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WILDLIFE RESEARCH

Detections of house mice on Gough Island approach zero within days of aerial baiting

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ABSTRACT

Context. House mice (*Mus musculus*) on temperate Gough Island (6500 ha) are known for their large size, boldness, and tendency to kill large prey such as albatross chicks and even adults. To remove this threat, a mouse eradication operation was implemented in June–August 2021. How mice react to bait during eradications is not well understood, so we capitalised on this operation and conducted the first study with wild house mice during an actual eradication. **Aim.** To document how rapidly mouse activity declined after application of rodent bait, to improve eradication guidelines. **Methods.** We set up a monthly monitoring regime using 10 trail cameras without lures, active for three nights in various habitats around a research station, because this area supported the highest abundance of mice and was logistically feasible. Monitoring commenced before the mouse eradication operation (January–May 2021), and continued when rodent bait was spread (from June 2021), when mouse activity was monitored for 17 consecutive nights, starting the day before baiting. In addition, an increasing number of cameras (up to 15) associated with lures were set further afield in July–August to detect survivors. **Key results.** In the months before bait application, mean daily mouse activity was 3.2 detections/camera (range: 0–56 detections/camera). Immediately after the first bait application, detection rates declined dramatically, from 9.6 to zero detections/camera per day on Day 4 post-baiting. From 1 week post-baiting, mouse detections were extremely rare on both cameras with and without lures. Our last mouse record, 27 days after the first bait application, may be related to initial rapid bait disappearance. Opportunistic camera traps first detected surviving mice 6 months after the first bait drop. **Conclusions.** The rapid decline in detections suggests that most mice consumed bait as soon as it became available, which is faster than what laboratory trials suggest. Future similar operations can expect that mouse activity will decline sharply within 1 week, although some mice may survive longer. **Implications.** Documenting similar declines in mouse activity using cameras could inform operational decisions such as timing of a second bait application or non-target monitoring on future eradication projects. Cameras, particularly with attractive lures, are an effective addition to the mouse detection toolkit, and facilitated a timely confirmation of eradication outcome.

Keywords: absence confirmation, camera, detection devices, invasive rodents, monitoring, *Mus musculus*, restoration, scent lures.

Introduction

Invasive rodents (*Rattus* spp. and *Mus musculus*) are the taxa most frequently targeted for island eradications because of both their widespread distribution and the dramatic negative impacts they inflict on natural ecosystems (e.g. Howald *et al.* 2007; Russell and Broome 2016). Fortunately, achievements have demonstrated that the benefits of removing invasive rodents from islands are profound and long-lasting (e.g. Jones *et al.* 2016; Benkwitt *et al.* 2021).

House mice (*M. musculus*), whose impacts were once under-appreciated, are now recognised as a serious threat to biodiversity (Angel *et al.* 2009; Broome *et al.* 2019). On Gough Island (hereafter Gough) in the South Atlantic Ocean, mice are about twice the size (Jones *et al.* 2003; Cuthbert *et al.* 2016), bolder and more exploratory (Stratton *et al.* 2021) than are their mainland counterparts, and consistently kill large prey such as albatross chicks and even adults (Caravaggi *et al.* 2019; Jones *et al.* 2019). The mouse eradication on Gough, implemented in June–August 2021, was the largest eradication attempt targeting only mice. Island size, together with rugged terrain and remote location, demanded a highly efficient aerial baiting strategy (McClelland 2021). However, a key aspect, the time mice remain active after a baiting operation using anticoagulant rodenticides (e.g. brodifacoum, the most commonly used), is not well understood.

Examples of target species monitoring during rodent eradications are rare (but see Samaniego *et al.* 2020*a*). Recommendations on crucial operational aspects such as time between bait applications and time required with bait on the ground exist (Broome *et al.* 2017*a*), but are still open to debate given the lack of empirical data. Understanding time to zero rodent activity can also improve management strategies aiming to avoid secondary poisoning of non-target species. For example, knowing that fresh poisoned rodents are available only for a short period may help shorten the time for which certain captive populations are held, reducing stress on native species and financial costs. Finally, for small islands where rapid confirmation of eradication success is affordable and feasible (Russell *et al.* 2017), in some cases in the same trip as the eradication operation (Samaniego *et al.* 2018), knowing when it is acceptable to start monitoring for success can make projects more cost-effective.

Trail cameras have become a common survey tool to assess population ecology and behaviour of a wide range of animals, particularly those that are rare or elusive (Glen *et al.* 2013). An advantage of cameras is the ability to record animals remotely and non-invasively, thus avoiding limitations of more invasive or targeted survey methods that require interaction with devices or direct observation. A disadvantage is the relatively small detection zone a camera can monitor. However, lures are commonly used to encourage focal species to enter a camera's detection zone; there are multiple options depending on the focal species and the habitat type (Holinda *et al.* 2020).

Here, we used trail cameras to assess mouse activity in the months prior to and during the eradication attempt on Gough in 2021. Based on prior experience, we expected a rapid decline of the mouse population, and therefore an equally rapid decline in activity and detections following the first bait application. For the second part of this study, we used standard detection devices for rodents as lures and paired them with cameras. This would attract mice within camera detection zones and increase the time mice stayed in such zones, increasing the effectiveness of cameras to detect mice at low density. Our lures can be used as stand-alone detection tools; however, mouse sign can often be misinterpreted (either as false positive or false negative). In contrast, definitive mouse detections are more likely using cameras.

Materials and methods

Study area

Gough Island (~6500 ha), part of the Tristan da Cunha island group, lies about 2700 km west-southwest of South Africa. It is a volcanic island that rises to 910 m asl, and for the most part is encircled with up to 300 m-tall cliffs. The mean annual rainfall is 3236 mm. The island is uninhabited except for the Gough Meteorological Station (hereafter Base), which typically hosts 5–10 scientists and support staff.

Wace (1961) distinguishes five types of vegetation on Gough across an altitudinal gradient (tussock grassland, fern bush, wet heath, peat bogs, and moorland and montane rock); however, for simplicity we distinguish between the highlands (≥400 m asl) and the lowlands (<400 m asl). The vegetation in the highlands is mainly moss and lichen with large boggy flats; in the lowlands it is a mix of tall *Spartina* tussock, *Scirpus* (a grass-like sedge), ferns (primarily *Histiopteris incisa* and *Blechnum palmiforme*), and *Phylica arborea* trees. Mice are typically more abundant in the lowlands, although they are found in all habitats across the island, given they are the only invasive vertebrates and the only land mammals on Gough (Rowe-Rowe and Crafford 1992). The mouse population has a single breeding season, typically from September to March, and their omnivorous diet varies seasonally (Jones *et al.* 2003). Comprehensive mouse monitoring on Gough was not feasible due to the scale and terrain of the island. However, the location of the Base in the south lowlands of the island make this an appropriate location to study mouse presence, given that mice are abundant in the lowlands and exploit the natural and commensal environment surrounding the Base.

Gough is internationally renowned for its birdlife (Dilley *et al.* 2015; Caravaggi *et al.* 2019). Breeding species consist of 22 species of seabirds, including six globally threatened species, and two endemic species of land bird, the Gough finch (*Rowettia goughensis*) and the flightless Gough moorhen (*Gallinula comeri*), which were at risk of poisoning during the mouse eradication.

Mouse eradication operation

During the austral winter of 2021, Pestoff 20R bait (2 g, 10 mm pellets with 20 $\mu g\ g^{-1}$ brodifacoum) made by Orillion (Whanganui, New Zealand) was spread across Gough, mainly by helicopter. Two bait applications were undertaken over the entire island, each with target rates of 8 kg ha^{-1}. The southern area, where the Base is located (Fig. 1), was treated on 13 June and 11 July. A third application with a target rate of 10–12 kg ha^{-1} was undertaken on 1–2 August over areas of

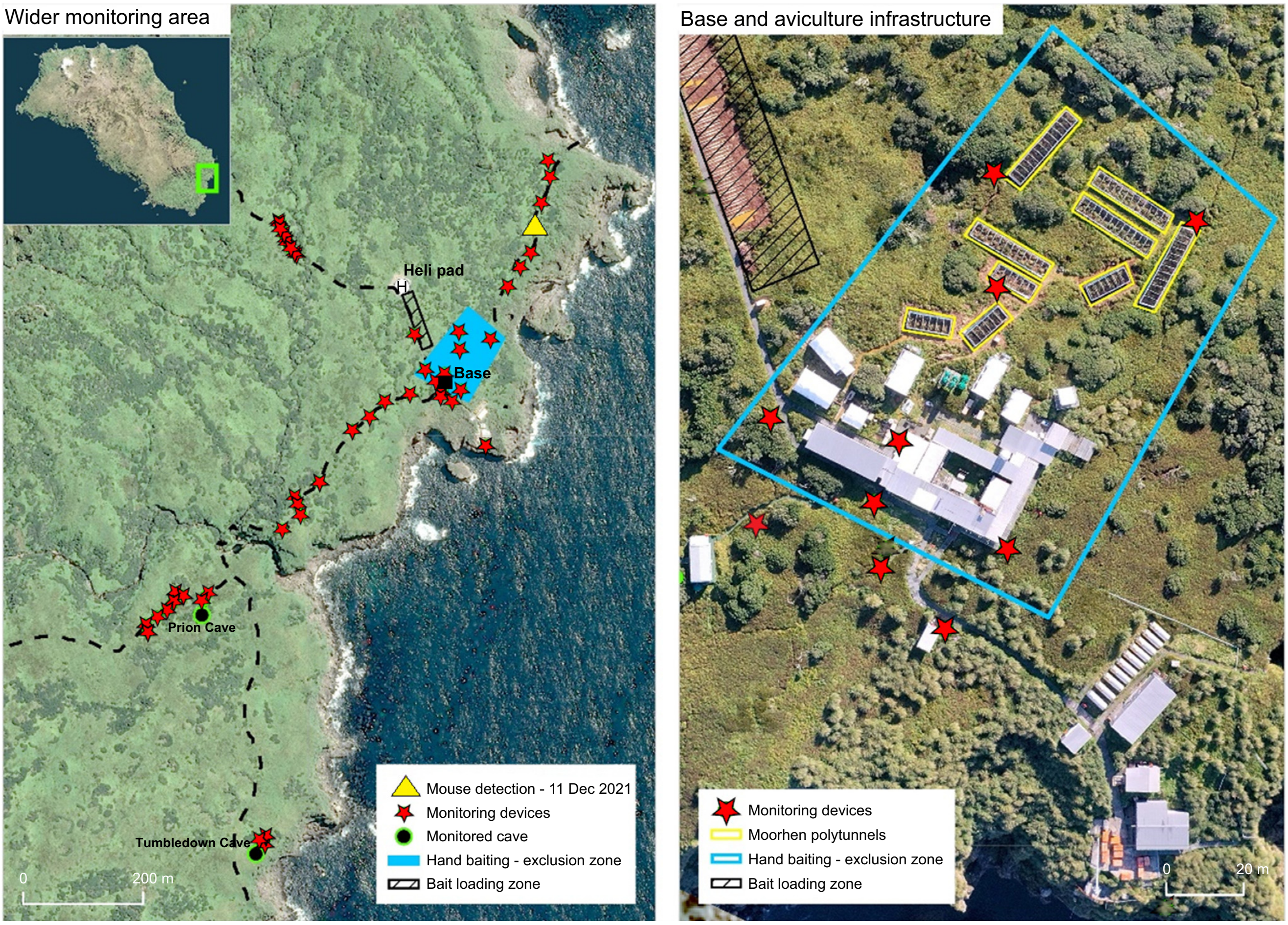

Fig. 1. Map of mouse monitoring sites. Sites around Base (right panel) had only cameras (systematic monitoring), all other sites had cameras and flavoured devices (opportunistic monitoring). Yellow triangle shows a moorhen release area, where mice were first detected after the eradication attempt.

operational concern (Fig. S1), which included areas perceived to be at highest risk of remaining mice and included much of the lowlands following the discovery of significant interference by slugs in this area (Samaniego *et al.* 2022). The Base and surrounding bush in the lowlands (~2 ha) were hand-baited at similar rates and times as the aerial applications, mainly because of the presence of a facility to safeguard the two endemic land bird species with temporary captive populations (Oppel *et al.* 2016). Details of the wider eradication operation will be published elsewhere.

Camera monitoring

Trail camera settings

Fifteen trail cameras were used throughout the study, 14 Bushnell and one Reconyx. We used opportunistically available cameras already on Gough, which resulted in a mix of models (BushnellHD 119439, 119537, 119740, 119774, 119876; ReconyxUltraFire UXP9 BK 04) and colours (green and brown). Cameras were attached to 0.5-m PVC poles to hold them above ground (Fig. 2); poles were 1 m from the target point, where mice would be expected to walk and be visible. When set for more than 3 days, cameras were checked, and batteries and SD cards were replenished every ~5 days.

For the pre-baiting monitoring (January–May 2021), all cameras were set to take three pictures plus a 20-s video (Full HD) when triggered by movement. Earlier trials showed no diurnal mouse activity, so cameras were set to night-time mode. Delay time between events was set to 1 min, flash intensity was set to low (to avoid overexposure at short distances), sensor sensitivity was set to high (recommended for small, fast mammals), trigger speed was set to fast, and detection range was set to short. The four elements (three pictures plus a video) that comprise each trigger event were treated as one detection for calculations. For example, a mouse showing in each of the three pictures and in the video was counted as one single mouse detection. Likewise, pictures or videos with more than one mouse were counted as one detection, because such events were rare and never exceeded two mice.

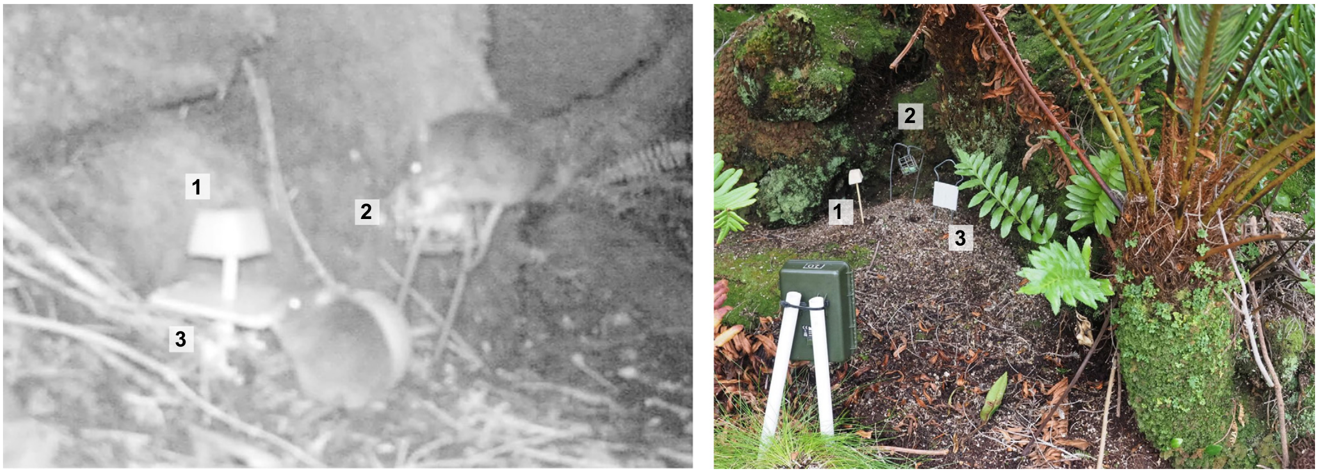

Fig. 2. Mice interacting with detection tools (YouTube: mice interacting with detection devices, https://www.youtube.com/watch?v=xhGQTRqguH0) (left), and example of monitoring set up (right). Lure cages had Pestoff bait inside. 1 = wax tag, 2 = lure cage, 3 = chew card.

For the post-baiting monitoring (i.e. immediately before, during and after baiting in June), we made the following two changes: recording only a 20-s video and operating 24 h. Because we were expecting poisoned, disoriented mice, we wanted to capture behaviour at any time of the day. However, for quantitative comparisons we used only footage of mice recorded at night-time.

Systematic monitoring

Trials were conducted to identify the most suitable sites to place cameras (i.e. those with a non-zero level of detectable mouse activity) and the best camera settings. On the basis of these results, we established 10 fixed locations around Base (Fig. 1; Fig. S2), each with one camera with no lure. Pre-baiting, cameras were deployed for three consecutive nights every month at all 10 locations simultaneously. Logistical constraints prevented longer monitoring periods. Post-baiting, cameras were deployed for 17 consecutive nights, from 12 June (the day before baiting) to 29 June, at the same locations simultaneously. The goal was to quantify the decline of the mouse population during the actual eradication operation, which has never been documented for house mice.

Opportunistic monitoring

In addition to the simultaneous monitoring at 10 fixed locations, further mouse monitoring was conducted in the southern area, both near the Base and as far from Base as logistically possible (Fig. 1). First, five additional cameras were set from 20 June until 31 July (1 week after baiting for 41 days), with two cameras set adjacent to the closest rivers, and three more inside an accessible cave (25 m × 3 m) where mouse attacks on seabirds had been frequent (Jones *et al.* 2021). From 30 June (i.e. 2.5 weeks after baiting), the 10 cameras that had been previously used at the fixed locations for the systematic monitoring at Base were set further afield along the three paths going away from Base, to spatially expand the potential mouse detection coverage (Fig. 1; Fig. S2). Cameras were regularly checked and systematically moved further along the paths, away from Base, about every week until 4 August, when all devices were retrieved. The main difference compared with the systematic monitoring was the use of flavoured devices as lures, intended to increase the chances of detecting any mice present, given the expected population collapse after baiting. Flavoured devices included wax tags (peanut butter–chocolate-flavoured), chew cards (peanut butter-flavoured) and lure cages (enclosing two pellets of Pestoff bait), which were all hand-made locally and therefore fresh (Fig. 2). Lures were not used prior to 30 June so that mice were not distracted from eating toxic bait during the main eradication period. Wax tags and chew cards are widely used in New Zealand and elsewhere to monitor rodent activity (Thomas *et al.* 1999; Sweetapple and Nugent 2011; Samaniego *et al.* 2018).

Following the release of the temporary captive population of Gough moorhens in November, four camera traps were opportunistically set up in areas where moorhens were released to monitor their fate (Fig. 1). These camera traps had lures intended for detecting moorhens (dried fruit soaked in fish oil) rather than mice, and recorded three photos and a 10 s video whenever triggered by an animal, day or night.

Data analysis

We summarised data as the number of mouse detections per night per camera-trap station. This summary statistic is a crude index of mouse activity because it was impossible to distinguish between individual mice that may have contributed >1 detection on a given night. Nonetheless, this statistic is appropriate to determine when detectable mouse activity reached zero after the bait application.

We present our data as the mean and 95% quantiles of the number of mouse detections per night across the 10 monitoring stations for the months before the baiting operation and for the month of June after baiting.

Results

Systematic monitoring

The total effort was 320 camera-nights (150 pre- and 170 post-bait application). In the months before bait application, we detected mice frequently every night. The mean daily rate of detection was 3.24 (range: 0–56) mouse detections per night. Shortly before the first bait application on 13 June, mouse activity around Base increased from a mean of 3.24 to 9.6 mouse detections per station per night. Detection rates dropped dramatically within 3 days following initiation of baiting and reached zero in the fourth night. From 17 June, detections were rare (Fig. 3). The last record of mouse activity around Base was from 19 June (i.e. 1 week after the first bait application).

Opportunistic monitoring

The total effort was 465 camera-nights, commencing 1 week after the first bait application on 13 June. Detections were rare, even in caves that used to be centres of mouse activity. In fact, mouse activity was detected only once on a path (one mouse on 23 June, which did not interact with lures), and for a few days at a seabird nesting cave. Interestingly, the detections at this seabird nesting cave were from 5 to 10 July, despite cameras being active since 20 June. In this period, up to two mice were recorded daily, and always interacting with our flavoured devices (YouTube: mice interacting with detection devices, https://www.youtube.com/watch?v=xhGQTRqguH0). Both mice appeared to be in good condition and interested in the toxic bait inside our lure cages. After 5 days of daily detections, detections stopped in the night of the second bait application on 11 July despite cameras being active until 4 August. During the entire opportunistic monitoring, the only flavoured devices with mouse chews were the devices at the cave where mice were detected with cameras. Here, mouse chews on flavoured devices coincided in time with mouse detections in cameras.

Cameras set up on 3 December to monitor the fate of released moorhens operated for a total of 38 camera-days before a single mouse was observed on 11 December 2021 about 300 m from Base. Subsequent intensive trapping and monitoring confirmed that the mouse eradication had been unsuccessful, and details of the continued presence of mice will be published elsewhere.

Discussion

Understanding how target animals react to bait during eradications is crucial to improve procedures. To our

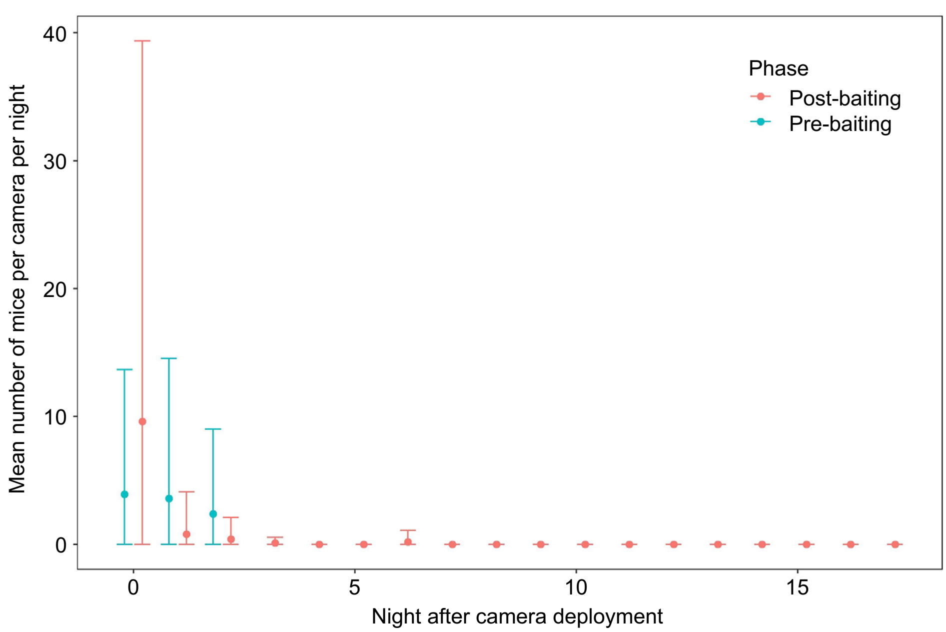

Fig. 3. Mean and 95% confidence interval of daily mouse activity per camera location, pre- and post-first bait application, during the systematic monitoring. The pre-bait application period included January–May 2021 (3 nights per month); the post-bait application period included 12–29 June 2021 (17 nights).

knowledge, this is the first such study with wild house mice during an eradication operation. We show that, on Gough, detectable mouse activity in prime habitat ceased within four nights of the first bait application, providing evidence that the planning for the timing of the second bait application within 2–3 weeks was appropriate (McClelland 2021). The use of camera traps facilitated efficient monitoring of the rapid decrease in the mouse population to near zero, and inadvertently also provided initial evidence for the continued presence of mice on Gough 6 months after the bait applications.

Our results showing rapid mouse population collapse are in line with recent field studies with other invasive rodent species (Daltry and Bell 2018; Samaniego *et al.* 2020*b*), suggesting that most rodents consume bait and die faster than previously thought, assuming the eradication strategy is planned and implemented to a high standard (Broome *et al.* 2017*a*). This evidence differs from that of past studies performed in laboratories, where mice have been found to survive for 4–21 days (Broome *et al.* 2017*b*). A palatability trial on Gough mice reported that some mice were still alive at Day 25 after consuming brodifacoum bait (Cuthbert *et al.* 2011*a*). One possibility is that, under natural conditions including stress from exposure to predation, competition for food and shelter, dehydration, and extreme temperatures (none of which affect animals in lab trials), rodents are more susceptible to the effects of anticoagulant rodenticides. Another possibility is that rodents under natural conditions have higher energetic requirements, thus they eat more bait at first exposure and die faster. Nonetheless, there are rare examples of mice surviving for weeks after aerial baiting operations. During a successful mouse eradication on a New Zealand island, a sexually mature female appeared to have survived about 60 and 37 days after the first and second bait applications respectively (Broome *et al.* 2019). We found only an extremely small proportion of wild mice on Gough that were still detected >2 weeks after the first bait drop, and it is unknown why a very small number of mice evidently did not consume a lethal dose of brodifacoum, although it may have been due to lack of exposure to bait (see below). Similar studies on islands where mice and rats are simultaneously targeted are encouraged, to investigate whether mice are able to eat bait as quickly as rats when sympatric.

In the months before bait application, mouse activity around Base was easily detectable. Shortly prior to the first bait application, mouse activity increased around Base (Fig. 3) even though natural food availability declined at the same time. The increased activity around Base was believed to be due to increased food availability from the arrival of bait pods, two of which were damaged and allowed mice to access the bait (extra footage not included in the study showed extremely high mouse activity). This meant some mice had access to toxic bait prior to the general bait application; however, bait loss from bait pods was negligible. The temporary increase in mouse activity allowed for a stronger contrast with the rapid decline after bait application, with similar trends across all sites, suggesting that the extra exposure for mice around bait pods had little effect.

The reasons for the rare mouse detections weeks after the first bait application are unclear. However, it may be related to the unexpectedly fast bait disappearance (i.e. up to 3 kg ha^{-1} per night) caused by non-native slugs (Samaniego *et al.* 2022). Some mice may not have encountered bait from the first application, rather than rejecting the bait. The two mice filmed in early July repeatedly tried to access the toxic bait inside our lure cages, which suggests that they were interested in the bait. Moreover, after 5 days of daily detections, these mice stopped visiting our monitoring station from the night of the second application. It is likely that these mice lost interest in inaccessible bait in front of cameras when large quantities of identical bait were freely accessible elsewhere. No mice were detected for 5 months after the second bait application, which highlights the importance of the second application. A third bait application was undertaken over areas of operational concern (Fig. S1), including around the Base, triggered by the significant interference by slugs in this area; however, bait kept disappearing within days, much faster than expected (Samaniego *et al.* 2022). Yet, the lack of mouse sign was encouraging. Mice were not detected for several months despite ongoing biosecurity checks around Base (using multiple devices) that are designed to detect and eliminate any newly arriving rodent. Camera traps that were originally set up to monitor birds detected a surviving mouse on 11 December 2021, 6 months after the first aerial bait application. Monitoring increased, eventually finding more mice, at which point the eradication operation was declared a failure. A review of the operation is ongoing.

Bait was not manually spread inside the two monitored caves, nor in any other cave on Gough. Aerially spread bait can cover only the entrances of caves. Hand-baiting was not practical in most caves, both logistically and because there are almost certainly caves that have not been recorded. Preliminary data from the caves that were monitored suggest that mice living inside caves can detect and access bait spread outside caves, which supports the results from previous trials (Cuthbert *et al.* 2011*b*; Wanless *et al.* 2008). These are encouraging results, in line with the findings on other islands where caves have been present during eradications, and bode well for future eradication projects dealing with rodents living in subterraneous environments, such as, for example, large islands with inaccessible caves.

Cameras proved to be an effective mouse detection tool on Gough, sensitive enough to detect the rapid decline in mouse numbers even without the use of lures. The monitored area is a small fraction of the island, but is arguably one of the most favourable for mice, given the combination of commensal and productive natural habitats. At a later stage, combining cameras with flavoured devices as lures increased our confidence in detecting mice at low density. Lures may help both to attract the mice within the range of the cameras and ensuring they stay in range for long enough to be recorded. However, maintaining lures is more time-consuming than is camera monitoring alone, particularly when non-target species (in this case slugs) interfere with the detection devices. New tools such as acoustic lures, currently being tested, may significantly improve detection strategies as sound can travel far, cannot be consumed, and does not decompose (A. Glen, Manaaki Whenua – Landcare Research, New Zealand, pers. comm.). Camera models and survey methods are also constantly improving, and recommendations for small-mammal surveys are available (e.g. Glen *et al*. 2013; Hobbs and Brehme 2017; Dundas *et al*. 2019). We recommend the use of cameras as part of the monitoring toolkit for future eradication projects, both during the implementation and confirmation phases.

Supplementary material

Supplementary material is available online.

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Data availability. The data that support this study are available in the article and accompanying online supplementary material.

Conflicts of interest. This work was conducted during the implementation of the Gough Island Restoration Programme, led by the Royal Society for the Protection of Birds (RSPB) in partnership with the Tristan da Cunha Government. The authors were involved in the mouse eradication and were RSPB staff (Steffen Oppel, Kim Stevens and Vonica Perold) or contracted by RSPB as operational managers (Pete McClelland and Araceli Samaniego).

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