New Zealand Journal of Ecology (2022) 46(3): 3499 © 2022 New Zealand Ecological Society.

NEW ZEALAND JOURNAL OF ECOLOGY

RESEARCH

A trial on Te Pākeka/Maud Island for reducing aerial baiting sow-rates for the eradication of house mice

Emmanuel D. Oyston[1*], Stephen R. Horn[2] and Elaine C. Murphy[3]

[1]Department of Conservation, Te Pākeka/Maud Island, Private Bag 65005, Havelock 7150, New Zealand
[2]Department of Conservation, PO Box 743, Invercargill 9840, New Zealand
[3]Department of Conservation, Private Bag 4715, Christchurch 8140, New Zealand
*Author for correspondence (Email: eoyston@doc.govt.nz)

Published online: 28 November 2022

Abstract: The house mouse (*Mus musculus*) is considered the most difficult rodent species to eradicate from islands. Eradication projects require careful planning and execution of an 'over-engineering' approach to ensure every individual of the targeted population is encountered and removed. Aerial broadcasting of rodenticides has been the method of choice for island rodent eradications since the 1990s and the methods and parameters continue to be refined. Mice were recently eradicated from Te Pākeka/Maud Island (318 ha) in winter 2019 using an aerial baiting prescription that was 50% less than the current best-practice baiting prescription. Using a rapid eradication assessment, it was proven that a combination of static and mobile surveillance devices could provide a high level of confidence of eradication success early on (4 months post-bait application). This paper describes the context, methodology, and outcomes of this low-sow rate trial in order to inform future projects. DNA profiling from the most recent mouse population established on Te Pākeka/Maud Island identifies the challenges of maintaining island biosecurity with the current available tools and in a context of increasing invasion pathways. The ability to adopt lower sowing rates for island mouse eradications reduces both financial and logistical barriers thereby allowing wildlife managers to implement mouse eradications on the world's most remote islands.

Keywords: eradication, Maud Island, *Mus musculus*, rapid eradication assessment, rodent, sowing rates

Introduction

Island ecosystems are extremely important to international biodiversity given their high rates of species endemism. Invasive rodents are a significant threat for the majority of the world's islands due to their ability to prey upon and ultimately wipe out vulnerable endemic wildlife in these unique ecosystems. Although smaller than its *Rattus* relatives, the common house mouse (*Mus musculus*) is a direct threat to island ecosystems, preying upon invertebrates, herpetofauna, vegetation, and birdlife (Howald et al. 2007; Campbell et al. 2015; Broome et al. 2019). Eradication of mice from islands is an important management action to prevent species extinctions and protect international biodiversity values in these ecosystems (Campbell et al. 2015; Holmes et al. 2019).

While eradication through hand laying (manually spreading by hand) of rodenticides is feasible for rodents on smaller islands with benign topography, the aerial application of rodenticides is currently the most effective and efficient way of eradicating mice and other rodent populations from islands (Holmes et al. 2015). Aerial broadcast of toxins for wild animal control began in the 1950s but was refined and developed for rodent eradications in the 1990s. Since then, the methodology has improved as lessons learnt were applied to projects of increasing size and complexity (Towns & Broome 2003). Modern day aerial baiting operations in New Zealand take place using a helicopter-slung mechanical spreader bucket distributing cereal baits containing the second generation anticoagulant rodenticide brodifacoum, over an operational area with GPS-level precision.

Due to their comparably smaller home ranges, the eradication of mice from islands is deemed a more difficult task than the eradication of rats. As such, the international track record for mouse eradications has a higher failure rate compared with rat eradications (MacKay et al. 2007). To date, 41 island mouse eradications have been attempted in New Zealand – with 33 successes and 8 failures (K. Broome, pers. comms.). The largest island internationally where mice have been eradicated is Macquarie Island (12 785 ha) in 2011, where mice were eradicated in the presence of ship rats (*Rattus rattus*) and rabbits (*Oryctolagus cuniculus*) (Springer 2016). The largest eradication to date of mice as the sole mammalian pest species was on Antipodes Island (2025 ha) in 2016. In New Zealand, the failure rates of island mouse eradications led the Department of Conservation's Island Eradication Advisory Group to create recommendations and eradication best practice methodology in 2010, in order to ensure robust planning and operation consistencies in future projects. One

DOI: https://doi.org/10.20417/nzjecol.46.3499

of the key parameters of this best practice was the prescribed minimum sowing rate.

As eradications have the challenge of removing every individual, eradication projects have generally implemented an 'overengineering' approach to project design with the perception that an excess of bait increases the likelihood of eradication success through ensuring every target individual encounters bait (Cromarty et al. 2002; Will et al. 2019). The higher rate of failure for mouse eradications and the smaller home ranges of mice relative to rats (MacKay et al. 2011) has potentially driven a reluctance to trial reduced sowing rates.

Using higher bait application rates than required increases the financial costs of a project as greater volumes of bait need to be produced, transported, stored and distributed. Handling costs increase with bait volume at every step of the supply chain, which is complex particularly for remote sites. Using Antipodes Island as an example: bait was bagged at the factory and trucked to a storage warehouse where it was loaded into large wooden boxes (bait pods) typically holding 700 kg of bait. Bait in pods was then trucked to the port for shipping, where it was handled port-side, loaded and stowed on a ship and shipped to site. Helicopters were then used to unload bait pods one at a time from the ship and position them on land ready for bait to be spread by helicopter when the weather allowed (Horn et al. 2019). Higher bait application rates also decrease the feasibility of projects through the competing logistical constraints such as transport and completing bait application in limited weather windows; and can increase risks to non-target species (Parkes et al. 2011).

The recommended bait sowing-rate for island mouse eradications in temperate or subantarctic climates are two separate applications of 8 kg per hectare, which incorporates a 50% swath overlap (Broome et al. 2017). When other species that create significant competition for bait consumption exist, it is standard practice to increase this sowing rate to ensure all individuals of the target species encounter bait. The eradication of mice from Antipodes Island used a baiting prescription of 16 + 8 kg ha^{-1} (Horn et al. 2019) prior to the existence of best practice specifically for mouse eradication in New Zealand. Bait application rates on other successful larger island eradications where mice were targeted as part of multi-species eradications were on Macquarie Island with bait application rates ranging from 24–44 kg ha^{-1} (Springer 2016); and parts of South Georgia (range of mice covered 58 000 ha over several discrete blocks isolated by glaciers) where Norway rats (*Rattus norvegicus*) were also present, and bait application rates of 10 kg ha^{-1} were used (Martin & Richardson 2019). The mouse eradication project on Gough Island (6500 ha), a project that faced logistical difficulties, used a baiting prescription of two applications of a minimum of 10.5–13.4 kg ha^{-1} (Samaniego et al. 2022).

The New Zealand Government's Predator Free 2050 programme has an interim goal of eradicating all mammalian predators from uninhabited offshore islands by 2025 (DOC 2020). There are 15 islands around New Zealand greater than 1000 ha with rodents present (see Table 1), totalling c. 392 510 ha. Of these, Auckland Island, Resolution Island, Long Island and Cooper Island are the only Crown-owned uninhabited islands. The latter three are located in Dusky Sound, Fiordland, and hold significant risks of reinvasion from rodents post-eradication given their close proximity to the mainland (500 m, 500 m, and 200 m, respectively). Challenges around the social acceptability of best-practice rodent eradication methods (i.e. the use of rodenticides) are likely to be the current significant barrier to the feasibility of eradicating rodent populations on the remaining 11 islands that are at least partly privately owned and inhabited. Reducing the amount of bait used in aerial bait applications for rodent eradications on inhabited islands may help increase the social acceptability of the method at these sites.

Auckland Island (45 891 ha) is being scoped for the feasibility of the eradication of all mammal pests present, which include pigs (*Sus scrofa*), mice, and cats (*Felis catus*) (Horn et al. 2022). Eradicating mice from the main Auckland Island using the current best-practice mouse eradication sowing rates would require approximately 1000 tons of bait to be applied. Due to the logistical constraints of transporting and spreading bait in such a remote area, and limited weather periods for

Table 1. New Zealand islands >1000 ha where rodents are present.

English name	Size (hectares)	Land tenure	Permanent human habitation
Stewart Island	168 538	Crown & private	Yes
Chatham Island	74 572	Crown & private	Yes
Auckland Island	45 891	Crown	No
Great Barrier Island	27 721	Crown & private	Yes
Resolution Island	20888	Crown	No
D'Urville Island	16 529	Crown & private	Yes
Waiheke Island	9221	Crown & private	Yes
Arapaoa Island	7603	Crown & private	Yes
Pitt Island	6501	Crown & private	Yes
Matakana Island	6070	private	Yes
Kawau Island	2033	Crown & private	Yes
Long Island, Southland	1899	Crown	No
Cooper Island	1779	Crown	No
Ponui Island	1797	private	No
Ruapuke Island	1468	private	No

bait application, this would not be a feasible option. The most obvious way to manage these constraints is to look at the feasibility of using a significantly reduced baiting density that could still achieve the eradication of mice.

Two past mouse eradication operations have been successful with lower sowing rates, albeit on much smaller islands. These include the Enderby Island rabbit and mouse eradication project (695 ha), which used a sowing rate of two applications of >5 kg ha^{-1} (Torr 2002); and Adele Island (87 ha) where mice were re-eradicated following a mouse reinvasion with a single application of 3 kg ha^{-1} in 2017 (Livingstone et al. 2022). A non-toxic low sowing rate trial on Auckland Island's Falla Peninsula (Russell et al. 2019) involved a single application at 4 kg ha^{-1} and bait uptake results indicated that two applications should be successful at targeting every individual mouse in the environmental context of that study.

In 2019, a mouse eradication operation on Te Pākeka/Maud Island took place, trialling a low sowing rate that equated to 50% of the standard best-practice rates used for the eradication of mice in temperate environments (Broome et al. 2017). At 318 ha, Te Pākeka/Maud Island presents a useful site to test a baiting prescription with lower bait application rates to increase confidence in lower sowing rate baiting prescriptions for island mouse eradication projects. The outcome of this operation could inform the feasibility of eradicating mice on larger remote islands in New Zealand through using a significantly reduced sow rate. This paper discusses the methodology and outcomes of the operation on Maud Island.

Methodology

Study site

Te Pākeka/Maud Island is a 318 ha predator-free scientific reserve located in the Pelorus Sound, Marlborough, New Zealand (Fig. 1). The pyramid shaped island rises from sea to a summit of 369 meters above sea level and has an outlying peninsula that runs out to the east for c. 2 km. The island has extensive moderate slopes (<45 degrees), with areas of the coastal perimeter (13 km) holding cliff faces ranging from 2 to 10 meters.

After severe deforestation in the late 19th century, the island's habitat predominantly consists of mahoe (*Melicytus ramiflorus*) and five-finger (*Pseudopanax arboreus*) dominated regenerating forest; mānuka (*Leptospermum scoparium*) and flax (*Phormium cookianum*) dominated coastal shrubland; and rank exotic grasslands regenerating to mānuka/tauhini (*Ozothamnus leptophyllus*) shrubland. Significant tracts of the exotic tree lucerne (*Cytisus proliferus*) and Spanish heath (*Erica lusitanica*) exist on the drier western side, which is slowly giving way to native succession. A 15 ha tract of intact virgin coastal broadleaf forest dominated by kohekohe (*Dysoxylum spectabile*), pukatea (*Laurelia novae-zelandiae*), and nikau palm (*Rhopalostylis sapida*) survived earlier forest clearance. This area of habitat preserved a diversity of rare and threatened invertebrate and herpetofauna that continue to recover and disperse throughout the island as habitat recovers. Some of these species include the Hamiltons frog (*Leiopelma*

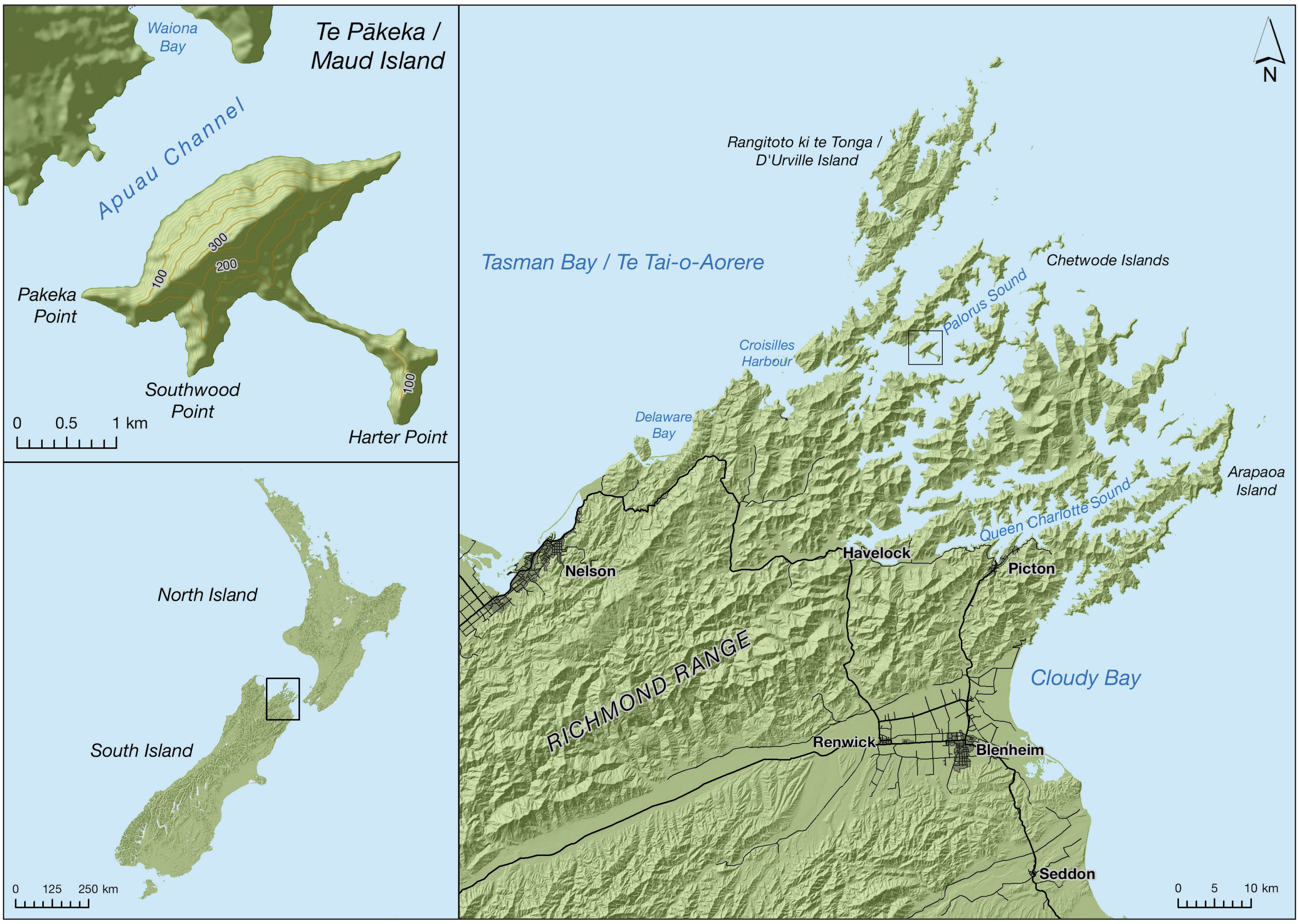

Figure 1. Map of Te Pākeka/Maud Island. Inset map shows wider Marlborough Sounds region.

hamiltoni), forest gecko (*Mokopirirakau granulatus*), Cook Strait click beetle (*Amychus granulatus*), Giant land snail (*Powelliphanta hochstetteri obscura*), southern striped gecko (*Toropuku stephensi*) and Cook Strait giant weta (*Deinacrida rugosa*). The main ecological value of the island lies in the past and present absence of introduced mammalian predators and browsers, resulting in some of the best examples of remnant coastal broadleaf forest left in the Marlborough Sounds; and a full and dense complement of invertebrates rarely found elsewhere (Notman 1984), with some species now absent from mainland areas.

Mice have made their way to Te Pākeka/Maud Island twice previously. A single mouse was detected and caught by staff in 2006. The origin of the mouse was unknown, and a population did not establish as a result of this incursion. In 2013, mice were detected on the island and further investigation confirmed their establishment. Investigation on the biology of individuals caught revealed that this population had likely arrived in 2012, and genetic profiling indicated that the population was founded by a single pregnant female (Pichlmueller et al. 2020). This population was successfully eradicated with an aerial baiting operation in 2014 using a baiting prescription of 8 + 8 kg ha^{-1} (see Broome et al. 2019). Following on from the 2012 mouse invasion and subsequent eradication in 2014, the island's biosecurity practices were improved. More rigid quarantine procedures were established for approved vessels and materials coming to the island, and an improved network of detection devices were installed across the island that until then was more targeted to the detection of mustelids.

Mouse invasion

In June 2018, a mouse was detected by resident rangers, and further investigation of previously collected tracking cards showed mouse tracks at several locations on the island. Additional snap traps and tracking cards were deployed, as well as a rodent detection dog. By late June the extent of detections and captures around the island indicated removal was beyond the feasibility of an incursion response operation, and the eradication of mice from the island was identified as an opportunity to trial a low sow rate aerial baiting eradication.

Mice caught and analysed for age structure and genetic relatedness showed that colonisation likely occurred as early as November 2017 (based on eight mice that were caught and autopsied that were 4–8 months old based on tooth wear). Genetic profiling of the established population identified the mice as distinct from the population that had established in 2012 that was subsequently eradicated in an aerial baiting operation in 2014 (see Broome et al. 2019).

Genetic profiling of the 2017 mouse invasion showed that they were closely related and were likely created from very few founders (R. Fewster pers. comms.) and their relatedness was closest to populations of mice on the mainland peninsula immediately west of the island. Given the lack of permanent residence in this area, and boat landings on the island being authorised by permit only, it is likely the mice arrived through swimming or rafting on flotsam. The closest distance between the island and the western mainland is approximately 900 metres.

Standard biosecurity checks on the island consisted of monthly checks of peanut butter lured wax tags at approximately 300 m intervals around the 18 km track network, 2-monthly checks of pre-baited Connovation chewcards (left in situ) spaced at 100 m along the track network, and a 3-night tracking tunnel survey spaced at 100 m along the track network. Tracking tunnel cards prior to June 2018 had been discarded so re-checking of these for detection of mice prior to the survey of June 2018 was not possible. Presence of significant numbers of weka (*Gallirallus australis*) on the island also meant interference with detection devices was common. Rodent detection dogs had monitored the island in November 2017, February 2018 and March 2018 but had not detected mice.

Prior to implementing the mouse eradication in 2019, improvements in the island's biosecurity detection network were made. These improvements included running tracking tunnels monthly and leaving tracking cards *in situ* for the whole month; intensifying the density and extent of detection devices where authorised vessels and materials landed on the island; increasing the density of detection devices and including tracking tunnels on the coastal perimeter of the island; including victor snap traps targeting mice in all trap boxes; and using high oleic content peanut butter as the main rodent lure in detection devices. The use of chew cards was disestablished after paired testing compared pre-baited Connovation chew cards (n = 166) and high oleic peanut butter baited tracking tunnels (n = 166) for the detection of mice across the island for a one month period, revealing a 2% vs 100% detection rate. Significant numbers of weka were functionally eradicated in line with the island's management to protect endangered herpetofauna and invertebrate species, and to eliminate interference with biosecurity devices and non-target bait consumption during aerial baiting for the mouse eradication. The presence of relatively high weka densities (approximately two per hectare) on the island during the time of a mouse population establishing indicates that weka are a relatively poor bio-control agent for mice, contrary to recent discussions in the literature (Carpenter et al. 2021).

Mouse distribution and densities on the island saturated devices by December 2018 (100% tracking in 170 island wide tracking tunnels), with the population peaking between December 2018 to March 2019 based on trap catch and detection devices. Trap catch of mice around buildings tailed off in April 2019 and there was an indication breeding had stopped. Six female mice (14–17 g) caught in April/May 2019 were not sexually mature and 5 females (18–23 g) showed no sign of current breeding.

Although no specific population density analysis was done on the 2017 mouse invasion population on Te Pākeka/Maud Island, a population density study was done on the mouse population that established in 2012 that revealed the population densities to be high, reaching an average of 120 mice per hectare (Reynolds 2015).

Eradication methodology

The 2019 eradication of mice from Te Pākeka/Maud Island followed similar methods of aerial broadcasting of rodenticides for rodent eradications as developed and refined since the 1990s (see Towns & Broome 2003; Broome 2009; Russell & Broome 2016).

The aerial application of bait followed the current agreed best practice methodology for mouse eradications (Broome et al. 2017), with the exception of the reduced sowing rate – which was the focus of the trial. This methodology involves two separate bait applications spaced at least 14 days apart.

Bait was applied with a Bell 206 Jet Ranger helicopter towing an underslung bucket. The bait was Pestoff Rodent Bait 20R™ manufactured by Orillion, a 2 g cereal bait containing 20 parts per million of the anticoagulant toxin brodifacoum.

The underslung buckets used an air driven spinner to distribute baits in a circular pattern to a known extent, of which bait distribution and density was known through test calibrations of bait over a flat gridded surface where bait density was accounted for in a sampling grid. The flight characteristics for the calibration of the 100 m effective swath width used are shown in Table 2. This width is thought to be the largest swath width used to date in an island rodent eradication in New Zealand.

Each application of bait was applied at a rate of 2 kg ha^{-1}, with 50% overlapping parallel swaths to achieve an on the ground nominal rate of approximately 4 kg ha^{-1} (see Fig. 1 in Broome et al. 2019). An additional single swath of bait was applied around the 13 km coastal perimeter of the island, flown at half speed (35–40 km h^{-1} ground speed) to achieve the 4 kg ha^{-1} application rate.

The application of bait was timed for winter, to coincide with the time of year when food is relatively scarce for a mouse population. That said, the historical absence of mammalian predators on the island meant that it holds a relatively high biomass of invertebrate, herpetofauna, and palatable vegetation throughout the winter. Red deer (*Cervus elaphus*) were eradicated from the island and weka were reduced to very low levels prior to the baiting application in order to reduce non-target bait consumption that may have confounded the resulting outcomes of a low sow rate trial in the event of failure to eradicate mice.

The first application of bait occurred on 24 June 2019, and the second application occurred on 22 July 2019. A total of 1850 kg of bait was applied in both applications, and flying conditions were excellent (<3 knot winds at 370 MASL and 100% visibility) on each of the bait application days. Bait coverage, flight speed, and height was downloaded and monitored by the project manager and GIS analyst on every bucket (150 kg load) that went out. The helicopter used the TracMap DGPS system to record flight lines and bait coverage, while GIS analyses were done in ArcGIS using python scripts developed by the Department of Conservation GIS team for aerial baiting operations. Any gaps greater than 10 m between swaths were re-sown. Swath coverage and bait density mapping for the first and second baiting applications are shown in Figure 2. The parallel swathes/flight lines were offset by approximately 25 degrees between the first and second bait applications to further reduce the risk of gaps in coverage between the two applications.

Bait flow rates from the spreader bucket were tested on initial first loads of 50 kg during each application until correct flow rates were obtained to achieve the nominal bait density (see Broome et al. 2017). The flow rate was monitored throughout the operation. The initial on-site flow rate tests were important as baits were initially flowing at over twice the rate compared to the initial bucket calibration trials done on an airfield. It is unclear why the bait flow was significantly different, but it is assumed it was due to a slight difference in cereal bait batches of the non-toxic bait used for calibrating and the toxic bait used for the eradication. This difference has been known to occur in other cereal bait applications but usually not to such a dramatic extent.

In addition to the aerial application of baits, buildings on the island were baited by hand using several plastic trays containing PestOff 20R™ baits distributed at a minimum of one tray per 20 m^2 floorspace. These trays were replenished every 3 days until no further bait take had been observed and were removed after 2 weeks of no bait take. In situations where roofing spaces were not accessible, roofing iron was lifted and individual cereal baits were hand laid in these areas on each application.

Table 2. Flight characteristics for the 100 m effective swath calibration used.

Bait flow rate	23 kg per minute
Cone aperture	58 mm
Ground speed	70 km h^{-1}
Wind conditions	<5 knots
Flying height	150 feet above ground

Eradication confirmation

Traditional best practice in New Zealand for determining whether a rodent eradication has been successful is to monitor for presence of the target and declare the outcome 2 years post eradication effort (Broome et al. 2017). In recent times, a Rapid Eradication Assessment (REA) methodology has been developed as an alternative approach to monitor at a fixed time following an eradication and quantitively estimate the probability of eradication success using a statistical modelling framework (see Samaniego-Herrera et al. 2013; Russell et al. 2017; Kim et al. 2020). The REA tool (accessed online at http://rea.is) was used retrospectively to assess the probability of the island's surveillance network successfully determining eradication success in a relatively short time frame. Parameters used for the assessment can be found in Table 3 below.

The monitoring intensity and infrastructure on Te Pākeka/Maud Island was deemed significantly more intensive than normal remote unmanned island situations and, as such, a decision was made in consultation with DOC's Island Eradication Advisory Group that 6 months of the described monitoring regime should provide enough evidence that the eradication of mice was successful. A permanent network of 171 tracking tunnels with baited inked tracking cards (Gotcha traps™) were situated in wooden tunnels at 100 m spacings, and 120 Victor Mouse Traps at approximately 300 m spacings along the 18 km track network around the island. Tracking tunnels and traps were baited with high oleic content peanut butter and checked for sign and replaced/re-lured monthly. Figure 3 shows the distribution of tracking tunnels and traps monitored across the island.

A rodent detection dog and handler searched for sign of mouse presence along the island tracks, the coastal perimeter, and off-track areas where no detection devices were present. These checks occurred 4 and 7 months post the second application of bait. The search effort and coverage of the rodent dogs is shown in Figure 3.

Results

By February 2020 (7 months following the second application of bait), no signs indicating presence of mice had been detected through detection devices or searches carried out with rodent detection dogs. If potential breeding individuals had survived through both baiting applications, it is expected that they would have repopulated to a detectable level within this timeframe given the intensity and distribution of the monitoring infrastructure in place. Monitoring of hand laid baits in bait trays in and around buildings showed no interactions

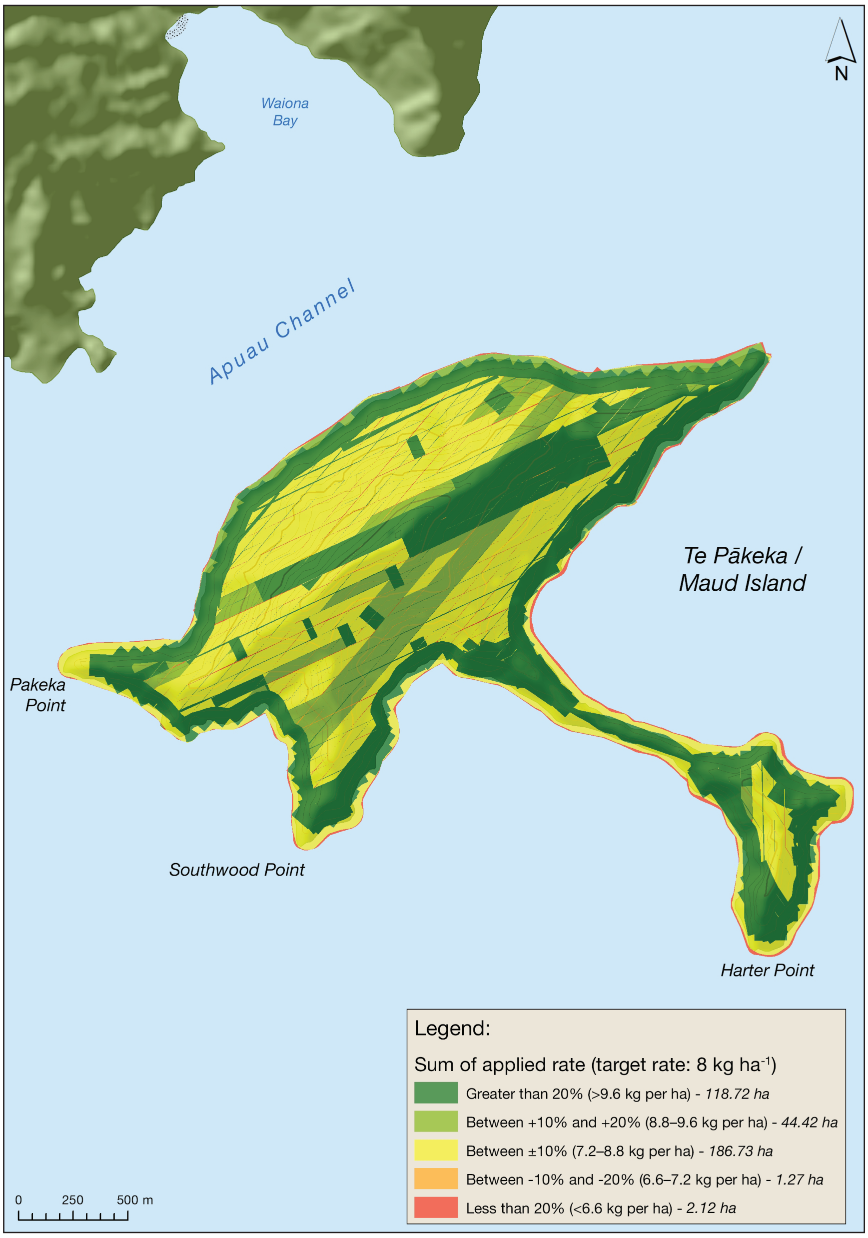

Figure 2. Map of bait coverage and density from the first and second bait applications, Maud Island 2019.

Table 3. Parameter values used in REA assessment of the Maud Island surveillance network.

Parameter	Likely	Min–max
Monitoring data		
spacing	0 (static and mobile devices supplied)	
iterations	2000	
target	0.99	
Years since eradication	0.08–0.58 (1–7 months)	
Device parameter		
$g0_1$ (tracking tunnels)	0.2	0.15–0.25
$g0_2$ (victor snap traps)	0.1	0.05–0.15
Biological parameters		
sigma	10	5–15
probability of eradication success	0.8	0.7–0.9
probability of reintroduction	0.01	0.01–0.02
population growth rate	7	5–10
juvenile dispersal	50	
incursion dispersal	200	

Values for mouse related parameters based on Nathan et al. 2013; Sagar et al. 2022; and Kim et al. 2020.

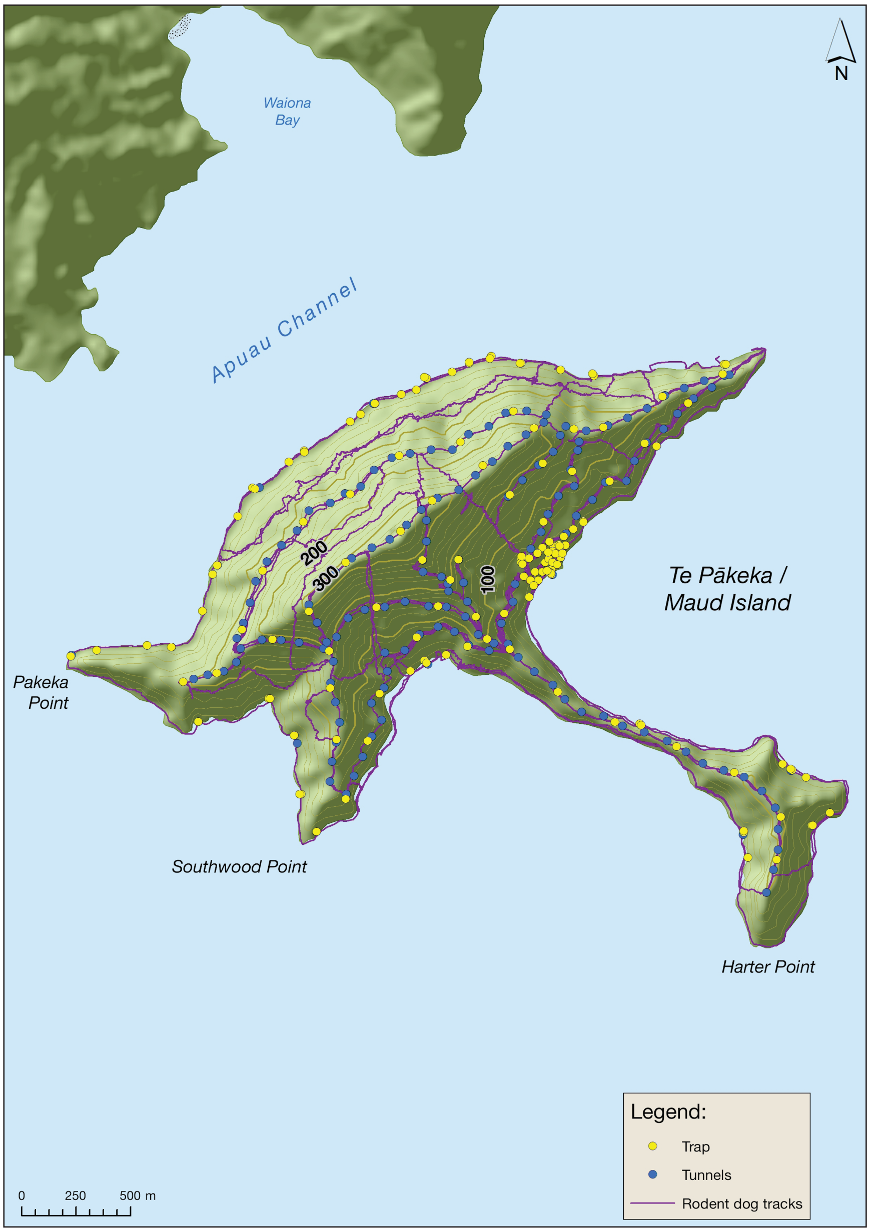

Figure 3. Post-eradication monitoring network on Maud Island 2019.

with baits by mice beyond 1 week following the first bait application. Based on these results, the project manager and DOC's Island Eradication Advisory Group were satisfied that the eradication attempt using low sow rates was successful in eradicating mice from the island. The cost implications of a 50% reduced sowing rate for the Maud eradication led to an approximate saving of 12% of the eradication project costs. These savings were primarily from bait purchase, but also included reduced costs for bait transport, storage, and a small saving in flight time.

Analyses from the REA calculated the island's static surveillance network as having 9.5% coverage for mice but this increased significantly to 36% coverage when factoring in the mobile surveillance provided by rodent detection dogs at 4 and 7 months post-bait application. Table 4 shows the REA output for Credible Interval Values (CIVs) for a >99% confidence threshold of determining eradication success using the surveillance network and rodent detection dogs on the island. The majority of the iterations run by the REA showed that by 4 months post-bait application, the monitoring network on the island provided over 99% probability of confidence in successful eradication. The REA analyses showed the significant difference rodent detection dog coverage made to the level of confidence achieved in simulations compared to using static devices alone (in month four 53% of simulations achieved >99% confidence of success, compared to 10% of simulations achieving >99% when not using detection dogs).

Discussion

Even when it was a farmed island without any biosecurity measures, rodent populations have historically failed to establish on Te Pākeka/Maud Island. During the last decade, there have been two separate mouse incursions that have each subsequently led to the establishment of mice populations. Genetic profiling of the most recent incursion and the context of the island (closed to public access and landings; and maintaining high biosecurity standards regarding materials and vessels landing) indicate that mice have potentially made

Table 4. REA simulation outputs for post-eradication monitoring on Te Pākeka/Maud Island.

Months post-eradication	CIV* (static devices only)	CIV* (static devices and mobile rodent detection dog tracks)
1	0.05	-
4	0.10	0.53
7	0.14	0.60
12	0.21	-
24	0.31	-

*= proportion of the posterior probability of eradication above the success target value (99%)

their own way to the island from the mainland to the west. This incursion pathway suggests a minimum swimming or rafting distance of 900 meters for mice arriving on the Island.

Climate change presents significant challenges for island biosecurity due to increasing surface water temperatures (allowing pests the ability to survive longer in the water and therefore increasing their swimming distances); more frequent storm events (creating stronger water currents and flotsam as a vector for pests to travel to pest-free islands); and increased frequency of vegetation masting (leading to increasing frequency of predator irruptions and therefore increased dispersal of individuals as a result of competition for territory and food). Aspects of island biosecurity, such as the quarantining of incoming vessels and materials, can be relatively easily ensured to maintain a rodent-free status. However, with the current tools and technology available, the odds are heavily stacked against conservation practitioners to detect and respond to the arrival of a single pregnant female mouse around 13 km of coastline before it gives birth to its litter.

The success of the 2019 eradication of mice from Te Pākeka/Maud Island has provided further confidence that mice can be successfully eradicated using a dramatically reduced sowing rate (two applications of 4 kg ha^{-1}) compared to current best practice (two applications of 8 kg ha^{-1}). These results provide increased confidence and a pathway to the feasibility of eradicating mice from Auckland Island, where current best practice sowing rates for island mouse eradications are impractical due to the logistics of transporting such high volumes of bait to a remote area, and aerial application of bait in an area with such limited windows for flying due to poor weather conditions.

Cost implications for other island mouse eradications will be contextual to the specific project, due to the scale and remoteness of the location exponentially affecting the costs associated with logistical factors such as bait transport and storage. The obvious immediate saving from using a 50% reduced sowing rate is a 50% reduction in bait purchase costs. For a project such as the Auckland Island mouse eradication, this reduction would equate to a saving of approximately $1.8 million (NZD) in bait purchase costs, with significantly more to be saved through reduced bait transport and storage requirements, and flying time to sow the bait. A gross and purely theoretical look at the cost implications of halving the bait application rate from 2 x 8 kg ha^{-1} to 2 x 4 kg ha^{-1} across the other sites identified in Table 1 would equate to a collective saving of over $13 million for the cost of bait production alone.

Post-eradication monitoring and evaluation using the REA tool has demonstrated a high level of confidence of eradication outcomes when using a combination of static devices and rodent detection dogs. The mobile coverage that is achievable on smaller islands with traversable terrain means that rodent detection dogs significantly increase the confidence of determining an eradication outcome in a shorter timeframe.

Acknowledging mice are a relatively difficult rodent species to eradicate from islands, the success of a low sowing rate for the eradication of mice suggests that island rat eradications in temperate climates could be achievable using similar low sowing rates. However, we acknowledge that behavioural and biological differences with *Rattus* species mean that mouse learnings are not directly transferrable and therefore a similar trial should be undertaken before changing current best practice for island rat eradications in temperate environments.

The results of this successful low sowing mouse eradication have several caveats. Mice were the sole target species and there was not competing bait take from other rodent or ungulate species. Although the mouse population was widespread and had saturated all monitoring devices at the time of the bait application, the mice caught and examined indicated the population had stopped breeding several months beforehand. This finding was unexpected due to the presence of available seed, fruit, and invertebrates that remained as viable food sources, and the relatively mild temperature on the island. Further work around low sowing rate baiting prescriptions should include testing the low sowing rate prescription when an island mouse population is confirmed to be breeding and expanding, and include monitoring measures of population densities. This information could allow wildlife managers to react faster to mouse incursions, reducing the impact on protected wildlife of high biodiversity value and also potentially reducing the eradication cost through a smaller operation area.

The small size of Maud Island meant that the completion of each bait application could be timed and achieved within single periods of good weather as baiting could be completed in a matter of hours. Bait application on larger islands could occur over several weeks due to size and required flying time, and as timeframes are constrained bait will likely be spread in generally poorer weather than was achievable on Maud Island, particularly for subantarctic Auckland Island. As a consequence, accurate bait application and monitoring is increasingly important due to the lack of redundancy that would have been provided with higher bait sowing rates. When considering a low sowing rate application for larger island mouse eradications, it is important that bait flow rates are constantly monitored as lower sowing rates will result in less margin for error in regards to bait coverage on the ground, relative to operations with higher sowing rates. Fluctuation in bait flow rates may be an issue that could be eliminated through innovation in the design of bait buckets.

Author contributions

EDO ran the operation and collected data; ECM analysed mouse demographics and provided interpretation of genetic analyses; SRH provided guidance on methodology; and EDO wrote the manuscript with input from SRH and ECM.

Acknowledgements

Many thanks to the field-staff involved in delivering the mouse eradication, and specifically David Rees for assisting in the early stages of the project planning. Technical advice regarding mice eradications was provided by the Department of Conservation's Island Eradication Advisory Group; and Rachel Fewster from the University of Auckland provided analyses and interpretation of mouse genetics. Thanks to Gérard Rocamora from the Island Biodiversity and Conservation Centre, University of Seychelles; an anonymous reviewer; and James Russell from the University of Auckland for reviewing and providing suggestions to the original manuscript as well as support with the REA tool.

References

Broome KG 2009. Beyond Kapiti – a decade of invasive rodent eradications from New Zealand islands. Biodiversity 10: 14–24.

Broome KG, Golding C, Brown KP, Horn S, Corson P, Bell P 2017. Mouse eradication using aerial baiting: current agreed best practice used in New Zealand (Version 1.0). New Zealand Department of Conservation internal document DOC-3034281. Wellington, New Zealand, Department of Conservation.

Broome KG, Brown D, Brown K, Murphy E, Birmingham C, Golding C, Corson P, Cox A, Griffiths R 2019. House mice on islands: management and lessons from New Zealand. In: Veitch CR, Clout MN, Martin AR, Russell JC, West CJ eds. Island invasives: scaling up to meet the challenge. Proceedings of the International Conference on Island Invasives 2017. Occasional Paper of the IUCN Species Survival Commission 62. Gland, Switzerland, IUCN. Pp. 100–107.

Campbell JK, Beek J, Eason CT, Glen AS, Godwin J, Gould F, Holmes ND, Howald GR, Madden FM 2015. The next generation of rodent eradications: innovative technologies and tools to improve species specificity and increase their feasibility on islands. Biological Conservation 185: 47–58.

Carpenter JK, Innes JG, Wood JR, Lyver PO'B 2021. Good predators: the roles of weka (*Gallirallus australis*) in New Zealand's past and present ecosystems. New Zealand Journal of Ecology 45: 3425.

Cromarty PL, Broome KG, Cox A, Empson RA, Hutchinson WM, McFadden I 2002. Eradication planning for invasive alien animal species on islands – the approach developed by the NZ Department of Conservation. In: Veitch CR, Clout MN eds. Turning the tide: the eradication of invasive species. Proceedings of the international conference on eradication of island invasives. Occasional Paper of the IUCN Species Survival Commission 28. Gland, Switzerland, IUCN. Pp. 85–91.

DOC 2020. Towards a Predator Free New Zealand - Predator Free 2050 Strategy. Wellington, Department of Conservation. 43 p.

Holmes ND, Griffiths R, Pott M, Alifano A, Will D, Wegmann AS, Russell JC 2015. Factors associated with rodent eradication failure. Biological Conservation 185: 8–16.

Holmes ND, Spatz DR, Oppel S, Tershy B, Croll DA, Keitt B, Genovesi P, Burfield IJ, Will DJ, Bond AL, Wegmann A, Aguiree-Muñoz A, Raine AF, Knapp CR, Hung CH, Wingate D, Hagen E, Méndez-Sánchez F, Rocamora G, Yuan HW, Fric J, Millett J, Russell JC, Liske-Clark J, Vidal E, Jourdan H, Campbell K, Springer K, Swinnerton K, Gibbons-Decherong L, Langrand O, de Brooke ML, McMinn M, Bunbury N, Oliveira N, Sposimo P, Geraldes P, McClelland P, Hodum P, Ryan PG, Borroto-Páez R, Pierce R, Griffiths R, Fisher RN, Wanless R, Pasachnik SA, Cranwell S, Micol T, Butchart SHM 2019. Globally important islands where eradicating invasive mammals will benefit highly threatened vertebrates. PLoS One 14: e0212128.

Horn SR, Greene T, Elliott G 2019. Eradication of mice from Antipodes Island, New Zealand. In: Veitch CR, Clout MN, Martin AR, Russell JC, West CJ eds. Island invasives: scaling up to meet the challenge. Proceedings of the International Conference on Island Invasives 2017. Occasional Paper of the IUCN Species Survival Commission 62. Gland, Switzerland, IUCN. Pp. 131–137.

Horn SR, Sagar RL, Frank VK, Cox FS, Jacques PM, Ware J, Hanley-Nickolls R, Leask EP, MacDonald NL, Kirby-Crowe MS, Le Lievre ME, Broome KG 2022. The next frontier: assessing the feasibility of eradicating mammalian pests from Auckland Island. New Zealand Journal of Ecology 46: 3500.

Howald G, Donlan CJ, Galván JP, Russell JC, Parkes J, Samaniego A, Wang Y, Veitch D, Genovesi P, Pascal M, Saunders A, Tershy B 2007. Invasive rodent eradication on islands. Conservation Biology 21: 1258–1268.

Kim JHK, Corson P, Mulgan N, Russell JC 2020. Rapid eradication assessment (REA): a tool for pest absence confirmation. Wildlife Research 47: 128–136.

Livingstone J, Horn SR, Broome KG, Sagar RL 2022. How low can you sow? House mouse eradication on Motuareronui/Adele Island. New Zealand Journal of Ecology 46: 3498.

MacKay JWB, Russell JC, Murphy EC 2007. Eradicating house mice from islands: successes, failures, and the way forward. In: Witmer GW, Pitt WC, Fagerstone KA eds. Managing Vertebrate Invasive Species. Fort Collins, USDA/APHIS/ WS, National Wildlife Research Center. Pp. 294–304.

MacKay JWB, Murphy EC, Anderson SH, Russell JC, Hauber ME, Wilson DJ, Clout MN 2011. A successful mouse eradication explained by site-specific population data. In: Veitch CR, Clout MN, Towns DR eds. Island invasives: eradication and management. Proceedings of the International Conference on Island Invasives. Occasional Paper of the IUCN Species Survival Commission 42. Gland, Switzerland, IUCN; and Auckland, New Zealand, Centre for Biodiversity and Biosecurity. Pp. 198–203.

Martin AR, Richardson MG 2019. Rodent eradication scaled up: clearing rats and mice from South Georgia. Oryx 53: 27–35.

Nathan HW, Clout MN, Murphy EC, MacKay JWB 2013. Strategies for detection of house mice on a recently invaded island. New Zealand Journal of Ecology 37: 26–32.

Notman PR 1984. An invertebrate survey of some Pelorus

Sounds islands with reference to their predator status. Unpubl. MSc thesis, Victoria University of Wellington, Wellington.
Parkes J, Fisher P, Forrester G 2011. Diagnosing the cause of failure to eradicate introduced rodents on islands: brodifacoum versus diphacinone and method of bait delivery. Conservation Evidence 8: 100–106.
Pichlmueller F, Murphy EC, MacKay JWB, Henderson J, Fewster RM, Russell JC 2020. Island invasion and reinvasion: informing invasive species management with genetic measures of connectivity. Journal of Applied Ecology 57: 2258–2270.
Reynolds KA 2015. Detection probabilities of mice to enable efficient management. Unpubl. Masters Thesis, University of Auckland, Auckland, New Zealand.
Russell JC, Broome KG 2016. Fifty years of rodent eradications in New Zealand: another decade of advances. New Zealand Journal of Ecology 40: 197–204.
Russell JC, Binnie HR, Oh J, Anderson DP, Samaniego-Herrera A 2017. Optimizing confirmation of invasive species eradication with rapid eradication assessment. Journal of Applied Ecology 54: 160–169.
Russell JC, Griffiths R, Bannister WM, Le Lievre ME, Cox FS, Horn SR 2019. Mouse bait uptake and availability trials on Falla Peninsula, Auckland Island. DOC Research and Development Series 363. Wellington, Department of Conservation. 11 p.
Sagar RL, Cox FS, Horn SR, Russell JC 2022. Population trends of house mice during tussock mast seeding on Auckland Island. New Zealand Journal of Ecology 46: 3497.
Samaniego A, Jolley W, McClelland P 2022. A lesson for planning rodent eradications: interference of invasive slugs during the Gough Island mouse eradication attempt in 2021. Wildlife Research: in press. https://doi.org/10.1071/WR22024
Samaniego-Herrera A, Anderson DP, Parkes JP, Aguirre-Munoz A 2013. Rapid assessment of rat eradication after aerial baiting. Journal of Applied Ecology 50: 1415–1421.
Springer K 2016. Methodology and challenges of a complex multi-species eradication in the sub-Antarctic and immediate effects of invasive species removal. New Zealand Journal of Ecology 40: 273–278.
Torr N 2002. Eradication of rabbits and mice from subantarctic Enderby and Rose Islands. In: Veitch CR, Clout MN eds. Turning the tide: the eradication of invasive species. Proceedings of the international conference on eradication of island invasives. Occasional Paper of the IUCN Species Survival Commission 28. Gland, Switzerland, IUCN. Pp. 319–328.
Towns DR, Broome KG 2003. From small Maria to massive Campbell: forty years of rat eradications from New Zealand islands. New Zealand Journal of Zoology 30: 377–398.
Will D, Howald G, Holmes N, Griffiths R, Gill C 2019. Considerations and consequences when conducting aerial broadcast applications during rodent eradications. In: Veitch CR, Clout MN, Martin AR, Russell JC, West CJ eds. Island invasives: scaling up to meet the challenge. Proceedings of the International Conference on Island Invasives 2017. Occasional Paper of the IUCN Species Survival Commission 62. Gland, Switzerland, IUCN. Pp. 71–78.

Editorial board member: James Russell
Received 30 January 2021; accepted 7 May 2021