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PERSPECTIVES AND PARADIGMS

Diagnosing and responding to causes of failure to eradicate invasive rodents

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Abstract Eradicating invasive rodents from islands is a common and powerful tool for conserving and restoring island ecosystems and populations. However, a variety of practical and ecological factors make rodent eradications susceptible to several different types of failure. If an eradication operation is not successful, we are faced with many difficult decisions on how best to proceed, particularly whether to continue actions or to wait before attempting eradication again. We can pro-actively prepare for the possibility of failure by developing failure response plans during the operational planning stages. A well-developed failure response plan includes data collection processes necessary to identify correctly the type of failure: (1) an incomplete eradication effort, (2) eradication effort complete, but individuals survived, or (3) rapid recolonization resulting from a breach of biosecurity measures. Data are also needed to meet

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pre-determined criteria to inform the decision when to reattempt eradication efforts, should an eradication fail. We provide a general conceptual framework for implementing failure response plans as a means of focusing limited conservation resources by expediently identifying the type of failure, reducing monitoring time-lines to determine if an eradication failed, identifying targets for when follow-up eradication efforts will be most successful, and if appropriate, modifying and updating biosecurity measures. Adopting this approach to pre-empt rodent eradication failures allows the island restoration community to maximize learning, base decision criteria on scientific evidence, and create a transparent decision-making process, thereby improving future eradication efforts.

Keywords Best practice · Contingency planning · Island conservation · Invasive species

Introduction

The eradication of invasive rodents from islands (i.e., completely removing all individuals) is one of the most powerful tools available for the conservation of island biodiversity (Jones et al. 2016; Russell and Holmes 2015). Invasive rats (*Rattus rattus*, *R. norvegicus*, and *R. exulans*) and house mice (*Mus musculus*) occur on > 80% of the world's major island groups (Atkinson 1985) and are likely responsible for the greatest number of extinctions of endemic island species and accompanying ecosystem changes (Doherty et al. 2016; Towns et al. 2006). Consequently, rodent eradication programs constitute the bulk of island vertebrate eradications, with nearly 60% of all attempts to eradicate invasive mammals from islands targeting rodents (Jones et al. 2016). Despite success rates of nearly 85% (Keitt et al. 2015), multiple practical (e.g., terrain, weather) and ecological (e.g., alternative food availability, life history characteristics) factors make rodent eradications susceptible to failure, particularly those targeting tropical islands (Howald et al. 2007; Keitt et al. 2015; Russell and Holmes 2015). Some proportion of failures reflects an accepted level of risk from pushing boundaries of scale and technologies, but it is important that we go beyond simply acknowledging the possibility of failure (Meek et al. 2015, 2016). Work on organizational learning suggests that we learn more from failures than from successes (Madsen and Desai 2010) and the entrepreneurial literature indicates that the learning and growth resulting from failures helps to prepare entrepreneurs for future activities (Cope 2011; Politis 2005). Failures offer important learning opportunities and our motivation is to synthesize lessons learned from previous failures so that the global island eradication community can incorporate those lessons into their operational planning as best practices, and can improve our opportunities to learn from potential future failures.

Island eradication operations have unique combinations of local logistics, public support, economics, and benefits; as such, there is no boiler-plate approach to rodent eradications (Broome et al. 2005). Despite this context specificity, operations have benefitted greatly from conceptual frameworks derived from prior failures and successes (see Broome et al. 2017; Keitt et al. 2015). Priority has been placed on improving eradication success rates, while also scaling up in island size, but with less emphasis on what should be done in the case of failure. We lack guidelines for the period immediately following a failure, with a general lack of agreed-upon protocols to provide evidence-based criteria to inform decisions on when or if to recommence eradication efforts. Here we classify the different types of eradication failures and provide a conceptual framework for implementing failure response plans (Fig. 1) that includes best practices for evaluating future eradication actions in the event of an eradication failure.

This framework complements the project review outline for failed eradications as proposed by Keitt et al. (2015). If done appropriately, the project review provides important information diagnosing why the eradication failed. This information should then inform the decision-making process, defined a priori in the failure response plan (Fig. 1). Unlike the project review, the failure response plan is more than an attempt to elucidate the practical considerations of why an eradication attempt failed, but rather, details actions to be taken in the event of failure, particularly "go/no go" criteria and protocols for possible localized rapid responses. This includes documenting and archiving response outcomes so projects implementing localized rapid responses are easily identified and to facilitate comparisons between response actions and outcomes. As such it is not separate from, but

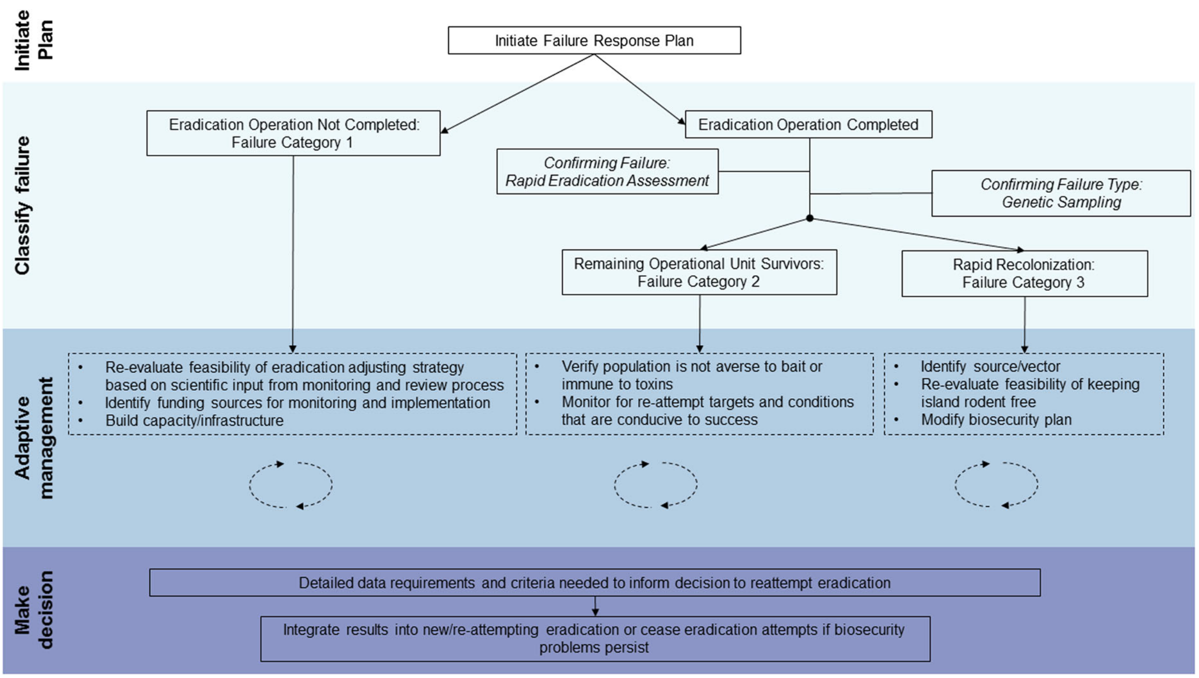

Fig. 1 Conceptual framework for actions following unsuccessful rodent eradications. Each arrow between boxes represents how to proceed. Italicized text indicates step(s) that may only be suitable for some operations and/or requires preliminary sampling prior to operational eradication efforts, but are not required for response plan to be effective. Solid arrows indicate monitoring is needed to inform the decision. Hatched arrows indicate refining plans based on adaptive management and progression should not occur until measurable targets articulated prior to eradications efforts for reattempting eradication have been met

rather a component of, the operational plan. Planning for failure should also explicitly consider the cost:benefit calculation (in the risk assessment that should be done as part of eradication permitting) when determining levels of monitoring effort and potential responses to failure. Implementation should occur as soon as it is indicated that eradication may have failed. Therefore, failure response plans should be developed as part of the contingency planning during the operational planning period (Russell et al. 2008), prior to initiating eradication attempts. Having a plan in place may allow operations to include resources needed to react rapidly to a potential failure as part of their contingency funding and response. This approach will also aid in securing advance permissions for potential failure-response actions, noting that post-hoc applications for permissions (e.g., to apply a third round of bait) may fatally compromise proposed failure-response actions. In addition, failure planning facilitates the gathering of standardized information that maximizes the ability to identify why an eradication may have failed, informs future eradication decisions, and integrates that information into future eradication campaigns. For example, genetic sampling confirming that the eradication succeeded but reinvasion occurred will inform biosecurity considerations before another eradication is planned. This may not necessarily inform immediate actions (because genetic samples take too long to secure, analyze and compare), but could inform why follow-up actions may not have succeeded. Most importantly, when used within the conceptual framework, well-designed failure response plans can help identify eradication efforts, and follow-up efforts if failure is detected early, that may have a low likelihood of success.

While the conceptual framework can be applied to island eradication projects targeting a variety of invasive species and employing a variety of removal techniques, we have focused on those targeting rodents, particularly those using aerial baiting. Unlike most other eradication projects, including ground baiting for rodents, which usually involve prolonged removal efforts based on individual sightings and multiple methods (often used sequentially), rodent eradications using aerial baiting typically involve a temporally concentrated toxic baiting effort that aims to remove the entire population in one discrete event (usually over a period of $\leq$ 12 weeks per discrete site). This allows for a clearer delineation between "success" and "failure", whereas other eradication programs may last years and provide managers with information during the course of the operation (e.g., numbers removed, locations of removal, bait take, etc.) that can be used to adapt plans to optimize success resulting in less obvious assessment of discrete binary outcomes. Further, the high number of eradications targeting rodents, recent high profile "failures", and the unique features of aerial rodent eradication projects necessitates a focused evaluation.

Even when implementing best practices (Broome et al. 2017; Keitt et al. 2015) the risk of failure when eradicating invasive rodents from islands > 100 ha is not negligible (Howald et al. 2007). There are different types of failures, therefore response planning should address the unique issues inherent for each of these. All failure response plans should identify the information needed to satisfy pre-determined criteria, including the type of failure that occurred, funding requirements and sources and ongoing monitoring and biosecurity efforts.

Classifying eradication failures

Eradication failures can be grouped into three categories: (1) the baiting component of the operation was not completed (removal efforts were incomplete) and therefore not all individuals were exposed to the eradication method (e.g., Springer 2016; see Table 1 for case study), (2) the operation was completed but not all individuals were removed (e.g., Amos et al. 2016), or (3) the operation was completed, all target animals were removed, but rapid recolonization occurred (e.g., Russell et al. 2010). Because the mechanisms responsible for each type of failure differ, it is important to identify the type of failure correctly to follow the appropriate steps in the conceptual framework (Fig. 1) and implement the appropriate components of the response plan.

Category 1: eradication operation is not completed

Incomplete eradications may not seem like a failure of the eradication technique, but given removal efforts were initiated and ceased without the eradication of the invasive rodent population, the same decisions will need to be made regarding whether to continue eradication efforts (see Table 1 for case study). This includes the significant investment in the planning process before bait is even spread. The framework differs slightly; it will be obvious that the eradication was not successful (Fig. 1). This type of failure can occur due to issues in the feasibility and/or operational planning stages of the project (e.g., project was not feasible, or had inadequate funding), social conflicts (e.g., insufficient public support, or active sabotage) or unexpected/unavoidable operational circumstances (e.g., unusual timing of inclement weather, or equipment malfunction/destruction). It may also be the result of regulatory restrictions, such as a coastal buffer to prevent bait from entering the ocean (e.g., on Lehua Island, Hawai'i; Parkes and Fisher 2017). Key managers and stakeholders should be interviewed, and a systematic review of the feasibility study, planning, fundraising, and operational reporting documents conducted as described by Keitt et al. (2015). The review process should identify, as much as possible, the mechanisms or processes responsible for operational causes of failure. Until these issues are addressed, future eradication efforts will likely also be unsuccessful and should not be undertaken.

Eradication operation completed: confirming failure

After operational implementation is completed, the priority shifts to assessing the outcome of the eradication. At this stage, well-designed failure response plans will overlap with post-eradication monitoring plans. Traditionally, confirmation of invasive rodent eradication outcomes requires two years of surveillance following the completion of active eradication efforts, or the equivalent of two breeding seasons of the target rodent species (Keitt et al. 2015; Russell and Broome 2016). This timeline increases the probability of detecting surviving rodents (Amos et al. 2016; Nathan et al. 2015) as a population can rebuild to more readily detectable levels over this timeframe. However, rapid eradication assessments (REA; Russell

Table 1 Case studies illustrating emergency responses to different failure categories and learning outcomes. These examples motivated the development of formalized failure response plans as part of eradication operational planning

Failure Category 1—Eradication not completed Macquarie Island, Australia and Lehua Island, Hawai'i
A planned eradication campaign to remove European rabbits (*Oryctolagus cuniculus*), Black rats (*Rattus rattus*), and house mice (*Mus musculus*) was interrupted during bait deployment due to an unseasonably prolonged period of inclement weather (Springer 2016). The prolonged interruption prohibited the successful completion of bait deployment, so the operation was postponed to the following year when conditions were likely to be more favorable for success. This is an extreme case where the cause of "failure" was obvious and never in doubt, but it serves as an example of the response when such a failure occurs
On Lehua Island, Hawai'i, a regulatory restriction prevented spreading bait within 30 m of the coast, which was likely a contributory factor to the failed 2010 *Rattus exulans* eradication operation (Parkes and Fisher 2017)
Failure Category 2—Remaining operational unit survivors Henderson Island, Pitcairn Islands Group
A comparison of genetic samples from rats captured before and after completion of operational deployment of bait revealed that rats observed after the eradication were survivors from the original population (Amos et al. 2016). This excluded a category 3 failure and identified these individuals as descendants of the original population who must have survived the initial eradication attempt. Thus, efforts focused on addressing theories on how this may have happened rather than on potential bio-security measures (see Griffiths et al. (2019) for a more detailed discussion)
Failure Category 3—Rapid recolonization Pearl Island, New Zealand
Comparing an opportunistically collected genetic sampling of rats from before implementation of an eradication campaign with individuals observed following the operation revealed that the rats present after the operation were from a different population (Russell et al. 2010). A category 3 failure, because the island's rapid recolonization was due to rats dispersing from a neighboring island. At the time, genetic sampling prior to eradications was not a component of most operational plans, but this step is now a component of best-practice protocols, which was instrumental in the second case study above

et al. 2017) should only be considered when the cost of reacting quickly is low and the likelihood of success of immediate continuation of eradication efforts is high. This includes scenarios with small or easily accessible islands, localized instances of invasive rodent survivors, or when decisions about native species conservation are time sensitive (i.e., re-release of captive individuals). Rapid eradication assessment is a powerful new modeling tool that utilizes traditional monitoring techniques to quantify the probability of eradication success within weeks of completion (Samaniego-Herrera et al. 2013). When appropriate to employ, REA reduces this post monitoring commitment from years to potentially weeks, resulting in cost-savings (Samaniego-Herrera et al. 2013) and if necessary, the ability to implement a failure response plan sooner than using traditional monitoring methods. However, REA may not be practical for all islands (e.g., where complete coverage is not possible), in which the traditional 'wait and see' approach may be more appropriate. Nevertheless, the ability to detect and remove rodents at very low densities should not be underestimated; it is exceptionally difficult (Russell et al. 2005), and increases with size of the island and topography.

Category 2: operation survivors

This occurs when some individuals survive the eradication operation (see Keitt et al. 2015 for discussion on why this may occur; see Table 1 for case study). Early detection of failure may allow the eradication team to locate individuals and implement appropriate localized eradication measures before these individuals can repopulate the island (Russell et al. 2017; Samaniego-Herrera et al. 2013). However, while this may sound appealing, we stress that given the difficulties and costs associated with detecting the last remaining individuals (Russell et al. 2005; but see Nathan et al. 2013) and the high intrinsic population growth rates of rodents (Nathan et al. 2015), intensive follow-up actions may have a low likelihood of success. For example, on Frégate Island, Seychelles, the eradication efforts of a newly established population (i.e., at low densities) of Norway rats was stopped because the high population growth rate required they commit to on-going, high-cost control efforts that were not effective in eradicating or even controlling the population (Thorsen et al. 2000). The operational plan should identify a priori whether or not monitoring for survivors should be undertaken immediately post-operation and clearly define "go/no go" criteria for whether or not to implement localized eradication measures. In our view, given the low probability of detecting survivors over large aerially baited landscapes (Amos et al. 2016), and the current limited experience in eradicating a recovering or growing rodent population, efforts to monitor immediately following completion of baiting, may do little more than rapidly confirm failure. However, if monitoring immediately following completion of baiting is feasible, high-risk areas such as around human accommodations where rodents' food supply is high and other areas of high biosecurity risk should be prioritized.

Category 3: recolonization

A failure response plan builds on traditional operational procedures by relying upon the collection of genetic samples from the targeted eradication population(s) prior to the eradication (Keitt et al. 2015; Russell et al. 2010; see Table 1 for case study). This is vital because it distinguishes between recolonization and the failure to eradicate all individuals. This is particularly important in the event of recolonization as this information can be used to determine the source populations of the individuals (Abdelkrim et al. 2005). Pre-eradication planning will also consider the likelihood of a reinvasion based on each site's proximity to a source population, the means of arrival, and biosecurity measures in place. The implementation of this practice has been instrumental in identifying recolonization by two rat species on Pearl Island, New Zealand (Russell et al. 2010) and an eradication where all individuals in the original population were not killed, on Henderson Island, Pitcairn Islands (Amos et al. 2016). It can also be used to identify (post-hoc) the source of the re-colonizers, including a natural recolonization by swimming or hitch-hiking on a vessel. This can then inform reviews of relevant operational protocols and biosecurity systems.

Guidelines following failed rodent eradications

Following a failed eradication operation, the failure response plan should be implemented, beginning with classifying which category of failure they are dealing with (i.e., "Classify failure", Fig. 1). In some cases, the distinction between Category 2 and 3 is less operationally relevant as the response to both upon the discovery of a small localized number of individuals immediately following (i.e., 1–2 months) the cessation of baiting would likely be the same until the extent of the failure is better understood [i.e., localized trapping or supplementary baiting and initiate intensive data collection on the possible extent of failure, keeping in mind that detecting lone individuals is extremely difficult (Russell et al. 2005)]. Once the nature of the failure is determined, an assessment can be made of whether to continue these localized control measures or to wait and reattempt eradication efforts when conditions for success are optimal. In some cases, resources or logistical constraints may curtail these localized measures. The decision whether to continue localized control, escalate to a larger-scale reattempted eradication or delay action will vary based on the unique circumstances of the eradication effort, but will hinge on (a) the estimate of numbers and distribution of target individuals present, (b) likelihood of exposing them to bait, (c) the likelihood they will be motivated to take bait, (d) cost estimates for immediate and potentially ongoing efforts, and (e) reputational risk of ongoing efforts versus failure outcomes with funders and stakeholders. If rapid localized responses are implemented, documenting and archiving failure-response actions and outcomes is an extremely important step to facilitate comparisons that may identify best practices for this particularly challenging issue. Because the suppression of invasive rodents can lead to changes in population trajectories of native species (e.g., Bond et al. 2018), an important consideration in this decision is that recovery of prey populations invariably provides additional resources for target individuals that remain (e.g., Amos et al. 2016). Therefore, reattempting eradication too soon after the failed effort may violate one of the guiding principles for rodent eradication, namely that all individuals are exposed to an adequate dose of rodenticide (Broome et al. 2005). All target individuals must be exposed to toxic bait, susceptible to the toxin, and motivated to take it in sufficient quantities. If there is neophobia, an abundant alternative food supply, or insufficient bait, all rodents are not likely to take, or be exposed to bait, making failure more likely. If individuals are detected immediately (i.e., 1–2 months) following completion, it is likely that there will be a small window of opportunity for immediately reattempting localized baiting efforts, as was the case on Palmyra Atoll (B. Keitt pers. comm.).

Ideally, embarking on localized baiting efforts should include data collection to confirm that all individuals will be motivated to take toxic bait while recovering from low densities with abundant food. However, before another island-wide eradication operation is attempted, the timing of the operation in relation to periods of reduced alternate food abundance must be examined.

Integrating failure response within operational planning

Like biosecurity plans that are developed before and implemented following successful eradications, failure response plans should also be developed as part of the operational planning for eradication projects with a non-negligible risk of failure (i.e., islands > 100 ha; Howald et al. 2007). Given the considerable time, money and resources that are invested in feasibility testing, operational planning, execution, and monitoring, a response plan and decision framework for outcomes other than success is prudent (Fig. 1). This serves both to make the decision-making process transparent and the monitoring and data collection for informing these decisions explicit. It should also help improve our understanding of the mechanisms responsible for failures and increase our ability to learn from them and integrate that learning into future eradication projects.

The conceptual framework for identifying causes of eradication failure and laying out the appropriate associated timelines relies on the response plan having scientifically and operationally supported criteria that must be met before reattempting an eradication operation. The response plan and criteria will depend on project-specific features necessarily, including the vulnerability to extinction of the extant native species (or eradication urgency), the ecology and demographics of the rodent population(s), including any possible interplay between multiple invasive species (e.g., competitor release), environmental factors (e.g., seasonal food availability), and logistical constraints (e.g., remoteness and size of the island). Future decisions should be based on the information gathered from collected records, interviews, and post-monitoring activities. Adaptive management is a necessary and integral part of the post-eradication failure process as it ensures progress toward achieving global eradication goals and that these are reevaluated according to input from science, society, and management throughout the decision-making process (Armstrong et al. 2007). Ideally, this iterative process will continue until the target indicator criteria are reached, at which point reattempting eradication efforts may be warranted.

Following this approach will not ensure that subsequent eradications attempts will be successful. However, by identifying the factors for initiating future eradications and making the decision process transparent to project stakeholders, we maximize the opportunity to learn from failures and improve future decision-making and failure responses (Cope 2011; Politis 2005) by incorporating that learning into future failure response plans. Eradication campaigns are often treated as having a binary outcome of either success or failure, but with the recommendations we make here, "failures" need not, and should not, end that way.

Conclusions

The eradication of invasive species is essential for global biodiversity conservation, with successes spurring greater research effort, larger fundraising campaigns and more technically and logistically challenging attempts in a positive feedback loop (Simberloff 2001). Our focus is on rodent eradications, given the specific nature of those operations, however, the principles considered here can be applied to other eradication efforts, particularly those that also have once-off, short time-frame operational components. While failures may not seem like they are a part of this positive feedback loop, we believe that if they are properly planned for, they can provide an opportunity to learn, and can play an important role in informing future successful eradication attempts. Incorporating failure response planning and decision-making guidelines into eradication planning best practices can minimize delays between eradication attempts, reduce risks of repeated failure, stream-line post-eradication decision-making processes, improve transparency, inform the development of more robust eradication plans, and may improve cost savings by facilitating decisions when operations are not successful. We believe that with proper planning, the "failures" of today can be mitigated and used to inform future eradication projects that become the successes of tomorrow.

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