Eradication of mice from Antipodes Island, New Zealand

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Abstract In winter 2016, the New Zealand Department of Conservation (DOC) eradicated mice (*Mus musculus*) from the Antipodes Islands located at 49°S 178°E, 760 km south-east of New Zealand's South Island. Mice were the only mammalian pest species present. They have extensively impacted the abundance and survival of invertebrates, with likely secondary impacts on endemic terrestrial birds and nesting seabird fauna. Public-private partnerships with DOC instigated the project and provided essential financial support. Baseline scientific data for operational planning and outcome monitoring were collected by a research expedition in July 2013 and project planning began in 2014. At the time of writing, this is the largest eradication of mice undertaken where mice are the sole mammalian pest species. Logistical challenges were complicated by a broad range of regulatory obligations. The expedition-style project used a ship to deliver a team and equipment to Antipodes Island where they established camp and remained until the completion of baiting. Bait spread was completed incrementally as weather allowed, comprehensively covering the islands in two separate treatments between 18 June 2016 and 12 July 2016. The last sign of mice was detected 20 days after the first application of bait and the eradication of mice was confirmed by monitoring in late summer 2018. Public engagement was achieved with regular operational updates across multiple platforms and positive media coverage. Non-toxic bait trials accurately predicted some by-kill of pipit (*Anthus novaeseelandiae steindachneri*) but did not anticipate poisoning of some Antipodes parakeet (*Cyanoramphus unicolor*) and Reischek's parakeet (*Cyanoramphus hochstetteri*). Known pest-free islands were not baited, providing refuge for land birds to mitigate the risk. Fledging success of Antipodean albatross *(Diomedea antipodensis antipodensis)* chicks was not impacted by the operation and those species that were affected had recovered by summer 2018.

Keywords: brodifacoum, house mouse, Million Dollar Mouse, *Mus musculus*, non-target impacts, subantarctic

INTRODUCTION

The Antipodes Islands group (2,100 ha) is in New Zealand's Subantarctic Islands region and was gazetted as a Nature Reserve in 1978 and a World Heritage site in 1998. The group comprises six islands and one islet located in the Southern Ocean, at 49°41'S, 178°48'E, 760 km from New Zealand's South Island (Fig. 1). The islands are uninhabited and administered by New Zealand's Department of Conservation (DOC). House mouse (*Mus musculus*) was the only mammalian pest species present and known only on the main island, Antipodes Island (2,012 ha).

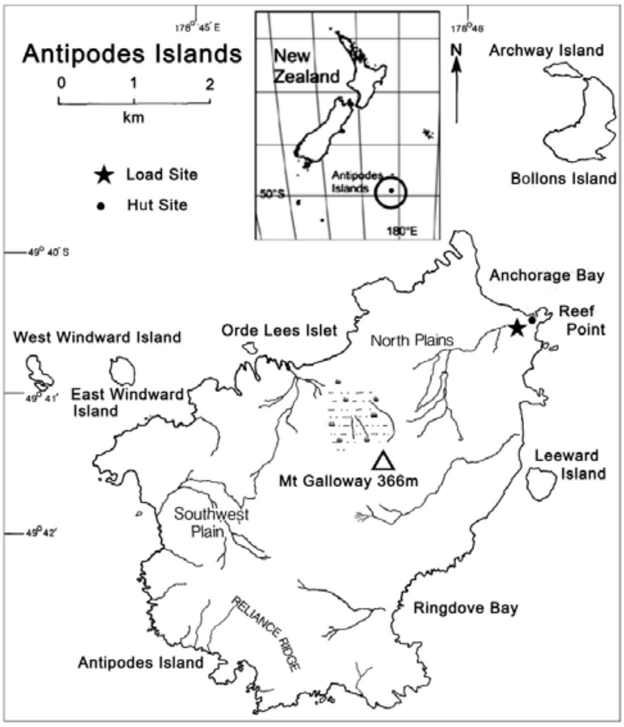

Fig. 1 Map of the Antipodes Island group.

The Antipodes were discovered in 1800 and sealers arrived by 1804 (Taylor, 2006). A small shelter (castaway depot) was built in 1886 to support shipwreck survivors. It was resupplied periodically until 1927 (Taylor, 2006). Mice were first recorded on Antipodes Island in 1907 but probably arrived earlier (McIntosh, 2001) with sealers or as the result of a foreign shipwreck (*Spirit of the Dawn*) in 1896 (Taylor, 2006). DNA studies of the mouse population identified a mtDNA haplotype also found in Spain but not elsewhere in New Zealand (Searle, et al., 2009.).

Mice were abundant; their density has been recorded as high as 147/ha in the coastal zone (Russell, 2012). They have had a significant detrimental impact on the endemic, rare and threatened animal species. Invertebrates have been severely depleted. Mice are responsible for the general absence of large beetles and the extirpation of at least two taxa: *Loxomerus* n.sp. and *Tormissus guanicola* (Marris, 2000); and several large ground dwelling species are severely restricted in distribution (Marris, 2000; Russell, 2012). Mice also compete with the four endemic land birds and have suppressed at least two species of burrowing seabirds: black-bellied storm petrels (*Fregetta tropica*) and subantarctic little shearwater (*Puffinus elegans)* (Imber, et al., 2005).

The aim of the project was to eradicate mice from the archipelago to halt the degradation of biodiversity and allow native species to recover and flourish. Eradicating mice would also protect potentially vulnerable species, for example the nationally critical Antipodean albatross *(Diomedea antipodensis antipodensis)*, from potential attacks as recorded on Gough Island and Marion Island (Davies, et al., 2015; Dilley, et al., 2016).

The site has good ongoing biosecurity integrity. The islands are remote and isolated, landing requires a permit and the coastline is generally inaccessible, with no harbour. In 2012, DOC partnered with the Morgan Foundation to initiate the project. The Morgan Foundation fronted a highly publicised fundraising campaign "Million Dollar Mouse" (MDM), and matched public donations dollar for dollar. Additional funding came from DOC and other partners, WWF New Zealand and Island Conservation.

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MATERIALS AND METHODS

Planning

DOC planned and managed the operation from its Murihiku Office in Invercargill. Planning started in February 2014, with the employment of a full-time project manager, and took two and half years with a core team of two increasing to four in the last six months. A much larger DOC team supported pre-departure preparations. The Department's Island Eradication Advisory Group (IEAG) was engaged from the start, providing technical oversight. Eradication design was based on agreed best practice (Broome, et al., 2019). DOC's Animal Pest Framework and elements of DOC's Project Management Framework (PMF) provided the tools to manage the project.

Procurement

Helicopter and shipping services were sourced using government processes. In early 2016, DOC contracted the services of the M.V. *Norfolk Guardian*, a coastal freighter flagged in Kingdom of Tonga and a yacht, S.V. *Evohe*, to supplement passenger transport.

An experienced eradication pilot was engaged as a consultant to progress planning while a helicopter supplier was being sought. Following consultation with potential suppliers, a temporary hangar (16 m × 12 m × 5. 6 m high) and a large wooden platform (29 m × 13.8 m) incorporating a helipad were added to the planned infrastructure to help protect helicopters and other sensitive equipment from the elements. The hangar was fastened to the wooden platform and the whole structure anchored with 38 t of water ballast positioned around the base of the hangar frames in palletised 1,000 l cage tanks (Intermediate Bulk Containers). The anchoring system was designed for easy installation and extraction and to withstand winds of up to 190 km/hr.

A specialist company "Island Aerial Solutions Ltd" (IASL) was contracted to supply helicopter services and a helicopter engineer. Three helicopters were taken to the island, two AS350 Squirrels (1 × B2 and 1 × FX2) and one Robinson R44. The R44 provided contingency for marine search and rescue, enabling baiting to continue using one AS350 if the other became inoperative.

Preparations

The hangar construction was trialled in a large warehouse prior to departure. The International Chamber of Shipping Guide to Helicopter/Ship Operations (2008) was used in the development of protocols for managing shipborne helicopter operations. Ship preparations included establishing a helipad and upgrading emergency response capabilities onboard. Two months before departure, interaction trials allowed pilots to practice shipborne helicopter operations and familiarise the ship's crew. Two methods were also trialled for loading helicopters onto the ship and baiting systems were tested during the same period. Bucket calibration was done by sowing non-toxic bait across a line of marked quadrants (5 m × 10 m) extending 65 m perpendicularly from each side of a flight line over tarmac. Baits were counted in every quadrat to determine "usable swath width" – the distance to which bait is reliably spread at or above the desired rate.

An experienced operational team was selected, with additional skills and experience including engineering and mechanical repairs, a recovery doctor with extensive patient extraction and remote emergency medicine experience, biodiversity monitoring, bait bucket mechanics, technical eradication knowledge, remote construction, digger driving and rigging and receiving external helicopter loads.

Biosecurity was a significant part of preparations, and actions were coordinated with a biosecurity plan. A dedicated DOC team quarantined equipment and supplies arriving from all around New Zealand. Quarantined items were generally wrapped in plastic or sealed in plywood boxes (pods). Pest detection and prevention devices, including inked tracking cards in tunnels, insect traps, and rodent bait stations, were in place at the ports of departure and facilities where equipment and supplies were stored. The cargo ship's holds were fumigated for insects. Transport vessels required a certified clean hull to travel to the island. A dive inspection of the *Norfolk Guardian* discovered biofouling on its hull and the invasive organism Mediterranean fan worm (*Sabella spallanzanii*) in the seachests. A hull clean and treatments of the seachests were completed and inspected before each voyage to the island.

Animal Control Products (ACP now trading as Orillion) based in Whanganui, New Zealand, produced 65.5 t of Pestoff® 20R Rodent Bait containing 20 ppm brodifacoum between 21 April 2016 and 3 May 2016. ACP analysed samples from each 500 kg batch of bait, measuring toxicity using Liquid Chromatography Mass Spectrometry with a detection limit of 1×10^{-5}% (0.1ppm). The agreed acceptable range was 16 ppm to 24 ppm brodifacoum by weight.

The bait was packed in four-walled paper bags each containing 25 kg of bait and transported and stored on Antipodes Island in large plywood boxes (pods) portable by forklift and helicopter. The maximum safe load capability of the helicopters determined the size of the pods (each contained 28 bags of bait and weighed a total of 805 kg). The weatherproof pods included a large plastic liner to protect bait against water ingress.

On 23 May 2016, the *Evohe* departed Dunedin, New Zealand, for Antipodes Island with 12 of the project team onboard. On 25 May 2016, the *Norfolk Guardian* departed Timaru, New Zealand with seven project team members, three helicopters, bait in 94 pods, 30 t of jet fuel and 20 t of sundry equipment and supplies. Two 1.6 tonne diggers were taken to the island to prepare a level site for the helicopter hangar. A satellite dish was installed, providing a fast internet connection. The *Evohe* remained at the island while the cargo ship was present, transferring personnel between ship and shore, and ready to respond in case of an incident over water during helicopter unloading of the ship.

Poison baiting

Bait uptake trials were conducted on Antipodes Island in winter 2013 to assess the palatability of the proposed bait to mice and the potential risks to non-target species. The trial used a non-toxic version of Pestoff® 20R Rodent Bait with the biotracer pyranine added. Baits were spread by hand over 6 ha at 16 kg/ha. Subsequently, mice were captured in a grid of Longworth live capture traps and land birds were captured with hand nets. Captured individuals were inspected for signs of bait consumption using a UV light. Observations of birds interacting with baits were also recorded. Bird faeces were collected opportunistically along a transect and inspected under UV light. Faecal samples were assigned to a species by visual inspection or by DNA analysis for a subset of samples that tested positive for pyranine (Elliott, et al., 2015).

A boundary flight recorded the treatment area as 2,114 ha before baiting commenced. The boundary was flown again more tightly before treatment two, recording the area as 2,075 ha. An advisory team (technical advisor, chief pilot and assistant project manager) assisted the project manager with finalising the load site location and layout, and daily assessment of conditions for baiting. AS350 helicopters, directed by Tracmap GPS systems, spread

65.5 t of 2 g Pestoff® 20R Rodent Bait from underslung bait buckets to complete two comprehensive treatments. The nominal application rate was 16 kg/ha for treatment one and 8 kg/ha for treatment two. A minimum interval of 14 days between treatments was preferred, to increase the likelihood of bait availability for emergent young if mice were breeding. Parallel flight lines were set at 45 m apart for a usable swath width of 90 m, giving 50% overlap of baiting swaths to minimise the risk of gaps. During each treatment, additional bait was applied to the coastline, steep slopes (50° to 70°), cliffs (greater than 70°) and other areas of concern to the pilots or identified by geospatial analysis as having potentially insufficient coverage. An observer in the back of the helicopter monitored distribution of bait on cliff baiting flights, which were undertaken at about 40 metre vertical increments.

Bait was made available inside storage containers and the interior and sub floor spaces of buildings by hand spreading or placing baits in bait stations. A bait station comprised a numbered shallow clear petri dish with ten Pestoff® 20R Rodent Bait pellets. These were placed in each compartment or room of a structure and checked daily. A total of 72 bait stations were placed in structures on 18 June. Baits were thrown by hand to achieve coverage of approximately four bait pellets per square metre under the hut and Castaway Depot and in the open wastewater drain. Toilet pits were checked daily and a handful of baits were scattered down each pit as required to maintain availability to mice. Holes were drilled in the floor of the helipad and hangar to access the subfloor space, and baits dropped through. Mouse activity was monitored around the accommodation area using inked tracking cards secured in tunnels (tracking tunnels) and baited with Pestoff® 20R Rodent Baits; and three trail cameras focused on bait stations under the hut and Castaway Depot. Approximately 4 kg of bait was used for structure baiting.

West Windward Island (7.0 ha) and East Windward Island (8.5 ha) were not baited during the first treatment as it was unknown if mice were present. These islands were monitored for mice between treatments using ten inked tracking cards baited with peanut butter and placed in tunnels (tracking tunnels) for 12 nights. Bollons Island (52.6 ha) was believed to be mouse-free prior to the operation but six tracking tunnels were installed between bait treatments for 12 nights and baited with peanut butter to provide further confidence in its status.

Monitoring to determine if mice had been eradicated occurred in late summer 2018, approximately 18 months after the baiting operation. By this time, a surviving mouse population should have recovered to detectable levels. Late summer was chosen as any breeding would have peaked and juveniles would have been present. Monitoring for mice was undertaken using 280 inked tracking cards in tunnels baited with peanut butter and distributed along 28 transect lines. Each transect comprised 10 tracking tunnels spaced 200 m apart. The transects were distributed extensively across Antipodes Island. They were placed in all habitat types, particularly in areas where mice had previously been in high abundance (e.g. near penguin colonies) and adjacent to inaccessible terrain. Tracking cards were checked and replaced approximately every five days for a period of three weeks. Supplementing this, two rodent detection dogs and their handlers searched the island for mice between 21 February and 15 March 2018. The dogs searched in accessible areas across the plateau and southern coast.

Non-target species

A non-target species technical advisory group recommended a strategy for managing risks to native species that did not include captive management but relied on natural populations outside of the treatment area. This strategy became part of the application to DOC, as administrators of the site, for consent to spread bait. Three of the four endemic land bird taxa were considered at risk from either primary or secondary poisoning. Bollons Island (52.6 ha) and Archway Island (6.2 ha) were excluded from the treatment area during planning because evidence from historic studies of invertebrates (Marris, 2000; McIntosh, 2001; Russell, 2012) and limited monitoring for mice on Bollons Island in 2014 (B. Rance pers. comm. 2014) gave sufficient confidence that mice were not present. These islands provided a natural refuge of 58.8 ha, 1.5 km north of Antipodes Island, where species would not be exposed to bait.

Baseline monitoring of endemic land bird taxa was conducted on Antipodes Island between 2013 and 2016 including immediately prior to bait application in winter 2016. Post-eradication monitoring occurred in the weeks after bait application in July 2016, and in the summers of 2017 and 2018, to record any population impacts of the operation. Distance sampling (Buckland, et al., 2001) was used to estimate the density and abundance of the endemic Antipodes parakeet (*Cyanoramphus unicolor*), Reischek's parakeet (*Cyanoramphus hochstetteri*), and the endemic subspecies of the New Zealand pipit (*Anthus novaeseelandiae steindachneri*). The perpendicular distance to individuals or groups of birds was measured from transect lines of variable length to the nearest metre using a laser range-finder. Transects were distributed throughout the island and repeated as often as practicable. The aim was a sample of 60 to 80 encounters of each species for robust modelling of the detection probability and resultant population density. The technique relies on sightings of birds, so sampling was generally avoided when the weather was wet and cold as birds are less conspicuous. The computer software 'Distance 6.2' (Thomas, et al., 2010) was used to analyse the data and compute population estimates. As the number of detections recorded was low for many of the survey periods, data were pooled and a global detection function was computed, from which survey specific estimates of density were calculated (Buckland et al. 2001). Visual comparison of point estimates and their 95% confidence intervals were reinforced using a comparison of Poisson rates (`poisson.test`; R Core Team, 2013) for three paired pre- and post-toxin application survey dates and departures from a hypothesis of no change in density tested.

Antipodes snipe (*Coenocorypha aucklandica meinertzhagenae*) were monitored by recording the number of snipe seen per hour by observers traversing the island on foot, to give an encounter rate. The change in encounter rate between years was assessed using a generalised linear model with negative binomial errors.

To determine if the breeding success of Antipodean albatross was impacted by the operation, the fledging success of Antipodean albatross chicks within 50 m of the load site was recorded in summer 2017 by visiting the nests prior to chicks fledging. The results were compared with fledging success of chicks, alive at the time of bait application, in two study areas on Antipodes Island.

No formal searching for potentially poisoned animals was done but carcasses found opportunistically were examined. The gut cavity was opened and inspected for haemorrhaging and or the presence of green bait in the stomach or intestines indicating poisoning by brodifacoum. Liver samples were collected from the carcasses of pipits and snipe and stored frozen. Samples were sent to Landcare Research and analysed using High Performance Liquid Chromatography with a detection limit of 1×10^{-6}% (0.001ppm).

Project communication

Public engagement was measured by recording the number of media articles about the project (on television, radio, print) and visits to the project's website www.milliondollarmouse.org.nz) and Facebook page (www.facebook.com/milliondollarmouse) during the operational phase.

RESULTS

The baiting operation was implemented and completed in winter 2016. Insufficient resourcing in the first year of planning and competition with other organisational priorities put pressure on the project team and risked delaying implementation. The development of project knowledge and a wealth of experience enabled quality advice from DOC's IEAG. Their strong support maintained focus on objectives and influenced the prioritisation of resources in the preparation phase. Procuring helicopter services and a cargo ship were the crux of logistics planning but proved difficult due to a small pool of suitable suppliers and complex processes. Over a year and a half was spent investigating options and developing trust with potential suppliers to prove the viability of the work and find capable operators who were willing to commit.

Calibration of bait buckets gave a usable swath width of 90 m for standard buckets (360° spread) and 40 m for the deflector bucket (180° spread). Pre-departure trials identified important improvements in systems and componentry including changes to the pneumatic feed from helicopters to the bait bucket, replacement of incorrectly sized bracing elements on the hangar and refinement of the system for its construction. Trials identified that lifting helicopters by the rotor head was the best technique to manoeuvre them in and out of the ship's hold.

The toxicity of all 131 batches of bait supplied met the contract standards. The average toxicity was 19.8 ppm of brodifacoum and the range was 16.5 ppm to 23.9 ppm ± 7%. The operational team arrived at Antipodes Island on 27 May 2016. It took approximately 90 minutes to extract each helicopter from the ship's hold and ready them for flying. Ship unloading was completed with 250 loads flown ashore over 12 days with suitable weather for helicopter operations occurring periodically on five of those days. Helicopter long-line operations to unload and load the ship were challenging and required precision from the pilots and a strong communicator on the deck of the ship to inform the pilot of the position of the hook and help direct the work. The construction team of six people established the field camp, completed complex site preparations and safely installed temporary infrastructure within 11 days before departing with the transport vessels on 7 June 2016. An emergency response exercise was conducted on 8 June to practice helicopter recovery of a person from the water with a rescue scoop net and a rescuer in a human sling on a long-line.

Readiness for baiting was achieved by 9 June 2016 but poor weather delayed baiting until 18 June 2016 when a brief respite in conditions allowed baiting of a small area (54 ha). This gave the opportunity for an initial test of personnel, loading systems and equipment ahead of better weather windows. The baited area incorporated the field camp and load site, enabling structure baiting to be completed to make bait available early in the programme around the accommodation area where there was the highest risk of alternative food sources for mice. Aerial baiting continued incrementally as the weather allowed until coverage was complete. Suitable weather windows for baiting operations were generally short, and conditions were changeable and generally windy. The longest continuous period of bait application achieved was 3.5 hours. Each day's baiting built on previous work using a "rolling front" approach, with the aim of minimising the area needing rebaiting if work was interrupted for too long.

Treatment one was completed on 29 June 2016 with bait application occurring on 18, 21, 22, 27, 28 and 29 June. The interruption after baiting on 22 June was greater than three days, so the last two bait swaths sown that day were sown again on 27 June with 50% overlap. A total application of 45.6 t of bait was applied during treatment one at an average rate of 21.6 kg/ha. No mouse sign was detected on either of the Windward islands so neither were baited, increasing the area where land birds would not be exposed to bait to 75.3 ha.

Treatment two commenced on 8 July, continued to 10 July and was completed on 12 July 2016. A total of 19.9 t was spread at an average application rate of 9.6 kg/ha. The average sowing rate for both treatments combined was 31.2 kg/ha, including application of all the contingency bait. Contingency bait was additional bait (20% of the planned total) taken to mitigate the risk of loss or damage during transport and storage, or of the treatment area being larger than expected. The rate of bait spreading averaged 1.79 t/hr for the first treatment and 0.93 t/hr for the second, giving an overall average of 1.44 t/hr. The interval between treatments was at least 16 days for 97% of the area, and between ten and twelve days for the remainder. Few technical issues with bait spread were encountered and none limited operations.

Rainfall data were collected daily, and some form of precipitation fell most days. A total of 7.9 mm fell in the 48 hours following application of 15.6 t of bait on 22 June in treatment one. Bait degradation was not formally monitored. However, visual inspection showed baits were weathered but generally intact at the start of treatment two, 20 days after application.

Analysis of GPS flight records for aerial bait spread showed that comprehensive bait coverage was achieved with no apparent gaps. The total maximum amount of bait taken from all bait stations set up for structure baiting was 240 g of the 4 kg available. Most of the bait take occurred in the first three nights and 73% of consumption occurred by night six. Imagery from a trail camera showed mice picking up and carrying away the 2 g bait pellets. Two mice were last recorded taking bait on 7 July, 20 days after application. Dissection of a mouse trapped nearby on the same day showed the stomach and intestines were green and full of bait.

Table 1 Incidental dead bird finds on Antipodes Island following bait application.

Species	Autopsy	Brodifacoum (µg/g) ± 6%
Antipodes parakeet *Cyanoramphus unicolor*	1 poisoned	Unknown
Reischek's parakeet *Cyanoramphus hochstetteri*	1 poisoned	Unknown
Pipit *Anthus novaeseelandiae steindachneri*	3 poisoned	0.028; 0.034; 0.01
Snipe *Coenocorypha aucklandica meinertzhagenae*	2 no sign	0.015; 0.031
Mallard duck *Anas platyrhynchos*	1 poisoned	Unknown

Table 2 Comparison of Poisson rates at two time points pre- and post-application of toxin on Reischek's parakeet, Antipodes parakeet and Antipodes pipit. Rate ratios, their 95% CI's and tests of departure from a hypothesis of no change in density between surveys are reported. Rate ratios <1.0 indicate population decline and those >1.0 population increase between surveys.

	Comparison of Poisson rates between surveys		
	Pre-drop 2016 & Post-drop 2016	Pre-drop 2016 & Jan/Feb 2018	Post-drop 2016 & Jan/Feb 2018
Reischek's parakeet	0.17 (0.13–0.23)**	0.85 (0.63–1.17)#	4.97 (3.92–6.30)**
Antipodes parakeet	0.57 (0.36–0.95)*	2.91 (1.81–4.88)**	5.09 (3.81–6.77)**
Antipodes pipit	0 (0.05–0.10)**	1.38 (1.08–1.76)*	19.44 (13.84–27.94)**

** P <0.001; * P <0.05; # not significant

No mouse sign was detected from 7,170 tracking tunnel nights and searching with dogs during mouse monitoring in summer 2018. The search effort and the evidence were reviewed by DOC's Island Eradication Advisory Group and the eradication of mice from Antipodes Island was declared successful in March 2018.

Non-target species impacts

Bait trials in 2013 demonstrated 100% uptake of the bait by mice and suggested a risk of primary poisoning for pipits but not for parakeets or snipe (Elliott, et al., 2015). During the eradication operation itself, eight dead birds of five species were found incidentally and all had been poisoned (Table 1). The associated search effort was at least 103 hours of extensive field work for monitoring land birds. Additionally, staff walked an 800 m route between Reef Point and the load site (Fig 1) almost daily for the six weeks between initial bait application in the area and departure. During the operation, some pipits were observed occasionally pecking at baits and some baits were found to have been chewed by parakeets, but most baits were untouched.

Despite the use of a global detection function, low numbers of observations led to large confidence intervals about density estimates derived from distance sampling (Figs 2, 3 and 4). Prior to 2016, only the sampling of Reischek's parakeets in October 2014 (61 encounters) reached the desired sample size of 60 to 80 encounters. In 2016, pre-baiting sampling for Antipodes parakeets (22 encounters) and post-baiting sampling for pipits (40 encounters) failed to reach this target. Overall, more sampling was done immediately post-baiting in 2016 (329 encounters) than before (186 encounters) due to time constraints. Poor weather also often constrained the method. The results (Table 2; Figs 2, 3, and 4) suggest that a significant number of pipits and parakeets probably succumbed to brodifacoum poisoning immediately following the application of bait. However, the populations of pipits and both parakeet species were able to persist and have increased greatly each year, recovering to densities that are similar to or higher than pre-eradication estimates by summer 2018 (Table 2; Figs 2, 3 and 4). Pipits have responded particularly strongly with very large year on year increases in density estimates since 2016. Anecdotal observations in summer 2018 were consistent with the reported increase. On most occasions when monitoring team members sat down in the field, pipits would immediately appear and walked around and on them, finding food items such as caterpillars within minutes (F. Cox, pers. comm. 2018).

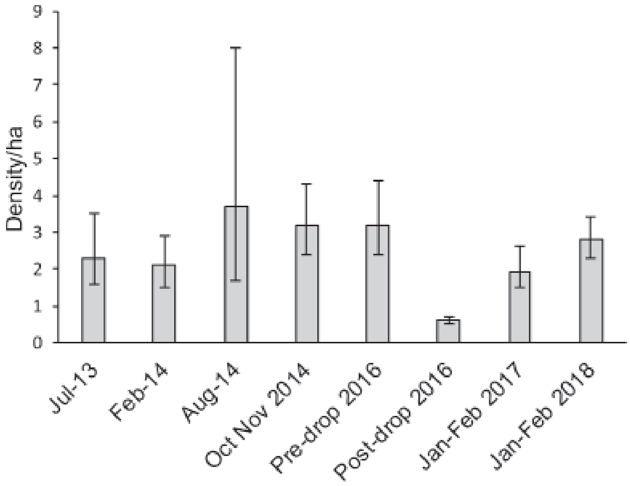

Fig. 2 Distance sampling results for Reischek's parakeets, Antipodes Island.

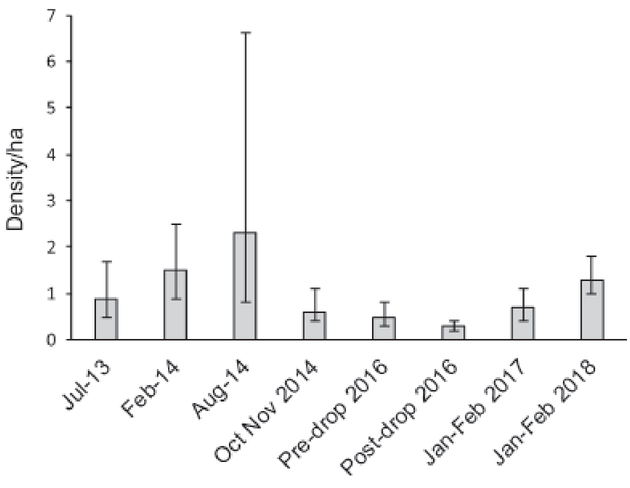

Fig. 3 Distance sampling results for Antipodes Island parakeets, Antipodes Island.

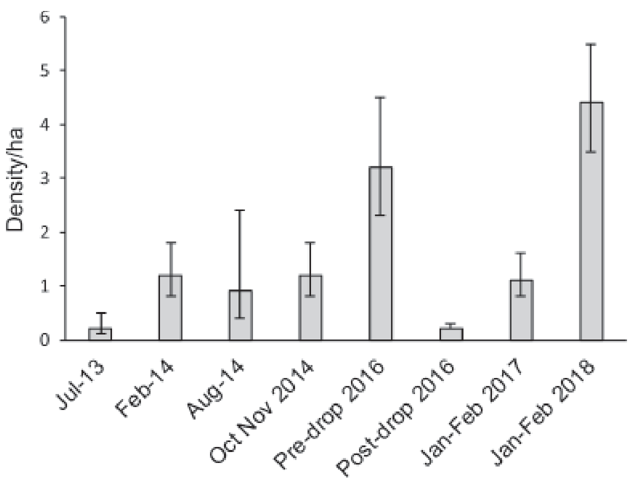

Fig. 4 Distance sampling results for pipits, Antipodes Island.

Table 3 Results of snipe encounter rate surveys recorded on Antipodes Island between 2013 and 2017.

Year	Person hours	Snipe seen	Snipe seen per hour	Change between years (%)	p
2013	341	38	0.1079		
2014	206.75	26	0.1322	123	0.4938
2015	140.5	17	0.1279	97	0.9267
2016	178	6	0.0330	26	0.0085**[a]
2017	224	8	0.0345	105	0.9373
2018	783	132	0.1640	475	0.0001***[b]

[a] Note significant difference in encounter rate between 2015 and 2016 prior to the eradication operation.
[b] Note significant difference in encounter rate between 2018 and 2017.

Snipe have been monitored each summer between 2013 and 2018. Snipe were more abundant in 2018 than ever before, but there has been considerable inter-annual variation in snipe abundance and the difference between 2018 and all the other years is not significant (Table 3). The between-year change in snipe abundance is probably more informative. Significant changes in snipe abundance occurred in 2015–2016 (a decline) and 2017–2018 (an increase). The large decline (72%) in the snipe encounter rate between 2015 and 2016 occurred before the mouse eradication so was not a result of the poison operation. The reason for this is unknown. There was a small, non-significant increase in the snipe encounter rate between 2016 and 2017 (Table 3), suggesting little or no by-kill of snipe during the mouse eradication. In contrast a dramatic increase (475%) occurred in snipe encounters between 2017 and 2018.

Helicopter activity did not have a detrimental effect on nearby Antipodean albatross chicks. All seven chicks within 50 m of the bait loading site were alive at the completion of operations and six out of the seven of them (86%) fledged successfully in early 2017, comparable with 90% outside the load site.

Scientists visiting Antipodes Island in summer 2017 and summer 2018 also noted a greater abundance of moths and the endemic fly (*Xenocalliphora antipodea*) than before the eradication of mice, observing them on flowers of the native groundsel (*Senecio radiolatus*) and Macquarie Island cabbage (*Stilbocarpa polaris*). This endemic fly was also abundant inside the Antipodes Hut for the first summer in over 20 years of visitation. A gathering of hundreds of large noctuid moths, suspected to be *Graphania ustistriga*, was also observed for the first time in 2018 despite 10 previous month-long summer visits to Antipodes Island between 1996 and 2017 (K. Walker, pers. comm. 2018). Large caterpillars, suspected to be larvae of the same noctuid moth species were regularly seen and observed being preyed on by pipits (K. Walker, pers. comm. 2018).

Project communication

Media coverage of the operation included seven prime-time television news stories and several radio interviews, print and online stories. Social media engagement peaked in June 2016 with 23,906 views of the MDM website and 71,967 on the MDM Facebook page. DOC social media also peaked at 77,710 views for the month. Outreach was amplified through the communications networks of project partners, the Morgan Foundation, WWF-New Zealand and Island Conservation.

DISCUSSION

A robust plan was formulated and delivered despite initial difficulties sourcing shipping and helicopter services. Complex projects require good resourcing in the planning phase and organisational prioritisation with significant scale up in resourcing for the preparation phase. Key factors for the delivery of the project were a) quality technical advice, b) single point accountability for overseeing the work and a team approach during preparations and operational phases, c) use of experienced personnel in key roles, d) a proven bait product, e) dependable and tested equipment, f) extensive contingency planning, g) a partnership approach with suppliers and e) the financial and moral support of private and public partners.

The brevity and inconsistency of weather opportunities in this environment showed the importance of being prepared and effectively using every opportunity to complete baiting. Additional skills and operational experience improved team performance and self-sufficiency. Equipment could generally be maintained on site and situational decision-making benefitted from the advice of senior team members. High speed internet access and video production capabilities enabled the team to communicate the project directly and engage an audience. Pilots' long-lining capabilities for ship operations could be considered a separate skill from baiting and, if necessary, pilots with specific skills should be engaged for the task. Similarly, coastal baiting with the deflector bucket requires specific attention and experience.

Non-target impacts

Monitoring evidence suggests the adverse effects of the operation on land birds were short lived. These impacts are expected to be outweighed by the long-term benefits to native species from the permanent removal of competition with mice. The risk to non-target species was effectively limited by relying on natural populations on Bollons and Archway Islands where they weren't exposed to bait. Prior to the mouse eradication, both parakeets and the pipit had rarely been observed making flights of more than 100 m on Antipodes Island, so while they are capable of crossing the 1.5 km strait between Bollons Island and the main Antipodes Island, it must have been a rare event. The risk of parakeets and pipits, resident on Bollons and Archway Islands, being killed by poison when they commuted across the strait was judged low. This reasoning eliminated the need to catch and maintain a captive population. During the bait uptake trial neither parakeet species was detected eating bait, yet both species were killed by the poison. Parakeets may have become habituated to the bait during the operation because of the longer exposure (more than 35 days) and changing palatability of baits as they weathered relative to the non-toxic trial (14 days). The large variability in population density estimates derived from distance sampling were largely driven by the relatively low encounter rates for all three species monitored using this method and should be treated as indicative only. More data would have improved the robustness of the results as would an improved sampling design to account for only recently discovered shifts in winter distribution for both parakeet and pipits. This, however, is difficult to achieve for such a remote and expensive site to visit and for one that frequently experiences less than ideal survey conditions in generally time-constrained survey periods.

It is unlikely that recruitment alone could account for the apparent rapid recovery of pipits and parakeets by summer 2017 (Figs 2, 3, and 4), suggesting the distance sampling results overestimated the losses and/or recovery. For both parakeet species, the large increases in population density, relative to post-baiting lows, were observed before most chicks had fledged (G. Elliott pers. comm. 2017). Pipits are unlikely to have raised more than one clutch by January 2017 which doesn't account for the nearly 500% increase in the population density estimate in summer 2017 since their post-baiting low. The similarly large increase in the estimated density of pipits between 2017 and 2018 (Fig. 4) is more likely to be real considering the observations of field staff.

The very large increases in the encounter rate of snipe and the density estimate of pipits in summer 2018 are presumed to be the result of large increases in the abundance of invertebrates following the eradication of mice and the resultant increases in reproductive output and survival.

Effective distance sampling for pipits within dense coastal vegetation, a habitat favoured by pipits in winter, was problematic. The short time-frames available during the operation for monitoring immediately before and after baiting meant distance sampling occurred in variable conditions and with variable effort across different habitat types, which may have exaggerated the estimated population declines following bait application. The extraordinarily large estimate of pipit population density pre-baiting in 2016 (Fig. 4) is possibly biased by proportionally greater sampling effort of abandoned penguin colonies (where pipits and parakeets are now known to congregate in winter) relative to that within the island interior (and where most of the 2013 counts were done). This reinforces the uncertainty of results.

The seasonal timing of distance sampling for land birds before and after baiting was also inconsistent (Figs 2, 3 and 4). The observed changes in seasonal distribution of these species therefore makes the use of a global detection function (which assumes constant detectability across surveys) problematic and dilutes direct comparability of the density results. Changes in detectability caused by movements to and from the coast may be biasing the results and at least partly account for the relatively low population density estimates so soon after the bait spread. It is recommended that results from surveys done at the same time be pooled if sufficient data are available.

The eradication of mice from Antipodes Island is a huge achievement for conservation in New Zealand. Hundreds of years of ecological devastation by mice has been halted and indigenous wildlife has started to recover. The importance of the result is reflected by the national and international protection of the site, recognising its special natural heritage values. The result provides momentum to New Zealand's Predator Free 2050 initiative and is a step closer to the vision of a New Zealand Subantarctic Islands region free of mammalian pests. Of the five island groups in the region, only Auckland Island now has mammalian pests: pigs (*Sus scrofa*), cats (*Felis catus*) and mice (*Mus musculus*). Over time it is expected that the invertebrate fauna on Antipodes Island will recover to reflect the abundance and species diversity recorded on Bollons Island and Archway Island, where no mice were present. It is hoped that species of larger-bodied ground invertebrates (for example tenebrionids), reduced to low abundance, will recover and others which became extinct on Antipodes Island through predation by mice (for example the unidentified weta and *Loxomerus* sp.), can be successfully reintroduced from the offshore islands where they may survive. The population densities of land bird species are expected to further increase and stabilise with the recovery of food sources and lack of competition with mice. Absent burrowing seabirds, for example black-bellied storm petrel, are also expected to recommence breeding on Antipodes Island. Further monitoring for land birds will occur opportunistically on an annual basis in conjunction with albatross research. Broader outcome monitoring will be repeated in approximately five to ten years' time and will include a repeat of invertebrate sampling, sampling of the seabird species breeding on Antipodes Island and measurement of change in vegetation monitoring plots.

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