year	1990-1991, 2004, 2006	As soon as an operational plan is developed and reviewed

Target species	Ship rat	Ship rat
Season + month	1990-1991: year-round 2004: June 2006: June	Driest month
Environmental conditions	Normal	Monitor local conditions
Land crabs present	Yes	Monitor closely

Factor	Initial attempts	Recommendations for next attempt
Coconut palms present	No	Monitor for other potential sources of food
Agriculture present	No	Record absence/presence of human activities
Human habitation	No	Monitor for signs of visitation
Rodent ecology	Not assessed; most likely at high density and breeding at the time of eradication	Assess rodent density and breeding status during the eradication
Method	1990-1991: bait piles at each interstice of a 10 × 10 m grid; inaccessible cliffs baited using slingshots. Total of 3 applications 6 months apart 2004: combination of elevated bait stations for 10-14 days and hand broadcasting: 1 application, with inaccessible slopes and crevices treated as much as possible 2006: hand broadcast; 19.25 kg/ha on a ~25 × 25 m grid on central part of island, while the rocky eastern and western ends baited without grid	Develop a feasibility study Aerial broadcast by drone Treat both Congo Cay and Lovango Cay simultaneously
Bait	1990-1991: probably Talon WB 2004: bait block with molasses and peanut butter lure 2006: Conservation 25-D	Conservation 25-D

Active ingredient	1990-1991: brodifacoum 2004: diphacinone 50 ppm 2006: brodifacoum 25 ppm	Brodifacoum 25 ppm
Organization	1990-1991: Toledo Zoo, USVI Territorial Gov. Div. of Fish and Wildlife 2004: USDA-Wildlife Services 2006: USDA-Wildlife Services	Include in the team people familiar with the target islands
Notes	1990-1991: using slingshots for the cliffs was reported as not effective 2004: leftover bait was left on island for rats to consume	Assess daily rate of bait consumption Assess time to zero rat activity, potentially with camera traps

Factor	**Initial attempts**	**Recommendations for next attempt**
	2006: the difficulty of exposing all rats to bait, given the terrain with deep fissures, was noted Rats caught again in April 2007	
Risk of reinvasion	High (Lovango Cay ~ 240 m away); genetic analysis suggests that at least after the 2006 failure reinvasion was likely	Develop and implement a biosecurity plan before conducting a rat eradication
Best practice (BP) followed	N/A (pre-BP)	Strictly follow best practice
References	Pierce 2004, 2007, Hall et al. 2006, Savidge et al. 2012, G. Witmer pers. comm., P. Tolson, pers. comm.	Document every step of the process

4.8.3.1 Diagnosis

Although it is probable there was an eradication attempt in the 1980s (G. Witmer pers. comm.), the literature suggests the first attempt was in 1990. Bait pellets were placed directly on the ground in small piles of 8-10 pellets at every interstice of a 10 × 10 m grid, which meant some bait was lost to land crabs. According to project leader there were also '*several areas of the cay that were inaccessible due to the steep cliffs'* (P. Tolson, pers. comm.), so the cay was circled in a boat and slingshots used to catapult pellets to inaccessible areas, with mixed success. Rats were only recorded after three years although trapping was sporadic. It is possible that some rats were not exposed to bait due to gaps in coverage, but three years to rebound is a long period for ship rats given their fecundity, as evidenced by the rat recovery reported from other failed eradications in a matter of months. Risk of reinvasion is high given the short distance to other cays, but the lack of genetic samples and continued monitoring means operational failure cannot be ruled out.

The second operation (2004) used elevated bait stations to reduce hermit crab interference (Pierce 2004). Bait stations with diphacinone bait were placed every ~45 m along two transects that ran east-west along the length of the cay. The southern transect midway across the cay followed a zig-zag pattern until it joined the northern transect. This had spurs running off it, in an attempt to cover home ranges of all rats (Pierce 2004, Hall et al. 2006). By days 7-9 of 14 days of baiting, bait consumption was very low. Initially this attempt was thought to be successful, but rats were caught again in 2006.

The final attempt occurred in 2006 when rats were discovered during post-monitoring surveillance following the 2004 attempt. USFWS received emergency approval to re-attempt the eradication using Conservation 25-D. This time bait was hand broadcast using a grid system of 40 × 40 m on the central part of the island. On the rocky ends of the island it was deemed that bait coverage was sufficient without a grid system but broadcast in eight compass directions. If the most northerly or southerly points couldn't be reached bait was thrown from the nearest 12 m (Hall et al. 2006). This may have left gaps in coverage, as David Nellis pointed out '*Because of deep fissures on Congo it is probably very difficult to get all rats exposed to the rodenticide bait when it was put out for only a relatively short period of time. Some rats may live deep down in the fissures at time and probably have access to foods'* (Gary Witmer pers. comm.). However, the case of Teuaua (see Section 3.3.2) was similar in that there were many fissures and the cliffs were difficult to bait by hand, yet rats were eventually eradicated using a systematic manual baiting approach.

An important oversight during the planning of Congo Cay across attempts is the high risk of reinvasion given its proximity to other rat-infested locations. Indeed, Lovango Cay is only 240 m south of Congo Cay and could serve as a source population of rats. The conclusion of the genetic analysis presented in Savidge et al. (2012) is that the lack of pre-eradication samples precludes ability to rule out an eradication failure, but that reinvasion from Lovango is highly probable, therefore they recommend treating Lovango and Congo as an eradication unit/pair in the future. At present, risk of reinvasion is an important consideration when evaluating feasibility of an island eradication. We agree with the recommendation of treating Lovango and Congo cays as an eradication unit.

4.8.3.2 Conclusion

The first attempt was ground based mainly using bait clumps on the ground on a grid pattern and was not successful. Operational failure and reinvasion are both potential explanations. Gaps in bait coverage likely occurred, but rat reinvasion is most likely a constant phenomenon given the distances between these cays and the swimming capabilities of the target species.

The second attempt also was ground based, using a combination of elevated bait stations and hand broadcast. Possible causes for failure were gaps in bait coverage around the cliffs and what appears to be a short time period of exposure to diphacinone bait (i.e. only one application for 10-14 days).

The third attempt was ground based again, using hand broadcasting of brodifacoum bait and a more systematic approach. A subsequent genetic analysis concluded reinvasion is highly likely the reason why rats are still present on Congo Cay. A potential source population of rats is only 240 m away. Yet, operational failure cannot be ruled out given the lack of pre-eradication genetic samples. At present, any island or archipelago located <1 km away from a source population of ship or Norway rats is considered at high risk of reinvasion.

4.9 Applying the lessons learnt: Planning the second attempt for Wake Atoll (696 ha, 6.4 m maximum elevation)

Island description (from PACAF 2017): Wake Atoll (US territory in the tropical Pacific) is a small coral atoll consisting of three islands, namely Wake (526 ha), Peale (95 ha) and Wilkes (76 ha). Peale is separated from Wake Island by ~100 m and at low tide Wilkes and Wake are essentially connected. The climate is tropical maritime, dominated by northeast trade winds. Temperature variation is minimal, with monthly averages of 24.4°C to 28.3°C.

Rainfall is light, averaging only about 890 mm per year, with rain showers occurring most often between midnight and sunrise, and heaviest rainfalls during the July to October Pacific typhoon season. The distance to the closest source of invasive rodents, another atoll, is 850 km.

Current vegetative cover on unimproved grounds comprises three natural plant associations. The driest plant association is xeric forest dominated by *Tournefortia*, with shrub-like expression at 1-2 m along beaches and inland stands reaching as high as 6 m. *Cordia* forest occurs in mesic conditions and grows to an average of 7-10 m. *Pemphis* habitat is found on sandy and saturated coastal substrates. Other vegetation communities include casuarina forest, ruderal vegetation, and mowed/maintained vegetation. The atoll supports a large and diverse assemblage of migratory seabirds and shorebirds, with the largest colonies (e.g. >100,000 breeding pairs of sooty terns *Onychoprion fuscatus*) on Wilkes and the northern tip of Peale.

Rats on Wake are known to prey on seabird eggs and chicks, native plants, and invertebrates. Chewing by rats on Wake causes damage to military infrastructure, contaminates food stores, and constitutes a potential health threat to the island community of military personnel and base operations contractors.

Conservation/ownership status: US Air Force.

Figure 17. Wake Atoll, tropical Pacific (Photo: US Air Force).

Table 18. Comparison of operational and environmental factors across eradication attempts and recommendations for next attempt on Wake Atoll, US territory.

Factor	Initial attempt	Recommendations for next attempt
Year	2012	As soon as the operational plan is approved, and funding is secured
Target species	Asian house rat (eradicated) + Pacific rat (survived)	Conduct extensive trapping to make sure Pacific rat is the only species present. Survey Peale to ensure it remains rat free
Season + month	Dry season (May)	Dry season (driest month) Avoid the main nesting seabird season
Environmental conditions	Normal	Avoid abnormally wet conditions
Land crabs present	Yes (primarily *Coenobita* spp.)	Monitor diversity and abundance
Coconut palms present	Yes	Remove big piles of coconuts or leaves on the ground

Factor	**Initial attempt**	**Recommendations for next attempt**
Agriculture present	Yes (Thai gardens)	Remove edible parts (e.g. fruits) and apply supplementary bait. Monitor closely
Human habitations	Yes	Bait every room of every building, inside, outside, underneath, and any roof spaces; including service ducts and sub-surface spaces
Method	Combination of aerial baiting (18 + 9 kg/ha, 2 applications, total of 27 kg/ha), hand broadcast, and bait stations (until Nov 2012)	Ideally bait 100% of island aerially. Use ground methods to apply extra bait in and around human structures, applying bait at higher rates in problem areas (e.g. waste facility) Appoint an experienced practitioner as eradication manager, with a support team familiar with country regulations and local conditions
Bait	Conservation 25-W	Use the same bait as it has been trialed on Wake, has a proven track record and is already registered in the United States
Active ingredient	Brodifacoum 25 ppm	Brodifacoum ≥20 ppm
Organization	USAF 15th Airlift Wing, Pacific Air Forces, USFWS, IC	Include key people involved with the first attempt as well as new experienced practitioners so the experience is retained but new ways of thinking are also incorporated

Notes	Aerial broadcast (590 ha), bait stations (commensal areas; 4.2 ha), & hand broadcast (Pemphis habitat/coastal areas, bunkers, underground, cantonment areas, and overlap areas; 32 ha), combined aerial & hand broadcasting (~11 ha); 59.5 ha not baited (runway and bunded fuel storage areas) No sightings of Asian house rat on any of the islands since May 2012 Pacific rats removed from Peale but survived on Wake. Monitoring is ongoing	A new operational plan is being developed. It should ensure that application rates are not compromised by permitting constraints and that USAF prioritizes the operation during implementation Fuel storage areas should also be baited
Risk of reinvasion	Low	Develop/ refine/ enforce biosecurity plan
Best practice (BP) followed	Overall, yes	Strictly follow best practice, from planning to implementation to biosecurity
References	Wegmann & Hanson 2012, Brown et al. 2013, Griffiths et al. 2014, PACAF 2017, Hanson et al. 2019	Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019, this review

4.9.1.1 Diagnosis

The 2012 eradication targeted both Asian house rats and Pacific rats. The Asian house rat was successfully eradicated from the entire atoll. The Pacific rat was eradicated from Peale but a few individuals survived on Wake and/or Wilkes and have repopulated both islands (Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019). At the time, this was considered one of the most complicated rat eradications attempted, particularly because of the permanent human settlement and the number of restrictions placed on the implementers by the USAF. Given the complexity, it is difficult to identify one single factor responsible for the failure, but likely there were several overlapping issues including:

- bait gaps or localized shortages due to inadequately designed baiting methodology in commensal and intertidal (*Pemphis*) habitats and complicated combinations and integration of various baiting methodologies, all of which were exacerbated by known application errors or difficulties.
- low overall bait rates with insufficient buffer (Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019).
- bait preference/aversion issues coupled with availability of alternative natural or commensal foods (Brown et al. 2013, Hanson et al. 2019), but lack of observed commensal foods and the success on Peale and Wilkes indicate this might not be an issue (Griffiths et al. 2014).
- rat breeding during the operation causing temporal or spatial unavailability of bait to juveniles emerging from natal nests; or, speculatively, behavioral avoidance of bait by some breeding females (Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019), although there is conflicting evidence (Samaniego et al. 2018, Samaniego et al. 2020a).

- poor understanding of habitats that are underground and/or abandoned structures.
- insufficient understanding of interactions between the two species resulting in inadequate bait accessibility for Pacific rats (Brown et al. 2013, Griffiths et al. 2014, Hanson et al. 2019).

One of the known application errors is pilot error, which is rarely talked about during project reviews. There is evidence of the pilot sowing lines but with no bait in the bucket. Although this may not have resulted in a physical gap, bait would have been at a lower density in these locations. Furthermore, the lack of a single operation manager diffused responsibilities. Divisions in roles between agencies led to shortfalls and lack of integration in planning, miscommunications between individuals and agencies, and lack of "ownership" of the project (Brown et al. 2013). Additionally, there is doubt about the comprehensiveness of coverage within buildings; commensal waste management did not go according to plan, which may have resulted in availability of alternative food sources for rats; and it is possible there was competitive exclusion of Pacific rats from bait stations by Asian house rats (Hanson et al. 2019). The project was also understaffed and staffed with inexperienced practitioners, which may have also contributed to the failure by elevating the likelihood of errors (Wegmann & Hanson 2012). Finally, outreach to build Wake Island community buy-in and support could have been improved (Hanson et al. 2019).

4.9.1.2 Remedial activities

Subsequent to the review by Brown et al. (2013) the USAF embarked on sponsoring a course of literature review, research, and planning efforts to identify and resolve all knowledge gaps and methodological shortcomings in anticipation of a future successful eradication of Pacific rats from Wake Atoll. Below we summarize the activities associated with addressing causes of eradication failure associated with the possibility that rats could not eat enough bait (Table 19) or would not eat enough bait (Table 20).

Table 19. Risk factors identified in the review process that could have caused failure because rats could not eat enough bait, recommendations and research conducted to address those concerns or knowledge gaps, and reference(s) addressing recommendation or indication if work has been completed to address recommendation. All bait trials used Bell Labs Conservation 25-W bait (hard) as the rodenticide. Soft bait in 2019 trials was Bell Labs FINAL Soft Bait with Lumitrack®.

Risk Factor	**Recommendation**	**Reference or technical or methodological advance**
Insufficient Bait	Supplemental label(s) to increase bait application above maximum, to the rate determined by onsite trials	Keitt et al. 2015
	Supplemental label to increase 2nd application to be as robust as initial application	Keitt et al. 2015
	Supplemental label to increase number of applications	Keitt et al. 2015
	Extend interval between applications to increase period of availability of palatable bait on the ground (e.g. for breeding behaviors)	Keitt et al. 2015
	Focus on comprehensive bait coverage	Samaniego et al. 2020a,b

	Stratify application rates to specific areas only if necessary: • Describe treatment locations • Accurately identify boundaries • Determine appropriate bait application rates based on onsite trials • Ensure minimum desired rates are applied in all habitats, i.e. extra care at buffers • Solid waste aggregation area study	Niebuhr et al. 2018: • Keitt et al. 2015 • Keitt et al. 2015 • Keitt et al. 2015 • Pott et al. 2015 • Scheduled 2020 (NWRC)
Gaps in coverage: complex baiting strategy	Pre-determine and verify application technique for each zone	Hanson et al. 2019
	Minimize the number of exclusion zones for aerial baiting, e.g. also treat fuel storage areas	Hanson et al. 2019
	Lift restrictions that reduce baiting efficiency, e.g. coastal baiting, aerial baiting over commensal areas, bunded fuel areas etc.	Hanson et al. 2019
Gaps in coverage: tidally inundated habitat	Tested variety of delivery methods and proposed bait application strategies	Siers et al. 2018
Gaps in coverage: structures poorly known	Detailed update of structure data base with all above and below ground structures	Completed 2019 (NWRC unpubl. data)
	Geo-reference all above and below ground structures into digital database	Completed 2019 (NWRC unpubl. data)
	Assess if bait can be delivered for rodents utilizing subterranean habitat	Completed 2019 (NWRC unpubl. data)

Table 20. Risk factors identified in the review process that could have caused failure because rats would not eat enough bait, research conducted to address those concerns or knowledge gaps, reference(s) addressing recommendation or indication if work has been completed to address recommendation.

Risk Factor	Research	Outcome	Research/Reference
Aversion/palatability issues: Preference for natural food items	2-choice trial between toxic bait and natural food items	Preferred bait	Shiels et al. 2015
Aversion/palatability issues: Localized dietary preferences	2-choice trial between soft and hard formulations of toxic bait with rats from commensal, bush, and solid waste aggregation locations	No soft bait consumed 27% of rats (mostly from commensal and bush locations) consumed no bait	Completed 2019 (NWRC unpubl. data)

Tolerance to bait	No-choice efficacy trial	100% mortality	Shiels et al. 2015
	No-choice efficacy trial	Hard bait: 100% mortality Soft bait: 80% mortality	Completed 2019 (NWRC unpubl. data)

As part of these efforts, USAF also funded a supplemental review (Hanson et al. 2019) to identify all remaining knowledge gaps and to make recommendations for their resolution prior to a second eradication attempt. They have identified several risk factors that still need to be addressed, which are summarized in the remainder of this section.

Both Brown et al. (2013) and Hanson et al. (2019) have noted that community understanding and buy-in during the previous attempt was not sufficient. Prior to another eradication attempt, a robust community outreach program will need to be developed. Emphasis should include educating the Wake community about eradication fundamentals and facilitating community buy-in by involving them in the planning process and implementation of a zero waste program. The zero waste program addresses the risk factor that rats could have access to alternative anthropogenic food sources and will require community participation and commitment to be successful. While the majority of previous eradication projects have been conducted on uninhabited islands, community buy-in has been an essential component of eradications on inhabited islands. Lessons learned from eradications on other inhabited islands, such as the Lord Howe Island Rodent Eradication Project (Harper et al. In press) and Ascension Island (Ratcliffe et al. 2009), include the development of a robust outreach program. To be most effective these programs should be administered by a professional social scientist, and have proven to require a substantial commitment of time and resources that are easy to underestimate (Harper et al. In press). Importantly, Wake is a special case where everyone is employed by the military, either directly or indirectly, to be there.

Future efforts will continue to resolve areas of uncertainty, particularly regarding how aspects presenting a risk to eradication efficacy are addressed. For example, rather than estimating appropriate bait rates for Wake Island's solid waste aggregation area (SWAA), it would be ideal to remove the condition which necessitates an adjustment. Previous studies have been unable to meet best practice guidelines for bait persistence outlined in Pott et al. (2015) due to rapid and complete consumption by a hyperabundance of rats in this area. Practitioners undertaking a future effort on Wake Atoll should also strive for continuity of staff within key roles and avoid including a high proportion of inexperienced participants (Brown et al. 2013, Hanson et al. 2019, Samaniego et al. In press). In particular, it will be important to ensure that the operation is managed by an experienced project leader who has spent substantial time working with the island residents and has a thorough understanding of the environmental and on-island social conditions under which the eradication will occur. The continuity of having this individual in place, with well-established relationships to both the island and military command structure, will allow them to minimize compromises to best practices and give them the authority to postpone the project if substantial concerns are raised throughout the planning process and/or if critical pre-operational conditions are not met (Brown et al. 2013). Every effort is being made to incorporate these recommendations into the operational planning for a future eradication attempt on Wake.

4.9.2 Conclusion

The failed 2012 eradication attempt was an extremely complex project, but what appear to be the most important factors that played a role in the failure were gaps in baiting from known malfunctions, poor bait application methodologies and integration of different methodologies, overly complex operational command structure with understaffed and inexperienced practitioners in key positions, poor outreach and buy-in from the local Wake community and lack of understanding and documentation of abandoned structures and subterranean habitat/structures leading into the eradication.

As emphasized throughout this review, factors leading to initial failure can be remedied and subsequent eradication attempts can be successful. The operational plan for a future eradication on Wake Atoll should incorporate the lessons learned while resolving existing knowledge gaps particular to Wake Atoll, and reflect explicit consideration of the factors leading to successful subsequent eradications highlighted throughout this broader review. With proper permitting, preparation and implementation, Wake Atoll may be added to the list of successful island rodent eradications following initial failure.

5 Discussion

Island rodent eradications are highly effective conservation interventions (Russell & Holmes 2015). Despite the increases in island size and complexity, success rates have also increased over time and solutions to remaining challenges are being investigated (Veitch et al. 2011, Veitch et al. 2019). For example, although house mice appear to require proportionally higher doses of anticoagulants than some rat species (Broome et al. 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, by implementing high-standard eradication operations ensuring no gaps in bait coverage (Broome et al. 2019, Horn et al. 2019). Lab trials are useful, but the need for follow-up trials in natural situations (e.g. Wanless et al. 2008) as well as detailed documentation during actual eradications is evident.

Practitioners are better at reporting successes than failures and reviews of either are rare. In addition, there is a tendency to avoid discussion of potential human errors and this 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 if we are to learn from failure and clarify what is required for success. Every eradication project should include a comprehensive post operational report as part of the overall strategy, so time and funding are 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 fields that any post operational report should include.

Compared to temperate islands, rodent eradications on tropical islands are currently considered more prone to failure given their lower success rate, so specific guidelines (Keitt et al. 2015) were recently developed to help remedy this difference. It is expected these guidelines for tropical islands will be constantly improved as we learn from projects. Holmes et al. (2015b) concluded that the factors associated with failure in tropical environments appear to be many, and potentially multiplicative, with environmental factors such as presence of coconut palms, land crabs and agriculture showing clear association with failure. Griffiths et al. (2019) added that year-round rodent breeding and diet of reproductive individuals might be some of the underlying causes of eradication failure. However, Samaniego et al. (2020a) suggested these factors, although needing attention, might not be as significant as previously thought. Nonetheless, we emphasize that these factors inherent to tropical islands result in less room for errors such as gaps in bait coverage – partly due to the diversity and abundance of bait competitors and alternative food, and higher relative rodent population densities. While we agree that environmental factors need to be locally monitored and carefully managed, we note that the quality of the eradication operations and the significance of human error had not been formally assessed as contributing factors to eradication failure. We aimed to address this gap by studying rodent eradications where initial attempts failed but were eventually successful. This approach allowed us to focus on the changes between attempts given that other important parameters such as island size, topography, target population, local environment, and human influence remained constant.

We found evidence of operational faults for all initial attempts (e.g. poor planning, low quality bait, inadequate spacing or coverage of the baiting grid, inexperienced pilots with no GPS in the helicopter, insufficient baiting around human structures, insufficient treatment of infestation hotspots such as long term accumulation of green waste, or poor adherence to prepared operational plans), although in a wide spectrum of significance. In particular, the cases up to the 1990s, before eradication principles and best practice guidelines were available, clearly had operational issues, which once corrected in a later operation often resulted in eradication success. This process has and still is informing the refining of best practice. A remarkable exception is the case of Montebello, which operated with high standards despite occurring in the 1990s. Conversely, more recent cases tend to consider best practice, albeit to different degrees. For some initial operations (e.g. Teuaua, Desecheo, Wake) the quality of the planning was high, and the potential faults during the implementation phase did not become apparent until the review process. There are also complex cases where operational and environmental factors are confounded, i.e. the eradication strategy improved but the island conditions were also more favorable during the subsequent successful attempt. For some of these cases it was a matter of 'correcting' the timing of the operation for a seasonal environment (e.g. Isabel), whereas for other cases the unusually wet conditions present during the first attempt (e.g. Desecheo) were difficult to predict. Therefore, eradication planning requires consideration of both typical seasonality and potential interannual deviations, ideally informed by on-island monitoring (Will et al. 2019b). Finally, in a few cases it is likely the eradication went well but rodents reinvaded (e.g. Congo Cay), which is still considered project failure.

In summary, failed attempts may not have met the eradication principles of exposing all rodents to sufficient toxic bait and being closed systems (i.e. with zero immigration). This can cause operational failure on any type of temperate or tropical island, although the latter appear to be less tolerant to bait gaps. The documentation of a high proportion of bait quickly removed by land crabs on Desecheo is a good example (Shiels et al. 2019). We found that the main contributing factors leading to successful rodent eradications are:

- thorough planning
- anticipating problems and overengineering (e.g. removing artificial food sources)
- deep island knowledge
- expert advice
- sufficient funding
- clearly defined management structure
- high standard baiting operations involving motivated, trained and experienced staff
- highly motivated and collaborative local stakeholders (e.g. resident communities and hotels)
- project managers with exceptional problem-solving and decision-making skills
- quality bait, ideally containing brodifacoum (for example from Bell Labs or from Orillion)
- suitable equipment (e.g. helicopters with GPS and specialized spreader bucket or bait stations adapted to function under local conditions)
- well organized, resourced, and reliable operational logistics, especially when operating on remote islands
- skilled baiting pilots to apply the bait for aerial operations
- realistic and flexible permits and deadlines
- strict biosecurity procedures
- pre- and post-eradication project reviews

In addition, issues that we repeatedly found being underestimated include: land crab interference with bait and devices (Wegmann 2008), under-baited cliffs and intertidal areas as potential rodent habitat and food sources (Siers et al. 2018), presence of mangroves (Harper et al. 2014, Samaniego et al. 2018), accuracy of baiting grid (Samaniego et al. 2020b), baiting of human structures and removal or adequate treatment of infestation hotspots including green waste piles and other food sources (Rocamora 2019, Harper et al. In press), abundance of coconut trees, intensive postbaiting surveys (trapping, gnawing sticks etc.) for early detection and treatment of survivors (Rocamora & Henriette 2015, Russell et al. 2017), training and mindset of staff (Samaniego et al. In press), confusion caused by complex management structures (Brown et al. 2013, Stringer et al. 2019), multi-species or multi-island eradications (Springer 2016, Dérand et al. 2017), reporting (Keitt et al. 2015) and biosecurity (Kennedy & Broome 2019).

As each island is different, experience with the methods, the specific island and the country regulations are essential. Signs of poor planning include risks and solutions not identified, trials not performed, plans not developed/reviewed, external consultation not sought, training and quality control not put in place, communication not flowing and agendas from stakeholders competing or being inconsistent. Moreover, as Parkes et al. (2011) explain, direct extrapolation of application methods developed for eradication using brodifacoum to baits containing diphacinone does not take adequate account of the differences in the toxicity profiles of the two anticoagulants. Regarding eradication techniques, aerial broadcast applications have a high success rate but they are not exempt of logistical, regulatory, and environmental challenges. Will et al. (2019a) 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.

It is also extremely important that eradication projects are adequately budgeted, with an appropriate contingency to respond to unexpected, and unpredictable challenges. A good operational plan is key, but a quality implementation by a trained team is equally important. Rushed deadlines are unfortunately a common reality. Funding, permitting and politics sometimes dictate crucial operational components such as timing, sometimes conflicting with best practice. In-depth discussions can be found in Broome et al. (2017b), Keitt et al. (2015) and Pacific Invasives Initiative (PII; 2011). When establishing protocols for nontarget and environmental protection, the perceived benefits of bait application restrictions, such as setbacks from coastlines, should be balanced with the potential for additional environmental contamination if the operation fails and bait applications must be repeated; practitioners may elect not to implement eradication activities if environmental compliance parameters are too restrictive. Likewise, practitioners should have the ability to postpone eradication implementation if unexpected environmental conditions are encountered.

As for our questions:

1) *Can faults in operational factors explain the failures?* Mostly, yes. Particularly for older cases, the faults are evident and the solutions clear, as later successful attempts were executed under similar environmental conditions. Even for the cases where confounded factors occurred, operational improvements were suggested after the initial attempt, largely as a result of independent reviews. Likewise, all operations on the three islands where eradication was not ultimately achieved appear to have had major operational issues.

2) *Can improvements in operational factors explain the successes?* Mostly, yes. Although in some cases (e.g. Desecheo and Isabel) the more favorable environmental conditions during the second attempt most likely contributed to success, there are 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 more islands after initial eradication failures?* Yes. The evidence suggests that with proper planning and 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 never highly favorable (e.g. Wake Island) or where such periods may be difficult to predict (e.g. Kayangel).

Environmental factors inherent to tropical islands indeed pose extra risk that must be managed; nevertheless, to encourage thorough planning and implementation of eradication projects it is extremely important to recognize that project managers are largely in control of the result. Given that our findings indicate that failures were related to human error to a great degree, we believe that tropical island eradications have similar chances of success as those for temperate islands, providing that best practice is strictly followed.

Overall, our results are encouraging. In most cases rodent eradication was eventually achieved, conservation managers have greatly learned from failure, and techniques and theory are constantly improving. All of the factors examined here are discussed across several best practice and guidelines documents available (Broome et al. 2011c, Broome et al. 2011b, PII 2011, Keitt et al. 2015, Broome et al. 2017a, Broome et al. 2017b, Thomas et al. 2017, Phillips 2019), which contain management recommendations and research suggestions to address the pending questions. At present, conservation managers have extraordinary advantages over their predecessors and robust starting points for planning island rodent eradications in complex systems with a high degree of confidence.

6 General conclusions

The role of operational factors contributing to eradication failure is frequently underestimated prior to operations and not always evaluated post operations, despite best practice calling for high standards. Operations that meet best practice have higher probabilities of success regardless of the type of island, although it appears that tropical islands have less room for errors such as gaps in bait coverage.

In most failed attempts, faults in a variety of management and operational factors were identified, but rodent eradications are complex operations. In some cases, operational faults were unarguably the cause of eradication failure. In other cases, the significance of such faults was impossible to tease out in the presence of other confounding and possibly synergetic factors such as considerable environmental changes. Reinvasion cannot be discarded as cause of failure in a few cases. We are not denying the importance of managing environmental factors (e.g. alternative natural foods) but illustrating the potential implications of errors in operational factors. In any case, conservation managers have more control over operational than environmental factors overall, so striving for excellence at each attempt contributes to a higher chance of eradication success.

- Conservation managers have greatly learned from failure in favor to endangered species. To continue this trend, we encourage practitioners to:
- Keep planning and conducting island rodent eradications, always to high standard and in adherence to best practice. As every island is different, a principle-based approach can be useful.
- Ensure detail reporting, pre and post operation, is prepared and independently reviewed for all projects, successful or not.
- Refine best practice recommendations based on evidence.
- Conduct reviews and research to fill out information gaps, for example impacts of bait drift into the marine environment and helicopter disturbance on seabird colonies. These issues have been overregulated in the past, forcing practitioners to compromise best practice, sometimes resulting in eradication failure.
- Keep monitoring outcomes to increase the evidence of the social, economic and ecological benefits resulting from island rodent eradications.

7 Follow-up research

There were only three islands (Adele, Kayangel and Congo Cay) where subsequent attempts did not achieve eradication, and one of them (Congo Cay) is at high risk of reinvasion. The risk of reinvasion is nowadays an important factor while assessing feasibility of a project; reinvasion, rather than operation failure, may be the reason why some of these islands are rodent infested at present. Hence, future research evaluating the importance of certain operational factors as causes of eradication failure should be conducted on islands with low risk of reinvasion.

Aiming to identify more candidate islands with low risk of reinvasion to undertake future research, we used the list obtained from the DIISE (see methods) to identify the cases where a single eradication attempt has been conducted, and failed, and a subsequent attempt has not yet occurred. For these islands, the proximity to either inhabited islands or islands with rodents was determined using Google Earth. We used a nominal cut-off distance of <500m between islands as an indication that reinvasion could occur by rodents swimming the gap. We assumed that inhabited islands had invasive rodents. In addition, any islands that had high likelihood of regular visitation by either tourists, fishers or farmers shown by the presence of buildings, livestock or wharfs were also recorded.

We identified 45 rodent eradications on islands from 20 countries that had not been repeated after initial failure. Of these, 35 (77.8%) are probably under constant reinvasion pressure: 27 (60%) are within 500 m of another rodent population source (e.g. an inhabited or rodent infested island) and eight more (17.8%) appear to have high visitation rates. This suggests that some projects may have failed due to biosecurity breaches or failure to recognize the ability of rodents to swim and reinvade, or a combination of both, rather than operational failure. Some projects were conducted before the swimming capabilities of invasive rodents were understood; however, for other projects it appears that a lack of, or poor, feasibility planning was the lead cause for the oversight of such significant risks. Future eradication projects on these islands would require extending the eradication unit (e.g. archipelago wide) or implementing strict biosecurity protocols.

The remaining ten islands (22.2%) appear to be at low risk of rodent reinvasion and are scattered across a variety of climatic zones with varied landforms, vegetative cover, non-target species and tenure (Table 21). Several of a small to moderate size could be re-attempted after careful re-analysis of the possible causal factors leading to failure. Well planned and executed re-attempted eradications on these islands could confirm the conclusions laid out in this report, that eradications can be successfully conducted despite apparent problems causing initial failure.

From the 45 islands considered, the high percentage with high risk of reinvasion was surprising. We dissected the data further to explore the timeline of these eradications: one (2.1%) was first attempted between 1980-1989, seven (15.6%) were first attempted between 1990 and 1999, 21 (46.7%) between 2000 and 2009, and 16 (35.5%) between 2010 and 2018. There appears to have been a rush to implement rodent eradications in the early 2000s, probably without rigorous planning and/or poor assessment of failure or reinvasion risks, which may have led to an apparent decline in failures in the following decade. Further research is warranted.

Table 21. Islands with low risk of reinvasion where initial rodent eradication attempts failed, and no further attempts have been conducted up to 2020.

Island	Area (ha)	Country	Climate zone
Morts	5	France	Temperate
Teberon	7	France	Temperate
Beautemps Beaupre	45	New Caledonia	Tropical
Island	**Area (ha)**	**Country**	**Climate zone**
Fanna	50	Palau	Tropical
Kamaka	50	French Polynesia	Tropical
Nu'utele	108	Samoa	Tropical
Stephenson	112	New Zealand	Temperate
Eagle	250	Chagos (UK)	Tropical
Pitcairn	400	Pitcairn	Tropical
Henderson	4,000	Pitcairn	Tropical

8 Acknowledgements

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.

We thank Andrew Burbidge, Rohan Clarke, Tommy Hall, Peter Tolson, Tehani Withers, Gary Witmer and Jason Zito for providing unpublished material and comments on operational details. We also thank Kate Lawrence for helping with formatting and proofreading.

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