



Special Issue Article: Tropical rat eradication

Best practice guidelines for rat eradication on tropical islands

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ABSTRACT

Invasive vertebrates are a leading cause of extinction on islands and rats (*Rattus* spp.) are one of the most damaging to island ecosystems. Methods to eradicate rats from islands are well established and there have been over 580 successful eradications to date. Increasingly, rat eradications are being implemented on tropical islands, a reflection of the need to protect the threatened biodiversity in the tropics. Yet rat eradications on tropical islands fail more frequently than those in temperate climates. In an effort to identify the main reasons for the lower success rate on tropical islands and possible solutions, a workshop was convened with 34 experts in rat eradication, tropical rodent and island ecology and toxicology. The workshop focused on projects using aerial broadcast of brodifacoum, a 2nd generation anticoagulant, because this approach has provided the highest success rate for eradicating rodents from islands. The workshop participants reviewed previously identified challenges to successful rat eradications on tropical islands including increased insect and crab densities resulting in competition for bait, year round or unpredictable timing of breeding rats and increased or unpredictable availability of alternative, natural foods. They also identified a number of new, likely reasons for the lower success rate on tropical islands and provided recommendations for how to address these risks in the planning and implementation of rat eradications. While the success rate of aerial broadcast rat eradications in tropical environments is quite high at 89% ($n = 47$), it is hoped that by following the recommended best practices provided in this paper, future success rates will be closer to the 96.5% ($n = 116$) demonstrated for aerial broadcast rat eradications on temperate islands.

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1. Background

In an effort to address the negative impacts of introduced rats on islands, eradication techniques were developed (Howald et al., 2007; Broome et al., 2014). As practitioners learned from both successes and failures, new tools and methods were developed and refined. Techniques for the aerial broadcast of rodenticides were developed in the 1980s (Townsend and Broome, 2003) and this approach now provides the highest success rate for eradicating

rodents from islands as well as enabling eradications to be carried out on larger and more topographically complex islands (Parkes et al., 2011). Much of the work developing the aerial broadcast approach was conducted on islands around New Zealand. Based on this experience, the New Zealand Department of Conservation has developed Current Agreed Best Practices (CABP) for implementing aerial broadcast rat eradications in New Zealand (Broome et al., 2014). The CABP are specific to the temperate climate islands of New Zealand. While it is critical that rat eradications are planned using direct knowledge of the target island and following local regulations, these CABP provide valuable information for planning and implementing rat eradications outside of New Zealand, especially in other temperate areas.

Increasingly, rat eradications are being attempted on tropical islands, in part in response to the unique biodiversity and high

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numbers of threatened species at risk of extinction due to introduced rats (Dirzo and Raven, 2003; Keitt et al., 2011). Many eradications on tropical islands have been successful despite the presence of conditions that may increase risk of eradication failure, such as increased bait competition (Griffiths et al., 2011), lack of seasonal variability and year round rat breeding (Wegmann et al., 2011), and increased natural resource availability (Merton et al., 2002). Indeed, a recent analysis of historical rat eradications indicates success rate is slightly lower on tropical islands (Holmes et al., 2015). Based on analysis of the Database of Island Invasive Species Eradications (DIISE) using island latitude, aerial broadcast operations targeting rats on temperate islands have a success rate of 96.5% ($n = 116$) and on tropical islands it is 89% ($n = 47$) (DIISE, 2014).

In an effort to better understand the reasons underlying the lower success rates for tropical rat eradications and identify possible solutions a global review was initiated. The review had three main components: (a) an historical review of rodent eradications using the DIISE to look for trends (Holmes et al., 2015), (b) in depth reviews of four recent unsuccessful rat eradications on tropical islands that used aerial broadcast of brodifacoum and (c) a workshop that convened 34 global experts in eradications, tropical rodent and island ecology and toxicology (Appendix B). The Recommended Best Practices (RBP) presented here were developed by the steering group for the workshop, with assistance and review by the workshop participants and highlights key issues associated with eradications on tropical islands and are not designed to provide guidance on all aspects of planning and implementing an eradication. Additional resources such as the DOC Current Agreed Best Practice for temperate islands and the Pacific Invasives Initiative Resource Kit (<http://rce.pacificinvasivesinitiative.org>) can assist with project planning and should be combined with expert input, external review and extensive knowledge of the local environment.

The review that was undertaken as part of the workshop, and thus the RBP presented here, are restricted to rat species (*Rattus* spp.) and aerial broadcast of brodifacoum, the most commonly used 2nd generation anticoagulant rodenticide in broadcast eradications (Howald et al., 2007). House mouse (*Mus musculus*) eradications were excluded because there was insufficient data on eradications in the tropics for meaningful analysis. It is relevant, however, that house mouse eradications have been reported to fail at a much higher rate than rat eradications (62% and 69% success rate reported in MacKay et al. (2007) and DIISE (2014), respectively). Presumably the same challenges to rat eradication in the tropics also apply to mouse eradications. But recent analyses showing that mouse eradications in all latitudes using aerial broadcast of 2nd generation anticoagulant baits have a very high probability of success suggest tropical mouse eradications may not be as challenging as previously thought (15 of 16 mouse eradication attempts since 2005 have been successful, DIISE, 2014).

The RBP presented here are not designed to assist in determining the best method for eradicating rats on a specific island. Hand broadcast, bait stations, toxicants other than 2nd generation anticoagulants, and traps have been successful at eradicating rats on islands and should be considered when assessing project feasibility. Prior to settling on a proposed method, issues such as efficacy, risk to non-target species, island size and accessibility are among the criteria that must be assessed and these topics should be included in a feasibility study. However, many of the RBP presented herein will also be relevant to other tools used for the eradication of rats on tropical islands.

Similarly, there is a need for new tools and approaches to rat eradications on islands to reduce non-target risks and increase social and regulatory acceptance (Campbell et al., 2015); develop-

ment and testing of new tools and approaches should be prioritized. However, we are facing an extinction crisis (Barnosky et al., 2011) and many threatened species cannot wait for the uncertain promise of future tools. Carefully planned and executed eradications using the existing tools of aerial broadcast of 2nd generation anticoagulants should thus be considered a key part of efforts to protect threatened species and restore island ecosystems (Townes et al., 2013).

The RBP for aerial broadcast rat eradications on tropical islands will evolve as more information becomes available. This paper reflects the current recommendations at this point in time following the workshop and the RBP will be maintained and made available through the Pacific Invasives Initiative website (<http://www.pacificinvasivesinitiative.org>).

2. Methods

A challenge faced when evaluating unsuccessful eradication projects is that there is rarely one clear reason for the failure. Rather, there is a suite of possibilities that each have varying probabilities. The approach taken in the tropical rat eradication review workshop was to first learn as much as possible from previous rat eradications. This was accomplished through a review of the Database of Island Invasive Species Eradications (DIISE), an online database of all reported successful and unsuccessful invasive vertebrate eradications on islands. The results of this review are discussed in depth in Holmes et al. (2015). This analysis confirmed the underlying assumption of the tropical rodent eradication review by demonstrating a negative correlation between a measure of tropical climate (temperature) and project success. While there have been many successful eradications of rats on tropical islands, the rate of success regardless of method is lower on tropical islands (81%, $n = 285$) than for temperate islands (91%, $n = 365$).

The other key piece of historical information supporting the review was the detailed analysis of four recently implemented but unsuccessful rat eradications using aerial broadcast of brodifacoum: Desecheo Island, Caribbean; Henderson Island, Pitcairn group; Wake Atoll, western tropical Pacific; Enderbury, Phoenix archipelago. The approach to these project reviews helped guide the structure of the workshop, which separated the key potential reasons for project failure into two main categories: 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. Other possible reasons for eradication failure such as reinvasion and resistance were not considered in this review because they were not considered unique to tropical islands. The structure of the project reviews conducted by Brown et al. (2013), Brown and Tershy (2013) provided the basis for the recommended review process.

2.1. Workshop structure

Thirty-four experts were convened at the University of Auckland for a workshop on 19–21 August, 2013 (Appendix B provides a list of participants). Presentations were made on the review of historical eradications (Holmes et al., 2015), the suite of recently failed projects and an evaluation of unsuccessful projects that were later implemented successfully (Samaniego-Herrera unpubl. data). These presentations were used to seed a brainstorming session where possible reasons for lower success rate on tropical islands were shared and broken into the two key categories of bait availability and bait palatability.

The leading hypotheses from the brainstorming session were then evaluated by breakout groups of 4 to 8 individuals. These groups reviewed the evidence for and against each hypothesis as

a factor in tropical rat eradication project success and identified the factors that most likely contributed to project failure.

3. Results

A primary requirement in evaluating eradication success in the tropics is defining and characterizing the tropics. The geographical definition of tropical is for locations between the tropics of Cancer (23° 26' north of the Equator) and Capricorn (23° 26' south of the Equator). However, one of the central tenets of rat eradication in a temperate environment is to apply bait when rat populations are most likely to ingest bait, which usually corresponds with declining rat population, when island productivity is at its lowest and when there is a very low probability of rat breeding. In temperate regions the timing of such a period is usually similar from year to year and occurs in late fall, winter, or early spring (Broome et al., 2014). Yet, the tropics are characterized by reduced seasonal variation in temperature (Kricher, 2011) and productivity is more closely tied to rainfall (Osborne, 2000). The relative unpredictability of rainfall events, both within and among years, means that it is harder to reliably predict on tropical islands when there will be a low point in productivity and an associated decline in rat population, if it occurs at all. It is important to acknowledge that islands fall on a continuum from extreme wet to extreme dry and it is not possible to put all islands in distinct categories (Weigelt et al., 2013; Russell and Holmes, 2015). This highlights the importance of extensive knowledge specific to the island in question. For the purposes of these RBP a 'tropical' island is considered to include all islands between the tropics of Cancer and Capricorn and those islands where the timing of highs and lows in terrestrial ecosystem productivity cannot be predicted with a high degree of certainty. For example, for these RBPs we include islands in the Pitcairn group as tropical even though they lie south of the tropic of Capricorn because of their relatively aseasonal and unpredictable climate.

Another key factor identified by workshop participants was the difference between dry tropical islands and wet tropical islands. Wet tropical islands are characterized by high rainfall and relatively high productivity in all months. Many islands within the Intertropical Convergence Zone fall into this category and they present unique challenges to planning rat eradications including abundant rat breeding year round and a high probability of non-target bait competitors. Dry tropical islands are characterized by low rainfall and low productivity, punctuated with rainfall events and flushes of primary productivity. Following Weigelt et al. (2013), Russell and Holmes (2015) further divide dry islands into savanna islands with periods of extreme dry and unpredictable rainfall and tropical forest islands with greater seasonality to the dry and wet periods. These dry islands present their own challenges to rat eradication planning, primarily identifying the best time of the year to implement and the variability of that timing from year to year.

4. Recommended best practice

The following RBPs are organized following the same layout used by Broome et al. (2014) for the DOC Current Agreed Best Practice and the PII Resource Kit (<http://www.pacificinvasivesinitiative.org/>) to facilitate cross referencing those tools while planning for a successful project.

It is important to reiterate that these are guidelines. Many eradications on tropical islands have been successful without following these recommended guidelines. In some instances, likely often due to funding limitations, it will be appropriate to proceed with an eradication project without implementing many of these

recommendations. In these cases it would be appropriate to advise project stakeholders of the increased risk associated with not following these recommendations.

4.1. Feasibility

1. Clearly **acknowledge and identify risks** to project success and share with project partners and key interested parties, including funders. The fact that rat eradications in tropical environments have a lower rate of success than rat eradications in other climate zones must be acknowledged. Increased risks associated with eradicating rats on inhabited islands must be acknowledged. As other risk factors are identified, such as the potential for rat breeding activity or availability of alternate, natural food resources at the time of implementation, they need to be shared with project partners. Possible mitigation must be identified in the feasibility study. It is critical that all partners are aware of and acknowledge the known risk factors present before proceeding with the eradication.

Acknowledging these risks up front in the feasibility study stage will help partners appreciate the challenges associated with tropical rodent eradications and can help identify the appropriate financial resources and time investment needed to develop a well-planned and well-executed project to maximize probability of success.

4.2. Project design

2. Develop an **inventory of non-target** species, including bait-competitors, and a simple **food web model** for the island. The food web should include rodenticide exposure pathways to aid in identifying risk to non-target species (e.g. Innes and Barker, 1999). If possible, different potential scenarios for the time of implementation should be considered such as whether the island is wet or dry and if seabirds are breeding. Some tropical seabird species, such as sooty terns (*Onychoprion fuscatus*), do not always follow an annual breeding cycle and thus it is difficult to predict whether this resource will be present or not at the time planned for implementation.
3. Conduct an environmental assessment in compliance with the local regulatory requirements, or if absent, in line with DOC Current Agreed Best Practice, which recommends an **Assessment of Environmental Effects** of the operation and rodenticide. The assessment should be **peer reviewed** by experienced eradication practitioners and by several people experienced in tropical island ecosystems and tropical ecology.
4. **Applying additional bait to the forest canopy** should be considered for projects where portions of an island will be treated via hand broadcast or bait stations, the operation targets *are Rattus exulans*, *Rattus rattus* or *Rattus tanezumi*, and the island's forest canopy is capable of supporting rats. Strecker (1962) showed that *R. rattus* spend significant periods of time in the crowns of coconut palms (*Cocos nucifera*) on a tropical island. Radio-telemetry tracking of *R. rattus* on Palmyra Atoll documented significant use of the forest canopy, with a preference for coconut palms (Wegmann et al., 2012). An added benefit of this approach is that bait in the canopy will remain available to rats but not to ground-based non-target species such as land crabs.
5. Special consideration should be given to certain tropical habitat types. **Mangroves**, which can harbor rats (Wegmann et al., 2008b; Harper et al., 2015), present problems for aerial broadcast rat eradications because the land underneath them is regularly inundated with water that will wash away baits. This means alternative approaches, such as "bait bolas" that will remain in the canopy (Wegmann et al., 2008a,b) and bait

stations nailed to mangrove trunks should be considered. Other habitats, such as *Pemphis* intertidal zones, that may support rats, also require careful planning.

4.3. Planning

6. **Obtain sufficient inter and intra-seasonal information** on local climate and its impact upon rodent phenology and other key factors, such as non-target bait competitors, and use it to inform the optimal timing of the eradication operation. Rat populations should be targeted for eradication at a time when natural food resources are declining in availability or are at their lowest levels, a period that likely coincides with the driest period on the island (Ringler et al., 2014). On tropical islands the timing of this period of low productivity may vary from year to year and in some years not occur at all (Russell et al., 2011). What constitutes sufficient historical data to identify the optimal time for an eradication will vary from island to island. **Local knowledge** of the island can be very helpful. Historical remote sensing data to characterize changes in vegetation cover, correlated with rainfall data if available, may be useful in determining the best time for project implementation. Several years of data will likely be required to help make an informed decision. Data from a similar and preferably nearby island is better than no data. In some instances it may be cost prohibitive or otherwise not possible to collect climate data. Many projects have been successful without analyzing climate, however, the increased risk of proceeding without this information should be acknowledged in planning documents and with key stakeholders, including funders.

7. **Climate data** should be collected in the months preceding the planned implementation and **compared with conditions preceding and present during previous trials** and site visits that informed the operational plan. Establishing a weather station on island to monitor rainfall and temperature, the key drivers in many tropical island ecosystems, is recommended. If conditions are significantly different during the proposed implementation window, modifications to the operational plan should be considered. These could include a change in bait application rates or a delay in implementation for a few months or postponement of the operation to another year when conditions are more favorable. A scenario to avoid is conducting trials during a period of drought, or low productivity, and implementing during a wetter period with higher productivity.

A decision to proceed as planned is also a possibility; however, any potential increased risk associated with that decision should be shared with key stakeholders, including funders.

8. In tropical systems, a **bait availability trial**, such as described in Pott et al. (2015), should be completed on the island where rats are to be targeted **to inform bait application rates** to be used during project implementation.

Application rates should be set to provide a minimum of **4 nights of bait availability** across all habitats on the island. Thus, even in locations where bait disappearance is high, this means that bait should still be readily detectable on the fifth day after application, i.e. 4 full nights after application. In some locations bait will be available for longer than this.

There are several lines of evidence that suggest at least 4 nights of bait availability is required to achieve a high level of eradication success. A laboratory trial exposing *R. rattus* to brodifacoum bait did not result in 100% mortality after 3 days of exposure (Pitt et al., 2010). In addition, Barnett (1958)

demonstrated that Norway rats (*Rattus norvegicus*) showed marked exploratory and sampling behaviors when exposed to new foods and intake did not stabilize for one or two days. This suggests that a 1–3 day exposure period is inadequate to ensure 100 percent mortality of rats when using brodifacoum. Furthermore, it is recognized that bait availability must account for individual vulnerability due to age, behavior, body size, food supply, and range size (Cromarty et al., 2002). Given these conditions and behaviors, at least four nights of bait availability is necessary to maximize the chance that all individual rats in the population will consume a lethal dose of bait.

The key aspects of a comprehensive bait availability trial include:

- Study plots occur in all representative habitats across the island or at a minimum occur in areas where the highest bait consumption by rats and non-targets is expected.
- Bait availability studies should be designed to identify extreme minimum values of bait availability, i.e., the study site should include areas where low bait availability is expected.
- Bait availability trials should take into account non-target species that consume bait and reduce availability to rats, especially land crabs. Efforts to reduce non-target bait consumption should be employed if possible. Efforts to reduce non-target bait consumption must be weighed against their impact on bait availability to and consumption by rats.
- Application rates can best be calculated using the lower 99% confidence interval of the bait disappearance rate. Lowest measured bait availability over 4 nights in the trial plots can also be used, but as your sample sites are unlikely to include the sites where bait loss would be highest, this may underestimate bait application rates needed for those sites. Keep in mind that the study year may not be a great predictor of subsequent years.
- Weather data (rainfall leading up to trials, green index) and an assessment of natural food availability (fruits, insects, etc.) should be conducted concurrent with trials to provide for comparison with conditions during planned implementation of eradication.

Even if bait availability varies markedly between habitats or plots during trials, using different bait application rates across an island is not recommended beyond the existing recommendations in the DOC Current Agreed Best Practice of increased rates along coastal areas and areas of steep cliffs, as it complicates the application process and increases the risk of gaps. The same application rate should be used across the entire island unless areas of higher or lower bait consumption can be defined with a high level of accuracy and they are large enough from a logistical perspective to allow for stratification.

9. 20% more bait than is required to treat the island using the planned application rate should be ordered to account for potential loss or spoiling of bait during transport and storage. For islands under 50 ha or those with extremely indented coastlines, 20% is likely the minimum necessary to deal with contingencies. For very large islands 20% additional bait may be impractical.

For eradication projects on tropical islands there is a **greater risk of bait deterioration** prior to implementation due to condensation, humidity and often increased invertebrate activity. Additional bait would provide greater scope to adjust bait application rates in subsequent applications if bait availability decreases more rapidly than anticipated after the first bait application. Ability to adjust application rate would need to be provided in the regulatory consents for the project.

Plans for the safe disposal of any unused bait should be included as part of the project planning process.

10. Select a **bait product appropriate for the island conditions**. Increased moisture in tropical environments can cause some bait products to degrade quickly (Berentsen et al., 2013). The use of bait products designed to withstand wet conditions should be evaluated. Avoid baits with Bitrex®.

4.4. Implementation

11. Prior to bait application, a **rapid assessment of the island** should be made to assess rat body condition and reproductive status, and natural resource availability. If possible this could be conducted prior to bait shipment to the island and again immediately prior to the actual baiting. If conditions are measurably different than during pre-eradication trials and rats are in good condition and a high percentage of the population is breeding then delaying the implementation of the eradication should be considered. An eradication operation will have a greater chance of success if it targets rats when they are hungry, i.e. there is a shortage of natural food.

A rapid assessment is of greater importance on dry tropical islands where conditions are more variable. On wet tropical islands there may be high natural food abundance all year and little variation in rat breeding throughout the year and between years, thus the likelihood that conditions will vary greatly between trials and implementation is lower. However, even on wet tropical islands land crab populations may show patterns of activity that follow fluctuations in rainfall and cloud-cover, which could affect bait availability to rats (Samaniego-Herrera et al., In preparation). Thus, understanding crab activity patterns can help inform appropriate bait application rates and timing for implementation.

12. A **thorough assessment of risks** to project success should be conducted as close to implementation as is feasible and a decision to proceed or not should be made with key partners. Issues such as condition of the island, compliance with key aspects of the operational plan such as food and waste management in commensal environments should be reviewed and the risks thoroughly debated and assessed.

It is recognized that a decision to delay a project at this stage will be difficult as it would likely result in an increase in overall project cost. Carefully weighing this cost versus the potential impact of a failed eradication on other eradication efforts, on non-targets and on future project financial support is required.

13. Additional care to **preserve the quality of the bait prior to its use** should be observed. Bait should be kept dry at all times and isolated from extreme changes in temperature. Temperature loggers and moisture detectors can be used to monitor conditions during shipment. Transport times, storage periods, and large temperature swings should be minimized. Bait should be inspected for degradation and damage upon arrival at the project site and where possible while in transit so that any problems can be identified early.

Bait should be more palatable than natural foods. Transport of bait in the higher temperatures and humidity associated with tropical environments could cause bait to deteriorate quickly and reduce palatability.

14. Complete **at least two bait applications** with the second (or latter) application(s) designed to be as robust as the first, i.e., the same application rate and swath overlap should be used for all bait applications. A 50% swath overlap minimizes risk of bait gaps and is recommended.

In tropical environments, non-target bait competitors such as land crabs and other invertebrates, which are not thought to be negatively impacted by the rodenticide (Pain et al., 2000), can be responsible for significant bait uptake. On Palmyra Atoll monitoring showed an overall slight decrease in bait disappearance between the first and second applications, though individual plots varied and in some instances bait disappearance increased after the second application (Engeman et al., 2013). Thus, in tropical environments, and especially if high numbers of land crabs are present, rates of bait disappearance can remain high after the second application and an equal application rate for the second application may be justified to enable a minimum of four nights bait availability.

Maintaining the same swath overlap in the first and second application is recommended to minimize risk of gaps in bait coverage in the second application.

Two bait applications should be sufficient in most scenarios. Additional applications may be warranted, particularly where a weather event shortens the period of bait availability after either application, or where 2 species of rodent are targeted and the dominant species can limit access to bait. The recommended number of applications should be clearly justified in the planning process.

15. **Increasing the time between bait applications** may increase the chance that weanling rats are exposed to bait upon leaving the nest. DOC Current Agreed Best Practice suggests 10 days between the first and second application can reduce risks associated with breeding rats; however it is possible that in some situations this would be insufficient to expose all rats to bait on **tropical islands, where rat breeding should be assumed**.

Data from several rat eradication projects on tropical islands suggests that breeding rats and more specifically young rats emerging from nests after bait is no longer widely available may result in project failure. While a number of projects in the tropics have been successful with 10 days or less between applications, it is possible that a longer interval between applications could increase success rate of eradications on islands with breeding rats. Based on time to death of adult rats after brodifacoum exposure and rat breeding phenology it is possible that young rats could emerge from a nest 20 days or more after a first bait application.² In this scenario, a period of about 3 weeks between applications would be required to expose all rats to the bait. However, extending the period between applications significantly longer could result in an increase in natural food availability for rats on the ground due to the reduction in rat numbers from the first application, thereby potentially decreasing bait take by rats.

It should be noted that this recommendation generated much debate from both a cost and efficacy perspective. In addition to the concern of increased alternative food,

² To our knowledge the maximum time to death after brodifacoum exposure is 21 days, *R. rattus* (from an appendix by W. Pitt in Howald et al. (2004). Maximum weaning time for *R. rattus* is 25 days (Innes, 2005), though young rats are likely to begin emerging from the nest between 2 and 3 weeks of age (Strecker, 1962).

increasing the period between applications could be prohibitively expensive, especially when a support ship and helicopter(s) are on standby. The best period between bait applications on tropical islands is worthy of additional research.

16. **Bait availability monitoring** as described by Pott et al. (2015) should be conducted after each application. If bait availability is low, application rates for subsequent applications could be adjusted based on monitoring results if sufficient bait is available and the project permits allow. Information from bait availability monitoring will be useful for planning other projects on similar islands.

4.5. Monitoring and evaluation

17. **Confirmation of a successful project can occur after one year** on islands in tropical environments. Confirmation should involve the use of at least two independent detection tools such as traps, tracking tunnels, chew blocks, etc. (Russell et al., 2008). DOC Current Agreed Best Practice recommends waiting two breeding cycles as a good tradeoff between effort and efficacy; the longer you wait the easier it will be to detect animals. In temperate environments two breeding cycles often equates to two years. In tropical environments where rat reproduction can be aseasonal, rat generation time is approximately 0.3 years (Strecker, 1962), which allows for more than three generations within a one year period. On very dry tropical islands or in very dry conditions it may be prudent to wait two years to confirm eradications success.

In some cases it can be beneficial to know if a project was successful as soon as possible; for example when making a decision about releasing endangered species onto an island post rat eradication. Recent work provides a theoretical model that can be used to quantify probability of success of a project on small, accessible islands using traditional detection tools soon after implementation (Samaniego-Herrera et al., 2013).

It should be noted that land crabs can impact the efficacy of tracking tunnels and traps, and to a lesser extent chew blocks (Wegmann, 2008). Elevating detection devices can reduce interference (Griffiths et al., 2011) and placing them on overturned 4L plastic pails can reduce interference by most species of land crabs, although not for coconut crabs, *Birgus latro* (Alifano et al., 2010).

18. On islands where the project faces known issues that pose a high risk to the success of eradication, e.g. commensal environments, agriculture and livestock, **monitoring these areas for surviving rats in the months after the operation in combination with a planned response to any detection** should be considered. A very effective method for detecting presence of rodents at low densities across large areas is the use of rodent detection dogs (Gsell et al., 2010). Bait stations, chew blocks, track pads, and traps can also be used. If post implementation monitoring is undertaken with a goal of targeting any residual animals, a plan and funding for the response to the detection of rats after the implementation of an eradication project should be developed as part of the operational plan, appropriate permits secured and risks should be evaluated.

Whether it is for determining success soon after implementation (e.g. RPB 17 above) or to follow high risk areas, deploying intensive detection tools (such as detection dogs

or high densities of tracking tunnels and chew blocks) soon after implementation can be used to help better inform future eradications. These efforts can help illuminate how and why future projects fail and this can improve recommended best practices into the future and should be allowed for in the project budget.

4.6. Reporting recommendations

The following fields should be reported against in post operational reporting for all rat eradication projects undertaken.

Island data

Island name, island area, geographic location, habitat types, topography, substrate, climate, sites of human habitation, agricultural areas, other island uses, presence and population density of non-target consumers of rodent bait, target rat species, other target species and invasive species present not targeted, rat population density^a, rat breeding status, rat DNA reference samples collected

Island data (at the time of the operation)

Climate, rat population density, rat population breeding status and body condition, observation on natural food availability, non-target species, and presence and population density of non-target bait consumers

Operational design

Bait type, concentration of rodenticide in the bait, bait additives, bait reference samples, methods of bait application, bait application rate, total quantity of bait applied, spacing of flight lines or hand spreading points and transects, swath overlap, timing of bait applications, exclusion zones, tracking and attending to bait gaps, GIS data on the bait application, helicopter type, GPS unit type, spreader bucket type, deflector bucket type, number of bait applicators if hand broadcasting bait, details of bait station design and use (numbers, spacing, bait monitoring and refill schedules)

Operational monitoring

Bait availability over time, rate of bait degradation, rainfall, rodent mortality, impacts to non-target species, captive management of non-target species. Site/timing specific variations made in operational plan made and why

Organizational

Organization name, organization type, contact details for lead person (project manager), number of staff, number of volunteers and extent of training each received, pilot name, helicopter company, project team structure, project team roles and responsibilities

^a If the available time or resources do not allow for a robust estimate of rat population density, an index of abundance should still be measured.

4.7. Project review outline for failed eradications

A detailed review of the operational planning and implementation of failed projects provides value in helping to understand potential reasons for project failure. The following recommended structure for reviewing failed projects is based on that used by Brown et al. (2013) and Brown and Tershy (2013) in the reviews of the Wake and Desecheo island projects. Following the logic structure presented here will ensure that reviews consider the main reasons for project failure and it will also help with future meta-analyses of failed projects, which can help improve our approach to projects.

At the highest level there are only two possible reasons for rat presence after an eradication attempt: either rats reinvaded or some rats survived the eradication attempt. Following DOC Current Agreed Best Practice every project should have genetic samples to help address whether reinvasion is responsible for project failure (Russell et al., 2010). Additional evidence, such as characteristics of source populations and availability and timing of potential invasion routes/pathways can help determine the likelihood of reinvasion explaining the presence of rats after an eradication.

Assuming some rats survived the eradication attempt there are two simple scenarios to consider:

1. All rats **could** not eat a lethal dose of bait.³
2. All rats **would** not eat a lethal dose of bait.

Under scenario one, all rats could not eat a lethal dose of bait, the main reasons for this are:

- a. There was a gap in bait coverage.
- b. There was insufficient bait availability and bait disappeared too quickly.
- c. The rats had higher than expected tolerance to the toxicant and thus some individuals could not consume a lethal dose.
- d. The bait itself was insufficiently toxic (brodifacoum ppm was lower than required).

Bait toxicity is easily evaluated by analyzing bait samples prior to shipping the bait from point of manufacture and on site collection, however the lab conducting the analysis should have experience analyzing bait samples to maximize the quality of the data.

Detailed review of the GIS flight lines should answer whether there were possible gaps in bait coverage. Gaps can also occur as a result of “false sowing” where the pilot records bait as being sown but the bucket is empty or no bait is flowing out of the bucket. The post operational report and interviews with the pilot and bucket loading crew to confirm there was bait left in the bucket after every run can help identify how realistic it is that there was a gap.

If insufficient bait or bait availability was a factor, the data from bait availability monitoring recommended herein may support this.

Under the second scenario, all rats would not eat a lethal dose of bait, the main reasons for this are:

- a. Bait aversion by rats.
- b. Bait station aversion (in many aerial broadcast eradications some areas are treated with bait stations).
- c. Competitive exclusion caused by another rat species or non-target bait competitor.
- d. Bait was insufficiently palatable relative to alternative food sources to ensure rats switched to eating bait during implementation.

A review of a failed eradication should systematically review all available pieces of evidence from the planning documents and operational reporting documents. This will be facilitated if the recommended reporting guidelines above are followed. Each of these pieces of evidence should then be considered in light of the main possible reasons for failure listed in 1 a–d and 2 a–d above. It is unlikely a specific and single reason for project failure will be identified. Thus, the evidence must be weighed and all options presented.

³ In some situations, rodenticide exposure to rats through secondary pathways, such as consuming invertebrates, could play a significant role in the success or failure of an eradication.

5. Discussion

For invasive species eradications on islands success is easily defined; you either remove every individual or you do not. Given this, the general approach to implementing eradications has always been to thoroughly develop a plan focused on removing the last few individual animals. The focus of the recommended best practices outlined in this paper is on how to best achieve success in a tropical environment, while maintaining a socially and environmentally acceptable project.

The historical review of eradication projects identified temperature as the key aspect of latitude having the best correlation with project success and failure (Holmes et al., 2015). Workshop participants identified early on that there were two critically important categories of “tropical” islands – wet and dry – and also acknowledged that tropical islands fall on a continuum from very wet to very dry and there is no clear line between the two types of islands. Russell and Holmes (2015) demonstrated that islands without dry periods, i.e. constantly wet islands, have the highest historical failure rate, suggesting they are the hardest to implement. Yet, workshop participants acknowledged that dry tropical islands, which lack a predictable window for optimal implementation, present the most challenging planning scenario.

In the wet tropics conditions are relatively consistent throughout the year and across years and thus any trials informing the operational plan are likely to have been conducted in conditions that are similar to the conditions at the time of implementation. Thus, wet tropical islands have similarities to temperate islands in that productivity and conditions are predictable (Ringler et al., 2014). On many dry tropical islands productivity is closely tied to unpredictable rainfall. Therefore, it can be challenging to predict the best time to implement a project. Furthermore, there is a high probability that the conditions on island when trial data are collected to inform the operational plan will be different than those encountered during the planned implementation period on dry tropical islands. If trials to set bait application rates and assess non-target take and bait take are conducted in dry conditions and implementation occurs during a wetter period the risk of failure likely increases. Alternative foods, increased insect activity, increased rat population density and breeding activity, and increased non-target activity could all impact the probability of success. Thus, monitoring of conditions on dry tropical islands during trials and leading up to a planned implementation is recommended to increase success rates.

While wet tropical islands do not present issues with climate variability as much as dry tropical islands, they do present their own suite of challenges. Wet tropical islands can support large numbers of land crabs and baiting rates may need to be significantly higher to allow for sufficient bait to be available to rats, even in the presence of efforts to reduce bait exposure to non-target species. On Palmyra Atoll extensive bait uptake trials were conducted and two applications of 84 kg/ha and 79 kg/ha were used to successfully eradicate rats in 2011 (Wegmann et al., 2012; Engeman et al., 2013). It can also be harder to identify the ideal timing for an eradication on a wet tropical island, and indeed there may not be much variation in natural resource availability or rat breeding activity within and between years (Osborne, 2000; Kricher, 2011). A robust second application with a rate equal or similar to the first, with swath overlap to minimize gaps, is recommended to help address the issue of breeding rats and higher natural food availability on wet tropical islands.

During the workshop a number of research questions were identified that would help refine recommended best practices for tropical rat eradications. These are summarized in Appendix A. The research questions were separated into three broad categories of rodent ecology, toxicants, and island ecology. Returning to the

paradigm that rat eradication projects fail either because a rat did not eat a lethal dose of bait or a rat could not eat a lethal dose of bait, the results from several recent and well documented but unsuccessful projects provide a number of interesting research opportunities. During the eradication attempt on Henderson Island bait appears to have been uniformly available across the island for over 20 days. If true, this indicates rats would not eat the bait and suggests that alternative, natural foods were more appealing. Thus, would different bait formulations afford higher efficacy? Are there specific types of rats that avoided the bait on Henderson, for example lactating females that may have had different nutritional requirements at that point in time not met by the bait matrix (Leshner et al., 1972)? Evidence complicating these conclusions comes from Palmyra Atoll where monitoring during a successful rat eradication indicated some plots had undetectable bait availability after only 2 nights. Palmyra involved a higher than normal bait application rate to account for a high abundance of land crabs. Does this suggest that a higher application rate on Henderson would have somehow increased bait acceptance rate (e.g. through higher encounter rates) and been successful? These are just examples of the kinds of questions that have been raised by evaluating past projects and could be answered through targeted research projects in the future.

The recommended best practices covered here and in the DOC Current Agreed Best Practice (Broome et al., 2014) provide guidelines that are designed to maximize the probability of a successful rat eradication. As such, these recommendations focus on meeting the two most basic rules of rat eradication using a toxicant: bait is put into every rat territory and is available long enough for every rat to consume a lethal dose (Howald et al., 2007). These recommended best practices should not be considered hard and fast rules, as reality will sometimes conflict with the ability to fully implement these recommendations. For example, extending the time between bait applications could have significant ramifications on the logistics and cost of a project. Similarly, some recommendations may increase risk to non-targets and may need to be adaptively managed. The key point is that the recommended best practices describe an approach that should have the highest probability of success. Any decision to do something different than the recommended best practice should be acknowledged and shared so that partners understand the risks.

Invasive rats are one of the greatest threats to island biodiversity (Townes et al., 2006; Jones et al., 2008). To date there have been more than 447 successful eradications of rats on 416 islands worldwide (DIISE, 2014) with profound benefits to native biodiversity (Townes et al., 2013). Yet, there is much still to be done as rats remain widespread on islands worldwide and continue to drive native species towards extinction (TIB Partners, 2012). While success rates of rat eradications using aerial broadcast in the tropics (89%) are lower than in temperate islands (96.5%) this is not a reason to avoid implementing eradications in the tropics; the impacts of rats are simply too high and the demonstrated benefits of rat eradications are too great to do nothing. The recommended best practices provided here are designed to maximize the probability of success for tropical rat eradications and provide confidence in this tool to land managers and regulatory agencies responsible for the protection of native species and their habitats.

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Author contributions: SB, KB, SC, RG, BK, JM, WP, AS helped design the structure and content of the workshop. RG and BK wrote the manuscript. SB, KB, SC, JM, WP, AS provided comments and edits on multiple drafts of the manuscript.

Appendix A. What are the knowledge gaps for tropical rodent eradications? A summary of ideas presented at the workshop

A.1. Rodent ecology: diet

How do better, more abundant and attractive food items (e.g. fruiting after a rainfall event) guide foraging decision making by rodents (i.e. optimal foraging theory) and how does this interact with increasing bait availability? What are the outliers in diet preferences under such conditions?

A.2. Rodent ecology: population dynamics

What changes in behaviour occur at low density (foraging, breeding, home range, etc.), and how does that affect efficacy of a second or third bait application?

How does breeding behavior affect bait interaction? What are the changes in the behavior and diet of breeding females? What are nursing times and how do young in the nest emerge and interact with bait?

Can 'hotspots' of higher abundance/likely survivorship be more effectively identified, e.g. habitat, commensal areas, or is survival a stochastic process?

What are the most effective methods for characterizing rodent population dynamics on island leading up to/during eradication? Potential indicators include population trend (declining/increasing), presence/abundance of juveniles in the population, body composition in the rats.

A.3. Toxicants: delivery

If rodent breeding is occurring during an eradication, optimum baiting strategies should cater for delayed access to bait by breeding females and new kits. What is the optimum period between applications, considering extreme scenarios, in order to ensure adults and weanlings have sufficient access to bait? Is there a risk of having a significant period between applications with no bait on the ground? What is the optimum number of bait applications? Can greater efficacy be gained by applying the same amount of bait with different techniques, e.g. higher frequency bait 'pulses' with lower bait volume?

How can we improve bait application and availability in known high risk habitats such as mangroves, intertidal habitats, tree canopies and commensal areas?

A.4. Toxicants: formulation (addressing questions related to bait delivery are considered higher priority than bait formulation)

Can bait palatability be enhanced to overcome competition with native food sources?

How can baits be optimized for breeding and lactating females and kits emerging from the nest?

Can effective deterrent compounds for key non-target bait competitors, e.g. crabs, be developed?

Can different matrices be developed to cater for different nutritional spectrums of proteins, lipids and carbohydrates? What matrices perform effectively for rodents experiencing dehydration stress?

A.5. Island ecology: operational implementation

Can a rapid assessment approach be developed for potential eradications, with a focus on identifying triggers of known complexity/higher risk (mangroves, people, size, sociopolitical constraints, etc.).

What is the most effective way weather data and forecast tools can be effectively used to characterize islands to inform planning (e.g. were bait uptake trials undertaken during a unusual year?), and assess conditions leading up to the eradication? Can remote sensing tools such as NDVI or greenness be used to characterize intra and inter-annual variation in environmental conditions, and improve any forecasting leading up to the eradication?

At what scale can forecasting effectively inform delaying an application within a season, or inform stopping an eradication? How can the different cost components of an eradication be optimized with forecasting models?

A.6. Island ecology: non-target bait competitors

What is an optimal food web model template with bait as a food item that can be developed to identify non-target bait competitors for eradication projects?

Improve understanding of non-target bait competitor behavior over time, e.g. crab activity in wet and dry application periods, invertebrate blooms or hatching events, to understand how application during different periods affects bait availability.

A.7. Research strategies

Define key monitoring information (e.g. bait uptake, presence of breeding rodents, characteristics of surviving rodents) that can be collected during an eradication to better inform a post operational review (of both failed and successful projects). Undertake standardized post-operational reviews regardless of outcome, and these reports should be made available to industry partners.

Continue building an appropriate research network focused on eradication outcomes, including developing collaborations, attracting new researchers and identifying sources of funding to pursue some of these research questions. Take advantage of opportunities of planned eradications to undertake research questions.

Identify dedicated research islands for eradications where rodents can be re-introduced and eradications repeated. This will also aid an understanding of reinvasion ecology. Consider working on islands that will help build the knowledge base but may not otherwise be a priority for eradication.

Appendix B. List of participants and affiliation

Last name	First name	Affiliation
Cuthbert	Richard	Royal Society for the Protection of Birds
Harper	Grant	NZ Department of Conservation
Kelly	John	Royal Society for the Protection of Birds

Millett	James	Royal Society for the Protection of Birds
Griffiths	Richard	Island Conservation
Holmes	Nick	Island Conservation
Howald	Gregg	Island Conservation
Keitt	Brad	Island Conservation
Wegmann	Alex	Island Conservation
Bell	Biz	Wildlife Management Int. Limited
Boudjelas	Souad	Pacific Invasives Initiative
Broome	Keith	NZ Department of Conservation
Cox	Andy	NZ Department of Conservation
Cranwell	Steve	Birdlife International
Fisher	Penny	Landcare Research
Garden	Peter	Independent
Martin	Peter	Bell Laboratories
Pierce	Ray	EcoOceania Pty Ltd.
Priddel	David	Office of Environment and Heritage, Australia
Russell	James	University Auckland
Samaniego-Herrera	Araceli	Grupo de Ecología y Conservación de Islas
Towns	David	NZ Department of Conservation
Brown	Derek	Independent
McClelland	Pete	Lord Howe Island Board
Pitt	Will	US Department of Agriculture
Shiels	Aaron	US Department of Agriculture
Tershy	Bernie	University of California Santa Cruz
Torr	Nick	Independent
Varnham	Karen	Independent
Duron	Quiterie	Development Research Institute, New Caledonia

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