Feasibility of a Successful Rat Eradication on Wake Atoll Following Initial Partial Failure: Potential Causes, Remedial Actions, and Remaining Knowledge Gaps

Chad Hanson
Island Conservation, Santa Cruz, California
Kristen Rex
Center for Environmental Management of Military Lands, Colorado State University, Fort Collins, Colorado; and Biosecurity Program, Pacific Air Forces Regional Support Center, Joint Base Pearl Harbor-Hickam, Hawaii
Peter J. Kappes and **Shane R. Siers**
USDA APHIS Wildlife Services, National Wildlife Research Center, Hawaii Field Station, Hilo, Hawaii

ABSTRACT: A 2012 attempt to remove two rat species (*Rattus tanezumi* and *R. exulans*) from Wake Atoll was partially successful. *R. tanezumi* was eradicated from all three islands (Wake, Wilkes, and Peale), and *R. exulans* was eradicated from Peale. However, *R. exulans* remained on Wake and Wilkes and have since recovered to very high densities. In 2013, a panel of experts reviewed the eradication operation and offered a list of possible causes of the partial failure. Since that time, further research has been conducted to address several of the issues identified in the review. In this paper, we conduct a current review of the remedial studies, identify remaining knowledge gaps, and make recommendations for ensuring the feasibility of a future operation to remove *R. exulans* from Wake and Wilkes Islands.

KEY WORDS: anticoagulant, best practices, brodifacoum, eradication failure, feasibility assessment, invasive species, island restoration, post-operation review, *Rattus exulans*, *Rattus tanezumi*, rodent control, rodenticide, tropical, Wake Atoll

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INTRODUCTION

In May 2012, an attempt was made to eradicate *Rattus tanezumi* and *R. exulans* from Wake Atoll. The operation targeted both species of rats with a compressed cereal bait containing 25 ppm of the toxicant brodifacoum. A combination of baiting strategies including aerial application, hand broadcast, and the utilization of bait stations were employed to target all potential rat home ranges. The project successfully eradicated *R. tanezumi* while failing to remove *R.exulans*. *R. exulans* remained on at least one island: Wake and/or Wilkes Islands, which are connected by a causeway. Both species of rats were successfully removed from Peale Island.

Genetic analysis of remnant DNA conducted by EcoGene® (Auckland, New Zealand) indicated that the cause of eradication failure was unlikely to be reinvasion (D. Gleeson, pers. commun. 22 Jan 2013). At this point, a review document was commissioned to critically assess the campaign and identify potential causes of eradication failure (Brown et al. 2013).

OBJECTIVE

This document reviews possible reasons for failure provided by Brown et al. (2013) and provides an assessment of the work to date that contributes to the success of a future eradication attempt of *R. exulans* from Wake Atoll. Specific objectives include:

1. Outline all potential causes for the 2012 *R. exulans* eradication failure indicated by Brown et al. (2013), and
2. Accompany each potential cause of failure with a narrative indicating:
   a. If sufficient information is available (i.e., have potential causes of failure since the review document been scientifically criticized or been addressed by new standards of eradication practice), or
   b. What future efforts could be undertaken in order to fill knowledge gaps not outlined in the 2013 review document to support the decision to conduct a subsequent eradication attempt.

Additionally, recommendations related to the operational strategy are provided throughout the narratives.

ANALYSIS OF POSSIBLE CAUSES OF FAILURE AND RECOMMENDATIONS

Effectively described by Brown et al. (2013), failure to eradicate rats from Wake Atoll is the result of one or both of two fundamental scenarios: 1) All rats could not eat a lethal dose of bait (or a lethal dose via secondary consumption of other bait consumers), and 2) all rats would not eat a lethal dose.

As with any eradication attempt, 100% certainty of success is not possible. Although this is the case, planning each component of the operation in a fashion to reduce the risks associated with both fundamental factors (i.e., rats could not access a lethal dose, or would not eat a lethal dose) will provide for a high likelihood of eradication success.

Brown et al. (2013) outlined a series of possible causes related to each fundamental factor which may have contributed to the failure to eradicate *R. exulans* from Wake Atoll in 2012. The analysis of these causes of failure are provided below, and recommended actions to reduce risks on a future eradication attempt are provided.

Factors Limiting Rodent's Ability to Eat a Lethal Dose of Bait

Cause of Failure #1: "Overall bait rates may not have been sufficient or may not have had sufficient 'buffer' or margin for error. Any errors in baiting could have created pockets of land where lower than desirable bait rates were applied that could easily have led to a small number of rats not being able to readily access bait."

The target goal of the aerial application was to achieve a bait density on the ground of 18 kg/ha for the first application and 9 kg/ha for the second application. This rate was selected based on the mean bait availability over time from data collected during a biomarker study (Wegmann et al. 2009). Bait availability was again monitored during the 2012 implementation. On average, bait remained available for at least 20 days after the first application (Figure 1). The number of bait pellets remaining within some monitoring plots on Wake and Peale fell to zero four and five days, respectively, after the first application (Figure 2). Bait availability within these plots remained zero for four days until the second aerial bait application occurred (Figure 2). As shown in Figure 2, following the second aerial bait application, bait in some plots disappeared after six days on Peale, and after nine days on Wake (Island Conservation 2013, Griffiths et al. 2014).

Although these figures remain within Pott et al. (2015)'s recommended target of having bait available for at least four nights, it remains unknown if the density of bait present was great enough to ensure pellets were readily detectable, a variable identified as important by recent review of tropical rodent eradications (Keitt et al. 2015).

Assessments by Pott et al. (2015) and Keitt et al. (2015) reviewed tropical rodent eradication projects, including Wake Atoll, and provide guidance on how to utilize bait availability trials to aid in selecting bait application rates. The summary of their results indicates that tropical environments including the presence of bait competitors (e.g., land crabs), wet tropical conditions, and widely available alternative food sources may all contribute to a need to exceed the mean quantity of bait considered necessary to eradicate rodents across all project environments. As a result, conservatively calculating bait application rates using a 99% t-statistic confidence interval that includes data from all study plots is recommended (Keitt et al. 2015, Pott et al. 2015).

Data specific to Wake Atoll is available for analysis from previous bait availability monitoring in February/ March of 2009 (Wegmann et al. 2009), May/June of 2012 (Island Conservation 2013), and recent work over November/December of 2017 by Niebuhr et al. (2018). All

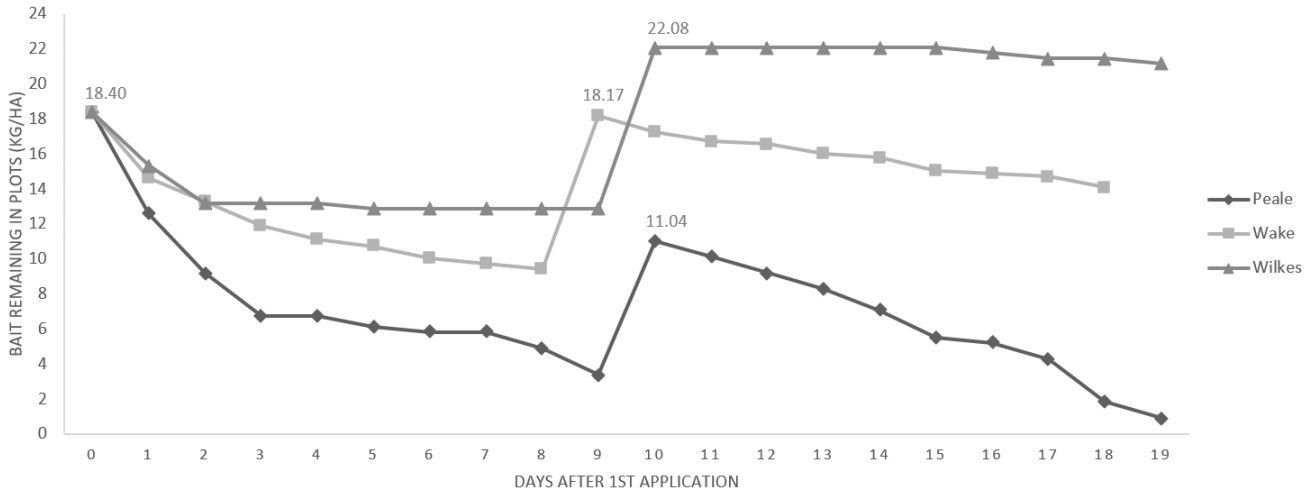

Figure 1. Average amount of bait remaining on each island after the first application. Data points show the representative application rate on the ground after the first and second bait application respectively (Island Conservation 2013)**.**

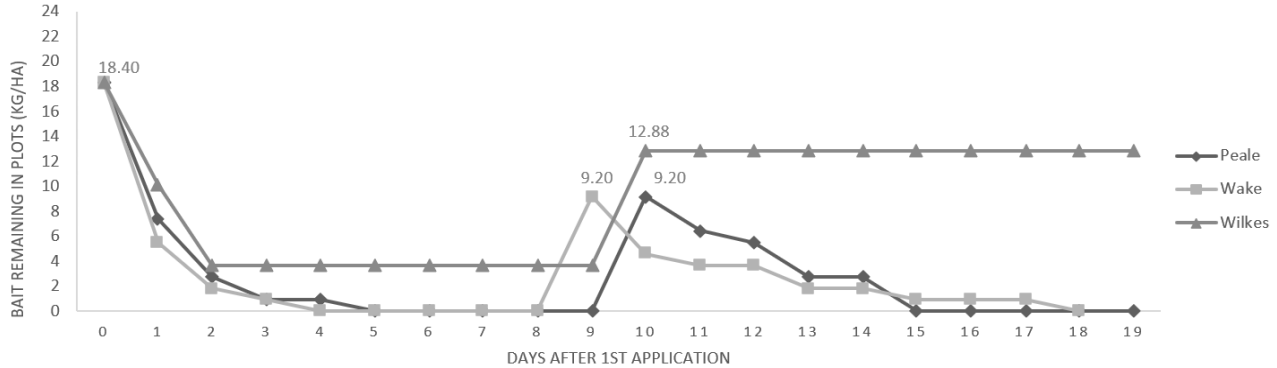

Figure 2. Minimum amount of bait remaining on each island after the first application. Data points show the representative application rate on the ground after the first and second bait application respectively (Island Conservation 2013)**.**

monitoring assessed two applications of Conservation 25W rodent pellets of 18 kg/ha and 9 kg/ha respectively. Placebo bait which did not contain toxicant was used in 2009 and 2017.

If past information is analyzed using a 99% t-statistic confidence, several assumptions must apply regardless of the data set utilized, as not all study years are suitable predictors of subsequent years (Keitt et al. 2015). If either assumption cannot be validated, then confidence of eradication success will be reduced. Assumptions include: 1) The bait availability study was conducted at a time of year which represents similar on-site conditions (e.g., competing bait consumer density, abundance and quality of alternative food sources, humidity) which coincide with the future implementation timing; and 2) habitats sampled demonstrate the highest rate of bait disappearance.

To validate assumptions and address uncertainty, the implementation window must be identified before a data set can be selected for analysis. Seasonal changes in *R. exulans* abundance, body condition, population structure and distribution, and alternative food abundance should contribute to the selection of the baiting widow (Griffiths et al. 2014). If the stated assumptions do not apply to the proposed baiting window, then additional field trials are justified to generate a suitable data set.

By using the lower 99% confidence interval, risk of underestimating bait disappearance is managed, and a conservative bait rate generated. As a result, bait rates capable of accommodating a wide variety of conditions would be provided and a more appropriate margin of error to address uncertainty would be built-in as suggested by Brown et al. (2013). It is important to note that if additional bait availability trials are conducted, trial bait rates should overshoot the anticipated application rate to ensure bait availability can be measured for at least four nights (Pott et al. 2015).

To add further confidence that baiting rates are sufficient, Keitt et al. (2015)'s recommended best-practice for eradications on tropical islands should be applied. Key updates to the 2012 Wake Atoll bating strategy include extending time between applications to three weeks and designing the second bait application to be as robust as the first. This would result in the second application being applied at the same rate as the first with a continued use of a 50% overlap in baiting swaths to minimize gaps in baiting (Keitt et al. 2015). Additional research that indicates ranging behavior related to lactating females and emerging young specific to Wake Atoll may allow best-practice recommendations to be refined (i.e., tailored) to the operation (Griffiths et al. 2015).

Review of macro habitats show that *Pemphis acidula* shrubland habitat on tidal flats (hereafter 'pemphis') and sealed surfaces including the runway and fuel spill catchments around bulk fuel storage tanks are not represented within any previous bait availability monitoring. It is worth noting that these two habitats are unlikely to be treated by an aerial broadcast and will likely use bait bolas or bait stations (Siers et al. 2017). Additionally, canopy baiting should be prescribed within hand-broadcast zones as recommended by Keitt et al. (2015) and described within 2012 operational planning (USFWS and Island Conservation 2011). If this is the case, no further assessment of these locations is warranted to increase confidence in a selected application rate.

Niebuhr et al. (2018) documented rapid disappearance of placebo bait from the Wake Island solid waste separation facility. The necessary bait application rate to ensure that adequate bait availability in this area persists throughout the entire treatment window remains unknown. Furthermore, although placebo bait uptake has been documented in this area, there remains an elevated risk that some rodents accustomed to foraging in the solid waste facility may be conditioned to alternative food sources and the relative palatability of rodenticide pellets would be reduced. Rather than conducting trials to determine what, if any, increase in the volume of bait would result in all rats consuming sufficient bait within this area, risks to eradication success would be more effectively mitigated by removing the presence of this alternative food source. Until this alternative food source is removed, confidence that all rats would eat a lethal dose of bait will remain in question.

In certain circumstances, stratifying bait application rates as suggested in Niebuhr et al. (2018) could be considered to minimize volume of bait applied to areas where low bait disappearance occurs, or alternatively, where bait disappears more rapidly. For this to be administered effectively, further study will be required to effectively: 1) Describe individual treatment sites, 2) define treatment borders with a high level of accuracy, and 3) propose bait application rates for each stratified zone (Keitt et al. 2015). Additionally, stratification should only be considered if chosen areas do not increase the complexity of the operation and subsequent risk of a bait gap (Keitt et al. 2015), a factor repeatedly highlighted as having contributed to the 2012 failed eradication attempt (Brown et al. 2013).

Recommendations for #1

- The implementation window must be identified before a data set can be selected for analysis.
- Research with the objective to demonstrate trends in rodent abundance, breeding cycles and status, seasonal trends in local food sources (e.g., termites) and climate will help indicate appropriate bait application window/s.
- Research indicating ranging behavior of females and emerging young would be beneficial and allow best practice recommendations to be tailored to Wake Atoll.
- Once a management strategy has removed the presence of alternative food sources within the solid waste separation facility, verify that proposed baiting rates offer sufficient bait availability as recommended by Pott et al. (2015) and Keitt et al. (2015).

Cause of Failure #2: "There was a very complex array of different treatment zones for the rest of the island. The merging of the different treatment zones via hand-baiting was somewhat ad hoc and open to subjective assessments by sometimes inexperienced operators, so it is feasible that baiting gaps or under-application occurred in the treatment of one or more of the buffer areas."

Cause of Failure #3: "The numerous exclusion zones for aerial baiting would have created a very difficult 'stop-start' nature to the aerial baiting for the pilot, while some evidence of false sowing (baiting being recorded when the bucket was in fact empty) would have created pockets of land where bait density was considerably lower than planned."

Cause of Failure #4: "There were large total exclusion zones where no bait was applied at all, and these appeared to be identified only subjectively as 'rat-free', or at least it was considered an acceptable risk to exclude them from bait spread."

Overall bait sowing rates may have been impacted by several instances of gaps in coverage which were identified or theorized by Brown et al. (2013). A representative list of such cases includes: 1) Small areas which may not have received bait while others appear to be been under-sowed, 2) several buildings and vessels were missed in the first bait application causing a delay in their treatment, 3) false sowing by the baiting pilot was recorded in at least three separate instances, and 4) possibility of hand-baited zones excluded from the aerial application not being fully meshed with the aerial broadcast.

Many of these examples can be attributed to the complexity of the operation due to regulatory constraints and on-site restrictions (Island Conservation 2012, 2013; Brown et al. 2013). As a result, planning and management effort should focus on reducing breaks in the bait application both spatially and temporally to allow for a uniform and consistent distribution of bait. This will serve to reduce the risk of having gaps in bait coverage while simplifying the overall operation.

Recommendations for #2-4

- Design second application to be as robust as the first application and consider additional applications if warranted (Keitt et al. 2015).
- Extend interval to roughly three weeks between bait applications to address the likelihood of rats breeding and young emerging during the bait application (Keitt et al. 2015).
- Reduce the number of areas excluded from aerial bait application.
- Pre-determine and verify application strategy at all treatment zones.
- Lift restrictions which reduce baiting efficacy (i.e., allow for the broadcast of bait up to the exterior of structures, utilize open bait trays in places where tamper-proof stations are not legally required, bait over buildings and across sealed surfaces.).
- Consolidate manual broadcast areas into a single treatment zone with pre-selected baiting points.
- Staff all project positions with individuals that are experienced in eradication and are committed to the success of the project (i.e., demonstrate an eradication ethic throughout all responsibilities).
- Select project team members with relevant experience and skills for operational activities that contribute to the likelihood of project success.

Actions that would benefit from further research include additional investigation as to whether or not *R. exulans* are capable of surviving indefinitely within sealed surfaces including runways, taxiways, fuel spill catchments around bulk fuel storage tanks, as well as on rooftops. Restrictions prevented the broad application or use of bait stations on these surfaces. Similar to eradication efforts on Palmyra Atoll, onsite inspections of each site did not identify suitable habitat or resources which could sustain rats indefinitely, and it was considered appropriate to exclude these sites from baiting (R. Griffiths, pers. commun.) Although this is the case, best-practice suggests that all potential habitat should receive an open (i.e., aerial) broadcast (Broome et al. 2017). If a future effort would remain under similar restrictions as found in 2012, proceeding with implementation should be contingent upon research which indicates whether *R. exulans* can persist solely within these sites, or alternatively, bait is allowed to be applied either as an open broadcast (best), on bait trays (better), or within bait stations (good) along a grid set with maximum of 20-25 m spacing.

Underground and aboveground structures were described as being poorly known before implementation. New strategies have been developed for a suite of projects since 2012 including Lord Howe Island (Australia), Kayangel Island (Palau), Midway Atoll (U.S.A.), and Floreana Island (Ecuador) that improve on the approach and management of structure baiting (C. Hanson, pers. commun.). Key aspects which should be considered for Wake Atoll include the development of digitized monitoring applications, database structure, and floorplan management strategies. Furthermore, improvements in the management of the structure baiting, coupled with the utilization of bait trays as described in Griffiths et al. (2015) and prolonging the presence of bait stations for a minimum of six months or longer should occur to improve the likelihood of eradication success (Broome et al. 2017).

In an effort to maximize the chance of eradication success, the database developed in 2012 indicating the location and type of structures present on Wake Atoll should be updated. In particular, the use of LIDAR (light detection and ranging) to map the surface of the island would be beneficial. Effort to identify the condition of each structure will also serve to improve how structures are baited. Under conditions that do not pose a risk to human health and safety, a more effective form of bait distribution or presentation should be considered. Ideally, a shallow dish or plate with a known number of baits should be utilized (Broome et al. 2017).

Recommendations for #2-4 (cont.)

- If a future eradication effort remains under similar baiting restrictions as imposed in 2012, proceeding with implementation should be contingent upon research which indicates whether *R. exulans* can persist solely within excluded sites, or alternatively, bait is allowed to be applied either as an open broadcast (best), on bait trays (better), or within bait stations (good) along a grid set with a minimum of 20-25 m spacing.
- The structure database developed in 2012 should be updated and indicate the location and type of structures present across the atoll.

Cause of Failure #5: "The extent and nature of structures (above and below ground) was poorly known before implementation and could have resulted in a few areas not being adequately treated."

An area of limited understanding is the risk that underground structures, particularly sewer and conduit lines, pose regarding the possibility that a rodent home range may go untreated. Although the treatment of all identified underground structures in 2012 sought to address this uncertainty, it remains unknown whether or not all extant underground structures were discovered and recorded, or the treatment strategy utilizing open broadcast and/or bait bolas was effective at adequately addressing this habitat. As a result, a survey should be conducted to update and catalogue known underground structures as well as trials conducted which assess whether bait can be presented in a readily available fashion, and for sufficient time, to all rodents potentially utilizing this environment. In particular, several challenges associated with this environment include the presence of standing water, poor or no accessibility (to the site itself and extended lengths of pipe/conduit between sites), and variability in site construction limiting locations for bait placement and/or rodents to feed. Trials to improve the strategy to deliver bait to all potential home ranges should include the development and efficacy-testing of floating bait stations, bolas, and/or feeding platforms similar to what is described by Siers et al. (2017) for the treatment of inundated pemphis habitat.

Further effort to monitor the degree to which rodents utilize underground infrastructure would guide treatment strategies and build confidence in a future eradication attempt. Consider incorporating trail cameras into the trials to indicate the rate at which bait remains available and to guide the frequency of site assessment/checks during implementation.

Recommendations for #5

- Conduct an updated survey of Wake Atoll's infrastructure above and below ground which seeks to thoroughly identify, classify and categorize each structure to inform operational planning and implementation (e.g., baiting strategy). All information collected should be organized within a digital geo-referenced database.
- Trials should be conducted which assess whether bait can be presented in a readily available fashion, and for sufficient time to all rodents potentially utilizing infrastructure.
- Incorporate trail cameras into the trials to indicate the rate at which bait remains available and to guide the frequency of site assessment/checks during implementation.

Cause of Failure #6: "The baiting methodology for dealing with the pemphis habitat was poorly planned and largely untested and unproven, and this may have led to inadequate bait or baiting gaps in such areas."

Brown et al. (2013) theorize that pemphis zone is sub-optimal habitat that reduced the likelihood of *R. tanezumi* being present, a larger and presumably dominant species, which suggests how one rodent species was eradicated in the presence of another. Investigation with monitoring devices by Siers et al. (2017) since the 2012 eradication of *R. tanezumi* indicates that *R. exulans* extensively utilize the pemphis habitat. An additional finding of this study was that tidal fluctuations were unpredictable, and inundation of low-lying sites resulted in a need to suspend bait stations to prevent them from being flooded (Siers et al. 2017). Long-term monitoring of bait that was applied across this habitat was not conducted in 2012 and the duration that bait remained available is unknown. As a result, the minimum of four days suggested by Pott et al. (2015) may not have been achieved across areas within the pemphis landscape.

This gap in bait coverage should be addressed in a future eradication attempt. Effort by Siers et al. (2017) identified multiple strategies to treat the pemphis habitat that allow for prolonged availability of bait across all sites within the pemphis habitat and tidal flats. These strategies, coupled with efforts to improve station efficacy by using open trays or dishes, should be considered in the next eradication strategy. Regarding bait station efficacy, the successful eradication of *R. tanezumi* removes the need to assess inter-species competition. A delayed second application, in line with recommendations from Keitt et al. (2015) to extend timing between applications to three weeks and making the second application as robust as the first, will help address potential risks associated with intra-species dominance at bait stations.

This knowledge gap has been partially filled by the work described by Siers et al. (2017, 2018), and the recommendations therein should be considered in developing the operational plan for a future eradication.

Recommendation for #6

- Assess timing of application in relation to spring tide events to increase duration of bait availability.

Cause of Failure #7: "Total reliance on bait stations in some areas on Wake is highly undesirable from an eradication standpoint where two species of rodent are present, as individuals of the subordinate species may be excluded from access, while the design of the bait station types used may have deterred some rats."

The successful eradication of *R. tanezumi* removes the risk that interactions between the two species may deter some rats from entering bait stations in a future eradication attempt. Although this is the case, intra-species dominance may similarly deter subordinate individuals from utilizing stations. Examples of successful rodent eradications which utilized bait stations as the sole means of removal suggest that dominance can be overcome, or that this risk is not well understood and may be overstated (DIISE 2015). As a result, we suggest that best-practice recommendations for bait station operations are applied to a future operation if stations, of any design, are incorporated into the strategy. Key best-practice with the use of bait stations as described by Broome et al. (2011, 2017) should: 1) Allow bait stations to remain in place, and activated with a brodifacoum bait, for a minimum of six months due to human habitation, and stations should remain active for a minimum of one month after suspected rodent consumption; 2) only use bait stations with a proven track record under similar environmental conditions and for the same

species targeted; 3) ensure entrance opening/s do not restrict the target species (i.e., >60 mm); and 4) a secondary bait and toxin should be utilized to address possible aversion to the primary bait type.

Two bait station types were used in 2012. External stations were plastic tunnels consistent with best-practice recommendations (Broome et al. 2011). Internal stations were tamper-proof PROTECTA bait stations (Bell Laboratories, Madison, WI) which adhered to bait label use-restrictions within structures. Although interior stations are a commercial product widely used for commensal rodent control, precedent proving their success on prior eradications, as mandated by New Zealand best-practice (Broome et al. 2011), was not available due to Wake Atoll's environment including an expansive area of human habitation and infrastructure. It is our recommendation that restrictions which prevented open broadcast up to the edge of buildings in 2012 are unnecessary and should be removed in accordance to best-practice guidelines (Broome et al. 2017). This will reduce risks associated with possible aversion to bait stations across a significant area comparable to the 2012 operation. Furthermore, issues that arose with large snails filling bait stations, thus limiting access to rats, would be resolved (Island Conservation 2013; C. Hanson, pers. commun.).

Effective treatment of structure interiors is still in development with few best-practice guidelines directly related to this environment, none of which indicate a preferred bait station model. To reduce risks associated with bait station efficacy, a suite of station types including open tray, tubes, or enclosed tamper-proof stations should be considered and prescribed in accordance to structure use type and risk to human exposure (e.g., dining/sleeping facility, office/work space, utility house, uninhabited, etc.). Strategies to treat each environment should attempt to minimize restrictions which could deter some rats by utilizing bait trays wherever possible (Griffiths et al. 2015). If looking to utilize a novel bait station design, research to increase the likelihood of eradication success is recommended. Extensive field testing which demonstrates all rats accept bait utilized within bait stations and that rats show no aversion to entering bait stations should occur (Broome et al. 2011).

Recommendation for #7

- If looking to utilize a novel bait station design, field testing which demonstrates rats show no aversion to entering bait stations should occur.

Cause of Failure #8: "The period between the two bait applications was reduced by four days (from the planned 14 down to 10) due to external factors. This will have reduced the overall potential time for 'un-exposed' juveniles to emerge from natal nests and still have access to bait."

A series of eradication failures on islands, including Henderson Island, Desecheo Island, and Wake Atoll, occurred at roughly the same time (DIISE 2015). This came as a surprise to the eradication community and prompted several theories, including the suggestion that a reduced period between bait applications increases the potential of having 'un-exposed' emergent juveniles survive an eradication attempt as proposed by Brown et al. (2013). As a result, best-practice guidelines related to the delay between bait applications were deemed insufficient to successfully eradicate rodents on tropical islands. In response, a workshop was arranged to identify, then apply, new recommendations to address factors which may have contributed to a lower success rate on tropical islands compared to temperate rodent eradications (Keitt et al. 2015). This effort resulted in a panel of international experts developing best-practice guidelines specific to rat eradication on tropical islands.

Increasing the time between bait applications from 10 days as suggested by Broome et al. (2017) for temperate rodent eradications to three weeks between bait applications and designing the second application to duplicate the first is now recommended (Keitt et al. 2015). This addresses several risks including risks associated with rats breeding aseasonally. The extended time between applications consciously coincides with the end of the window when weaned juveniles would be emerging from nests and exposed to bait. Making the second application more robust (i.e., increasing the baiting rate to match the first application) attempts to ensure sufficient bait is available for the remnant population. As a result, a possible temporal and spatial gap in bait availability is mitigated and all rodents will be exposed to bait (Keitt et al. 2015). Similar to a successful follow-up attempt on Desecheo Island (Will et al. 2018), this guideline should be incorporated into a future eradication attempt on Wake Atoll. As a result, no further research to inform the period between bait applications is necessary to provide a high likelihood of eradication success.

Recommendation for #8

- We consider this knowledge gap filled by recommending adherence to the best management practices detailed in Keitt et al. (2015).

Factors Impacting Rodent's Interest to Eat a Lethal Dose of Bait

***Cause of Failure #9*:** "Prior long-term use of rodent baits and bait stations may have caused some increased tolerance to toxicants and/or aversion behavior amongst commensal rodent populations."

Awareness of anticoagulant tolerance and resistance has resulted in a growing interest to demonstrate efficacy of rodent control products, particularly on populations subjected to prolonged rodenticide exposure (Bailey and Eason 2000, Buckle and Prescott 2012). Recent examples of research on this includes brodifacoum lethality studies conducted on black rats (*Rattus rattus*) and mice (*Mus musculus*) on Lord Howe Island (NSW, Australia; Wheeler et al. 2019), Floreana Island (Galapagos, Ecuador; Island Conservation 2018) and on *R. exulans* on Wake Atoll (Mosher et al. 2008, Shiels et al. 2015). Although trial methodology differed between studies, results do not indicate that prior long-term use of rodent baits caused a tolerance to brodifacoum.

It is our opinion that tolerance was not a factor in the failed eradication based on evidence generated by Shiels et al. (2015), Mosher et al. (2008) as well as the prevalence, density and pattern of detection of surviving individuals

post-implementation (Island Conservation 2013, Griffiths et al. 2015). Aversion to bait and/or bait stations is discussed elsewhere in the document. We propose that this knowledge gap has been sufficiently addressed by Shiels et al. (2015).

Cause of Failure #10: "Results of bait acceptance and bait toxicology trials during the Feasibility Study should have triggered concern amongst operational planners (and been reflected in subsequent planning or research) that some rats on Wake Atoll had either bait aversion or bait tolerance issues."

Bait aversion or aversion to bait stations is a regular concern amongst practitioners. As a result, best practice references are routinely used to guide operations. Recommendations generally include ceasing all use of control products (e.g., rodenticide bait) that are intended to be used in the eradication for two years prior to implementation; this timing coincides with the lifespan of a rodent potentially adverse to a bait station or bait matrix (C. Hanson, pers. commun.). Additionally, bait stations should be installed at least one week or more before implementation in an effort to reduce potential neophobia (Broome et al. 2011). Lastly, minimizing the necessary change in a rodent's behavior is likely to increase their interest to encounter and consume bait. As a result, bait placed on a tray or paper plate (best) is considered more accessible than bait in a tube (better), which is more accessible than bait within an enclosed bait station (good).

Recommendations for #9 and #10

- Looking forward, we do not see a need for additional scientific study to address bait aversion or aversion to bait stations unless novel bait and/or stations are proposed for use. Alternatively, a revision of regulatory language and reduced on-site restrictions which more closely align with best practice guidelines is adequate to reduce these risks related to eradication success.
- No further research on this potential cause is required unless novel bait and/or bait stations are proposed for use. Mitigation of this risk is possible through future management actions. Bait tolerance was addressed above and in Shiels et al. (2015).

Cause of Failure #11: "Rats were assumed and later proven to be breeding during the baiting operation, and a small proportion of the *R. exulans* population may have exhibited atypical behavior that meant they did not eat bait, and/or some juveniles within nests or in subsequent post-emergence did not have access to bait."

Cause of Failure #12: "Anecdotally, there were abundant alternative natural food options (as per usual on Wake and many tropical islands) present at the time of the baiting operation, including obviously targeted foods such as ironwood seeds, and termite hatches very close to the time of baiting, and this could have exacerbated any bait palatability or bait aversion issues."

Aseasonality, mild climate, and regularly available food resources presents conditions to support breeding throughout the year on Wake Atoll. Expanding the time period between bait applications to three weeks and making the second bait application as robust as the first is considered appropriate to address the risk of rodents breeding through the operational window, minimizing temporal and special gaps in bait availability (Keitt et al. 2015). Although this is the case, factors contributing to rodent fecundity, including a high prevalence of alternative food sources, may increase the proportion of rodents breeding, emergent young, and statistically elevate the risk that some rodents may not have access to bait or may not have interest in bait (Griffiths et al. 2014). As a result, it is ideal to target periods of the year where rodent breeding and accessibility to desirable alternative food sources are at their lowest (Broome et al. 2017).

As mentioned previously, research with the objective to demonstrate trends in rodent abundance, breeding cycles and status, seasonal trends in local food sources (e.g., termites) and climate will help indicate appropriate bait application window/s (Griffiths et al. 2014, Keitt et al. 2015). Note that research will aid in selecting an implementation window and prescribing an application rate, while annual variation presents inevitable risk to project success relying on previously collected data. For a future attempt, a rapid assessment of rat body condition and alternative food availability should be conducted just prior to implementation. Results from this assessment should be discussed with partners and if conditions on island are no longer representative of planning conditions, then the decision to proceed with the eradication should be evaluated (Keitt et al. 2015).

It is assumed that alternative food sources will be available regardless of the time of year on Wake Atoll. As a result, bait products used for eradication must offer a high likelihood that all rodents will consume the bait when encountered in their natural environment. The palatability of bait has since been trialed on Wake Atoll. Results indicate that the bait matrix used in 2012 was attractive and more palatable than naturally available food sources including nutsedge, ironwood, noni, and heliotrope (Shiels et al. 2015). As a result, no support can be found to validate Brown et al. (2013)'s suggestion that a proportion of the *R. exulans* population may have atypical behavior resulting in individuals that did not eat bait. It is likely that rodents did not have access to bait, further supporting an expanded time-period between bait applications to three weeks as recommended by Keitt et al. (2015).

Recommendation for #11 and #12

- Research with the objective to demonstrate trends in rodent abundance, breeding cycles and status, seasonal trends in local food sources (e.g., termites) and climate will help indicate appropriate bait application window/s.

Cause of Failure #13: "If bait coverage was an issue, it was an issue only for *Rattus exulans*, and not for R. tanezumi, which appears to have been eradicated. This may have been the result of chance alone, but it suggests a behavioural or niche separation that had not been adequately determined prior to the operation and which remains unknown."

The successful eradication of *R. tanezumi* removes the

risk that behavioral or niche separation may impact subsequent efforts to remove *R. exulans* from Wake Atoll. Future planning that adheres to rules outlined by Cromarty et al. (2002), with particular focus on placing all animals at risk by eradication techniques, will provide a high likelihood of removing *R. exulans* from Wake Atoll. Actions outlined elsewhere in this document are sufficient to accommodate for this rule. No further research is considered necessary.

Factors Associated with Planning and/or Management

Cause of Failure #14: "Commensal rodent eradication methodology was not ideal, and commensal waste management did not go according to plan, meaning there were identifiable risks including possible baiting gaps within buildings or in merging of treatment methodologies, doubts over comprehensiveness of coverage, possible alternative food sources, and possible competitive exclusion from bait stations."

Planning for a future operation should follow a structured project planning process. A freely-available example of this can be found within Pacific Invasives Initiative's rodent eradication resource kit (http://pacificinvasivesinitiative.org/rce/). Peer review of key planning documents including the feasibility plan, baiting strategy, and commensal management plan should be conducted by individuals experienced in rodent eradication. This is considered a critical part of the planning process to head off foreseeable risks as well as develop successful management strategies.

Additional research to inform planning should include a social engagement campaign which gauges and manages residents' support, or tolerance, of the proposed eradication and associated actions. Examples of such campaigns have occurred on Lord Howe Island, Kayangel Island, and Floreana Island, and include the development of individual property agreements that formalize what participation in the project entails (C. Hanson, pers. observ.).

Management action should include a rapid assessment prior to implementation that thoroughly assesses all risks to project success (Keitt et al. 2015). Ideally, personnel representing each operational planning component are provided the opportunity to evaluate project readiness and contribute to discussions weighing cost versus impacts of proceeding with the project in light of any identified risks. No further field research is necessary, although measures used in the first eradication attempt should be evaluated for areas for improvement and a literature review should be conducted to evaluate, and possibly incorporate, methods and strategies used to target rodents on similar projects implemented since this report was developed.

Recommendation for #14

- Additional research to inform planning should include a social engagement campaign which gauges and manages resident's support, or tolerance, of the proposed eradication and associated actions.

Cause of Failure #15: "The Wake Atoll project was a challenging and ambitious project, a step up in complexity from most previous eradication projects. The entire project possibly suffered from under-resourcing, while the confidence of implementing agencies toward eradication here was not matched by appropriate levels of preparedness in some aspects of the planning and implementation. The obvious complexities of the project demanded more thorough and detailed early planning, particularly with regard to baiting strategy for the pemphis habitat and underground structures, the possibility of bait-averse rats, the resource requirements and strategy around hand-baiting. Greater resources were required in some aspects of the implementation of the operation. Shortfalls in resourcing and preparedness can accentuate risk of errors."

Cause of Failure #16: "The eradication inexperience of many staff involved in the Wake project may have elevated the risk of errors being made."

Future planning and implementation efforts should seek to incorporate the highest level of experience and an appropriate number of staff with an eradication ethic to address complexity and meet all project needs (Thomas et al. 2017). At a minimum, Broome et al. (2011) suggests that "at least 50% of all staff should have prior eradication experience if at all possible, so each 'novice' can be assigned an experienced on-site 'mentor' or supervisor." Compromises in resourcing and preparedness should be assessed when evaluating risks as a lack of eradication ethic, commitment to the project, or lack of experience may reduce the likelihood of eradication success.

Furthermore, lessons learned which are proposed by Brown et al. (2013) and Griffiths et al. (2014) should be evaluated throughout the planning process to ensure implementation is offered the greatest chance of achieving the eradication of *R. exulans*. Although not considered necessary, DNA analysis to measure relatedness within the remnant *R. exulans* population is recommended to indicate the extent of survivorship after the 2012 eradication attempt (Griffiths et al. 2014). Results of the analysis will suggest if significant changes are warranted to future operational methods and strategies (Amos et al. 2016).

Recommendation for # 15 and #16

- None necessary, although consider DNA analysis to measure relatedness within the remnant *R. exulans* population to indicate the extent of survivorship after the 2012 eradication attempt.

AUTHOR CONTRIBUTIONS

Chad Hanson was the primary preparer of this report, with additional Island Conservation input and review by Richard Griffiths. Kristen Rex is the sponsor agency representative for AFCEC and contributed substantive comments and review. Peter J. Kappes provided substantial comments and review. Shane R. Siers coordinated and administered funding and agreements, project oversight, and contributed substantial comments and review.

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