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Temporary captive population and rapid population recovery of an endemic flightless rail after a rodent eradication operation using aerially distributed poison bait

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ABSTRACT

Operations to eradicate non-native invasive predators from islands generally have large conservation benefits, but may put native species at risk where poison bait is used for eradication. Whether the risk of unintentionally poisoning native species can be effectively reduced or mitigated is a critical determinant in deciding the potential utility of an eradication operation. Here, we describe the mitigation measures adopted for an endemic flightless rail species, the Henderson Crake (*Zapornia atra*), during a rodent eradication operation on Henderson Island, South Pacific, where aerially applied brodifacoum bait was used in 2011. We established a secure temporary in situ captive population of 108 birds, of which 22 individuals died due to initial complications in accepting artificial food. We used point counts and radio-tracking to estimate the effects of the eradication operation on the wild population of Henderson Crakes, and found the expected high mortality (83–97%) due to primary poisoning. Despite this mortality, the Henderson Crake population recovered from very low levels in 2011 (9 birds at 25 point count locations) to 2015 numbers similar to those in the 1980s and 1990s (228 birds at 25 point count locations), despite the eradication operation failing to remove all rats from Henderson Island. The recovery of the natural population was supplemented by 89 individuals released from temporary captivity 2–3 months after the eradication attempt. We conclude that, despite the high mortality of Henderson Crakes during the eradication attempt, the mitigation measures taken to safeguard this endemic species were effective and contributed to the rapid recovery of the species following the eradication operation.

1. Introduction

Introduced rodents, and rats (*Rattus* spp.) in particular, cause significant damage to island ecosystems through direct predation, competition with indigenous species, and alteration of ecosystem energetic pathways (Croll et al., 2005; Harper and Bunbury, 2015; Jones et al., 2008). Conservation efforts on hundreds of islands globally have therefore focused on eradicating introduced rodents as part of island restoration programs (Howald et al., 2007; McClelland, 2011; Towns and Broome, 2003). Such successful efforts often result in the restoration of ecosystems, and in particular, avian communities, in a relatively short time (Jones et al., 2016; Lavers et al., 2010; Russell and Holmes, 2015).

Since the early 1990s, rodent eradications on large islands (>100 ha) have been typically performed using the aerial distribution of an anticoagulant rodenticide in cereal pellets, which is both palatable and toxic to rodents. This approach ensures rapid coverage of the entire island with a sufficient density of bait to expose all individuals of the introduced rodent species to a lethal dose, and this technique is therefore highly successful (Keitt et al., 2015; Towns and Broome, 2003). However, aerial bait applications are not without risks, as non-target species may consume the bait directly, resulting in primary poisoning, or scavenge on dead rodents or other non-target species, causing secondary poisoning (Eason et al., 2002; Pitt et al., 2015; Wanless et al., 2010). The ultimate success of island restoration programs to safeguard native species therefore depends critically on appropriate actions to reduce or mitigate non-target mortality, while at the same time ensuring that the eradication operation will be successful. Typical measures to reduce non-target mortality include operational decisions on the distribution, type, and size of cereal bait pellets used (Parkes et al., 2011), the timing of

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eradication operations (Howald et al., 2007), or the establishment of a captive population of potentially vulnerable non-target species (Empson and Miskelly, 1999). Maintaining a temporary captive population of a wild native species can, however, be a formidable challenge. To our knowledge there has been no thoroughly documented case study about the establishment, maintenance, and subsequent release of a captive population of a wild native species in association with a rodent eradication operation using aerial bait application. Here, we describe a case study of a globally threatened bird species vulnerable to non-target mortality; we report the pre-operational planning, mitigation measures implemented, and post-operational monitoring to demonstrate that appropriate mitigation resulted in no negative long-term population-level effects of an aerial bait application.

Henderson Island (24° 20′ S, 128° 20′ W) is a 43 km^2 raised coral atoll in the Pitcairn Islands of the South Pacific Ocean where non-native Pacific rats (*Rattus exulans*) were introduced during Polynesian occupation, and have negative effects on native biodiversity (Brooke, 1995a, 1995b; Brooke et al., 2010b; Jones et al., 1995). Rat eradication on Henderson Island is a high priority to safeguard globally important biodiversity (Dawson et al., 2015), and an aerial baiting eradication operation was carried out in 2011 (though subsequently found to be unsuccessful; Amos et al., 2016). The island supports four endemic land bird species (Graves, 1992), an endemic petrel (Brooke and Rowe, 1996), 18 endemic invertebrate and nine endemic plant species (Benton and Lehtinen, 1995; Churchyard et al., 2016; Florence et al., 1995). The petrels and three volant species of land birds were unlikely to suffer non-target mortality during an eradication operation due to their ecology and diet (Brooke and Hartley, 1995; Brooke and Jones, 1995; Graves, 1992; Trevelyan, 1995). However, one flightless bird species – the Henderson Crake (*Zapornia atra*) – is a ground-foraging generalist (Jones et al., 1995) and such species may be susceptible to primary and secondary poisoning: populations of the closely-related Weka (*Gallirallus australis*), Buff-banded Rail (*G. philippensis*), and Pukeko (*Porphyrio porphyrio*) decreased considerably when populations had access to brodifacoum bait (Dowding et al., 1999; Eason and Wickstrom, 2001; Empson and Miskelly, 1999; Fisher et al., 2011). Consequently, careful measures to reduce non-target mortality were necessary to ensure the survival of Henderson Crakes during an eradication operation.

We developed and implemented mitigation strategies to minimize negative effects of an aerial baiting rodent eradication operation on Henderson Crakes. We then evaluated the effects of these mitigation steps on the Henderson Crake population both during the rat eradication operation and for four years following the operation using systematic point count surveys.

2. Methods

2.1. Estimation of minimum captive population size

The entire Henderson Crake population was potentially at risk of primary (ingesting bait directly) or secondary poisoning (ingesting poisoned rats, or invertebrates) (Brooke et al., 2013; Brooke et al., 2011). The general guideline for preserving the genetic diversity of populations in the short term (5 generations, or 14 years for Henderson Crake; Birdlife International, 2016; Frankham et al., 2014) is an effective population size (N_e) ≥ 50 (Franklin, 1980), though this has recently been revised to N_e ≥ 100 (Frankham et al., 2014). To allow for operational complications and logistical complexities our minimum target for maintaining short-term genetic diversity was a temporary captive population of 100–120 individuals during the eradication operation.

2.2. Establishment and maintenance of a captive crake population

Extensive work during a preliminary field expedition in August–September 2009 was necessary to determine the techniques required for the successful capture and maintenance of captive Henderson Crakes (Brooke et al., 2010a). The developed techniques were implemented and refined in preparation for the eradication operation in 2011. Between 16 July and 26 August 2011, we captured Henderson Crakes using water traps and mist nets positioned along a ~7 km network of trails (Fig. 1). Traps consisted of a 60 × 40 cm wooden base with an inset plastic water bowl and a spring-powered flip-net that was triggered when a bird bathed in the bowl. Mist nets were set at ground level along paths and birds were guided into the nets through a combination of tape-luring or through herding individuals. Mist nets were used due to higher than expected rainfall in the initial stages of the capture period, which reduced the efficacy of water traps.

Captured crakes were weighed upon capture to the nearest 1 g using an electronic balance, and sex determined by using the colouration of their bill and legs (Jones et al., 1995). When we captured both members of a breeding pair from a territory, they were housed together, otherwise birds were caged individually. Crakes were housed in 1.5 × 3.0 × 0.8 m cages, with side walls comprising a 10 m length of 90 cm wide wire mesh dug about 10 cm into the ground. The four corners were supported by 1.2 m metal reinforcing rods hammered into the ground. Cages were roofed with bird netting sewn onto the wire sides, and supported by a central wooden post. Roofs had a small opening with a sliding bolt to allow access for providing food and water. All cages were shaded by natural vegetation, or fronds from coconut (*Cocos nucifera*) trees. We placed natural vegetation inside each enclosure, including small logs and rocks, as shelters for birds. Crakes were also provided with two plastic bowls 17 cm in diameter and 3 cm deep for water and food that could be covered during heavy rain.

Each morning, crakes were fed with 15 g of Wombaroo Insectivore Rearing Mix (Wombaroo Food Products, Glen Osmond, Australia; 52% protein, 18% carbohydrate, 12% lipid, maximum 5% fibre, 2% calcium, 500 mg/kg taurine, 500 mg/kg carotenoids; metabolisable energy 15 MJ/kg) mixed with water to form a firm paste, and combined with dried raisins; food was replenished at midday if the bowl was empty. A calcium supplement (Vetark Nutrobal, Vetark Professional, Winchester, UK) was added every 3–4 days. Crakes were provided water ad libitum, which was replenished through the day, and an avian probiotic and a critical care formula (Vetark Avipro plus, and Vetark CCF, Vetark Professional, Winchester, UK) were added to the water for the first few days of captivity to combat the effects of stress. These served to replenish vitamins and minerals, gut flora, maltodextrins and included a protein concentrate to aid birds that were reluctant to consume food. Food and water bowls were removed at night to avoid attracting rats and crabs into aviaries; water bowls were scrubbed each morning before refilling with water, and food bowls were cleaned with detergent every evening and allowed to air dry to reduce the risk of bacterial build up and contamination to food in the warm humid conditions. To ensure food recognition and acceptance in the days immediately following capture, we provided live sphingid moth caterpillars (*Gnathothlibus erotus*) or small hermit crabs with shells removed together with the Wombaroo Insectivore Rearing Mix until we observed crakes eating the mix directly. Similarly, we provided live prey to chicks hatched in captivity (see Results) to aid their development and assist natural instincts and prey recognition.

On 15–17 August 2011, cereal bait pellets (Pestoff 20R, Animal Control Products, Whanganui, New Zealand) with 20 μg/g (ppm) brodifacoum and a mean mass of ~2 g were spread aerially using helicopters across the island at a density of 10 kg/ha on inland areas, and 40–60 kg/ha in beach areas with high densities of hermit crabs *Coenobita* spp. The second bait drop of 6 kg/ha followed on 21–22 August 2011. During the aerial application of rodenticide pellets, all aviaries were covered with heavy transparent plastic sheets to exclude all pellets from the inside of aviaries and ensure that captive birds had no access to poison baits. Cages were thoroughly checked after each bait drop to ensure that no bait pellets had entered the cage, and in the following days to ensure any bait falling into the cage after being lodged in

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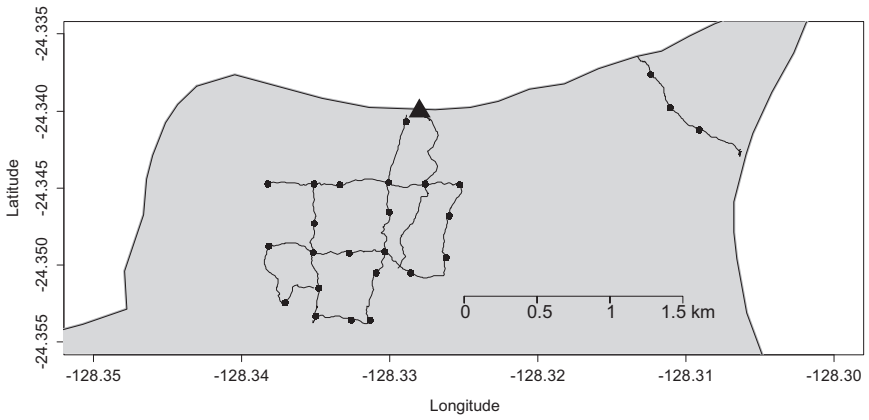

Fig. 1. Map of the northern part of Henderson Island showing the research camp where Henderson Crakes were held in temporary captivity (black triangle), the trail network along which crakes were captured and tracked, and the location of survey points (black dots) used for abundance monitoring.

overhanging *Pandanus tectorius* foliage was removed immediately. We kept a supply of vitamin K, an antidote to the anti-coagulant brodifacoum used in the cereal bait pellets, in the form of Konakion MM Phytomenadione (Vitamin K1 10 mg/ml) to be administered by intramuscular injection or orally, in cases of primary poisoning. We also had a trained aviculturalist (GH) present on the island, with veterinary support off-island, to administer first aid and medication to injured birds.

2.3. Estimating the magnitude and cause of mortality in the wild crake population

To provide information on survival of the wild population of crakes while bait was available, we captured an additional 19 wild birds from 5 to 14 August 2011 and equipped them with radio transmitters prior to the first bait drop. Crakes were captured within a ~4 ha area on the northern edge of the plateau using the same methods as for the captive population. This area was adjacent to the trails used for capturing birds for the captive population in order to monitor an undisturbed sample of birds more representative of the rest of the island. Birds were sexed, weighed, and measured, banded with a unique colour combination of plastic rings and fitted with a radio transmitter. Transmitters were two-stage 2.5 g radio tags fitted with a variable pulse activity signal (Biotrack, Wareham, UK), mounted on 20 × 30 mm fine cloth and attached with cyanoacrylate ('superglue') to feathers on the bird's lower back. Prior to attachment, the feathers on the lower back were wetted with acetone to remove feather oils and dirt from the area, and provide a better bond with the cyanoacrylate. After gluing, the visible area of gauze surrounding the tag was coloured with a black permanent pen in order to camouflage the tag amid the bird's feathers. The 2.5 g tags were approximately 3.4% of the mean mass of Henderson Crakes (73 g in 2009; Brooke et al., 2010a), which was judged acceptable for this flightless species.

Tagged crakes were located from trails cut through the forest up to 1.5 km inland from the beach. Signals from located birds were monitored for up to 5 min until there was either a clear change in radio-pulse (indicating activity) or until the bird was seen and identified. If no activity signals were detected after 5 min the bird was tracked and approached on foot until its status could be determined.

To estimate the mortality in the wild population, we first removed data from crakes that either had a malfunctioning transmitter or had left the study area prior to the bait drop ($n = 3$, see Results). We recorded how many of the 16 remaining marked birds were found dead. To estimate a confidence interval around this point estimate of mortality, we simulated mortality rates ranging from 50% to 100% at 1% increments, and drew 10,000 random binomial trials with a sample size matching the number of marked birds ($n = 16$). We then determined the lower and upper 95% confidence interval as those mortality rates where 2.5% or 97.5% of the 10,000 simulations included as many dead birds as we observed in the field, essentially simulating under what range of mortality rates we could have observed our outcome in 95% of cases.

Due to the high mortality observed in the initial sample of radio-tagged birds and in the wild population, a further seven free living crakes were captured from 9 to 16 September in the captive catchment area. These birds were radio-tracked as described above to ensure that it was safe to release the captive population, because bait was no longer easily available three weeks after the second bait drop (Cuthbert et al., 2012).

On 6 October 2011, six weeks following the second bait application, and after all cereal bait pellets had been consumed or degraded, eight of the captive crakes (both members from four pairs) were fitted with radio tags, released, and monitored as described above to assess the potential for secondary poisoning (Brooke et al., 2013; Brooke et al., 2011). A further 10 captive crakes were similarly tagged and released on 17 October once we had determined that all previously released birds had survived.

We collected the carcasses of any dead crakes found after the baiting operation. We examined dead birds internally for abnormalities or gross pathology under the skin, on top of the thoracic cavity and on the surface of internal organs. Following necropsy, two small samples of liver tissue (~0.3 g in total) were collected and stored in 4 ml glass vials containing 1.5 ml acetonitrile. Samples were analysed for brodifacoum by liquid chromatography-mass spectrometry using a triple quadrupole system. Methods for detecting brodifacoum in liver tissue samples followed Albert et al. (2010) and Jin et al. (2007) as modified by Brooke et al. (2011).

2.4. Estimating population size after eradication

To determine the population-level effects of the rat eradication operation on Henderson Crakes, we established a monitoring scheme using point counts along the network of paths used for crake capture and monitoring (Fig. 1). We established 25 point count locations, and surveyed crakes in 12 time periods between August 2011 and October 2015 (four years after the captive population had been released). Monitoring periods were not equally spaced apart due to the difficulty of reaching Henderson Island, and therefore coincided with the original eradication operation (5 survey periods from early August to late October 2011), and subsequent expeditions in November 2012, July and August 2013, and May–October 2015. During each survey period, up to three repeat surveys were conducted at each point count station within 5–7 days to ensure that populations were demographically closed during the survey period. The timing of surveys varied among

years: between 10:00 and 14:00 UTC-8 (2011), or between sunrise (06:00) and 10:30 (2013), so in 2015 we ensured that at least one of the three repeat visits in each month was in each of the two time intervals to maximise comparability with previous survey efforts. We recorded all crakes that were visually or acoustically detected during a 10-minute period.

We estimated Henderson Crake abundance around the point count stations using binomial mixture models, which use the repeated observations at a given sampling station to estimate the probability of detecting birds and the number of birds that use the habitat around the sampling station (Kéry et al., 2005; Royle and Nichols, 2003; Royle et al., 2005). As Henderson Crakes frequently reaffirm their pair bond using a particular duet call, the acoustic detection of both members of a pair is not independent. We therefore used beta-binomial mixture models that accounted for the non-independence of multiple detections during a given survey (Martin et al., 2011). This model formulation introduces another parameter into the binomial mixture model and modifies the binomial trials that are used to estimate detection probability to allow subsequent trials to be correlated (Martin et al., 2011). The correlation parameter mimics the calling behaviour of birds, which is the most common cue for detection.

We estimated the population trajectory of Henderson Crakes using a model adapted from open population binomial mixture models (Kéry et al., 2009). Because models using a linear trend or a logistic growth curve did not converge due to the unequal time intervals between primary survey periods, we estimated population size for the two periods of major management interest using fixed intercepts, assuming that population size differed between 2011 (immediately post-eradication), and 2012–2015 (>1 year after the eradication operation). To assess whether this model provided an adequate fit to the data, we applied a Bayesian posterior predictive check (Gelman et al., 2004), and we report the Bayesian *p*-value as an indicator of model fit (Kéry and Schaub, 2012). We ran four Markov chains each with 150,000 iterations and discarded the first 75,000 iterations, and report posterior mean estimates and 95% credible intervals for total abundance summed across all survey points and detection probability averaged across survey points and repeat counts. We fit all models in JAGS 4.2 using the R2jags package (Su and Yajima, 2015) in R 3.2.4 (R Core Team, 2016).

We used a similar model to provide an independent estimate of the mortality of wild Henderson Crakes as a consequence of the bait drop. In this model, we only considered the 10 point count locations that were surveyed prior to the first bait drop, and we only considered the first four primary survey periods, before captive rails were released in the vicinity of point count locations and may have contributed to crake detections during surveys. We used a simplified binomial mixture model with a standard binomial detection probability because the very few surviving rails did not exhibit typical pair-bonding behaviour and duet-calling. We fit the model with primary survey period as a fixed effect and estimated the survival of wild Henderson crakes as the mean abundance estimated around the 10 point counts in late September and mid-October (2–6 weeks after the bait drop) divided by the abundance estimated around the same 10 points prior to the first bait drop in early August. We converted this proportion into a mortality estimate and present the mean and 95% credible interval of this mortality estimate as an independent validation of the mortality estimate obtained from radio-tracking.

Finally, we estimated the population size of Henderson Crakes in 2015 by calculating the density of individuals assuming that point counts would sample individuals from a radius of 100 m around each point count location. This radius was based on the observed movements of 16 radio-tracked birds in 2011, but given that population estimates were highly sensitive to this radius, we also explored a range between 64 and 131 m corresponding to the range of movements observed in tracked birds. We then extrapolated this density to the available habitat on the island, which we assumed had remained unchanged since 1991 at 73% of the island area (Jones et al., 1995). We adjusted previous estimates of Henderson Crake's total population (Graves, 1992; Jones et al., 1995), which used incorrect estimates of the total island area (37 km^2, rather than 43 km^2), or failed to account for the proportion of suitable habitat. We assumed 2.3 individuals/territory in 1987 and 1991 (Jones et al., 1995), and calculated total populations based on 0.95–1.53 territories/ha in 1987 (Graves, 1992), and 1.00 territories/ha in 1991 (Jones et al., 1995).

3. Results

3.1. Establishment and maintenance of a captive crake population

We captured 108 crakes (54 females, 47 males, and 7 of unknown sex), of which 1 escaped, 2 were released intentionally, and 22 died in captivity, leaving a captive population of 83 individuals (41 females, 35 males, 7 of unknown sex) surviving until 5 months after capture when no more poison bait was available on the ground. Birds weighed 76 ± 9 g when captured, and there was no difference in mass between sexes ($F_{1,96} = 0.01$, $p = 0.94$). Crakes that died in captivity lost approximately 15–47% of their mass, weighing 52 ± 4 g when they died (4 ± 2 days after capture, excluding one bird that died after 77 days in captivity from an unknown traumatic event). There was no difference in the capture mass of birds that did and did not survive ($F_{1,102} = 0.06$, $p = 0.81$). The surviving 83 crakes were kept captive until release on 3 November 2011 ± 13 days (range: 6 October-20 November 2011), after a total of 93 ± 17 days in captivity (range: 41–127 days). Three breeding pairs each laid two eggs, similar to the size of those in the wild (Jones et al., 1995); all six eggs produced young that were released with their parents (age: 16 ± 1 days; range: 14–17 days). All 89 released birds were individually marked with a unique combination of plastic colour rings, and at least three of those birds released after captivity in 2011 were observed alive and breeding in 2015, at an age of >4 years.

3.2. Estimating the magnitude and cause of mortality in the wild crake population

We captured and placed radio transmitters on 19 crakes before the baiting operation in August 2011, two of which were not located after the day of capture and were either transient non-territorial individuals that moved out of the tracking area, or had transmitters that failed. A third individual was tracked intermittently in the first 9 days after capture but could then no longer be located, and the transmitter likely failed. The remaining 16 birds were all confirmed alive in the five days prior to the first bait drop. The first rail mortality was recorded two days after the first bait drop. All 16 marked birds had died within 15 days of the first bait drop (mean time to death: 7.3 ± 3.2 days following the bait drop). Although the observed mortality of radio-tagged birds was 100%, five wild Henderson Crakes were observed during point counts between 4 and 9 September 2011, and two were observed between 24 and 28 September 2011 (Fig. 2), indicating that population level mortality of free-living crakes was <100%. Based on our simulations we could have observed 16 mortality cases in 16 tracked birds with 95% confidence if population-level mortality rate had been between 79 and 100%.

A simplified binomial mixture model fit to data from 10 point count locations that were surveyed both before and after the bait drop indicated that the wild Henderson crake population around these points decreased from 9 (95% credible interval: 7–17) birds in early August to 1 (0–3) bird in late September to mid-October, resulting in an independent estimate of the mortality of wild crakes of 93% (83–97%).

All seven free-living crakes radio-tracked from mid-September 2011 survived until we departed from the island in mid-November 2011, as did the 18 radio-tagged captive birds released in October 2011. Seven of the nine pairs released in October held territories and were breeding by mid-November.

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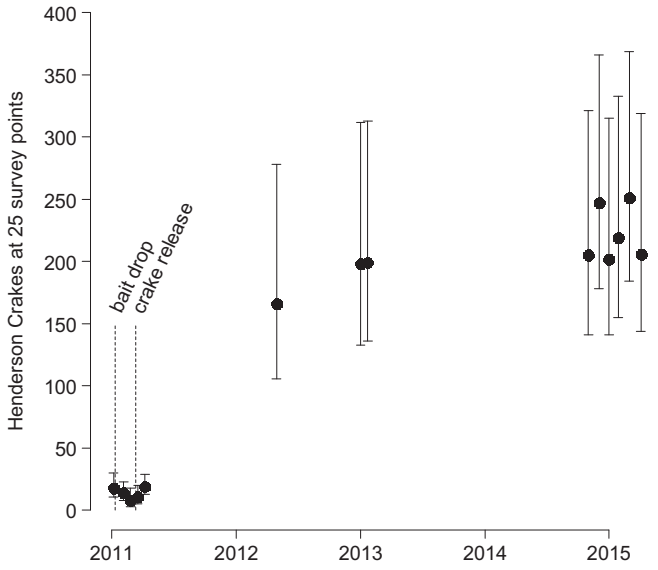

Fig. 2. The estimated population size (mean ± 95% credible intervals) of Henderson Crakes observed at 25 point count locations derived from a beta-binomial mixture model based on repeat surveys at each point within a given time period. The dates of the aerial baiting eradication operation and the release of the temporary captive population are indicated by dashed lines.

3.3. Brodifacoum analyses

We recovered 15 of the 16 radio-tracked crakes known to have died, along with 9 additional corpses (14 females and 10 males in total). Gross examination indicated that some birds had abnormally coloured heart ($n = 9$), pectoral muscle ($n = 15$), and liver tissues ($n = 17$), with very pale coloured muscle or organs. Seven of the 17 birds with abnormal livers showed signs of necrosis, with black-edged lobes to the liver. In total, 23 of the 24 birds had medium to large pooling of blood either within or on top of the abdominal cavity. Analysis of the liver tissue samples from 21 birds indicated the presence of brodifacoum in every bird analysed, with a mean concentration of 0.317 ± 0.189 μg/g wet mass (range 0.027–0.808 μg/g).

3.4. Estimating population size after eradication

Following the eradication operation in 2011, including two surveys (September and October 2011) that occurred after captive crakes had been released in the survey area, the Henderson Crake abundance ± SD around all 25 point count locations ranged from 9 ± 4 (95% credible interval: 3–18) to 20 ± 4 (13–29, Fig. 2; note that this estimate is based on a larger spatial survey area than the estimate of 1 bird at only 10 points provided above). Abundance increased rapidly to 174 ± 45 (106–298) crakes in November 2012, 205 ± 46 (133 − 312) crakes in August–September 2013, and 209 ± 45 (141–315) to 257 ± 48 (184–369) crakes in May–October 2015 (Fig. 2). The mean detection probability of Henderson Crakes at a given point count survey estimated from the beta-binomial mixture model was 0.227 ± 0.045 across all surveys. The model we used fit the data well (Bayesian p-value = 0.41), and all parameters had $\hat{R} < 1.09$, indicating that the model converged.

We estimated a mean of 228 crakes around the 25 point count locations in 2015 (Fig. 2), giving a total population estimate (95% CI) of 8513 birds (5755–12,749) if crakes detected at point count locations originated from up to 100 m away. Assuming a different radius of origin of the estimated local population in 2015 would result in total population estimates of 20,783 birds (14,050–31,126; radius = 64 m) or 4960 birds (3354–7429; radius = 131 m). Even the most conservative estimates from 2015 are of the same order of magnitude as extrapolations from previous expeditions of 6859–11,046 birds in 1987, and 7220 birds in 1991 (Table 1).

4. Discussion

We demonstrated that temporary captivity of a non-target species at risk of primary poisoning during an aerial rat eradication operation was both logistically feasible and highly effective in aiding in the long-term survival of a globally threatened flightless rail species. Based on information from related species, we anticipated that Henderson Crakes were at risk of poisoning from an aerial rat eradication operation on Henderson Island. We designed temporary captive management during a preliminary expedition to Henderson Island in 2009, and refined and implemented this management prior to and during the eradication operation in 2011. This management was designed to allow re-establishment of a wild population if mortality in the wild had been 100%.

Although mortality of wild crakes was high, our point counts indicated that some birds survived and the release of captive crakes contributed to the rapid recovery of the wild population. The wild survivors, supplemented by the released captive crakes, ensured that the wild population returned to pre-eradication abundance levels within four years after the operation, despite the operation having failed to remove all invasive rats. This project therefore demonstrated that temporary captive management can insure against the negative side-effects of a poison-based rodent eradication operation, and supplement natural recovery when free-living individuals survive.

Rodent eradications are an important conservation tool to safeguard or restore unique island biodiversity, and reducing non-target mortality during such operations is one of the most important aspects to ultimately achieve the effective conservation of threatened species. The rat eradication on Henderson Island aimed at restoring a unique Pacific island ecosystem by removing invasive Pacific rats, but in the process a large proportion of the native Henderson Crake population was unintentionally killed. Our radio-tracking and point count results indicated that the eradication operation may have poisoned 83–97% of the wild population. The majority of Henderson Crakes found dead during the baiting operation (23/24, 96%) showed signs of brodifacoum poisoning, and liver samples from all 21 birds tested for brodifacoum had relatively high concentrations indicative of lethal exposure. The 25 crakes released >5 weeks after the bait drop all survived until our departure in November 2011, and the majority were breeding, indicating no, or very low secondary poisoning (Brooke et al., 2013; Brooke et al., 2011). Crakes readily consume wet cereal bait pellets identical to those used in the operation (Oppel et al., 2016). As abundant rainfall prior to and after the aerial bait drop would have rendered most bait pellets wet and palatable in 2011, we conclude that the observed mortality was the result of primary rather than secondary poisoning. For future eradication attempts on Henderson Island, aiming at a period of dry weather may reduce the poisoning risk to Henderson Crakes, but it is unlikely that primary poisoning risk can be eliminated and a temporary captive population such as described here will be necessary.

Despite the large non-target mortality of wild Henderson Crakes during the eradication operation in 2011, we estimated the island's population in 2015 to be similar to population sizes before the eradication, although this conclusion is complicated by the lack of robust and repeatable surveys prior to the eradication operation. The only two population size estimates prior to the eradication operation used ad-hoc methods (Graves, 1992; Jones et al., 1995) that we could not replicate in 2015, and there is considerable uncertainty surrounding the total population size of Henderson Crakes in 2015. Nonetheless, our surveys from 2011 to 2015 provide robust evidence that the Henderson Crake population in 2015 was almost 15 times higher than immediately after the eradication operation in 2011 (Fig. 2), and extrapolated total population size was similar to previous extrapolations (Graves, 1992; Jones et al., 1995). In 2010 and 2011, the island experienced a 6-month drought that may have naturally suppressed vegetation, invertebrates and bird

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Table 1
Estimates of the Henderson Crake population in 1987 (Graves, 1992), 1991 (Jones et al., 1995), and 2015 (this study).

Year	Available habitat (ha)	Crakes/ha	Total population (individuals)
1987 (min)[a]	3139	2.19	6859
1987 (max)[a]	3139	3.52	11,046
1991 (original)[b]	2701	2.30	6212
1991 (corrected)[b]	3139	2.30	7220
2015[c]	3139	2.71	8513 (5755–12,749)

[a] Assumes 2.3 crakes/territory (Jones et al., 1995).
[b] The original estimate assumed a total island area of 37 km^2, and the corrected estimate uses the measured area of 43 km^2.
[c] Mean (95% credible interval) based on a radius of 100 m around point count locations. See text for details.

abundance. Although we did not quantify Henderson Crake abundance in 2009 and 2011, we encountered fewer birds in 2011 prior to the eradication operation than in 2009, which resulted in substantial difficulty catching the minimum number of birds for temporary captivity. Our only pre-eradication census at 10 point count locations may therefore have occurred at a time of naturally low population abundance, which makes it difficult to put the subsequent estimates into context. Nonetheless, the rapid recovery of the crake population after 2011 is remarkable given that the rat eradication was unsuccessful, and rat abundance had recovered to near pre-eradication levels by 2013 (Churchyard et al., 2013). Rails are known to respond well to removal (or reduction) of problematic invasive species (Donlan et al., 2007), and flourish in predator-free environments (Hockey et al., 2011; Šúr et al., 2013; Woinarski et al., 2016). On Aldabra Atoll, Wanless et al. (2002) predicted that Aldabra White-throated Rails (*Dryolimnas cuvieri aldabranus*) reintroduced to rat-free Picard Island would saturate the island within 10 years, which was confirmed by subsequent surveys (Šúr et al., 2013). A re-introduction of the Buff-banded Rail on rat-free Horsburgh Island (Cocos (Keeling) Islands, Australia) indicated that the population increased five-fold in a single year following re-introduction (Woinarski et al., 2016). The temporary suppression of the rat population may have also contributed to the rapid recovery of Henderson Crakes, as the lack of rat predation may have increased the survival of very young chicks (Jones et al., 1995). We are therefore confident that the Henderson Crake population recovered to original levels within four years despite the substantial mortality during the eradication attempt, and the captive management aided in the survival and recovery of Henderson Crakes after the rat eradication operation in 2011.

There were considerable challenges to successfully capture and maintain a captive population of Henderson Crakes in situ for up to five months. Initial complications arose due to captive birds not accepting the artificial food provided: of the crakes that died in captivity, 21 out of 22 died in the days immediately after their capture, as a result of not accepting the artificial food. We overcame the artificial food habituation problem by providing live moth caterpillars or hermit crabs on top of the artificial food in bowls, which helped the crakes to associate the bowls with food, and boosted caloric intake during the crucial initial days in captivity. Once we adopted this approach, no crakes died due to malnourishment in captivity, and three pairs bred in captivity. A critical aspect to our success was having adequate avicultural expertise available for consultation on the island. Maintaining a captive population successfully on such a remote and uninhabited island required dedicated and well qualified individuals able to respond and adapt to unpredictable conditions. Similar attempts to mitigate non-target mortality require considerable resources for both a planning expedition and the actual captive management.

Our study provides detailed documentation of the extent and mitigation of non-target mortality during an aerial rodent eradication operation. We encourage other conservation managers to study and document the mitigation measures taken and their effectiveness during eradication operations to provide evidence that can help to promote the utility of eradications as a successful conservation management tool. Assessing population changes following a large intervention like an eradication operation is often hampered by lack of robust baseline estimates (Jones and Kress, 2012; Lavers et al., 2010). We therefore recommend robust monitoring of island populations prior to an eradication operation to facilitate quantitative estimates of the effect of and recovery after an eradication operation. The Henderson Crake recovered despite large mortality during an aerial bait-based eradication operation, and temporary captive management likely played an important role in this recovery, ensuring that a viable breeding population could be re-established in the worst-case scenario of complete mortality of free-living crakes. However, the life history of rails predisposes these species to rapid colonisation and population recovery following even extreme population bottlenecks (Donlan et al., 2007; Hockey et al., 2011; Woinarski et al., 2016), and we caution that other species that may be adversely affected by an eradication operation may not show similar rates of population recovery. A thorough assessment of all species at potential risk of mortality during an eradication operation is therefore essential to adequately plan appropriate mitigation measures prior to any operation.

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