Applying lessons learnt from tropical rodent eradications: a second attempt to remove invasive rats from Desecheo National Wildlife Refuge, Puerto Rico

D.J. Will[1], K. Swinnerton[1, 2], S. Silander[3], B. Keitt[1,4], R. Griffiths[1], G.R. Howald[1], C.E. Figuerola-Hernandez[1] and J.L. Herrera-Giraldo[1]

[1]Island Conservation, 2100 Delaware Ave Suite 1 Santa Cruz, CA 95060. <david.will@islandconservation.org>. [2]Current affiliation: The Island Endemics Foundation, P.O. Box 1908, Boquerón, PR 00622. [3]U.S. Fish & Wildlife Service, Caribbean Islands NWR, P.O. Box 510 Boquerón, PR 00622. [4]Current affiliation: American Bird Conservancy, 4249 Loudoun Ave, The Plains VA 20198.

Abstract The introduction of invasive rats, goats, and rhesus macaques to Desecheo National Wildlife Refuge, Puerto Rico led to the extirpation of regionally significant seabird colonies and negatively impacted plant and endemic reptile species. In 2012, following the successful removal of goats and macaques from Desecheo, an attempt to remove black rats using aerially broadcast rodenticide and bait stations was unsuccessful. A review of the operation suggested that the most likely contributors to the failure were: unusually high availability of alternative foods resulting from higher than average rainfall, and insufficient bait availability. In 2016, a second, successful attempt to remove rats was conducted that incorporated best practice guidelines developed during a workshop that focused on addressing the higher failure rate observed when removing rats from tropical islands. Project partners developed a decision-making process to assess the risks to success posed by environmental conditions and established go/no-go decision points leading up to implementation. Observed environmental conditions appeared suitable, and the operation was completed using aerial broadcast of bait in two applications with a target sowing rate of 34 kg/ha separated by 22 days. Application rates achieved on the ground were stratified such that anticipated high risk areas in the cliffs and valleys received additional bait. We consider the following to be key to the success of the second attempt: 1) monitoring environmental conditions prior to the operation, and proceeding only if conditions were conducive to success, 2) reinterpretation of bait availability data using the lower 99% confidence interval to inform application rates and ensure sufficient coverage across the entire island, 3) treating the two applications as independent, 4) increasing the interval between applications, 5) seeking regulatory approval to give the operational team sufficient flexibility to ensure a minimum application rate at every point on the island, and 6) being responsive to operational monitoring and making any necessary adjustments.

Keywords: bait availability, environmental conditions, operational monitoring, regulatory approval

INTRODUCTION

Tropical islands are rich in biodiversity but are susceptible to invasive species. Invasive species are the leading threat to island biodiversity (Tershy, et al., 2015), with invasive rodents known to be particularly harmful (Towns, et al., 2006). Eradications have been successful in removing invasive species (Veitch, et al., 2011), allowing island species to recover (Jones, et al., 2016), however there has been a greater record of success on temperate islands than on tropical islands (Russell & Holmes, 2015).

The two rodent eradication attempts (failed, then subsequently successful) on Desecheo Island, Puerto Rico offer an opportunity to explore the challenges of tropical rodent eradications. Here, we highlight the key changes that were made to the operational strategy during the second attempt, the role of the recently developed recommended best practices for tropical rodent eradications from Keitt, et al. (2015), and chronicle the recently confirmed successful project.

Study area

Desecheo is a small (117.1 ha) hilly island (18° 23’ N, 67° 29’ W) situated in the Mona Passage about 17 km offshore of the west coast of Puerto Rico (Fig. 1). Desecheo is composed of a peak of volcanic calcareous rock with a mosaic of grassy patches, shrublands, woodlands with candelabra cacti, and semideciduous forests dominated by *Bursera simaruba* (Woodbury, et al., 1971). The highest point is nearly 200 m with steep slopes ranging from 20 to 35 degrees

Historically, Desecheo was a major seabird rookery and in the early 1900s tens of thousands of seabirds nested on the island (Wetmore, 1918; Meier, et al., 1989) and it is home to three single-island endemic and two native reptile species (Evans, et al., 1991) and a US Endangered Species Act listed threatened cactus, higo chumbo (*Harrisia portoricensis*). Desecheo was originally set aside as a wildlife preserve in 1912, but the introduction of invasive goats (*Capra hircus*), rhesus macaques (*Macaca mulatta*), feral cats (*Felis catus*) and black rats (*Rattus rattus*), and human uses of the island, had a substantial impact on the island’s habitat, contributing to the collapse of the large seabird populations (Evans, 1989; Meier, et al., 1989).

In 1976, the island was transferred to the US Fish and Wildlife Service (USFWS) who currently manage it as

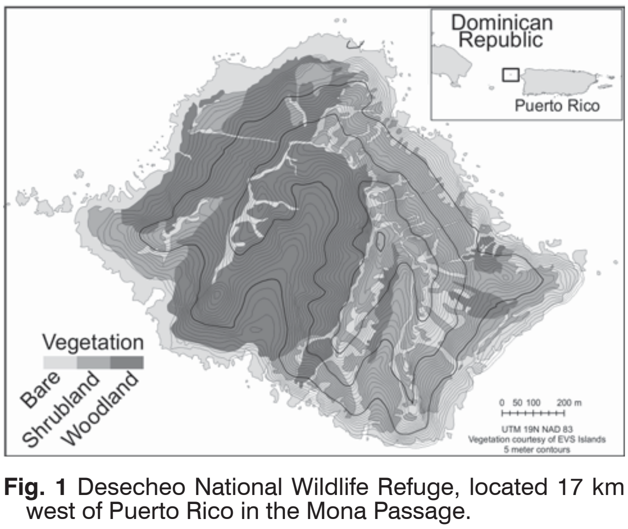

Fig. 1 Desecheo National Wildlife Refuge, located 17 km west of Puerto Rico in the Mona Passage.

In: C.R. Veitch, M.N. Clout, A.R. Martin, J.C. Russell and C.J. West (eds.) (2019). Island invasives: scaling up to meet the challenge, pp. 154–161. Occasional Paper SSC no. 62. Gland, Switzerland: IUCN.

Desecheo National Wildlife Refuge. To restore the island, the USFWS and collaborators removed feral cats in 1987 (Evans, 1989), feral goats in 2003 and the rhesus macaque population was reduced to being functionally extinct (i.e. reproduction ceased with only one wild macaque known to remain on the island) between 2009 and 2015 (Hanson, et al., 2019). In the absence of herbivory from goats and macaques, island species showed evidence of recovery, the higo chumbo resurged from the suppression caused by herbivory (Figuerola-Hernández, et al., 2017) and researchers detected seabirds prospecting for suitable habitat and attempting to nest on the main island in small numbers. However, recovery of the island ecosystem would not be possible until rats were removed.

MATERIALS AND METHODS

Project planning

Planning for the removal of black rats on Desecheo began in 2007 through the National Environmental Policy Act (NEPA) review process. The Finding of No Significant Impact (FONSI) identified aerial application of cereal bait pellets containing brodifacoum as the preferred alternative.

The 'dry' season from January to April was considered the ideal period for baiting because food for rats would be limited due to the dry environmental conditions and there was a higher likelihood of suitable weather for conducting an aerial application. Field trials were conducted in February and March 2009 and 2010 to evaluate rodent breeding status, presence of naturally occurring foods, abundance of non-target bait competitors, bait application rates, and detection capabilities of rodent surveillance devices.

Rats trapped during the 2009 (n = 33) and 2010 (n = 70) field trials indicated that rat reproduction appeared to be low during the dry season with no juvenile rats caught and no captured females showing signs of lactation or foetal development. The mean hermit crab density surveyed in 2010 was 696 crabs/ha but densities were higher in woodland sites (833 crabs/ha) than in shrubland sites (61 crabs/ha). Tomahawk live traps proved to be an effective surveillance device for rats with a 25% capture rate in 2009 and 55% in 2010.

In 2009, bait availability trials using a placebo biomarker in woodland habitat showed that bait applied at 18 kg/ha remained available in most plots for at least three days. The second trial in 2010 showed similar results for the same habitat. However, plots located on ridges in shrubland habitat exhibited a much faster rate of bait disappearance. Bait consumption by ants, considered to be in higher numbers on the island's exposed ridgelines, was suspected to be one of the key factors driving this result. Monitoring during the trials also demonstrated, through non-toxic biomarker bait, that native and endemic reptiles could be exposed. Additionally, all surveyed hermit crabs in woodland sites tested positive for the presence of biomarker; this, together with high densities of crabs, indicated that hermit crabs would be a significant consumer of rodent bait.

Based on trial data, a bait application strategy was designed to achieve a bait density on the ground of 18 kg/ha during the first application followed approximately 10 days later by a second application targeting 9 kg/ha. Desecheo has a planar area (2-dimensional) of 117.1 ha including the offshore islets, and a topographical surface area (3-dimensional) of 134 ha; the surface area is 13% higher than the planar area. To account for the island's steep topography, bait was sown at a rate of 20 kg/ha followed by 10 kg/ha to achieve the bait density required on the ground.

2012 eradication attempt

Brodifacoum Conservation 25-D (Bell Labs, Madison WI) 2 g pellets were applied aerially by helicopter in March 2012 using a spreader bucket slung below the helicopter. To minimise the risk of bait entering the marine environment, bait was applied along the coastal zone with a directional half swath bucket (deflector) and in the interior with a full swath starting and stopping inside of the coast. A full coastal swath was flown inland of the coast at the interface of the coastal and interior zones to provide sufficient overlap or 'safety buffering' and reduce the risk of bait gaps and areas of lower than target bait density (Fig. 2).

Additionally, to offset suspected ant consumption and supplement aerial broadcast in high risk areas bait stations were established at an interval of 25 m along two parallel transects on the ridgelines. Ant stations armed with Amdro®Pro fire ant bait (0.73% hydramethylnon) were placed within 1.5 m of each bait station. Stations were checked at least weekly and bait was replaced as needed for six weeks.

Bait availability transects were established across two of the same habitats as the trials (woodland and shrubland) measuring 1 × 25 m. The number of pellets in each transect was standardised and plots were sampled for seven consecutive days after each aerial broadcast or until all pellets had disappeared. At each visit, the number of pellets remaining was counted.

A captive programme was undertaken to hold representative samples of two endemic reptiles as a preventive action to reduce the risk of population-level impact from the application of rodenticide. A reptile mark-recapture monitoring study was done between February and April 2012 to confirm that the use of brodifacoum did not cause any observed population-level impacts in wild reptile populations on Desecheo (Herrera Giraldo, et al., 2019).

A live rat was found and captured 12 days after the 2nd application at the field camp and a buffer of bait stations was deployed in trees surrounding the field camp. No bait take was observed, and no additional rats were seen during the next week staff were on island.

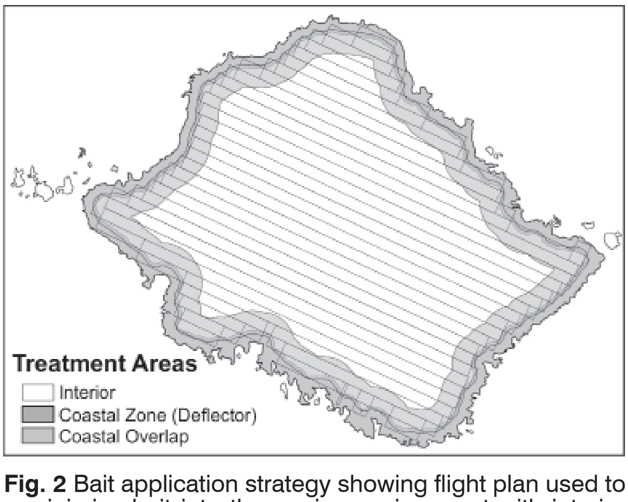

Fig. 2 Bait application strategy showing flight plan used to minimise bait into the marine environment with interior flight lines starting and stopping inside the coastal edge, a coastal half swath (deflector) along the coastal edge, and a full swath coastal overlap at the interface of the interior and coastal zones.

Eradication failure

Rats were not detected during fieldwork in October 2012 (six months post-operation), but in March 2013 (one-year post-operation) rats were observed and captured. Subsequent analysis of remote cameras deployed in 2012 showed the first rat detection in November 2012. Genetic testing indicated the eradication operation was not successful and the presence of rats was not the result of a reintroduction (i.e. operational failure).

To determine reasons why the operation may have failed, a review of the project investigated if rats *could not* eat a lethal dose because of gaps in bait coverage, insufficient bait availability, resistance to the toxin in the bait, or that the bait was not toxic enough; or if they *would not* eat a lethal dose of bait because of the palatability of the bait, availability of natural food resources, or breeding behavioural changes (i.e. pregnant females or emerging pups). Resistance to the toxin in the bait, bait toxicity, and bait palatability were not considered likely because the bait product had a proven record of success and rats captured during the biomarker trials showed a high level of acceptance. Despite implementing in the 'dry season', rainfall leading up to the operation was significantly higher than it was prior to either of the placebo bait trials, which may have resulted in a subsequent increase in the availability of natural food resources for rats and probable rat breeding. Bait disappeared quickly in several of the woodland plots with all bait disappearing within two to three nights of each application, likely the result of the significant crab densities in the woodland habitat. Finally, while there were few true gaps in bait coverage some areas during the first bait application received bait at less than half the prescribed rate. Thus, insufficient bait availability due to localised low bait densities during the first bait application and invertebrate bait competition, and an increase in the availability of natural food resources and rodent breeding due to above average rainfall, were identified as factors that could have individually or collectively contributed to the failure.

Tropical rodent eradication failures

About the same time that the 2012 attempt failed there were several other high-profile rat eradication failures on tropical islands, including Wake Atoll, western tropical pacific; Enderbury, Phoenix archipelago; and Henderson Island, Pitcairn group (Keitt, et al., 2015). A subsequent analysis of historical data showed that tropical rat eradications fail more than twice as often as temperate eradications (Russell & Holmes, 2015), resulting in a workshop attended by global experts to evaluate the possible reasons for this higher risk of failure and recommend solutions. The result of this workshop was a paper that provided recommended guidelines for rat eradications on tropical islands using aerial broadcast of brodifacoum (Keitt, et al., 2015).

Revised project approach

Starting in 2014, a steering committee of project partners (USFWS, USDA, and Island Conservation) was established to evaluate how to conduct a second attempt, the available strategy options, and how to manage ongoing project risk. A revised operational strategy was developed based on information from the review of the 2012 attempt and the recommended guidelines produced during the workshop on tropical rodent eradications (Keitt, et al., 2015). The following highlights the key changes:

1) Monitoring environmental conditions prior to the operation and proceeding only if conditions were conducive to success

A comprehensive review of factors influencing environmental conditions on Desecheo was conducted showing that rainfall and soil moisture content were key drivers of resource availability, typical of Puerto Rican subtropical dry forests. Inter-annual variability was evaluated using monthly rainfall totals and vegetation greenness, as a proxy for resource availability, between 2000 and 2013. Vegetation greenness was derived from remote sensing analyses using 30 m resolution 16-day MODIS Enhanced Vegetation Index (EVI) data. EVI data were smoothed using the HANTS algorithm (Roerink, et al., 2000) and mean monthly EVI were extracted from pixels that intersected the island using R (R Core Team, 2016).

Four assessments were conducted between three months and one week prior to implementation to evaluate the risk that short-term climatic changes could trigger higher biological productivity on the island prior to an irretrievable commitment of resources. Increased greenness represented more food availability via plants and invertebrates, and thus, increased opportunities for rodent breeding and increased bait competition due to invertebrate abundance. Each assessment included a review of regional climatic summaries, regional forecast products, and local weather conditions. Additionally, four island site visits were conducted to measure local rainfall, plant fruiting and flowering productivity, canopy cover and rodent breeding. To assist in data collection an automated logging rain gauge (WeatherShop, California, U.S.), three time-lapse cameras taking two photos per day (Day6Outdoors, Georgia, U.S.), and eight standardised photo point locations, were established on island.

A summary of conditions following each assessment was provided to the project steering committee for review. These summaries provided a subjective evaluation based on the team's knowledge of the island and the recommendations were used as part of a holistic evaluation of risk factors facing project implementation to make an operational go/no-go decision.

2) Reinterpretation of bait availability data

Using recent guidelines from Pott, et al. (2015) and data from the 2012 eradication attempt, bait availability was recalculated based on the lower-limit for a 99% t-based confidence interval. The linear rate at which bait disappeared was estimated by calculating the slope from four days of bait availability: 5.97 kg/ha per day in the woodland plots during the 2012 eradication attempt. This daily disappearance rate was used to calculate a conservative target bait density on the ground of 30 kg/ha to ensure that bait was available to rats for approximately five consecutive days after each application.

3) Treat the two applications as independent events

Following the guidelines outlined in Keitt, et al. (2015), the second attempt targeted the same application rate for each application and the target interval between application was increased to approximately 24 days. Two critical habitats, the valleys and steep cliffs identified in the review as areas of concern, were earmarked for additional supplemental bait application. On Desecheo, the predominant valleys and cliffs run perpendicular to one another, such that flights that are parallel to one are perpendicular to the other. To mitigate concerns about the impact on bait density caused by bait shadows on steep terrain (i.e. more bait downslope than upslope) and the higher rat and non-target bait consumer densities in the valleys observed during the 2012 attempt, additional flights were flown parallel to the valleys and cliff features to achieve higher application rates in these areas.

4) Seeking regulatory approval to give the operational team sufficient flexibility to ensure a minimum application rate at every point on the island

Some areas of Desecheo received bait below the desired bait density during the 2012 attempt. For the second attempt, the operational team sought regulatory approval to achieve a minimum bait density across every point on the island. This allowed for the retreatment of any areas that were estimated to be below the desired minimum bait density and limited the total amount of bait that could be applied per application rather than the application rate.

The project review also noted that the bait application strategy used to minimise bait in the marine environment created a risk of bait gaps and/or lower than planned baiting rates between coastal and interior zones. Regulatory approval was sought to ensure sufficient bait was available to treat the interface between the interior and coastal zones. This provided the flexibility to achieve the desired minimum bait density while also minimising bait entering into the marine environment.

5) Responding to operational monitoring in real time

To ensure quality coverage, bait sowing rates were carefully monitored and the helicopter shut down every five loads to download GIS files and review progress. During each application, a GIS specialist produced bait application maps estimating bait densities achieved on the ground. These data were used to identify any possible errors in flight lines, GPS logging, or bait application rates. Any gaps, identified as areas larger than 20 × 20 m receiving less than 15% (5 kg/ha) of the target bait density, were re-treated.

Greater emphasis was placed on operational monitoring than in 2012, including the deployment of additional bait availability monitoring transects and ground-truthing of bait application rates across the island. Additionally, communications between the environmental monitoring and bait application teams were improved by conducting the bait loading on island so that key project personnel were in the same place. In 2012 bait loading was done in Rincón approximately 17 km away on the main island of Puerto Rico. Following the first bait application, and prior to the second, a review of all operational data was conducted to allow for adjustments to the operational strategy.

2016 eradication attempt

The second eradication attempt was conducted in March and April 2016. The baiting strategy used was similar to the 2012 attempt albeit with an increased application rate and additional supplemental treatments along the cliffs and valleys. As in 2012, the sowing rate during the 2016 attempt was increased from 30 kg/ha to 34 kg/ha to accommodate the 3-dimensional surface area to ensure the desired bait density on the ground.

To allow comparisons with bait availability data collected during the previous field trials and the 2012 attempt, 25 m^2 sample transects were monitored in the woodland and shrubland habitats using the previous protocols. Additionally, a circular hoop sampling method (1 m^2) was used to estimate bait density on the ground following each application and collect additional bait availability across five different treatment zones.

Confirmation

In April 2017, one year after implementation, staff returned to the island and deployed chew tags, tracking tunnels, and live traps to confirm the absence of rats. Additionally, images from trail cameras were collected and analysed.

RESULTS

A summary of key differences between the two attempts is outlined in Table 1.

Environmental conditions

On first arrival at Desecheo Island on February 19, 2012, initial impressions were that the island's vegetation was more lush and green than observed during the same period in 2009 and 2010. Personnel recorded a total of 25.5 mm of precipitation on Desecheo between 10 March and 2 April 2012. Opportunistic necropsies of a small number of rats (n = 6) found dead during the 2012 operation showed one female rat with three embryos, and a male and the same female showed subjectively significant abdominal fat. However, the monitoring team did not observe any small juvenile rats suggesting breeding was not widely occurring for any prolonged period beforehand.

Retrospective analysis of precipitation recorded at the Rincón, Puerto Rico station (the closest point to Desecheo) showed that rainfall between January and March 2012 was above the annual average, and in February 2012 precipitation was 2.9 times higher than the 34-year average and the third highest rainfall for the month of February since 1968 (NOAA, 2015). Further, the remote sensing

Table 1 Summary of key differences between the 2012 and 2016 eradication attempts on Desecheo.

Factor	2012	2016
Month	March	March/April
Rainfall 6 months prior	4603 mm	772 mm
Rainfall during	25.5 mm	35.56 mm
Rodent breeding	One pregnant female observed (n=6)	None observed (n=44)
Canopy Cover	Flush vegetation	Post-peak vegetation followed by unproductive flowering after 31 mm rain event
Target bait density	18 kg/ha, 9 kg/ha	30 kg/ha, 30 kg/ha
Average application rate	17.1 kg/ha, 9.1 kg/ha	40.3 kg/ha, 39.9 kg/ha
Interval between applications	9 days	22 days

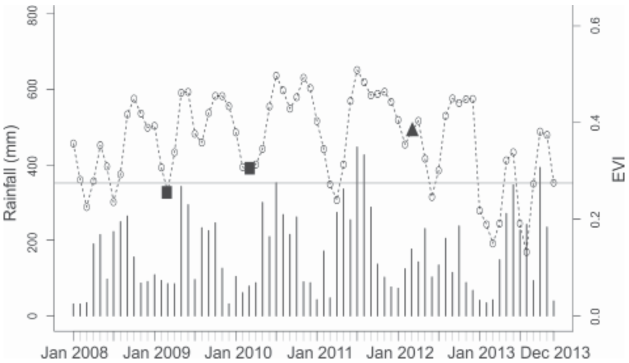

Fig. 3 MODIS Enhanced Vegetation Index (EVI) showing vegetation greenness vs rainfall in inches from Aguadilla, Puerto Rico. Dashed line represents EVI where higher EVI means greener and lower EVI means drier vegetation. Stacked lines represent rainfall in millimetres. The solid horizontal line represents the mean EVI for March, black squares EVI during placebo trials and black diamond EVI during the 2012 eradication.

analyses showed that March 2012 had significantly higher EVI than the same period during either of the 2009 or 2010 trials (Fig. 3).

During the assessment trips leading up to the 2016 attempt, observations showed that the island, while lush and green, was in post-peak greenness and starting to dry out in January 2016. This corresponded with a delayed and short wet season, likely the result of a record drought throughout much of Puerto Rico in 2015 (NOAA, 2015). By February there was a significant reduction in canopy cover; however, a significant rain event (31 mm in 24 hours) resulted in a large increase in canopy cover by March, mostly restricted to *Bursera* trees. Increased flowering was noticeable on some herbaceous shrubs and vine species; however, the fruits produced were not considered to be an alternative food source for rats. Increases in canopy cover continued through March, but by April 2016, after the second application of bait, most flower and fruit production had been abandoned. An irruption of caterpillars occurred after the second application, consuming much of the fresh *Bursera* growth (Shiels, et al., 2017).

Between 25 January and 10 April 2016, a total of 105.9 mm of precipitation was observed on Desecheo. Almost half of this precipitation was the result of two single events. In comparison, Rincón received a total of 239.3 mm of precipitation in the same period.

A total of 44 rats was captured during the 2016 attempt, all animals captured were adult size and none of the females showed signs of pregnancy, although some females showed indications (fat deposits and engorged uterine blood vessels) that breeding could have occurred soon after.

Bait application

During the 2012 eradication attempt, 3,588 kg of bait was applied on Desecheo as required by regulatory compliance, which resulted in an average application rate of 17.1 kg/ha and 9.1 kg/ha. An interval of nine days separated the first and second bait applications. Additionally, a total of 127 kg of bait was used in 107 bait stations placed along the ridges. The target application rates (18 kg/ha and 9 kg/ha) were at the upper limits allowed by regulatory requirements and the operational team was cautious in their approach with 1,000 kg of available bait unused. While the average application rates (total bait divided by island area) achieved were 17.1 kg/ha and 9.1 kg/ha, 76% of the island had a bait density on the ground below the target, with 8% less than half the target rate during the first application and 50% of the island below the target, with 4% less than half the target, during the second application.

In 2016, 10,650 kg of bait was applied according to regulatory compliance, resulting in an average application rate of 40.3 kg/ha and 39.9 kg/ha separated by 22 days. Regulatory approval was sought to allow for the retreatment of areas with less than the target bait density, ensuring a minimum bait density at every point across the island.

Table 2 Bait availability results from placebo trials and both eradication attempts on Desecheo. Bait availability is expressed as the 99% lower limit t-based confidence interval of mean bait availability to represent the "worst-case" scenario rather than the average case.

Habitat	Year	Plots	Target bait density (kg/ha)	Lower limit bait availability (kg/ha) after one day	Lower limit bait availability (kg/ha) after three days
1st Application					
Woodland	2009	6	18	0.5	0
	2010	9	18	3.2	0
	2012	5	18	6.9	0
	2016	6	45	7.8	0
Shrubland	2010	6	18	0	0
	2012	7	18	11.5	4.9
	2016	6	30	23.6	14.8
2nd Application					
Woodland	2009	6	18	-	-
	2010	9	18	-	-
	2012	5	9	0	0
	2016	8	45	36.0	24.0
Shrubland	2010	6	18	-	-
	2012	7	9	8.3	5.7
	2016	6	30	30.0	27.5

Using this strategy 11% of the island received less than the target bait density and 2% received less than half the target during the first application. During the second application 31% of the island received less than the target bait density and1% less than half the target.

A review of operational monitoring data following the first application during the 2016 attempt showed that bait disappeared faster than anticipated in the woodland valley habitat. In response, a total of 100 bait stations were installed in the valleys spaced at least 25 m apart. Bait stations were filled the day after aerial broadcast and elevated in trees wherever possible to reduce bait take by crabs. Each station was checked and replenished (if needed) three times during a three-week period. A total of 22.25 kg of bait was used in bait stations.

There was a small increase in the number of non-target carcasses observed between the 2012 (n = 4) and 2016 (n = 17) attempts, although a larger team was surveying the island for a longer duration in 2016. Few non-target species presented a high-risk exposure pathway so significant mortality was not expected following the 2016 attempt despite the increase in total bait applied to the island. Additionally, biological samples of rats, reptiles, and invertebrates were collected before and after the 2016 attempt to evaluate the persistence of brodifacoum in the environment four years after the 2012 attempt, if still detectable, and following the 2016 attempt, results of which will be reported elsewhere.

Bait availability

Observed bait availability was represented as the 99% lower limit confidence interval of mean bait availability (Table 2). The lower limit was used instead of mean availability to represent the "worst-case scenario" of bait availability rather than the average. During the first applications of both the 2012 and 2016 attempts, estimated bait availability reached zero in the woodland plots within three 24-hour periods despite the difference in application rates (Fig. 3).

Confirmation

A biosecurity monitoring trip was conducted seven months after the second attempt in November 2016 during which 10 A24 GoodNature traps, 40 bait stations, 10 Tomahawk live traps, 50 chew tags and 10 trail cameras were placed near possible landing sites. In April 2017, a total of 179 chew tags, 22 tomahawk live traps, 21 trail cameras and 20 tracking tunnels were placed across the island over a nine-day period for a total of 1,074; 124; 3,108; and 114 detection nights, respectively. No signs of rats were detected on any device during either monitoring trip. Following confirmation, monthly biosecurity monitoring trips between September 2017 and March 2018 continued to check the surveillance devices with no detections of rats.

DISCUSSION

The failure of the rat eradication on Desecheo in 2012 provided an excellent opportunity to better understand the reasons for failure, build upon the lessons learnt from other failed projects, and design a second attempt that addressed the key challenges. Keitt, et al. (2015) lays out a suite of recommendations to increase the probability of success for tropical rat eradications using aerial broadcast of brodifacoum based on reviews of several failed projects and input from a large group of experts. Desecheo was the first of these failed projects to be implemented a second time and enables review of the operational changes that contributed to operational success.

Environmental conditions

On tropical islands rainfall is a key driver of primary productivity and resulting elevated vegetation density is associated with an increase in rodent population densities (Harper & Bunbury, 2015). Like other dry tropical islands, primary productivity and resulting resource availability in the dry season on Desecheo (January–April) can be variable and is highly dependent on the amount of soil water recharge generated from successive rainfall events in the previous year's wet season (July–December) and the timing and amount of rain during the dry season. Environmental conditions leading up to the 2016 attempt were drier than those in 2012, primarily as an artefact of long term drought conditions experienced in 2015, resulting in lower primary productivity, less resource availability, and lower probability of rodent breeding. We feel that these 'favourable' conditions contributed to project success and had conditions leading up to the 2016 attempt been like those observed in 2012 the project would have been postponed.

Even though environmental conditions, and their subsequent implications for project success, are difficult to predict, the subjective assessments conducted on Desecheo were critical to the steering committee's confidence in proceeding with the bait application. They provided an opportunity to critically evaluate project risk and, more importantly, considered the consequences of postponement in advance of a final go/no-go decision. Where possible, future projects can improve stakeholder confidence by identifying the primary environmental drivers that pose risks to project success and developing a process that evaluates these risks to inform a final go/no-go decision. Projects should identify the worst-case scenario of alternative resource availability, non-target bait competitor abundance and rodent breeding, and plan accordingly.

Desecheo was relatively easy to access during day trips, but the deployment of an automated rain gauge and time-lapse cameras and use of remote sensing data provided valuable information on climatic conditions that could be replicated on remote islands. On islands where variability in environmental conditions pose a risk to operational efficacy projects should consider using these tools and others to better evaluate these risks. At the very least, projects can improve the collective knowledge of the challenges facing tropical rodent eradications by documenting and reporting observed environmental conditions, and subsequent perceived risks, leading up to and during implementation.

Bait availability

The review of the first attempt identified inadequate overall or localised baiting rates as one of the more likely causes of failure to eradicate rats. As described in Keitt, et al. (2015) eradications should strive to make bait available to rats for at least four consecutive 24-hour periods to maximise the probability that all rats are exposed to a lethal dose. The interpretation of the bait availability data for the 2012 attempt used mean bait availability to determine sufficient bait availability rather than the lower limit of 99% confidence intervals. Reinterpretation of the placebo trials using the 99% lower limit confidence interval method estimated that with a rate of 18 kg/ha the lower limit of bait availability would reach zero within two to three days. This was further supported by data from the 2012 attempt where the lower limit of bait availability went to zero by the third day after bait application (Fig. 3).

During the 2016 attempt bait availability observed in the transect sampling (25 m^2) roughly followed observations from the 2012 attempt where bait disappeared more quickly

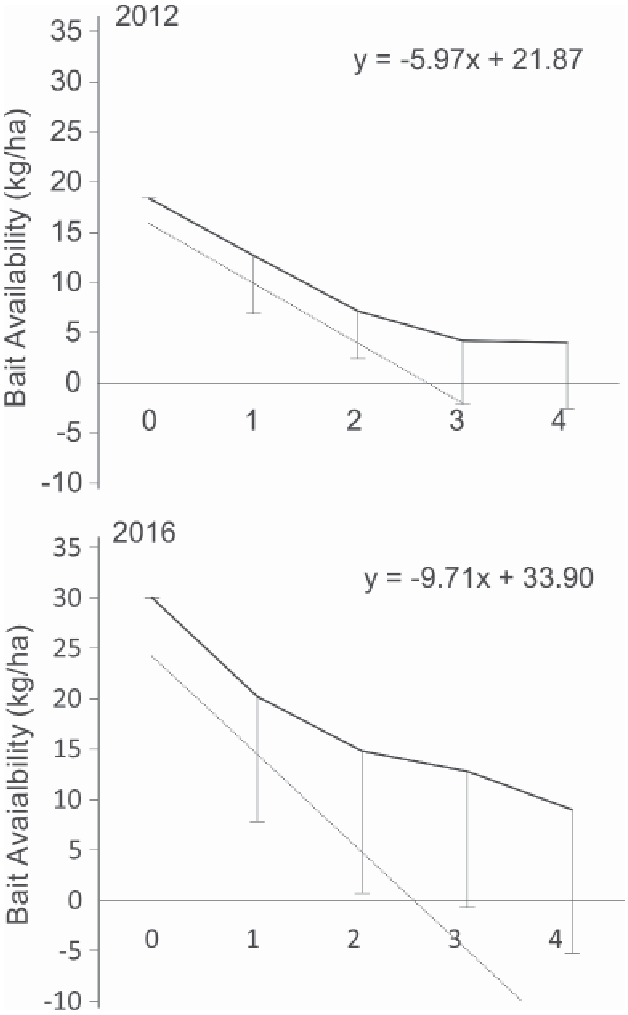

Fig. 4 The mean bait availability from the 25 m² bait availability plots set in the woodland habitats in 2012 and 2016. Day 0 represents the broadcast date and Day 1 represents the first 24-hour period during which bait is available to bait consumers (i.e. day 1 ends 24 hours after the end of bait application). The error bars represent the lower limit for a 99% t-based confidence interval. The trend line represents the bait disappearance rate based on the lower limit.

in the woodland than in the shrubland habitat. Although the revised strategy intended for bait to be available for at least four consecutive 24 hour periods after bait application, the lower limit of bait availability in the woodland plots was similar to the 2012 attempt and reached zero by the third day after bait application despite the nearly two-fold increase in application rate. This highlights some of the challenges tropical rodent eradications face in the presence of non-target bait competitors, supports the methods proposed in Pott et al. (2015) for evaluating bait availability data, and suggests that the higher application rate used in the 2016 attempt may have been necessary in the hermit crab-dense woodland habitat to ensure sufficient bait availability for all rats.

Regulatory approval

One of the criticisms of the 2012 attempt was that some areas received lower than the prescribed rates during the first application, particularly inside the coastal edge. This was potentially a consequence of the complex regulatory environment in the United States and the strategy employed to minimise bait spread into the marine environment. The desired target application rate on the ground was very near the maximum rate permitted by regulation and the operational team needed to strike a balance between achieving the desired application rate while staying within permitted limits. This was not an issue unique to Desecheo as, in general, aerial eradications conducted in the Unites States tend to use less bait than planned, compared to projects conducted elsewhere that use more than planned (Will, et al., 2019).

Leading up to the 2016 attempt the operational team aimed to address this challenge by engaging regulatory partners early in the project process as part of the project steering committee. The operational team justified, and sought approval for, a strategy that focused on achieving a site-specific minimum application rate based on the best available science. The justified strategy estimated the amount of bait needed to achieve a minimum rate at every point across the island, the amount of bait needed for overlapping flights necessary to minimise bait spread into the marine environment while minimising the chance of gaps along the coastal edge, and an additional amount of bait to fill unanticipated gaps and undertreated areas. Particularly in complex regulatory environments, future projects should consider seeking site-specific regulatory approval based on a justified strategy that maximises project success and bait quantities derived from a predicted flight plan.

Operational strategy

The justification for increasing the interval between applications was to reduce the risk posed by the scenario of pups emerging three weeks after the first application. The justification for using the same application rate in both applications was to ensure bait availability in the presence of non-target bait competitors. It should be noted that several tropical island eradications elsewhere have been successful with shorter gaps between bait applications. For example, in Mexico seven projects were successful with durations of 7–10 days between applications (Samaniego-Herrera, et al., 2014, 2017) even though rat breeding was confirmed. Additionally, an interval of three weeks could incur considerable operational costs while personnel and equipment are on standby. Alternatively, rodent breeding risks could be mitigated by increasing the application rate so that bait was available for a longer period, or conduct a third application; however, these would need to be balanced against associated non-target risk. As Keitt, et al. (2015) note, the recommendations should not be considered hard and fast rules as every island is different and we still have much to learn about tropical ecosystems.

The decision to apply additional bait in the valleys and on cliffs was based on the perceived risks justified from observations in 2012. These concerns appear somewhat validated because bait disappeared quickly in the woodland plots following the first application in 2016 despite the increased higher application rate from the 2012 attempt. It is difficult to evaluate what impact this strategy decision had on operational success but this stresses the importance of selecting bait application rates based on the best available science. Additionally, future projects should consider an additional treatment to increase confidence in areas of concern.

Operational monitoring

Intentionally slowing down the bait application in 2016 and reviewing bait density estimate maps improved the quality of the bait application and ensured that significantly less of the island was below the minimum bait density than during the 2012 attempt. Future projects should consider this strategy particularly on small islands where a single load treats a significant proportion of the island, and using bait density estimate maps to identify gaps or low treatment areas (Will, et al., 2019).

The second attempt put emphasis on near-real time information sharing to inform decision-making during the operation. While there is limited opportunity for adaptive management during aerial eradications, where success or failure is largely determined on the day, projects should put processes in place to ensure that data from the field are available to inform operational decision making and risk assessments during project implementation. Comprehensive operational monitoring allows managers to implement any available response options and, more importantly, allows stakeholders to understand project risk as the implementation unfolds.

CONCLUSION

Although we are unlikely to determine the influence environmental conditions, bait applications rates, or the interval between applications have on project success without experimentation, the variability in conditions observed on Desecheo during the 'dry' season and the consistently high rate of bait disappearance in crab-dense areas highlight the importance of understanding an island's ecosystem prior to implementing tropical eradications. The second attempt on Desecheo provided a significant opportunity to reconsider operational strategies for tropical eradications and marks the first of the high-profile failures to be successfully redone following the global review of tropical rodent eradications. The synthesis of recommended guidelines in Keitt, et al. (2015), and the process of reviewing project risks at pre-determined times, were necessary for increasing stakeholder confidence to make a second attempt. Ultimately, the rationale employed during the successful 2016 attempt should increase global confidence in rodent eradications on tropical islands.

ACKNOWLEDGEMENTS

The eradication of invasive rodents from Desecheo was led and funded by USFWS (Caribbean Islands NWR) and supported by Island Conservation and USDA – National Wildlife Research Center. We are very grateful to the donors who provided significant match funding including the David and Lucile Packard Foundation and the National Fish and Wildlife Foundation. In-kind assistance was provided by the Commonwealth of Puerto Rico Department of Natural and Environmental Resources, the Puerto Rico Department of Agriculture, and the Puerto Rico Electric Power Authority and a generous donation of bait by Bell Laboratories Inc. We would also like to thank the many other local companies, agencies, and individuals that assisted during project implementation.

REFERENCES

Evans, M., Herbert, H.J. and Rohnke, K. (1991). 'Observations on the status of the herpetofauna of Desecheo Island National Wildlife Refuge, Puerto Rico'. In: J.A. Moreno (ed.) *Status y Distribución de los Reptiles y Anfibios de la Región de Puerto Rico. Publicación Científica Miscelánea No. 1*, pp. 34–36. San Juan, Puerto Rico: Departamento de Recursos Naturales.

Evans, M.A. (1989). 'Ecology and removal of introduced rhesus monkeys: Desecheo Island National Wildlife Refuge, Puerto Rico'. *Puerto Rico Health Sciences Journal* 8(1): 139–156.

Figuerola-Hernandez, C., Swinnerton, K.J., Holmes, N., Monsegur-Rivera, O., Herrera Giraldo, J.L., Wold, C., Hanson, C., Silander, S. and Croll, D. (2017). 'Resurgence of *Harrisia portoricensis* (Cactaceae) on Desecheo Island after the removal of invasive herbivores: Implications and recommendations for the management of the species'. *Endangered Species Research* 34: 339–347.

Hanson, C., Hall, T.J., DeNicola, A.J., Silander, S., Keitt, B. and Campbell, K. (2019). 'Rhesus macaque eradication to restore the ecological integrity of Desecheo National Wildlife Refuge, Puerto Rico'. In: C.R. Veitch, M.N. Clout, A.R. Martin, J.C. Russell and C.J. West (eds.) *Island invasives: scaling up to meet the challenge,* pp. 249–255. Occasional Paper SSC no. 62. Gland, Switzerland: IUCN.

Harper, G.A. and Bunbury, N. (2015). 'Invasive rats on tropical islands: Their population biology and impacts on native species'. *Global Ecology and Conservation* 3: 607–627.

Herrera-Giraldo, J.L., Figuerola-Hernández, C.E., Holmes, N.D., Swinnerton, K., Bermúdez-Carambot, E.N., González-Maya, J.F. and Gómez-Hoyos, D.A. (2019) 'Survival analysis of two endemic lizard species before, during and after a rat eradication attempt on Desecheo Island, Puerto Rico'. In: C.R. Veitch, M.N. Clout, A.R. Martin, J.C. Russell and C.J. West (eds.) *Island invasives: scaling up to meet the challenge,* pp. 191–195. Occasional Paper SSC no. 62. Gland, Switzerland: IUCN.

Jones, H.P., Holmes, N.D., Butchart, S.H., Tershy, B.R., Kappes, P.J., Corkery, I., Aguirre-Muñoz, A., Armstrong, D.P., Bonnaud, E. and Burbidge, A.A. (2016). 'Invasive mammal eradication on islands results in substantial conservation gains'. *Proceedings of the National Academy of Sciences* 113(15): 4033–4038.

Keitt, B., Griffiths, R., Boudjelas, S., Broome, K., Cranwell, S., Millett, J., Pitt, W. and Samaniego-Herrera, A. (2015). 'Best practice guidelines for rat eradication on tropical islands'. *Biological Conservation* 185: 17–26.

Meier, A.J., Noble, R.E. and Raffaele, H.A. (1989). 'The birds of Desecheo Island, Puerto Rico, including a new record for Puerto Rican Territory'. *Caribbean Journal of Science* 25 (1–2): 24–29.

NOAA. (2015). *Climate Prediction Center: National Drought Predicition Center*. <http://www.cpc.ncep.noaa.gov/>. Accessed 11 November 2015.

Pott, M., Wegmann, A.S., Griffiths, R., Samaniego-Herrera, A., Cuthbert, R.J., Brooke, M.d.L., Pitt, W.C., Berentsen, A.R., Holmes, N.D., Howald, G.R., Ramos-Rendón, K. and Russell, J.C. (2015). 'Improving the odds: Assessing bait availability before rodent eradications to aid in selecting bait application rates'. *Biological Conservation* 185 :27–35.

R Core Team (2016). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Roerink, G., Menenti, M. and Verhoef, W. (2000). 'Reconstructing cloudfree NDVI composites using Fourier analysis of time series'. *International Journal of Remote Sensing* 21(9): 1911–1917.

Russell, J.C. and Holmes, N.D. (2015). 'Tropical island conservation: Rat eradication for species recovery'. *Biological Conservation* 185: 1–7.

Samaniego-Herrera, A., Russell, J.C., Choquenot, D., Aguirre-Muñoz, A. and Clout, M. (2014). 'Invasive Rodents on Tropical Islands: Eradication Recommendations from Mexico'. In: R.M. Timm and J.M. O'Brien (eds.) *26th Vertebrate Pest Conference*, pp. 43–50. Davis: University of California.

Samaniego-Herrera, A., Aguirre-Muñoz, A., Bedolla-Guzmán, Y., Cárdenas-Tapia, A., Félix-Lizárraga, M., Méndez-Sánchez, F., Reina-Ponce, O., Rojas-Mayoral, E. and Torres-García, F. (2017). 'Eradicating invasive rodents from wet and dry tropical islands in Mexico'. *Oryx* 10.1017/s0030605316001150: 1–12.

Shiels, A.B., Haines, W.P., Swinnerton, K.J., Silander, S., Figuerola-Hernández, C., Will, D., García-Cancel, J.G. and Torres-Santana, C.W. (2017). 'Sudden appearance and population outbreak of *Eunica monima* (Lepidoptera: Nymphalidae) on Desecheo Island, Puerto Rico'. *Florida Entomologist* 100(1): 176–179.

Tershy, B.R., Shen, K.-W., Newton, K.M., Holmes, N.D. and Croll, D.A. (2015). 'The importance of islands for the protection of biological and linguistic diversity'. *BioScience* 65(6): 592–597.

Towns, D.R., Atkinson, I.A. and Daugherty, C.H. (2006). 'Have the harmful effects of introduced rats on islands been exaggerated?' *Biological Invasions* 8(4): 863–891.

Veitch, C.R., Clout, M.N. and Towns, D.R. (eds.) (2011). *Island invasives: eradication and management.* Occassional Paper SSC no. 42. Gland, Switzerland: IUCN and Auckland, New Zealand: CBB.

Wetmore, A. (1918). 'The birds of Desecheo Island, Porto Rico'. *Auk* 35: 333–340.

Will, D., Howald, G., Holmes, N., Griffiths, R. and Gill, C. (2019). 'Considerations and consequences when conducting aerial broadcast applications during rodent eradications'. In: C.R. Veitch, M.N. Clout, A.R. Martin, J.C. Russell and C.J. West (eds.) *Island invasives: scaling up to meet the challenge,* pp. 71–78. Occasional Paper SSC no. 62. Gland, Switzerland: IUCN.

Woodbury, R.C., Martorell, L.F. and Tuduri, J.G. (1971). 'Flora of Desecheo Island, Puerto Rico'. *Journal of Agriculture of the University of Puerto Rico* 55(4): 478–505.