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Rodenticide application strategies for intertidal rat habitats

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Abstract

Context. Successful eradications of invasive rats from islands are paying tremendous conservation dividends, but failed eradications are economically and environmentally costly. For an eradication using rodenticides, every rat in every habitat must have sufficient exposure to toxic bait to receive a lethal dose. A post-operational review of a failed rat eradication on Wake Atoll, central Pacific Ocean, suggested that inadequate treatment of an intertidal habitat within the lagoon might have caused or contributed to the failure to kill all Polynesian rats (*Rattus exulans*), which have since recovered in number. This habitat could not be treated by aerial broadcast due to concerns about loss of bait to tidal action and perceived contamination of the marine environment.

Aims. In preparation for a second attempt, we developed two alternative bait application strategies to distribute enough bait for a long enough period of time to successfully target rats, while minimising bait entering the ocean.

Methods. We used camera traps and experimental bait provisioning methods to document rat foraging in the target habitat and uptake of bait. We developed two baiting strategy alternatives, and employed one of these strategies in a placebo bait application to demonstrate bait uptake by rats foraging within this tidally inundated habitat.

Key results. Our results show active foraging by rats in the target habitat. Provisioning of placebo bait by various means preventing bait spillage into the marine environment was followed by heavy feeding by rats and minimal bait interference by crabs.

Conclusions. We consider it likely that such a bait application strategy will be considered as an alternative during a future eradication attempt on Wake Atoll.

Implications. The techniques we explore here will be useful for rodent suppression in other wetland areas requiring rodent control while protecting sensitive aquatic resources.

Additional keywords: bait uptake trial, contamination mitigation, rodent eradication, rodenticide application strategies.

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Introduction

Invasive rats (*Rattus* spp.) have negative impacts on threatened species and ecosystem functioning (Towns *et al*. 2006; Mulder *et al*. 2009), particularly on islands. Eradications of invasive rats from small islands hold significant promise for recovering threatened species, habitat integrity and ecosystem services (Towns 2009; St Clair *et al*. 2011; Russell and Holmes 2015). However, rat eradications on tropical islands are 2 to 2.5 times as likely to fail as on temperate islands (Russell and Holmes 2015). When eradication fails, it is not only because of tropical climatic factors, but also geographic and ecological characteristics of tropical islands and complexity of project implementation (Holmes *et al*. 2015).

Rodent eradications on all but the smallest of islands typically involve the aerial broadcast of a pelleted rodenticide product. Drift of bait pellets from the intended treatment swath during aerial application can result in unintended bait spills into marine or freshwater environments, particularly under windy conditions. While there have been no documented long-term ecological consequences of rodenticide bait entering the marine environment, regulatory constraints may force eradication practitioners to avoid or minimise such aquatic inputs. Conversely, a regulation-driven excess of caution may lead to under-treatment of near-shore environments, leaving gaps in coverage that could lead to eradication failure. Effectively delivering an adequate amount of bait into the activity area of every rodent, while avoiding contamination of aquatic environments, may be particularly difficult when rodents forage in permanently or tidally inundated areas (Harper *et al*. 2014; Samaniego-Herrera *et al*. 2017). Failure to adequately treat such habitats can lead to failed eradications, which are economically and environmentally costly and erode public confidence in future actions. Development of strategies to effectively treat such problematic areas will increase the likelihood that an eradication attempt will be successful.

In 2012, Pacific Air Forces (PACAF), 611 Civil Engineer Squadron (611 CES), together with the United States Fish and Wildlife Service (USFWS) and Island Conservation (IC) undertook an attempted eradication of Asian house rats (*R. tanezumi*) and Polynesian rats (*R. exulans*) on Wake Atoll in the central Pacific Ocean. Wake Atoll is comprised primarily of Wake Island, Wilkes Island, and Peale Island. This project was successful at eradicating *R. tanezumi*, but failed to eradicate *R. exulans* (Brown *et al*. 2013). Polynesian rat populations have since recovered and are abundant. In a post-action review, Brown *et al*. (2013) indicated that lack of testing of techniques for treating *Pemphis acidula* shrubland habitat (hereafter 'pemphis') was a significant planning oversight, and one of the potential causes of the failure to eradicate Polynesian rats. Pemphis habitat is predominantly vegetated with pemphis shrubs on saturated sandy substrates. Pemphis is a closely branched shrub with very hard wood, which lines much of the atoll's lagoon margin, as well as a handful of small brackish ponds and retention basins. As per the Clean Water Acts (CWA), National Pollution Discharge Elimination System (NPDES) Pesticide General Permit (PGP) MWG87A005, obtained by the US Air Force 611 CES for this aerial application, it was determined that aerial baiting of the intertidal pemphis habitat would not be allowed by US regulatory standards. Tidal action could flush away pellets, making them unavailable for consumption by rats as well as leading to possible or perceived undesirable contamination of the marine environment. Additional baiting strategies for the pemphis habitat were not investigated.

Pemphis habitat is most fully developed in the lagoon 'elbow' of Wake Island (Fig. S1, available as Supplementary Material to this paper), where it comprises a complex mosaic of dense pemphis thickets, a patchwork of prostrate mat-forming seaside purslane (*Sensuvium portulacastrum*), saturated sandy sediments, tidal pools and channels (e.g. Fig. 1) covering over 40 ha. The combination of dense, nearly impenetrable pemphis thickets and yielding sandy sediments make access by foot inconvenient in some areas and nearly impossible in others. While most other pemphis zones lining the lagoon are in drier, rarely inundated tidal or surge zones, this marshy area is frequently inundated, with little permanently emergent substrate. Previous assessments suggested that rat use of this habitat was abundant and widespread (Brown *et al*. 2013).

Fig. 1. Marshy intertidal pemphis habitat on Wake Island. Lack of a strategy for treating this habitat while minimising toxic inputs into the marine environment may have led to the failure of the 2012 rat eradication attempt.

Our objectives were to: (1) confirm use of pemphis habitat by Polynesian rats; (2) investigate the role non-target species (primarily crabs) might play in bait consumption; (3) evaluate the utility of standard and novel rodenticide application techniques; (4) develop practical strategies to apply sufficient bait to ensure exposure of all rats foraging in pemphis habitat while minimising toxic inputs into the marine environment; and (5) implement one of the application strategies using placebo baits to assess bait uptake by rats.

Methods and results

Study site

This study took place from 14 April to 10 May 2016 on Wake Atoll, central Pacific Ocean (19°18′N 166°38′E), a 7.1 km^2 coral atoll 2416 km east of Guam, 3698 km west of Honolulu, Hawaii, and 3204 km south-east of Tokyo. It is considered one of the United States' Minor Outlying Islands and is administered by the United States Air Force.

Bait products

We employed two products manufactured by Bell Laboratories, Inc. (Madison, WI): a placebo/inert formulation of their Brodifacoum-25W pellet product and their standard DETEX non-toxic monitoring and tracking bait; both incorporate pyranine as a biomarker to indicate consumption via fluorescence under UV light of external orifices, gastrointestinal tract contents or faeces of rats. Brodifacoum-25W surrogates were chosen because this was the toxicant used during the 2012 eradication attempt (Island Conservation 2013). The product to be used in a future eradication has yet to be determined.

Rat use of pemphis habitat

Fundamental to the question of whether failure to treat pemphis habitat led to the survival of Polynesian rats is whether rats actually use this habitat in a way that requires treatment. Although it is clear that rats will not nest in frequently inundated soil burrows, they might burrow in drier embankments directly at the edge of the inundation zone, or nest in trees over or near such areas, where over-avoidance of the marine environment might have left areas undertreated. This might be particularly meaningful if rats preferentially forage in the pemphis habitat as opposed to inland where rodenticide pellets would have been abundantly available.

Rat movement and foraging within this habitat was confirmed by occasional sightings of rats by project personnel during field activities, by infrared photography on sentinel baits and by considerable bait block consumption during our later trial bait application.

Additionally, we deployed tracking tunnels (e.g. Brown *et al.* 1996; Whisson *et al.* 2005) to index rat activity in the area before baiting. We placed 30 tunnels baited with coconut chunks and swabbed with a mixture of printer's ink and mineral oil within pemphis habitat and monitored them for 4 days. To avoid inundation, tunnels were restricted to the road edge and a raised causeway within the plot. Over 120 tracking tunnel nights, 90% of tracking pads showed rat prints, clearly demonstrating extensive use of the emergent portions of this habitat by rats.

Two of our candidate methods for treating pemphis thickets relied on entanglement of baits in the tips of pemphis shrubs to avoid falling into tidally inundated areas. However, we were uncertain whether rats would forage in the terminal branches of the shrubs where baits would be suspended (as much as 2 m above the substrate). We confirmed foraging in terminal branches through infrared camera images and characteristic chew marks on sentinel bait blocks suspended at the tips of vegetation.

Bait competition by crabs and risks to other non-targets

Another question regarding eradication failure is whether non-target consumption of baits resulted in insufficient bait availability to rats (Brown *et al.* 2013). Crabs readily consume rodenticide baits, and rodenticide residues have been found in various crab species following rat eradication efforts (Pitt *et al.* 2015), but crabs have not been shown to be affected by consumption (Pain *et al.* 2000). However, crabs may significantly interfere with island rodent eradications by competing with rats for available baits (Wegmann *et al.* 2011), and their impacts on bait availability should be accounted for before or during eradication attempts (e.g. Berentsen *et al.* 2014).

We observed three crab species within the pemphis habitat on Wake Island: the strawberry hermit crab (*Coenobita perlatus*), fiddler crab (*Uca* sp.) and horned ghost crab (*Ocypode ceratophtala*). Fiddler and ghost crabs are restricted to the frequently inundated sand and silt sediments within the habitat matrix. Time-lapse camera monitoring of bait pellets on the ground within hyper-abundant fiddler crab colonies indicated no interactions of fiddler crabs with the bait pellets and a complete avoidance of these baits. Even after pellets had been softened by tidal inundation, fiddler crabs continued to avoid them. Although fiddler crabs on Wake Island did not appear to interact with bait pellets, brodifacoum residues were found in fiddler crabs following a rat eradication on Palmyra Atoll (Pitt *et al.* 2015). We rarely observed horned ghost crabs, and never observed them to interact with any bait.

Hermit crabs were extremely abundant on the emergent land mass of Wake Island, but their activity was restricted to the dry and infrequently inundated land areas and margins of the frequently inundated areas at low tide. During time-lapse photography of bait pellets on the dry land portions of the treatment area, hermit crabs were observed interacting with bait pellets, but the actual rate of pellet removal by crabs could not be determined. At no time did we have indication that hermit crabs interfered with any elevated baits or bait stations. There were no recorded indications of interactions between crabs and rats, e.g. bait guarding or other exclusionary behaviours preventing rats from obtaining baits.

Some bird species may also consume baits, as has been indicated during other eradication efforts (e.g. Pitt *et al.* 2015), and casualties from bait consumption have been reported (Samaniego-Herrera *et al.* 2017). In the post-operation report of the 2012 eradication attempt, Island Conservation (2013: p. 42) concluded there was 'no reason to believe any shorebirds were exposed to the bait'; however, a *USA Fish and Wildlife Service Annual Migratory Bird Treaty Act* (MBTA) report from 2013 declared incidental take of one Pacific golden plover

(*Pluvialis fulva*) and one ruddy turnstone (*Arenaria interpres*) as a result of the eradication attempt, though ingestion of bait was not confirmed. The only other non-target organisms regularly observed in the pemphis habitat were nesting red-tailed tropicbirds (*Phaeton lepturus*). We observed no interactions of adult tropicbirds with bait pellets or any other application type; there were no chicks observed during this time.

Tool development and evaluation

Typical uses of helicopter baiting, hand broadcast or bait stations would not effectively treat pemphis or other frequently inundated or semi-aquatic habitats while minimising bait spills into aquatic resources. Therefore, we experimented with various modifications of typical treatment strategies to develop one or more baiting methods to suit our objectives. For each of the baiting methods we devised and tested, we considered the following criteria: bait spillage into the marine environment; scenarios under which the tool would be suitable; precision of application; ability to preclude access by non-targets; requirements for direct access by personnel; ability to retrieve unconsumed bait; and the amount of labour required. Tools were assessed independent of the current labelled restrictions on use of active-ingredient rodenticide formulations, and their future applications would be dependent upon obtaining supplemental permissions.

Broadcast of pellets

Landscape-scale rodenticide application is typically performed by aerial broadcast from a helicopter. However, in the USA, aerial broadcast is not considered suitable for tidally inundated areas because of the perceived risk of rodenticide entering the marine environment. In a complex mosaic of tidally inundated habitat, there may be small islands of substrate that remain emerged for the duration of the eradication effort. These could be aerially 'trickle-baited', where the helicopter hovers or moves slowly, at a low altitude, over emergent land and bait is slowly and precisely dispensed. Hand broadcast of pellets allows for precision in pellet application directly up to the edges of inundated areas. However, personnel must be able to access the area or at least be within the distance to which pellets can be reliably thrown (~5 m). Within the pemphis habitat on Wake Atoll, there is not sufficient inaccessible habitat above the high-water line to necessitate trickle-baiting; all such habitat could be treated by hand broadcast.

Pellets are applied directly to the substrate, where they can easily be taken by hermit crabs or other non-targets, making the bait insufficiently available to rats. This can be overcome by increasing bait application rates to the point that more pellets are available than crabs can remove, but this also incurs greater expense and toxic inputs into the environment. There is no way to retrieve excess unconsumed bait pellets; however, since they are applied to semi-permanently emergent substrates the toxins are more likely to be bound in soils and degraded before ending up in the marine environment, barring extreme rain events, which may wash toxins into the nearshore environment.

Bait block 'bolos'

Bait 'bolos' used for canopy baiting in previous island eradication attempts (e.g. Wegmann *et al*. 2008) comprised two paper parcels of rodenticide pellets connected by a string and launched by slingshot. We determined that paper parcels would not be appropriate since, once they were compromised, the pellets would fall to the inundation zone below. Instead we created bolos of two bait blocks tied together on ~1 m of mason's twine (Fig. S2). These bolos could be easily thrown 25 m or further with relative precision. Throwing range could be increased by use of a slingshot (e.g. Wegmann *et al*. 2008) or other launching device. We found thrown bait bolos to be a practical means of suspending bait in inaccessible pemphis thickets within the inundation zone. However, within this habitat, once thrown, there is no practical method to locate and remove uneaten product, though Samaniego-Herrera *et al*. 2017 reported methods for deploying, locating and recovering uneaten bait from mangrove habitat. All bait delivered in this way would either be consumed or degrade and eventually fall into the inundation zone, causing some amount of marine contamination. Bait bolos are exposed to non-target organisms, but are not easily untangled and removed and, by virtue of being suspended well above the ground, are less accessible to hermit crabs. We did not observe hermit crabs or other non-targets interfering with bait bolos during any of our activities.

Bait block 'daisy chains'

Similar to bolos, we considered stringing multiple bait blocks spaced along longer stretches of twine (Fig. S3). Conceptually, these could then be stretched or thrown over pemphis thickets. A theoretical advantage of the interconnected bait blocks is that the excess unconsumed bait could be recovered by pulling the line back to the point from which it was applied.

However, throwing chains over vegetation while achieving maximum block spread without tangling proved to be challenging. Daisy chains were time consuming to produce, prone to tangling, and their application was inaccurate. Retrieving unconsumed blocks also proved impracticable because blocks and lines became firmly entwined in pemphis branches and exertion on the line caused bait blocks to crumble, resulting in a significant portion of the blocks falling directly to the ground in the inundation zone. These problems led us to eliminate this concept as a treatment option.

Elevated bait stations

Containment of baits in bait stations provides protection from weather and consumption by most non-target organisms; however, most bait stations are designed for use on terrestrial surfaces and their standard use patterns in tidal habitats would lead to frequent inundation and degradation of the baits contained. To prevent inundation, bait stations must be elevated above the high-water mark. This can be achieved by constructing an elevated platform or by affixing stilts; these must not be so high that a rat cannot jump to the entrance of the bait station. Pitt *et al*. (2011) recommends heights no greater than 40 cm for all rats to be able to gain access. In dense pemphis thickets, bait stations can be affixed to the vegetation effectively using the pemphis itself as 'stilts' that rats can easily climb for access.

Time-lapse infrared camera monitoring of a prototype bait station on stilts indicated repeatedly frustrated attempts of hermit crabs to access the bait station while rats easily gained access. There was no evidence of tampering by hermit crabs in any implementation of bait stations elevated in vegetation; such results are likely to vary on other islands with other types of crabs.

We experimented with traditional box-type bait stations but found the J.T. Eaton Top Loader ('T-type') bait stations (J.T. Eaton, Twinsburg, OH) to be more easily affixed to vegetation and serviced (Fig. S4). Bait stations can be placed precisely anywhere that personnel can access. However, large, dense thickets of impenetrable pemphis might be inadequately treated with bait stations around the perimeter alone, and supplemental treatment of thicket interiors by other means might be necessary.

Floating bait stations

Rat movement was observed within expanses of habitat with no tall vegetation from which to suspend bait blocks or bait stations. These low areas underwent high tidal ranges, making bait stations on platforms or stilts impractical and potentially difficult for rats to enter at low tide. We experimented with floating bait stations that could be accessed by rats at ground level at low tide, and then float on the incoming tide to avoid inundation. Two basic design concepts were explored: free-floating platforms tethered to a stake driven into the substrate; and stations that slid up and down a stationary pole driven into the substrate.

Free-floating platforms were constructed from 0.6 m × 0.6 m of 3.8-cm thick sections of closed-cell extruded polystyrene foam insulation board, with standard box-type bait stations affixed at the centre (Fig. S5, left). Approximately 1.5 m of paracord was tied from the corner of the board to a section of conduit pipe used as an anchor stake. While there was concern that these platforms may capsize in the wind, this did not occur during prototype trials and bait remained in good condition.

Centre-pole designs incorporated a 1.5-m long, 20-mm diameter extruded metal tube electrical conduit (Fig. S5, right). The first experimental design included a standard box bait station affixed to a foam platform with a hole drilled down through the middle through which the centre pole was inserted (Fig. S6, left). This proved functional, though the top hole let in rain water and the fixture had to be removed from the pole in order to access the interior of the bait station. A second suite of designs incorporated (1) a foam platform with a polyvinyl chloride guide tube or (2) a modified football-type net float, both in conjunction with the T-type bait station (Fig. S6, right). These latter configurations were easier to construct and service than the design with the box-type bait station, and were used in the bait uptake trial below.

In most cases, the prototype floating bait stations were successful at keeping baits from being immersed and were easily accessed by rats during low tides. These designs are suitable for treating areas with high tidal fluctuations and no existing vegetative structure to which to affix bait stations. Whether it would be necessary to place baits in these areas was not determined. During an eradication attempt, it may be advisable to implement such measures out of an abundance of caution.

Individually affixed bait blocks

We considered affixing individual bait blocks directly to vegetation above the high-water line using wire twist ties or plastic cable ties. However, this is only practical in places where personnel could easily access, would provide no protection from non-targets or environmental exposure, and would make retrieval of unconsumed baits difficult. The use of other methods that better met our criteria for tool selection made this option unnecessary.

Application strategies

After our assessments of the advantages and disadvantages of candidate tools, we developed two potential strategies for treating the primary pemphis habitat within the Wake Atoll lagoon.

Tailored application to mapped features

This approach entails mapping the microhabitats within the area to be treated, delineating the entire area into the following sub-types:

(1) *Lands above the high-water mark, accessible by personnel.* These would be treated by hand broadcast of pellets, with pellets thrown up to 5 m into inaccessible thickets; pellet treatment may be augmented or supplanted with bait station use.
(2) *Lands above the high-water mark, inaccessible.* If impenetrable pemphis thickets are so large that perimeter treatment with pellets or bait stations is insufficient to ensure that all rats will be exposed to enough bait, bait bolos can be thrown or launched into the interiors.
(3) *Frequently inundated tall vegetation, accessible by personnel.* These areas would be treated with bait stations affixed into vegetation at 0.5 m above the high-water line.
(4) *Frequently inundated inaccessible thickets.* Thickets would be treated on the perimeter with elevated bait stations affixed to the vegetation, with bait bolos thrown or launched into thicket interiors.
(5) *Fully inundated areas with no emergent vegetation.* Large expanses of such areas would be treated with floating bait stations.

Once these types of microhabitat formations are mapped out, treatments would be planned based on the extent and arrangement of these features. Features to receive pellet or bait bolo treatment would have areas calculated, and a prescribed amount of bait would be calculated. Each feature would have a bag of the pre-measured amount of pellets or bolos to be applied. Areas to be treated with bait stations should have bait stations at a density of no less than achieved by a grid of bait stations at 25-m intervals (the spacing used to control residual rats sighted after the previous eradication attempt; Island Conservation 2013), or ≥16 stations per hectare.

This approach requires accurate mapping and familiarity with the habitat for personnel to navigate to and treat the mapped features. Personnel would need to be well trained to navigate by map and use GPS for guidance and for treatment mapping.

The treatment manager would need to have access to personnel with GIS mapping capabilities. Ecological impacts of foot traffic by project personnel would be widespread but diffuse.

Gridded bait stations

Alternatively, a system of evenly spaced transects running perpendicular to the shore could be established, irrespective of the variation in the habitat type encountered. This would require no more planning or mapping than establishing transect spacing and following a compass bearing while clearing and flagging a trail. When dense thickets of pemphis are encountered, clearing crews would use bush-clearing tools to cut a narrow straight path through the thicket. Transects would continue until they reached the permanently inundated interior of the lagoon. Once the transect is cleared and flagged, bait stations would be installed at increments equal to the transect spacing to establish a grid. Bait stations may simply be placed on dry ground or tied above the high-water line in inundated vegetation. Where there is no vegetation in inundated areas, floating bait stations might be employed. A simple grid layout requires no special mapping or navigation skills and can be easily established and maintained by lay personnel.

Containment of all bait in bait stations creates essentially no contamination of the marine environment, minimises risk of access by non-targets, makes all unconsumed baits retrievable, and is more consistent with label restrictions on bait block usage (making supplementary approvals unnecessary or more easily obtained). However, bait stations can make rodent access to baits more complicated. Some conservation managers favour hand broadcast over bait stations because of the perception that some individual rats will not enter a station.

Although incurring more labour cost to cut through pemphis thickets, this labour may be performed by environmental or support personnel already on-island, reducing the costs associated with transportation and billeting of personnel with specialised training. Foot traffic associated with establishing and maintaining the grid would be reduced throughout the affected area, but be more intense along the transects. Wake Atoll natural resources managers would determine whether alteration of the pemphis habitat is justified by the benefits of this approach.

Trial application and bait uptake

Our objective for the trial application was to demonstrate an effective strategy for Polynesian rat control within pemphis habitat by provisioning ample bait with minimal spillage of bait into the marine environment. Follow-up trapping of rats occurred to validate that rats were consuming the baits by examination for biomarker fluorescence. Lacking equipment, manpower and environmental approval for clearing a system of transects, we chose to apply the ‘tailored application on mapped features’ strategy.

Feature mapping

We delineated a portion of the primary lagoon pemphis habitat that was representative of all microhabitat types to be treated, covering ~4.7 ha. Through review of aerial imagery and on-the-ground reconnaissance, we delineated areas of dry land that could be hand-treated with pellets and areas of impermeable pemphis thickets that required treatment by bait bolos with bait stations along the perimeter (Fig. 2; see also Fig. S7 for an alternative layout to treat the same area with a grid of bait stations).

Treatment and bait monitoring

Placebo baits were applied on 26 April 2015. We hand broadcasted 14 kg of pellets over 0.78 ha of dry land, comprising the road, elevated causeway and bordering vegetation. This matched the 18 kg ha^{-1} maximum labelled application rate for a first treatment with Brodifacoum-25W. We treated ~1.16 ha of impermeable pemphis thicket by distributing thrown bait bolos throughout each treatment block, entangling bolos in the vegetation above tidal height. We calculated the area of each block individually and distributed enough bait bolos to achieve the same 18 kg ha^{-1} application rate, distributing a total of 515 bolos. The remaining 2.76 ha were treated with 50 elevated T-type bait stations and six floating bait stations in the areas without emergent vegetation, for an average of 494 m^2 covered by each bait station, equivalent to a grid of bait stations spaced at 22 m. Each bait station was provisioned with four 20-g placebo bait blocks. See Fig. 2 for the distribution of bait application methods.

We selected 10 bait bolos and 10 bait stations to be monitored for condition and availability of baits. These were checked every other day for 14 days post-treatment. We also monitored pellet condition and persistence in three 1-m^2 monitoring plots containing six pellets each, for 7 days post-application, via daily visual checks and infrared time-lapse photography (Digital IR Model PC900, Reconyx, Holmen, WI). Cameras captured an image every 15 s, and images were used to identify and enumerate visitors to bait pellets. Bait pellets and bolos were not re-applied, nor were bait stations refilled.

By the end of the 14-day monitoring period, the majority of monitored bait bolos were completely consumed and most bait stations were emptied (Table S1 and Fig. S8). Bolos and bait station contents closer to the shoreline and causeway were consumed first. Five of the six floating bait stations had all bait consumed, and the sixth had 50–74% consumed.

By the sixth day, all pellets had been removed from the three monitoring quadrats (Fig. S9). Camera images revealed that Polynesian rats, hermit crabs and unidentified invertebrates (possibly ants) interacted with the pellets. All photographed pellet interactions occurred at night or in the cooler crepuscular hours. No birds or other non-target animals were seen in any of the photos, though we acknowledge that three plots is an insufficient sample to document infrequent occurrences. Rat interactions with baits rose from one on the first night to 60 by the sixth night, whereas hermit crab activity was relatively constant at low levels (Fig. 3). Rats exhibited food neophobia during the first 3 days – only 29% of photos (14/49) showed direct interaction with baits (handling/feeding). Rats were much more responsive to baits during Days 4–6, with 59% of photos (113/192) showing direct bait interaction (note relative positions of Polynesian rat bait interactions versus non-interactions in Fig. 3). Hermit crabs did not exhibit bait neophobia, with constant but low activity and bait interaction rates.

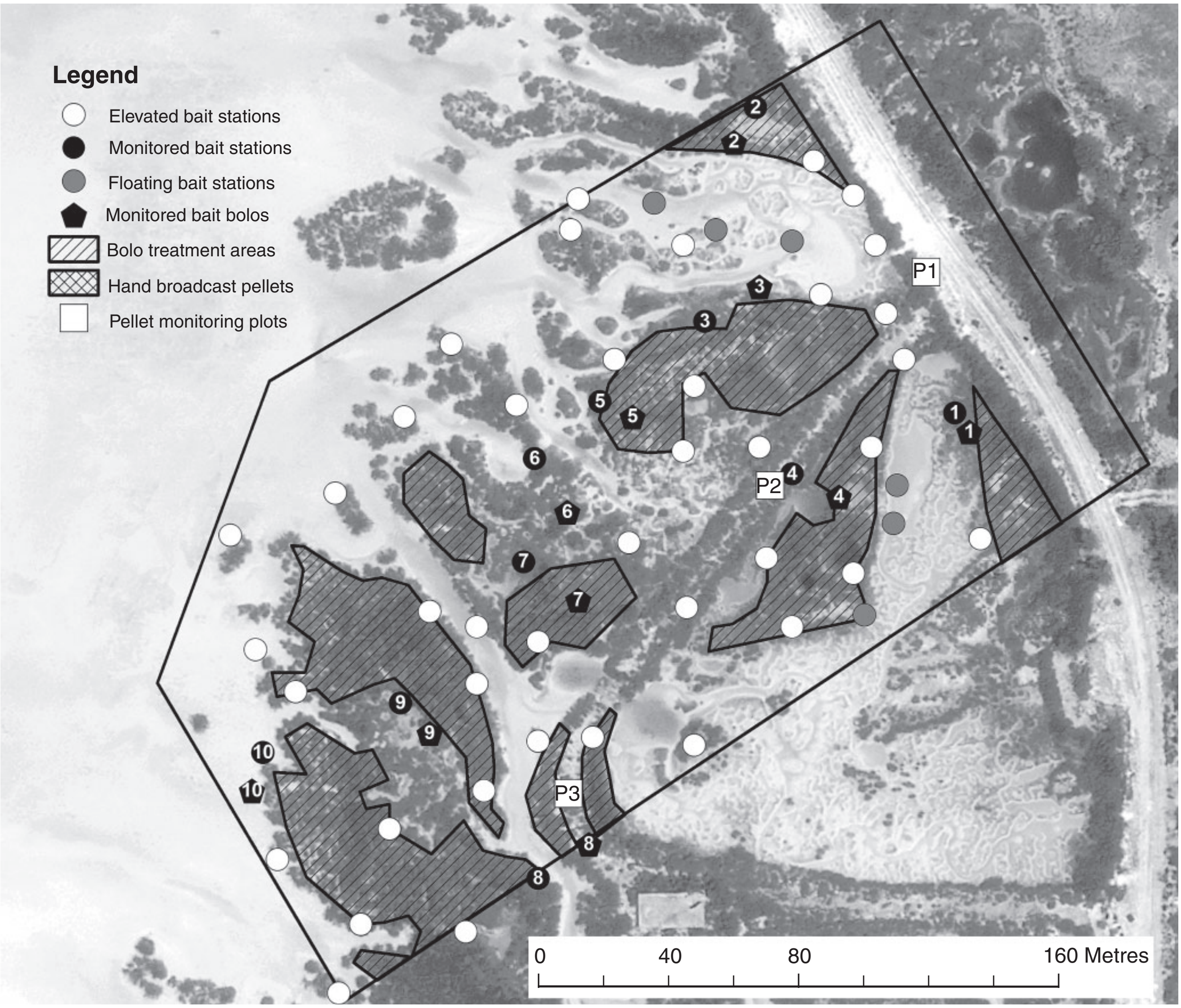

Fig. 2. Map of placebo bait treatment area and distribution of treatment types on Wake Island. Monitored bolo and bait station numbers correspond to Fig. S8.

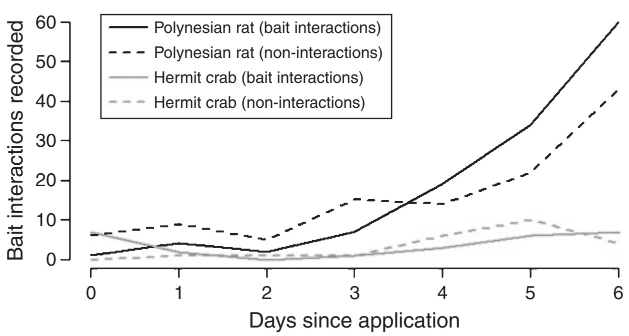

Fig. 3. Camera observations of Polynesian rat and hermit crab interactions and non-interactions with pellets in monitoring plots (all three plots pooled) within the study area on Wake Island. Non-interactions are photographic observations within the monitoring plot that do not indicate interactions with bait pellets.

The overall increase in rat observations after the third day is likely due to an increase in the number of rats using the study area as a result of the abundant food source constituted by the baits and/or overcoming of neophobia by rats. There was no similar increase in hermit crab activity. Both rats and crabs were photographically confirmed to have physically removed pellets from the quadrats, though we were unable to determine the proportion of pellets removed by each.

Rat collection and biomarker assessment

Post-treatment trapping was conducted to confirm bait uptake by rats. The majority of killed rats exhibited evidence of biomarker fluorescence (Figs S10, S11), confirming substantial bait consumption by rats. The study plot was too small to expect 100% marking of rats, which was not one of our study objectives.

Discussion

From our observations of rat activity in pemphis habitat, it is clear that failure to treat this area might lead to eradication failure. During the course of our field activities, we visited all other habitats indicated as pemphis on vegetation inventory maps (see Fig. S1). In most cases, other pemphis habitats were either on higher, drier, steeper coastal areas with little tidal inundation – which could be adequately treated by aerial broadcast or more precise hand broadcast – or were in wetlands that varied in water height more slowly, as a result of seasonal fluctuations in rainfall rather than frequent tidal movements, and could likewise be treated by pellets barring heavy rainfall events or strong storm surge.

At the application rate of 18 kg ha^{-1}, all monitored pellets were removed within 6 days, and the majority of bait bolos and bait station contents were consumed within approximately 10 days. While second-generation anticoagulants such as brodifacoum can kill after a single feeding, first-generation compounds such as diphacinone and chlorophacinone require sustained feeding over multiple days to be effective. Given our results here, a second application would be advisable after 6–10 days, and a third application might be advisable if first-generation anticoagulants are used. It should be noted that, during an active-ingredient treatment, consumption would decrease with time as lethally intoxicated rats begin to succumb. We suggest that the application rate of 18 kg ha^{-1} would be suitable for a first treatment, and that the timing and intensity of a second or third application should be guided by real-time monitoring of bait condition and bait persistence during the prior application.

Our camera monitoring of bait pellets on the ground did indicate frequent crab interactions, though we could not definitively identify how much bait was removed by crabs. Barring drastic temporal fluctuations in crab abundance or their consumption of baits, we suggest there would likely be little influence of crabs on the feasibility of rat control within pemphis habitat during future eradication actions on Wake Atoll; this determination should not be presumed to be valid on other islands with different crab communities. Pellets on the ground are at greatest risk of hermit crab interference, and monitoring of the persistence of pellets will indicate if supplementation is required to offset take by crabs. There was no observable impact of crabs on the availability of bait blocks in bolo or bait station configurations. Seasonal variation in crab activity and abundance should be assessed to determine if there is an optimal timing to apply baits while minimising bait interference by crabs. Aside from apparently discountable take by ants and occasional observations of crickets in bait stations, we observed no other non-target interactions with baits. The small number of red-tailed tropicbirds nesting within the treatment area appeared oblivious to bait pellets and other treatment options tested.

Rats and crabs having fed on baits will excrete a portion of un-metabolised toxicants into the marine environment, and tainted rat carcasses will constitute some level of marine inputs and potentially pose risk of secondary intoxication of scavenging marine life when the habitat becomes inundated. Rats have no terrestrial predators on Wake Atoll and do not pose appreciable secondary contamination risk; rat carcasses have been observed to be consumed by crabs within a few days (Samaniego-Herrera, pers. comm.). Unconsumed bait bolos will eventually degrade and fall into tidally inundated areas, and some thrown bolos are likely to fail to entangle in the vegetation and fall into the marine environment. If such inputs are deemed unacceptable, a strategy of gridded bait stations may be advisable. However, such a strategy would likely be labour intensive and require considerable clearing of vegetation through dense pemphis habitat to establish transects.

Of the bait configurations tested, we recommend hand sowing of pellets on elevated, drier ground, elevated bait stations where they can be reasonably accessed, and throwing of bait bolos into inaccessible/impenetrable pemphis thickets. Floating bait stations may be of some utility in areas likely to be frequented by rats but without sufficient permanently emergent vegetation to which to affix traditional bait stations, though we have no evidence to suggest that this might be necessary.

Use of the same biomarker in all bait products and delivery methods did not allow us to evaluate which method a given rat had consumed bait from. The intent of this study was not to test the relative efficacy of one delivery method against the others, but rather to tailor an application strategy that treated all microhabitats with a suitable delivery method. The high rate of bait consumption from all delivery methods demonstrates that each is effective at making baits available to rats and that rats foraged in all microhabitats treated.

Timing of eradications during dry seasons can increase chances of success; however, on tropical islands there may be minimal yet erratic fluctuations in rat populations and consistently available natural food resources (Russell and Holmes 2015). The favourable weather conditions experienced during our study period (only one notably heavy rainfall) resulted in sufficient bait longevity to ensure rats had ample opportunity to consume viable and palatable baits. Under less clement conditions, more frequent applications might be indicated if baits degrade more rapidly. Because heavy rainfall would more rapidly degrade exposed baits and hasten toxicant inputs into the marine environment (along with other operational disadvantages), it is obviously favourable that any eradication efforts target drier periods (e.g. Samaniego-Herrera *et al*. 2014).

The documented ecological impacts of rodenticide discharge into the marine environment during island rat eradication operations (e.g. Masuda *et al*. 2015; Pitt *et al*. 2015) have been relatively minor, with no observed long-term negative consequences. While small-scale fish mortalities have been observed (e.g. Pitt *et al*. 2015), these short-term costs have been offset by substantial conservation gains (Jones *et al*. 2016). In an extreme case of marine contamination by rodenticide baits, Primus *et al*. (2005) documented an accidental discharge of ~18 tonnes of rodenticide bait containing 0.002% brodifacoum into a New Zealand tidal marine environment resulting from a road transport accident. Samples of water, sediments, and marine species, including invertebrates, were taken from immediately after the spill to ~30 months after the spill. After the massive spill, congealed masses of dissolved bait material persisted in rock crevices and sheltered areas of the sea bed for at least 1 week. Between 36 h and 9 days after the discharge, water samples were below the minimum detection limit of 0.020 ppb. No dead fish were found, though it was acknowledged that mortality would be extremely difficult to measure in such mobile animals. The highest tissue residues found (0.41 ppm in one sample of a filter-feeding mussel) were low and dropped quickly to <0.05 ppm within a few months. This unprecedented incident led to no discernible ecological consequences; however, mussels did retain brodifacoum residues above the New Zealand food standard maximum residue level of 0.001 ppm to ~796 days. Contamination of the marine environment is of greater concern when marine resources are to be harvested for human consumption. To our knowledge, there are no documented cases of adverse human health effects from exposure to rodenticides through consumption of marine resources. The extent to which eradication practitioners will be compelled to minimise intentional or accidental marine inputs will be driven by case-specific risk assessments and regulatory constraints.

Conclusions

It is uncertain whether the failure to eradicate Polynesian rats from Wake Atoll could be attributable to failure to treat pemphis habitat. However, Polynesian rats on Wake Atoll do use the tidally inundated pemphis habitat, at least when food sources are present, and any future eradication attempts should ensure that ample bait is available in this habitat throughout the course of the eradication campaign. Careful application of baits will minimise undesirable inputs of toxicants into the marine environment. The techniques we explored and tested in the Wake Lagoon pemphis marsh may have much broader application wherever rodent control for conservation management is required in close proximity to sensitive aquatic environments.

Conflicts of interest

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