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RESEARCH

Rodent detection and monitoring for conservation on islands: gnawed seeds provide reliable indicator of rodent presence

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Abstract: Invasive rodents pose one of the biggest threats to island ecosystems globally. Reliable methods for detecting and monitoring rodent presence are essential for the effective conservation management of islands, but many detection devices fail to attract rodents when natural resources are abundant. Using a toolbox of detection methods is therefore key to detecting rodents as individual rodents vary in their susceptibility to detection devices. Rodents are well-established seed predators, and the distinct gnaw marks they create and leave on woody seedcases potentially add another method to the rat detection toolbox on islands where seeds are sufficiently large to preserve teeth marks. We tested the reliability of rodent-gnawed miro (*Prumnopitys ferruginea*) seeds as an indicator of rodent presence on fifteen islands and one mainland site in southern New Zealand. Seeds were collected from beneath one miro canopy at each site and examined for characteristic gnaw marks. Presence or absence of gnaw marks was compared with records of rodent presence obtained using traditional methods including tracking tunnels, kill traps, and/or rodent detection dogs. Measurements of bite marks on seeds suggested that mice create smaller bite marks on seeds than rats, allowing discrimination between the taxa. Gnawed seeds had a slightly lower probability of detecting rats than traditional methods (rats detected at 5/6 sites where they had been previously recorded using other methods), and a higher probability of detecting mice where they existed (mice detected at 7/8 islands where they existed, vs 5 for other methods). These results suggest that gnawed seeds can complement other rodent detection devices to increase the probability of detection. The method could be used to detect rodent presence on other island groups globally, e.g. using opened coconuts in the field as a kind of natural waxtag or 'cocotag'.

Keywords: detection; miro; monitoring method; mouse; New Zealand; rat; seed predation

Introduction

Invasive rodents pose one of the greatest threats to island biodiversity (Jones et al. 2016). Ship rats (*Rattus rattus*), Norway rats (*R. norvegicus*), Pacific rats (*R. exulans*), and house mice (*Mus musculus*) have invaded over 80% of the world's island groups (Moors & Atkinson 1984; Atkinson 1985), with often catastrophic consequences for native plants (Campbell & Atkinson 2002; Traveset et al. 2009; Shiels & Drake 2015), small mammals (Harris 2009), birds (Atkinson 1985; Jones et al. 2008; Innes et al. 2010), herpetofauna (Hoare et al. 2007; Caut et al. 2008; Hitchmough et al. 2013), and invertebrates (Angel et al. 2009; St Clair 2011; Ruscoe et al. 2013). Island biota are particularly vulnerable to the detrimental impacts of exotic rodents, due to their high levels of endemism, simplified trophic webs, and the intrinsic traits of native species (e.g. naievete towards exotic predators; Courchamp et al. 2003; Traveset et al. 2009). In addition, subsets of rodent-free islands in larger archipelagos often act

as refugia for threatened species, and are used as safe 'arks' for translocated species (Ostendorf et al. 2016), making ongoing monitoring of rodents essential to prevent re-establishment and protect native fauna and flora. Therefore, effective conservation management of islands frequently depends on accurate and reliable methods for determining rodent presence, whether for initial surveys, to verify the pest-free status of an island, or for routine monitoring to detect a rodent incursion. The ability to detect and eradicate invasive rodents from islands has been identified as a critical tool for protecting the world's most imperilled fauna (Jones et al. 2016).

Several methods have been developed for monitoring rodents, although the majority have been optimised for indexing species' relative abundance rather than detecting species' presence (Pickerell et al. 2014). The majority of these techniques rely on deploying monitoring devices over a few days with lures to attract rodents (e.g. wax tags, chew cards, tracking tunnels, camera traps, hair tubes, kill traps; Brown et al. 1996; Sweetapple and Nugent 2011; Pickerell et al. 2014;

Burge et al. 2017), although it should be noted that not all devices rely on attraction. While some of these methods are reasonably effective (i.e. have a high probability of detecting rodents where they exist), they can be expensive in terms of labour (because they are time consuming to deploy and check), device costs (e.g. for more expensive self-resetting kill traps), and may suffer from interspecies interference effects (Burge et al. 2017). In addition, lures do not always attract rodents when natural food is abundant. This problem is amplified when neophobic rodents also display device or bait aversion. For example, when Norway rats invaded Frégate Island in the Seychelles archipelago, the superabundance of natural food and presumed neophobic nature of the rats made it extremely hard to detect their presence using kill traps (Thorsen et al. 2000). Generally, the longer a monitoring device is left in the field the better the chance of detecting rodents where they are present, but longer durations can increase the expense of monitoring (Burge et al. 2017). For these reasons, a toolkit of various monitoring methods (some of which do not rely on lures or devices) is often called on to offer the best chance of success at detecting rodents (Russell et al. 2008).

The presence of rodent-gnawed seeds could offer a novel, low-cost technique for detecting rodents that circumvents issues with neophobia or lures and takes advantage of natural food. Rats and mice are well-known seed predators (Campbell & Atkinson 2002; Towns et al. 2006; Traveset et al. 2009), and seeds are usually widespread and abundant. While rodents usually consume small seeds whole or destroy them entirely (Williams et al. 2000; Grant-Hoffman & Barboza 2010), large seeds that are protected by woody endocarps (seedcases) require a different feeding technique, with rodents using their sharp incisors to nibble a hole in the endocarp to access the fleshy seed inside. This feeding technique leaves a distinct and long-lived signature of bite marks behind on the seedcase (Collinson & Hooker 2000; Wilmshurst & Higham 2004). The preserved gnawed seedcases of hinau (*Elaeocarpus dentatus*), pōkākā (*Elaeocarpus hookerianus*), mataī (*Prumnopitys taxifolia*), and miro (*Prumnopitys ferruginea*) were used to detect and date the earliest presence of Pacific rats in New Zealand by radiocarbon dating of c. 800 year old husks preserved in swamps (Wilmshurst et al. 2008). The results show the potential of this method for detecting the contemporary presence of rodents on islands. Similarly, preserved rat-gnawed seedcases have been discovered on Easter Island (Hunt 2007), and McConkey et al. (2003) opportunistically discovered 53 'husking stations' (safe places where rats consume seeds) filled with rodent-gnawed seed remains on eight Tongan islands, providing a clear indication of contemporary rat presence and potential wider application of the approach to other invaded island groups. Because depots of gnawed seeds can build up through a fruiting season or over multiple seasons, this technique presents evidence over a much longer time window than short-term monitoring methods such as chew cards, tracking tunnels or camera traps. Therefore, gnawed seeds act as *post hoc* long-term monitoring devices (i.e. when seeds are observed they have already been present for weeks if not months). However, for this reason using seeds to detect rodents will not work as effectively as short-term monitoring methods when the exact timing of detection is important.

Like most oceanic archipelagos, New Zealand's highly endemic flora and fauna evolved in the absence of native rodents or large predatory mammals. This isolation changed dramatically with the arrival of the Pacific rat c. AD 1280 (Wilmshurst et al. 2008), and then of Norway rats, ship rats and house mice (and many other vertebrate predators) several centuries later (> AD 1700s) with Europeans (King 2005). In common with many other islands, introduced rodents have had a devastating impact on the fauna of New Zealand (Towns et al. 2006), and are believed to be responsible for, or have contributed to the extinction of at least 23 bird species (Tennyson & Martinson 2006). Rodents continue to pose a threat to remaining indigenous fauna on New Zealand and many other island groups (Towns et al. 2006). By the mid-1980s, introduced rats had reached at least 142 of New Zealand's offshore islands ≥ 5 ha (Atkinson & Taylor 1992). New Zealand's predator free offshore islands are increasingly used as translocation sites for vulnerable native species, so understanding whether rodents are present on islands is critical for their ongoing conservation. New Zealand is an ideal site to test the reliability of rodent-gnawed seedcases as an indicator of rodent presence because (1) it has no other native seed predators that cause similar damage to seedcases (Wilmshurst & Higham 2004), (2) it has several widespread plant species with large, woody-endocarp protected seeds that are commonly consumed by rodents, and (3) the presence or absence of rodents on most islands is already known from other methods, providing a comparative record, which has not been tested before.

Here, we tested whether rodent-gnawed miro seedcases (hereafter simply referred to as seeds) act as a reliable indicator of rodent presence on 15 islands and one mainland site in Fiordland, New Zealand (Fig.1). Miro seeds are a preferred food for rats, with piles of rat-gnawed seeds beneath parent trees a common sight on the New Zealand mainland (North, South, and Stewart Islands; Beveridge 1964; Daniel 1973) as well as in prehistoric deposits (Wilmshurst & Higham 2004; Wilmshurst et al. 2008). We also tested whether differences in the size of incisor marks on the seeds could be used to differentiate between rat or mice presence.

Methods

Sites

Coastal Fiordland, in the south west of southern New Zealand, is highly indented and contains hundreds of islands, ranging from rock stacks to 208 km^2 Resolution Island. Miro trees are widespread throughout the area and are found on most islands large enough to support forest. Ship rats, Norway rats, and house mice occur throughout the area (King 2005). We tested for the presence of rodents using rodent-gnawed miro seeds on fifteen islands (Coal, Weka, Cormorant Cove, unnamed island south of Fixed Head, Anchor, Curlew, Shag, Resolution, Front, Heron, Petrel, Fergusson, Elizabeth, Rolla, and Big John Islands) and one mainland site (Pickersgill Harbour), located in Preservation Inlet, Breaksea Sound, Dusky Sound, and Doubtful Sound (Fig. 1). The New Zealand Department of Conservation (DOC) had previously determined whether rodents were present at these sites using tracking tunnels baited with peanut butter and left out for 6–12 months (P. McMurtrie, pers. comm.), kill traps (DOC 250 traps and Fenn traps), and/or rodent-detection dogs (Gsell et al. 2010) between 2000 and 2005. While this is a wide timeframe, further monitoring has occurred on most of the islands since and no changes to the rodent status of these islands have been recorded (except where eradications have since taken place, e.g. Coal Island). Using tracking tunnels and kill traps requires establishing devices in the field, then checked at a later date for rodent
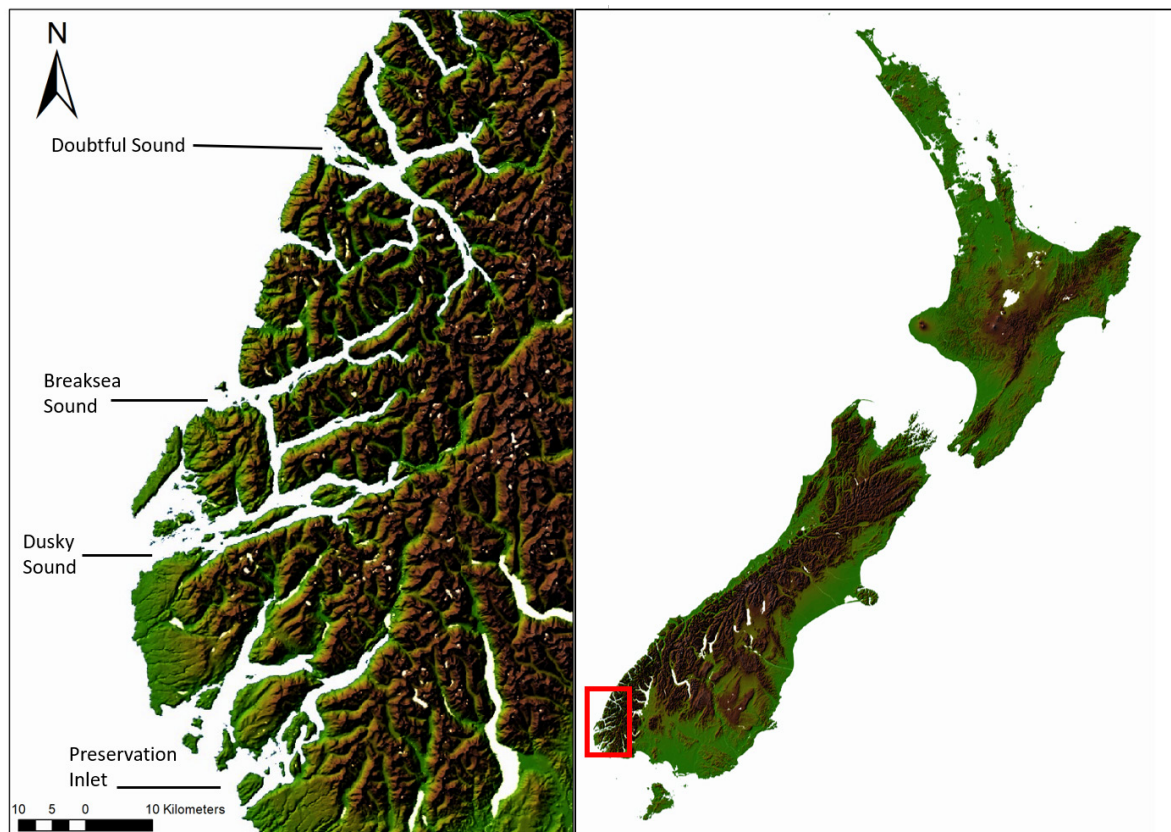
Figure 1. The Fiordland coastline where monitoring occurred (left); location of study area (right). Base map from www.geographx.co.nz.

presence (often necessitating at least two visits to a site). Rodent detection dogs typically only require one visit to a site to determine rodent presence, but adequately surveying the area can be time consuming (Gsell et al. 2010). The DOC rodent monitoring was a key preliminary stage in determining which islands were suitable for the subsequent translocation of threatened bird species, e.g. kākāpō (*Strigops habroptilus*) on Anchor Island. DOC had recorded ship rats on six of the islands (and the mainland site), and mice on five of the islands using a variety of detection tools. Five of the islands had no rats or mice detected on them previously. One island (Front Island) had not been surveyed by DOC.

Survey technique

Fourteen of the islands and one mainland site were visited in September 2004. Two observers spent between 5 and 360 minutes (an average of 54 ± 25 (SE) minutes) on each island looking for miro trees with seeds under their canopy. Once a tree with fallen seeds was found on each island (or site), then 10 minutes was spent under the canopy of that tree collecting as many miro seeds as possible in any condition (i.e. whole, gnawed, broken or cracked). On the larger islands it took longer to find a miro tree than on smaller islands, hence the variability in search time for trees. If rat-gnawed seeds were observed in the collection, then no further search for trees was undertaken, as presence was confirmed. If no gnawed seeds were found, other trees and rat-gnawed seeds were searched for. In all cases, gnawed seeds were found beneath the first tree found, if they were found at all on an island. In cases where no gnawed seeds were found in the first tree, they were never found in subsequent searches under other trees. Seeds were normally only taken from the surface forest litter, to avoid

collecting any older decomposing seeds partially buried in the soil below the litter. However, on Resolution Island where no rat-gnawed seeds were found, we also sampled 15 cm below the forest litter, to see if historic evidence for rodents existed. Two sites were sampled on Resolution Island (north and east) due to its large size.

Analysis of seeds

The collected seeds were taken to the Long Term Ecology laboratory at Landcare Research, Lincoln, where they were cleaned and examined under low magnification ($\times 10$), counted and separated into one of five categories: intact, parrot-cracked, rodent-gnawed, broken or insect damaged, as explained below. This assessment requires little time or skill, and although is easier to do using a stereomicroscope, it could also be undertaken in the field using a $\times 10$ hand lens to examine the teeth marks. Seeds were also examined from earlier collections made by DOC (using the same survey method detailed here) from three of the same islands: Weka Island (collected 1985), Heron Island (2000), and Petrel Island (2001); and an additional island: Big John Island (2000).

During seed predation, rats bite a well-defined hole in the top or on the side of miro seedcases (Fig. 2), large enough that they can scrape out the fleshy seed from inside using their incisors. The holes left by rodents are unique and edged with a series of distinctive sharp grooves made by the incisors which look like chisel marks. These can be reliably separated from those predation marks left by native seed predators such as endemic parrots (kākā *Nestor meridionalis septentrionalis*), and unknown insects (Wilmshurst & Higham 2004). Examples of these categories are illustrated in Fig. 2, which also shows an example of how miro seeds break open naturally along their
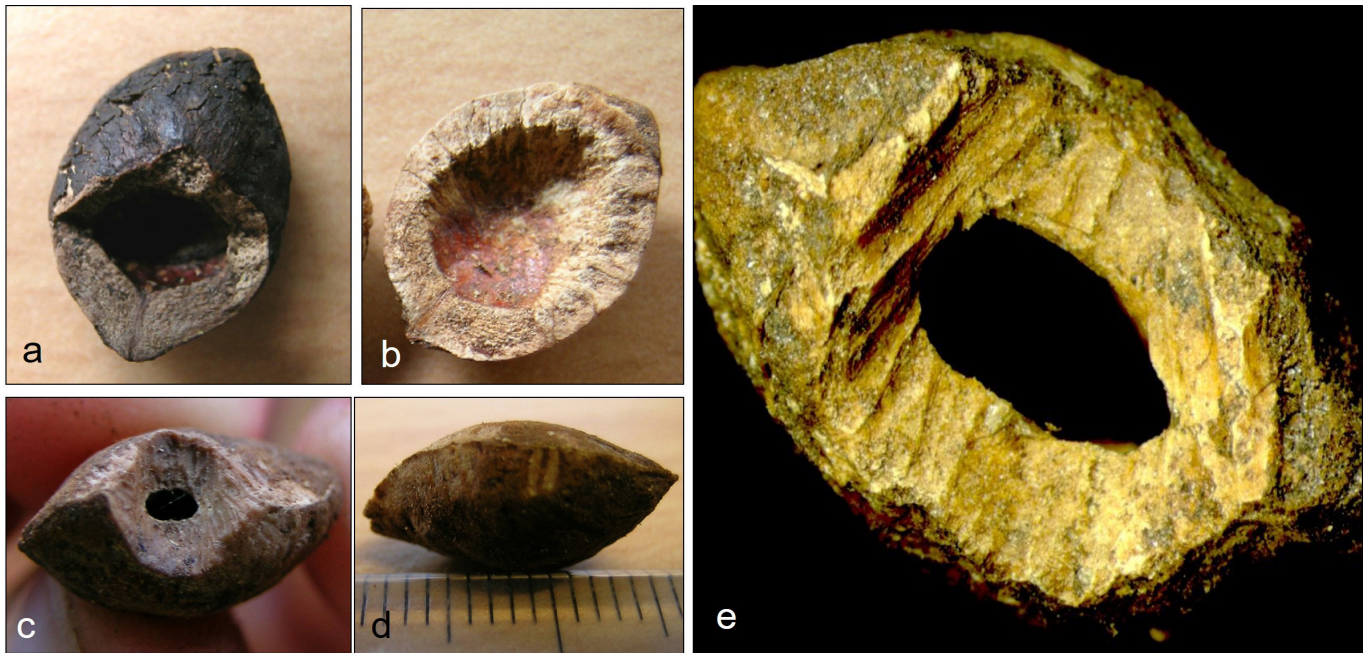
Figure 2. Typical examples of miro seed fates. Each seed is approximately 13 mm in length. (a) Kākā destroyed seed (clean broken edges, no gnaw marks). (b) Seeds that have cracked naturally along their margins. (c) Mouse-gnawed seed. (d) Another example of a mouse-gnawed seed - each bite scrape is made up of a pair of tooth marks (each incisor 0.25 mm wide). (e) Rat-gnawed seed opened from the side; each incisor bite mark is 0.5 mm wide.

margin during germination, as these split remains can often be mistakenly attributed to rat-gnawing. This misidentification can arise because once the woody shells dry out, the cellular structure along the inside edges of the margins can resemble bite marks to the untrained eye, although bite marks can be easily resolved under low resolution (× 10) magnification by their regularity and consistent grooved pattern (Fig. 2).

To distinguish between rat and mouse presence, the width of individual incisor marks on a maximum of 20 seeds per site (depending on availability of gnawed seeds) were measured using a calibrated measuring graticule under a stereomicroscope (× 10 magnification). We were careful to only measure clean grooves that appeared to not have been bitten over (i.e. making the groove narrower). We compared these measurements to measurements of bite marks from ship rats and mice on wax tags collected by Sakata (2011). We also measured the width of the cutting tip on the upper incisors of 25 wild ship rats and two wild house mice under a × 10 magnification stereomicroscope, to evaluate how these incisor measurements compared to the gnaw mark measurements.

Finally, evidence for rat or mice presence based on gnawed seeds was compared with the DOC record as detected by a range of other means (trapping, footprint tracking, and/or dogs) and the usefulness and reliability of the technique assessed against these data. When comparing the seed method to the DOC record, we assumed that every detection of a rodent on an island was legitimate (i.e. there were no false positives). We then calculated how many false negatives (i.e. where rodents existed but were not detected) occurred for the gnawed seed method compared to the DOC record, to give an overall success rate. We also performed randomisation tests on the seed collection data from each island that detected a rodent to estimate how many seeds need to be collected to be 95% confident of detecting a rodent. We randomly sampled data for each island 10 000 times and recorded the number of seeds

sampled before a rodent-gnawed seed was sampled for each iteration, then calculated the 95th percentile of all iterations. We did not conduct randomisation tests for islands where 100% of seeds were rodent-gnawed.
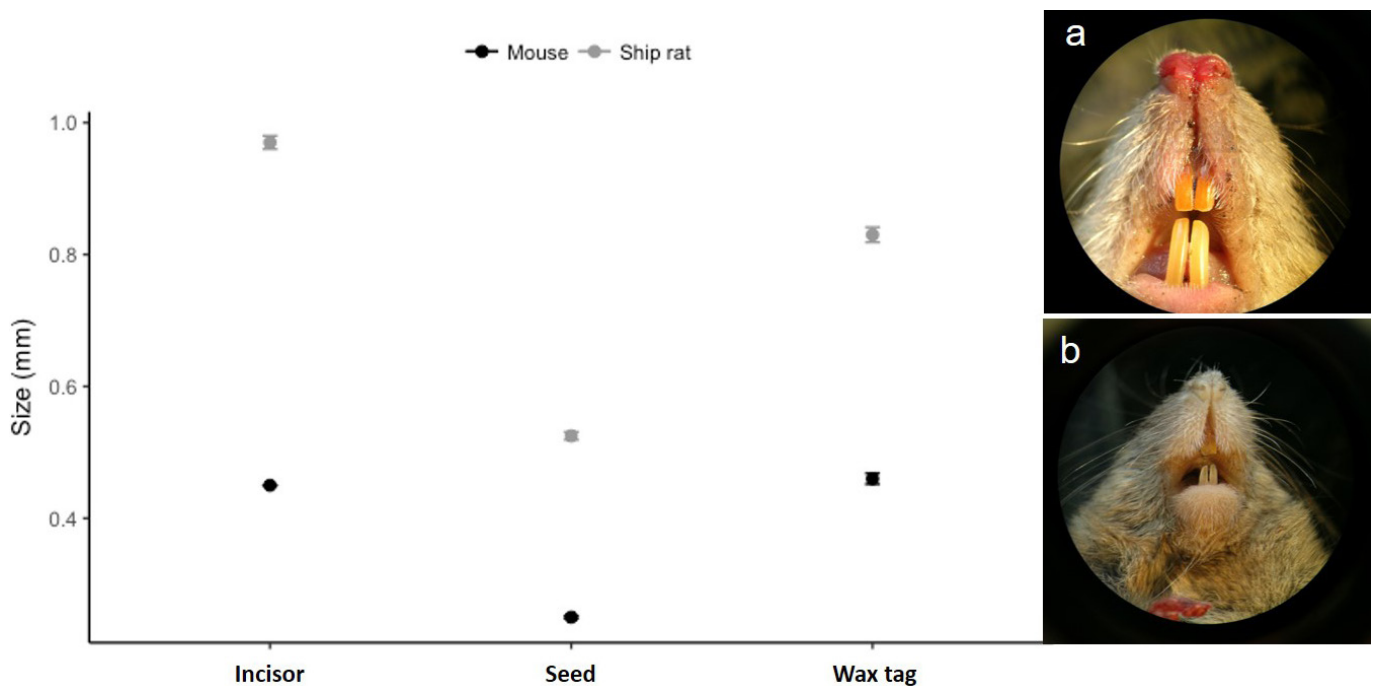
Results

Detecting taxa by their bite marks

A total of 3332 seeds were collected, of which 391 (11.7%) were rodent-gnawed. An average of 185 miro seeds were collected from each site (range 3–546 seeds per site). The percentage of seeds at each site that had been gnawed by rodents ranged from 0–100% (mean = 31.8%, SE = 10.2%; Table 1). Measurements of bite marks on seeds suggested that the width of the bite mark could be used to infer either mouse or rat presence. Bite marks on collected seeds clearly fell into two groups: narrow (mean width = 0.26 mm, SE = 0.002, n = 56) or wide (mean width = 0.53 mm, SE = 0.006, n = 44; Fig. 3). Occasionally seeds had both narrow and wide bite marks. Seeds that displayed narrow bite marks only, were often only superficially gnawed, lacking the hole in the endocarp that rats create. The clear delineation of the bite mark sizes into two distinct sizes with extremely low standard errors is to be expected if they were made by mice and rats. The lack of overlap between species is consistent with both species having monophyodont teeth (only one set of teeth in their lifetime). Thus narrow bite marks were assumed to indicate mice presence, while wide bite marks were used to infer rat presence. These results aligned well with the incisor measurements (mean rat incisor width = 0.97 mm, SE = 0.05, n = 25; mean mouse incisor width = 0.45 mm, SE = 0, n = 2) and gnaw marks from wax tags, which also both showed a clear delineation between gnaw marks from ship rats and mice (Fig. 3) (wax tag gnaw mark data taken from Sakata 2011). While the gnaw marks on wax tags

Table 1. Results from seed method vs DOC method for each site. DOC method refers to tracking tunnels (TTs), DOC 150 traps, and/or rodent detection dogs.

Sites	DOC method	Rats detected?		Mice detected?		No. rodent-gnawed seeds (∑ = 391)	Total seeds collected (∑ = 3332)	% seeds rodent-gnawed
		Seeds	DOC	Seeds	DOC			
Coal Island	TTs, traps			Y	Y	27	546	4.9
Island south of Fixed Head	TTs, traps			Y	Y	25	165	15.2
Weka Island	Traps			Y	Y	25	25	100
Cormorant Cove Island	TTs, traps, detection dog		Y	Y	Y	5	65	7.7
Elizabeth Island	Traps	Y	Y			6	6	100
Big John Island	Traps	Y	Y			3	4	75.0
Heron Island	TTs, traps	Y	Y			3	3	100
Curlew Island	TTs, traps	Y	Y	Y		114	155	73.5
Rolla Island	Traps	Y	Y	Y		3	84	3.6
Anchor Island	Traps					0	203	0
Front Island	Not surveyed		N/A		N/A	0	262	0
Shag Island	Traps					0	454	0
Resolution Island North (surface litter)	TTs, traps				Y	0	286	0
Resolution Island North (buried litter to 15cm depth)	TTs, traps				Y	0	81	0
Resolution Island East	TTs, traps				Y	0	498	0
Fergusson Island	Traps					0	291	0
Petrel Island	TTs					0	10	0
Pickersgill Harbour	Traps	Y	Y	Y		180	194	92.8

Figure 3. Width of cutting tip of upper incisors for wild house mice (n = 2) and ship rats (n = 25). Graph also shows the widths of gnaw marks on miro seeds and wax tags (wax tag data from Sakata 2011), for ship rats and mice. Gnaw marks on seeds were clearly delineated into two size classes (wide and narrow), these were assumed to belong to ship rats (a) and mice (b) respectively. Error bars are standard error of the mean.

were far larger than those on seeds, this is probably because of the soft texture of the wax that deforms when bitten. The magnitude of difference between mice and rat bite marks was similar for wax tags impressions, seed gnaw marks, and actual incisor measurements, suggesting that while the two taxa make slightly different sized bite marks in different substrates, there is consistently a clear difference between them.

Detecting rodent presence

When mice detections using both the DOC methods and the gnawed seed method were combined, mice were indicated to be present at eight sites. The gnawed seed method detected mice at seven of these sites (but failed to detect mice on Resolution Island). DOC had recorded mice at five of the sites (but failed to detect mice at Pickersgill Harbour, Curlew Island, and Rolla Island). Therefore, combining the gnawed seed method with traditional methods increased the probability of detecting mice.

When both the DOC methods and the gnawed seed method were combined, rats were indicated to be present at six sites. The gnawed seed method detected rats at five of these same sites (but failed to detect rats on Cormorant Cove Island), and the DOC methods recorded rats at all six sites. Therefore, the gnawed seed method was almost as efficient as the multiple DOC methods at detecting rats, but it did not increase the probability of detecting rats.

Our randomisation tests indicated that between 2 and 56 seeds should be collected from each island to be 95% confident of detecting a rodent. We suggest a minimum sample size of 56 seeds from each island in our study region, but note that our total collection of 865 seeds from Resolution Island (over two sites) was still not sufficient to detect mice.

Discussion

Early and reliable detection of exotic rodents is key to successful incursion responses and the ongoing conservation of threatened species on islands at threat from rodent (re)-invasions. We demonstrate that rodent-gnawed seeds act as a reliable indicator of rodent presence when combined with other monitoring techniques. Using a toolbox of detection methods is important for detecting rodents as individual rodents often have variable susceptibilities to detection devices (Russell et al. 2008). The gnawed seed method was almost as sensitive to rat presence as more traditional methods (tracking tunnels, kill traps, and/or rodent detection dogs), and more sensitive than these traditional methods when used for mice. The increased sensitivity of the method for mice is because two of the three sites where mice were detected by seeds but not traditional methods had kill traps only, which are designed for heavier animals (e.g. rats and stoats) and are, therefore less effective at detecting mice. As miro trees were easy to find at all the sites, seed assessment required less time and infrastructure than many other rodent detection methods. The results from this novel detecting technique (combined with results from more traditional methods) gave reliable information on the rodent status of Fiordland's islands, which resulted in several translocations of threatened bird species to rodent-free 'sanctuary' islands (e.g. a population of nationally critical kākāpō was translocated to Anchor Island in 2005 partly on the basis of its rodent-free status).

Our results also suggest that the size of the bite marks on seeds can be used to discriminate between rat and mice,

in much the same way as they can on wax tags. Similarly, Collinson and Hooker (2000) demonstrated that the size and shape of gnaw marks on fossil woody seeds could differentiate between several rodent species. Although it has been reported that mice do not eat miro seeds (Ruscoe et al. 2004), this evidence is based on captive mice not choosing to eat miro from a selection of smaller, more easily husked seeds like rimu (*Dacrydium cupressinum*) and *Lepidothamnus intermedius* in feeding trials, and may not apply to wild mice with few alternative food choices. The existence of both narrow and wide gnaw marks on some miro seeds suggests that mice sometimes scavenge miro seed remains after rats have created an opening in the woody endocarp. However, our method is probably not suitable for discriminating between different rat species, as Sakata (2011) demonstrated significant overlap between the size of gnaw marks of ship rats and Norway rats on wax tags. Pacific rats were not tested, but based on their size it seems likely that the size of their gnaw marks fall between ship rats and mice. DNA analysis of fresh gnawed seeds may potentially provide a (more expensive and time consuming) way to ascertain rodent identity if required.

As the density of rodents on the surveyed islands was unknown, we cannot comment on how sensitive gnawed seeds are to very low rodent densities. We failed to detect rats at one site (Cormorant Cove Island) where the DOC record indicated them to be present using a rodent-detection dog. We only had 15 minutes on this island during which time a rodent-gnawed seed was quickly discovered, but subsequent analysis showed the sampled seeds were mouse damaged rather than rat damaged, and therefore a longer duration sampling may have detected the presence of rats too. We collectively spent 90 minutes on Resolution Island and sampled seeds from two different sites, but still failed to detect mice (although the DOC record indicated they were present). Therefore, future work should ensure that an appropriate sampling regime is used which samples a wide distribution of trees over a preset timeframe (based on island size) and a minimum number of seeds collected (we would suggest a minimum of 56 based on our sampling randomisation), to avoid false negatives and increase the probability of detecting rodents even when they occur at very low densities.

Similarly, whether our method would work for rats at low density or newly invading rats (i.e. an incursion) still remains to be tested, although the technique's reliance on natural food sources may be advantageous when new invaders are not attracted to baits or lures (Dilks & Towns 2002; Russell et al. 2008). We opportunistically discovered 31 fresh rat-gnawed miro seeds (19.7% of seeds collected) under a tree near a rat trap on rodent-free Ulva Island in August 2004 (west of Rakiura/ Stewart Island) following a rat incursion (JMW, unpubl. data), so this method could potentially be quite sensitive. However, finding rodent-gnawed seeds while rats are at very low density may be too time consuming to detect an incursion rapidly on a large island.

As woody endocarp seeds typically persist on the ground for at least a year, this method offers a significant advantage over many other rodent detection methods in that the seeds accumulate and retain evidence of rodent presence for far longer time frames than other monitoring methods thus raising the chances of detection. Chew cards, tracking tunnels, and camera traps can only detect rodents during the window of their deployment (which is often only for a few days). This window of detection can then be affected by suboptimal monitoring conditions, making detection even less likely.
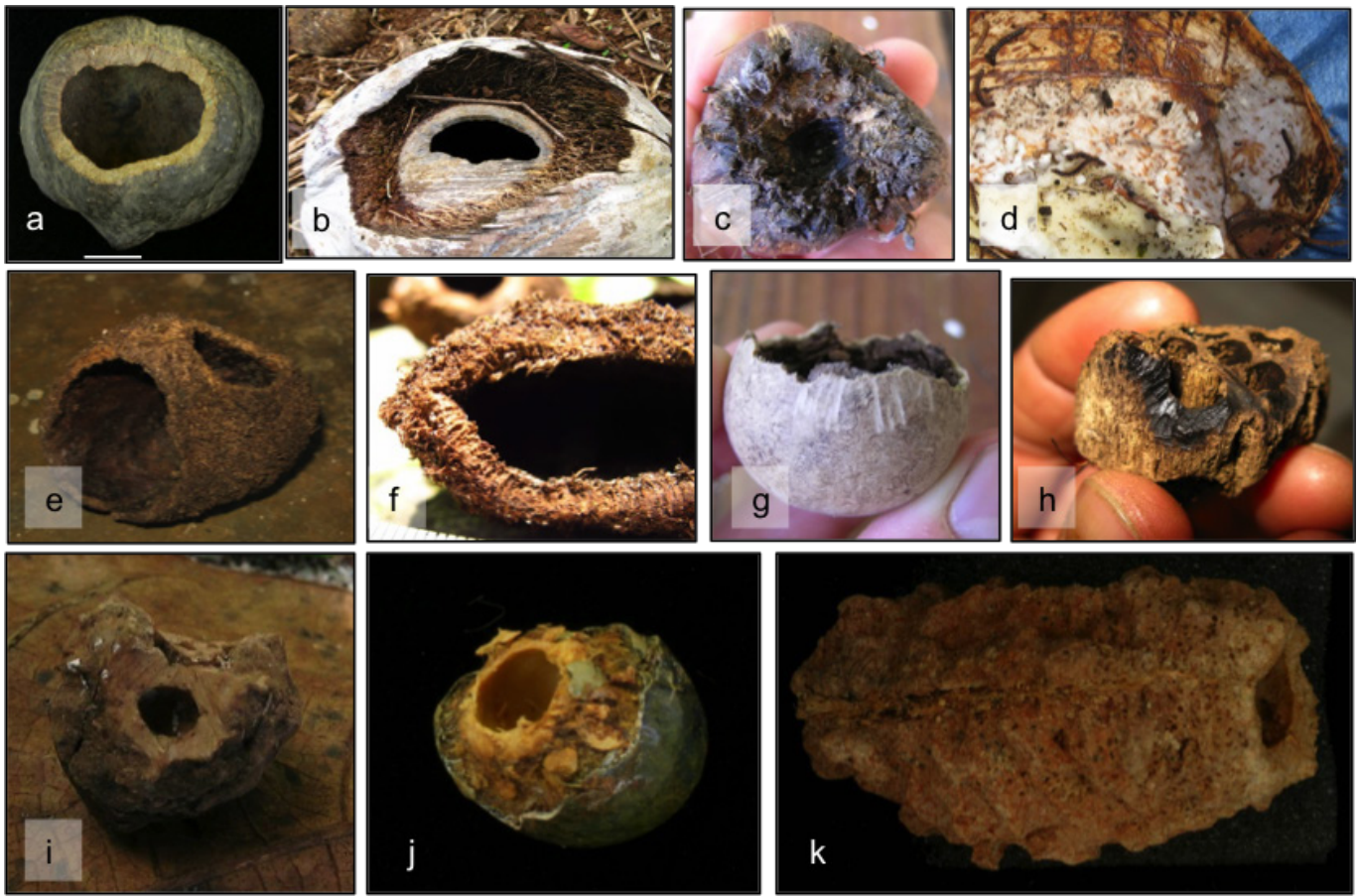
Figure 4. A selection of rat-gnawed seeds that are widespread on Pacific islands showing rodent predation. Many of these species are also globally widespread and common (e.g. *Cocos*, *Aleurites*, *Cordia*, *Pandanas*). (a) *Aleurites moluccana* (length of seed in photo is 3 cm). (b) *Cocos nucifera*, with rodent bites through the husk and into the hard shell of the coconut (20 cm). (c) *Cocos nucifera*, showing rodent bites at the base of a juvenile coconut (6 cm). (d) Fresh *Cocos nucifera* left out overnight in a taro garden in Mangaia showing distinctive rodent bites on the coconut flesh. (e) *Inocarpus fagifer*, showing distinct rat bitten holes (5 cm). (f) *Inocarpus fagifer*, with rodent bite details on edge of hole. (g) *Calophyllum inophyllum* (2.5 cm). (h) *Pandanus tectorius* (4 cm). (i) *Cordia subcordata* (1.8 cm). (j) *Elaeocarpus floridanus* (0.8 cm). (k) *Terminalia glabrata* (2.5 cm).

While the persistence of gnawed seeds may be problematic if rodent-gnawed seeds are sampled which predate a successful eradication program (as this poses a risk of obtaining false positives), sampling from the upper layer of the leaf litter increases the likelihood that gnawed seeds originate from that fruiting season. Another possible solution to this problem could be to rake or sweep away all seeds from under some sentinel trees before the fruiting season, so that all seeds date from that season. Where temporal assessment is especially important seeds can also be radiocarbon dated using bomb curve radiation (e.g. Uno et al. 2013), although this is expensive (c. NZ$700 per seed).

When woody endocarp seeds are buried in suitable conditions they can persist in the landscape for hundreds or even thousands of years, making them ideal for detecting initial rodent presence and impacts over long time-frames. While the majority of such studies have used rodent-gnawed seeds as a proxy for dating the initial arrival of rats with people to Pacific islands (e.g. Wilmshurst & Higham 2004; Hunt 2007) rodent-gnawed seeds could also be used to date the extinction of native rodent species. For example, the Canary Islands lost two giant endemic rats (*Canariomys* spp.), but the timing and drivers of their extinction are still unclear (Bocherens et al. 2006; Rando et al. 2014). These rats were apparently

herbivorous and probably exploited canopy fruits and seeds (Bocherens et al. 2006), so preserved and dated gnawed seed cases could provide further evidence for the precise timing of their extinction. Preserved seed cases could also be used to infer the presence of trees that have since been extirpated, and the causes of their extirpation (Hunt 2007; Prebble & Dowe 2008).

While we tested the reliability of this method in New Zealand, it could be used to detect the presence of rats on other island groups where native rodents do not exist (e.g. the several thousand islands of Polynesia and Micronesia). Plant taxa with woody seedcases that are consumed by rodents are common on many islands. For example in the Pacific island floras, the seeds of widespread species such as *Elaeocarpus spp.*, *Cocos nucifera*, *Pritchardia spp.*, *Terminalia spp.*, *Aleurites moluccana*, *Cordia subcordata*, and *Pandanus tectorius* commonly show distinct signs of rat predation (see Fig. 4; McConkey et al. 2003; Hunt 2007; Prebble & Wilmshurst 2009; Hays et al. 2018). Many of these species are extensively cultivated, making them easy to find and perfect to use as a monitoring tool for rodent presence. *Cocos nucifera* seeds in particular are very attractive to rats, and opened coconuts could even be left out in the field to accumulate rodent gnaw-marks as a kind of natural waxtag or 'cocotag'. Goodman

and Sterling (1996) also recorded ship rats gnawing holes in the woody endocarp seeds of *Canarium madagascariense* in Madagascar, although further investigation is needed to reveal whether these gnaw marks can be separated from those left by native Malagasy rodents. Rat-gnawed seeds can also be used to search for undiscovered native rodent species on islands, for example where chewed seeds of *Canarium indicum* and *Canarium solomense* were used to confirm the existence of the rare giant Vangunu rat (*Uromys vika*) on the Solomon Islands (Lavery & Judge 2017).

In conclusion, our study demonstrates that rodent-gnawed seeds act as reliable indicator of both ship rat and mouse presence, although we would recommend a more comprehensive and standardised sampling regime (search effort and minimum number of seeds collected) when using it to confirm the absence of these taxa. This low-cost, efficient method provides a welcome expansion to the current toolbox of rodent detection techniques as it avoids issues with neophobia and lures that many other rodent detection tools suffer from. The ubiquity of woody seedcase plant species in many other island groups suggests that this method should be widely applicable. Future research should determine how sensitive the method is to detecting rodents at very low densities.

Acknowledgements

References

Angel A, Wanless RM, Cooper J 2009. Review of impacts of the introduced house mouse on islands in the Southern Ocean: Are mice equivalent to rats? Biological Invasions 11:1743–1754.

Atkinson IAE 1985. The spread of commensal species of *Rattus* to oceanic islands and their effects on island avifaunas. In: Moors PJ ed. Conservation of island birds. Cambridge, International Council for Bird Preservation Technical Publication. Pp. 35–81.

Atkinson IAE, Taylor RH 1992. Distribution of alien animals on New Zealand islands. 2nd edn. DSIR Land Resources Contract Report 92/59. Lower Hutt and Nelson, DSIR Land Resources. 39 p.

Beveridge AE 1964. Dispersal and destruction of seed in central North Island podocarp forest. Proceedings of the New Zealand Ecological Society 11: 48–55.

Bocherens H, Michaux J, Talavera FG, Van der Plicht J 2006. Extinction of endemic vertebrates on islands: The case of the giant rat *Canariomys bravoi* (Mammalia, Rodentia) on Tenerife (Canary Islands, Spain). Comptes Rendus Palevol 5: 885–891.

Brown KP, Moller H, Innes J, Alterio N 1996. Calibration of tunnel tracking rates to estimate relative abundance of ship rats (*Rattus rattus*) and mice (*Mus musculus*) in a New Zealand forest. New Zealand Journal of Ecology 20: 271–275.

Burge OR, Kelly D, Wilmshurst JM 2017. Interspecies interference and monitoring duration affect detection rates in chew cards. Austral Ecology 42: 522–532.

Campbell DJ, Atkinson IAE 2002. Depression of tree recruitment by the Pacific rat (*Rattus exulans* Peale) on New Zealand's northern offshore islands. Biological Conservation 107: 19–35.

Caut S, Angulo E, Courchamp F 2008. Dietary shift of an invasive predator: Rats, seabirds and sea turtles. Journal of Applied Ecology 45: 428–437.

Collinson ME, Hooker JJ 2000. Gnaw marks on Eocene seeds: Evidence for early rodent behaviour. Palaeogeography Palaeoclimatology Palaeoecology 157: 127–149.

Courchamp F, Chapuis JL, Pascal M 2003. Mammal invaders on islands: Impact, control and control impact. Biological Reviews 78: 347–383.

Daniel MJ 1973 Seasonal diet of the ship rat (*Rattus R. rattus*) in lowland forest in New Zealand. Proceedings of the New Zealand Ecological Society 20: 21–30.

Dilks P, Towns D 2002. Developing tools to detect and respond to rodent invasions of islands: workshop report and recommendations. DOC Internal Science Series 59. Wellington, Department of Conservation. 18 p.

Goodman SM, Sterling EJ 1996. The utilization of *Canarium* (Burseraceae) seeds by vertebrates in the RNI s' Andringitra, Madagascar. In: Goodman SM ed. A floral and faunal inventory of the eastern side of the Reserve Naturelle Integrale d'Andringitra, Madagascar: with reference to elevational variation. Chicago, Field Museum of Natural History. Pp 83–89.

Grant-Hoffman MN, Barboza PS 2010 Herbivory in invasive rats: Criteria for food selection. Biological Invasions 12: 805–825.

Gsell A, Innes J, De Monchy P, Brunton D 2010. The success of using trained dogs to locate sparse rodents in pest-free sanctuaries. Wildlife Research 37: 39–46.

Harris DB 2009. Review of negative effects of introduced rodents on small mammals on islands. Biological Invasions 11: 1611–1630.

Hays BBR, Sperry J, Drake DR, Hruska AM 2018. Husking stations provide insight into the diet of non-native rodents on O'ahu, Hawai'i. Pacific Science 72: 335–344.

Hitchmough R, Anderson P, Barr B, Monks JM, Lettink M, Reardon JT, Tocher M, Whitaker T 2013. Conservation status of New Zealand reptiles, 2012. New Zealand Threat Classification Series 2. Wellington, Department of Conservation. 16 p.

Hoare JM, Pledger S, Nelson NJ, Daugherty CH 2007. Avoiding aliens: Behavioural plasticity in habitat use enables large, nocturnal geckos to survive Pacific rat invasions. Biological Conservation 136: 510–519.

Hunt TL 2007. Rethinking Easter Island's ecological catastrophe. Journal of Archaeological Science 34: 485–502.

Innes J, Kelly D, Overton JMC, Gillies C 2010. Predation and

other factors currently limiting New Zealand forest birds. New Zealand Journal of Ecology 34: 86–114.

Jones HP, Tershy BR, Zavaleta ES, Croll DA, Keitt BS, Finkelstein ME, Howard GR 2008. Severity of the effects of invasive rats on seabirds: A global review. Conservation Biology 22: 16–26.

Jones HP, Holmes ND, Butchart SHM, Tershy BR, Kappes PJ, Corkery I, Aguirre-Muñoz A, Armstrong DP, Bonnaud E, Burbidge AA, Campbell K 2016. Invasive mammal eradication on islands results in substantial conservation gains. Proceedings of the National Academy of Sciences 113: 4033–4038.

King CM ed. 2005. The handbook of New Zealand mammals.2nd ed. Melbourne, Oxford University Press. 630 p.

Lavery TH, Judge H 2017. A new species of giant rat (Muridae, *Uromys*) from Vangunu, Solomon Islands. Journal of Mammalogy 98: 1518–1530.

McConkey KR, Drake DR, Meehan HJ, Parsons N 2003 Husking stations provide evidence of seed predation by introduced rodents in Tongan rain forests. Biological Conservation 109: 221–225.

Moors PJ, Atkinson IAE 1984. Predation on seabirds by introduced animals, and factors affecting its severity. In: Croxall J, Evans P, Schreiber R eds. Status and conservation of the world's seabirds. Cambridge, International Council for Bird Preservation. Pp. 667–690.

Ostendorf B, Boardman WSJ, Taggart DA 2016. Islands as refuges for threatened species: Multispecies translocation and evidence of species interactions four decades on. Australian Mammalogy 38: 204–212.

Pickerell GA, O'Donnell CFJ, Wilson DJ, Seddon PJ 2014. How can we detect introduced mammalian predators in non-forest habitats? A comparison of techniques. New Zealand Journal of Ecology 38: 86–102.

Prebble M, Dowe JL 2008. The late Quaternary decline and extinction of palms on oceanic Pacific islands. Quaternary Science Reviews 27: 2546–2567.

Prebble M, Wilmshurst JM 2009. Detecting the initial impact of humans and introduced species on Island environments in Remote Oceania using palaeoecology. Biological Invasions 11: 1529–1556.

Rando JC, Alcover JA, Galván B, Navarro JF 2014. Reappraisal of the extinction of *Canariomys bravoi*, the giant rat from Tenerife (Canary Islands). Quaternary Science Reviews 94: 22–27.

Ruscoe WA, Wilson D, McElrea L, McElrea G, Richardson SJ 2004. A house mouse (*Mus musculus*) population eruption in response to rimu (*Dacrydium cupressinum*) seedfall in southern New Zealand. New Zealand Journal of Ecology 28: 259–265.

Ruscoe WA, Sweetapple PJ, Perry M, Duncan RP 2013. Effects of spatially extensive control of invasive rats on abundance of native invertebrates in mainland New Zealand forests. Conservation Biology 27: 74–82.

Russell JC, Beaven BM, MacKay JWB, Towns DR, Clout MN 2008. Testing island biosecurity systems for invasive rats. Wildlife Research 35: 215–221.

Sakata K 2011. Forensic approaches to monitoring and individually identifying New Zealand vertebrate pests. Unpublished PhD thesis, Lincoln University, Lincoln, New Zealand. 216 p.

Shiels AB, Drake DR 2015. Barriers to seed and seedling survival of once-common Hawaiian palms: The role of invasive rats and ungulates. AoB Plants 7: plv057.

St Clair JJH 2011. The impacts of invasive rodents on island invertebrates. Biological Conservation 144: 68–81

Sweetapple P, Nugent G 2011 Chew-track-cards: A multiple-species small mammal detection device. New Zealand Journal of Ecology 35: 153–162.

Tennyson A, Martinson P 2006. Extinct birds of New Zealand. Wellington, Te Papa Press. 180p.

Thorsen M, Shorten R, Lucking R, Lucking V 2000 Norway rats (*Rattus norvegicus*) on Fregate Island, Seychelles: The invasion; subsequent eradication attempts and implications for the island's fauna. Biological Conservation 96: 133–138.

Towns DR, Atkinson IAE, Daugherty CH 2006. Have the harmful effects of introduced rats on islands been exaggerated? Biological Invasions 8: 863–891.

Traveset A, Nogales M, Alcover JA, Delgado JD, López-Darias M, Gody D, Igual JM, Bover P 2009. A review on the effects of alien rodents in the Balearic (western Mediterranean sea) and Canary islands (eastern Atlantic ocean). Biological Invasions 11: 1653–1670.

Uno KT, Quade J, Fisher DC, Wittemyer G, Douglas-Hamilton I, Andanje S, Omondi P, Litoroh M, Cerling TE 2013. Bomb-curve radiocarbon measurement of recent biologic tissues and applications to wildlife forensics and stable isotope (paleo) ecology. Proceedings of the National Academy of Sciences 110: 11736–11741.

Williams PA, Karl BJ, Bannister P, Lee WG 2000. Small mammals as potential seed dispersers in New Zealand. Austral Ecology 25: 523–532.

Wilmshurst JM, Higham TFG 2004. Using rat-gnawed seeds to independently date the arrival of Pacific rats and humans in New Zealand. The Holocene 14: 801–806.

Wilmshurst JM, Anderson AJ, Higham TFG, Worthy TH 2008. Dating the late prehistoric dispersal of Polynesians to New Zealand using the commensal Pacific rat. Proceedings of the National Academy of Sciences 105: 7676–7680.