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A review of methods for detecting rats at low densities, with implications for surveillance

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Abstract Invasive rats are the biggest threat to island biodiversity world-wide. Though the ecological impacts of rats on insular biota are well documented, introduced rats present a difficult problem for detection and management. In recent decades, improved approaches have allowed for island-wide eradications of invasive rats on small-medium sized islands and suppression on large islands, although both these still represent a formidable logistical and financial challenge. A key aspect of eradication or suppression and ongoing management is the ability to detect the presence of rats, especially at low densities. Here we review recent developments in the field of rat surveillance and summarise current published literature to recommend practices and the factors to consider when developing a surveillance program for either eradication or suppression plans. Of 51 empirical studies covering 17 countries, 58% were from New Zealand. Although detecting rats at low density is extremely challenging, advances over the past 15 years, have significantly improved our ability to detect rats. Motion-sensored cameras and rodent detection dogs have greatly improved our ability to detect rats at low densities, with cameras consistently showing an ability to detect rats at lower densities than other techniques. Rodent detection dogs are also able to reliably detect even an individual rat, although there are challenges to their widespread adoption, particularly in developing countries, due to the cost and skills required for their training and maintenance. New monitoring devices, the use of eDNA and drones represent current and future innovations to improve detection.

Keywords Rat · Monitoring · Surveillance · Biosecurity

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Introduction

Invasive rat species have been transported widely across the globe by humans. Black Rats (*Rattus rattus*) and brown rats (*Rattus norvegicus*) have spread globally from their native ranges in south-east Asia and China respectively (Aplin et al. 2011) while Pacific rats (*Rattus exulans*) have spread across the Pacific from their native range in Indonesia (Matisoo-Smith and Robins 2009). The introduction of these three invasive rats species globally has had major negative effects on global biodiversity, with the effects most severe on islands (Capizzi et al. 2014; McCreless et al. 2016; Towns et al. 2006) and on vertebrates (Harper and Bunbury 2015; Jones et al. 2008; Spatz et al. 2017). Invasive rats can have major impacts on ecosystems (Mulder et al. 2009; Thoresen et al. 2017) as well as causing declines and extinctions in a wide range of vertebrates (Radley et al. 2021; Doherty et al. 2016; Jones et al. 2016). Consequently, eradications of invasive rats are increasingly being implemented to conserve biodiversity (Jones et al. 2016), primarily on small islands but also, recently during ambitious projects to suppress or eradicate invasive rats from mainland areas (Bell et al. 2019b; Owens 2017). Techniques to suppress or eradicate rats are continuously improving (Campbell et al. 2015; Keitt et al. 2015; Russell and Broome 2016; Spatz et al. 2022) and suppressions and eradications are being achieved on progressively larger islands and on areas of large landmasses (Bell et al. 2019b; Martin and Richardson 2019; Springer 2016). However, given the negative effects of invasive rats on ecosystems, including the vulnerability of many native species to rat predation, and the costs and challenges of suppression and eradication (Carrion et al. 2011; Griffiths et al. 2019; Holmes et al. 2015), it is critical to effectively detect rats at low densities. For suppression programs, this ensures that techniques are effective in reducing rat densities to a suitable level. If not, then either the density of control devices would need to be increased or, if rats were becoming habituated to specific control devices, new methods may be required. Rat behaviour is also an important consideration in eradications. Russell et al. (2010) found that invasive brown rats introduced experimentally to a rat free island had random movements, rapid increases in range size for the first week, a larger range size at low than high density and they conformed to central place foraging behaviour. Consequently, control or detection operations need to account for these behavioural factors and detecting rats at low densities (where home ranges are larger) is critical for effective surveillance as part of a biosecurity plan. Effective biosecurity measures involve a combination of quarantine, surveillance, and response (see Fig. 3 in Russell et al. 2017b) with the relative importance of these components varying depending on the species involved, the likelihood of individuals reaching the pest-free area and the costs of eradication (Jarrad et al. 2011; Rout et al. 2014). Given the expense of eradicating rats (Donlan and Wilcox 2007; Duron et al. 2017; Holmes et al. 2015), quarantine and surveillance are generally more cost-effective options than control (Rout et al. 2011). It may often be much cheaper to detect and control incursions of individuals, before a self-sustaining population has established, rather than detect and control invasions where an entire area has been invaded and a self-sustaining population has established (Moore et al. 2010; Puth and Post 2005). However, detecting single individual rats is extremely challenging (Russell et al. 2005, 2007, 2008a) and there is a period of only around 100 days before an incursion can develop into an invasion (Bell et al. 2019b), although sometimes sparser detection networks with delayed detection can be more cost effective. Whether islands are inhabited or uninhabited also adds to the challenges of effectively detecting rats at low densities because some surveillance methods (e.g. poison bait stations) may be socially unacceptable on inhabited islands.

Russell et al. (2008b) conducted a thorough review of surveillance methods and their recommendation for surveillance devices was a combination of poison bait stations, live and kill traps, wax tags, tracking tunnels, and trained dogs. However, since that review, there has been an improved understanding of the factors that influence the efficacy of existing devices in detecting rats at low densities, new surveillance devices have been developed, and there is an improved understanding of the types and combinations of surveillance devices that would be preferred in specific situations (Campbell et al. 2015; Gsell et al. 2010; Russell and Broome 2016). Hence, given the importance of detecting rats at low densities for both suppression and eradication programs, it is timely to review recent developments in the field of rat surveillance and summarise current published literature to recommend practices and the factors to consider when developing a surveillance program. Lastly, we explore developing novel methods to inform and improve future surveillance practices.

Methods

To search for recent (up until November 2022) published developments in the field of rat surveillance we used the Scopus search engine and searched for papers containing the keywords *Rattus* AND surveillance as well as biosecurity OR eradication OR detect* OR incursion. We then searched through the reference lists in the relevant papers to locate specific papers on rat surveillance. We retained all publications that involved the detection of rats using one of more surveillance devices or methods, provided a review of devices or methods, modelled rat detection using devices or methods or investigated factors (e.g. pheromones) that might influence rat detection rates. Publications were excluded if they detected species other than rats of if they simply described that rats were detected but presented no data on detection rates. We also searched the Database of Island Invasive Species Eradications (DIISE) and searched publications and grey literature related to these eradications. As a result, we retained 75 publications that contained empirical data relevant to rat detection, monitoring, and surveillance (Table S1).

Results

Of the 75 publications we retained that related to rat detection rates, four were modelling studies, 10 were reviews and the remaining 61 reported studies that included empirical data on rat detection rates, with a total of 23 countries, territories or dependencies represented. Of the modelling publications, two modelled data from Australia, one modelled data from New Zealand and the fourth simply described a modelling technique (i.e. no geographic location). Of the 10 reviews, four reviewed techniques in a global context, four reviewed techniques for New Zealand, one for Australia and one for eight countries in the Mediterranean region. The 61 empirical studies showed a strong geographic bias (Fig. 1) with most (54.1%) coming from New Zealand. Remaining studies were more even spread between France (4.9%), Antigua and Barbuda, Australia and Hawaii (all 3.3% each) and Anguilla, Chagos Archipelago, Falkland Islands, Indonesia, Marianas Islands, Mexico, New Caledonia, Palau, Puerto Rico, Saint Vincent and the Grenadines, Seychelles, South Georgia, Spain, Tonga, Tunisia, United Kingdom and US Virgin Islands (all 1.6% each). One study was conducted in a laboratory (1.7%) (Table S1).

Fifteen of the 75 publications (20.0%) investigated rats in general and did not specify which species they investigated, were mainly modelling studies

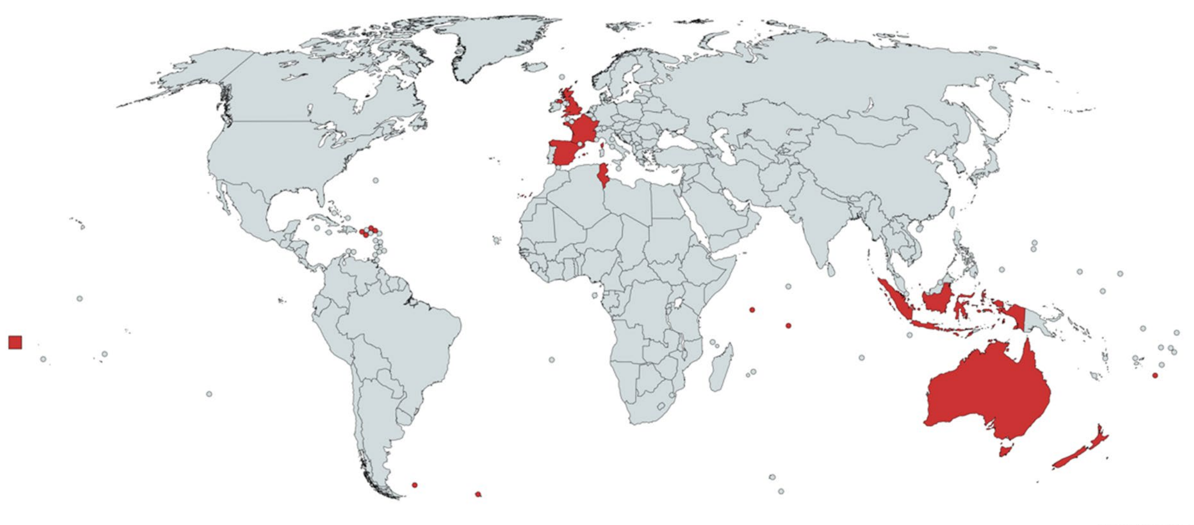


Fig. 1 Locations of studies focused on rat detection methods (see Table S1)

Table 1 Summary of the surveillance devices used in 21 biosecurity programs from the available literature

References	Location	Species	Techniques	Number	Frequency	Timeline
Bagasra et al. (2016)	New Zealand	Pacific and Black Rat	(1) Snap traps (2) Tracking tunnels	200 Snap traps 100 Tracking tunnels	Triannually	Indefinite
Bell and Challenger (2018)	Redonda I., Antigua & Barbuda	Black Rat	(1) Bait stations with rodenticide	39 Bait stations	Every 2 months	Indefinite
Bell and Daltry (2014)	Dog Island, Anguilla	Black Rat	(1) Non-toxic chocolate wax, candles and soap in bait stations (2) Tracking tunnels (3) Visual surveys around houses and seabird nesting areas	324 Bait stations 17 Tracking tunnels	6–8 weeks	Indefinite
Bourgeois et al. (2013)	Zembretta Island, Tunisia	Black Rat	(1) Bait stations with rodenticide	20 Bait stations	Unknown	Indefinite
Capizzi (2020)	Mediterranean Islands	Brown and Black Rat	(1) Bait station with rodenticide (2) Snap traps	Unknown	Unknown	Indefinite
Carey (2019)	Falkland Islands	Brown Rat	(1) Chew sticks with peanut butter flavoured wax (2) Visual searches	200 Chew sticks	Ad hoc, not more than annually	Indefinite
Harper et al. (2019)	Chagos Archipelago	Black Rat	(1) Snap traps (2) Wax tags (3) Coconuts (4) Visual searches	45 Snap traps 45 Wax tags	Ad hoc, when visiting islands	Up to 33 months
Houston (2002)	Maninita I., Tonga	Pacific Rat	(1) Bait stations with rodenticide	33 Bait stations	Monthly	Indefinite

Table 1 (continued)

References	Location	Species	Techniques	Number	Frequency	Timeline
Martin and Richardson (2019) Richardson and Croxall (2019)	South Georgia	Brown Rat	(1) Wax tags (2) Chew sticks impregnated with vegetable oil (3) Chew cards impregnated with peanut butter (4) Tracking tunnels (5) Remotely-activated cameras 6. Pre-baited trap boxes	146–815 devices Unknown trap boxes	Devices used 3 times over 2 years Trap boxes checked daily when vessel moored	Indefinite
Meier and Varnham (2004)	Sangalaki Island, Indonesia	Black Rat	(1) Bait stations with rodenticide	40 Bait stations	Unknown	Indefinite
Millett et al. (2019)	Seychelles	Brown and Black Rat	(1) Bait stations that are regularly maintained and refilled (2) Snap traps (3) Chew sticks	Unknown	Unknown	Indefinite
Orueta et al. (2005)	Chafarinas Archipelago, Mediterranean	Black Rat	(1) Snap traps (2) Bait stations with rodenticide	30 Snap traps 60 Bait stations	Unknown	Up to 36 months
Pascal et al. (2008)	Lavezzu Island, France	Black Rat	(1) Bait stations with rodenticide	65 Bait stations	2–4 monthly	Indefinite
Pearson et al. (2019)	Scilly Islands, UK	Brown Rat	(1) Flavoured wax, candles and soap (2) Tracking tunnels (3) Remotely-activated cameras	448 monitoring stations	Monthly	Indefinite
Robinson and Dick (2020)	Green Island, Australia	Black Rat	(1) Wax tags (2) Snap traps (3) Bait station with rodenticide	6 Wax tags 6 Snaps traps 38 Bait stations with rodenticide	3–6 monthly	Indefinite
Ruffino et al. (2015)	Bagaud Island, France	Black Rat	(1) Bait stations with rodenticide	20 Bait stations	Monthly for 7 months, then bimontly	Indefinite

Table 1 (continued)

References	Location	Species	Techniques	Number	Frequency	Timeline
Russell et al. (2010)	New Zealand	Brown and Black Rat	(1) Snap traps (2) Tracking tunnels (3) Bait stations with rodenticide	Unknown, in 4 lines 1 km long	Every 3 months	Indefinite
Veitch (2022a)	Browns I., New Zealand	Brown Rat	(1) Bait stations with rodenticide	50 Bait stations	Biannually	Indefinite
Veitch (2022b)	Tiritiri Matangi I., New Zealand	Pacific Rat	(1) Bait stations with rodenticide	51 Bait stations	Every 3 to 6 months	Indefinite
Will et al. (2019)	Desecheo Island, Puerto Rico	Black Rat	(1) Bait stations (2) A24 traps (3) Tomahawk traps (4) Chew cards (5) Remotely-activated cameras (6) Tracking tunnels	0–40 Bait stations 0–10 A24 traps 10–22 Tomahawk traps 50–179 Chew cards 10–21 Remotely-activated cameras 0–20 Tracking tunnels	7 and 12 months then monthly from 17 to 23 months	Up to 23 months
Witmer et al. (2007)	Buck Island, US Virgin Is	Black Rat	(1) Snap traps	93 Snap traps	Once or twice annually	Up to 62 months

The techniques used, the number of devices and the frequency and timeline over which the devices were checked are given for each study

or were those that used detection methods where it was not possible to distinguish rat species (e.g. chew cards and wax tags). Of the remaining publications, 45 investigated a single rat species with three publications investigating Pacific Rats (4.0%), ten investigating Brown Rats (13.3%) and 23 investigating Black Rats (30.7%). Eleven studies investigated two rat species with four studies investigating Pacific and Black Rats (5.3%) and seven studies investigating Brown and Black Rats (9.3%). Lastly, four studies investigated all three species of invasive rats (5.3%), of which three were review papers.

Of the 75 publications, 21 specifically investigated surveillance programs across 18 different countries, territories or dependencies. Of these 21 surveillance programs, 17 targeted a single species with two targeting Pacific Rats (9.5%), four targeting Brown Rats (19.0%) and 11 targeting Black Rats (52.4%), while four targeted two species with one targeting Pacific and Black Rats (4.8%) and three targeting Brown and Black Rats (14.3%) (Table 1).

Surveillance methods

A critical requirement of a surveillance device is its ability to detect rats at low densities (Barrett et al. 2010). Recent advances have included the development of new surveillance devices and an improved understanding of the efficacy of existing surveillance device at low rat densities. One of the most significant advances in the past 15 years have been the use of motion-sensored cameras to monitor for rats. These studies have shown that baited motion-sensored cameras are effective in detecting and monitoring rats at low densities and provide a useful surveillance tool (Dilks et al. 2020; Martin and Richardson 2019; Rendall et al. 2014; Robinson and Dick 2020; Smart et al. 2021). Another recent development in rat control and surveillance is the development of the Goodnature® A24 kill trap where a rat is attracted to bait and then killed with a piston fired by a small gas canister, which can fire up to 24 times (Shiels et al. 2019). These traps have not been widely used in surveillance (Robinson and Dick 2020) however, so their efficacy as a surveillance device has not been well quantified. However, Gronwald and Russell (2022) found that not all interactions resulted in triggers, and that activity and kill rates varied seasonally, indicating they may have limits as surveillance devices. Furthermore, there is also an issue of rat carcasses from A24s being consumed by scavengers, which would prevent the detection of rats even when present (Kreuser et al. 2022). Studies have also explored the use of trained dogs in detecting rats (Gsell et al. 2010) and found that they were very effective in detecting 87% of rats on a 63 ha island. Furthermore, very few false positives were detected and the dogs could cover up to 40 ha of steep, forested terrain in 6 h. A rodent detection dog located a Brown Rat on a small (181 ha) island off New Zealand within an hour of landing (Bassett et al. 2016) and a simulation study found that using trained dogs was the single most effective method of increasing rat detection probabilities (Kim et al. 2020). However, Glen et al. (2018) found that detection distances were small with an effective distance of only 8.4 m either side of the search path so the limits of what can be achieved with detection dogs needs to be understood if they are to provide an effective method of detecting rats at low densities, particularly individual rats.

Several studies have compared the efficacy of different surveillance techniques in detecting rats at low densities. Studies have found that baited motion-sensored cameras are more effective than baited tracking tunnels (Anton et al. 2018) and A24 kill traps (Gronwald and Russell 2021) but less effective than baited chew cards (Nottingham et al. 2021). However, the better detection rates for chew cards were likely due to using a more attractive lure (peanut butter) and a more appropriate spacing (50 m) than for cameras (with lures of quail eggs and crickets and spaced at 100 m) as another study found baited cameras detected rats at low densities more effectively than baited chew cards (Nichols et al. 2021). Using quail eggs and crickets as lures would likely be problematic in ecologically sensitive sites for biosecurity reasons. Cameras were also more effective at detecting rats than tracking tunnels, chew cards or live traps in forests and shrublands on a large (16 782 ha) island off New Zealand (Yiu et al. 2022). Cameras were also more successful at detecting rats than tracking tunnels or chew cards on small islands ($\leq$ 22.1 ha) in the West Indies (Smart et al. 2021), although the differing surveillance devices were not employed contemporaneously, precluding direct comparisons. Together, these studies indicate that cameras are an effective technique for detecting rats at low densities, however further quantitative studies are needed. Live trapping and baited wax tags were equally successful at detecting rats at a mainland site in New Zealand, and they both were able to detect rats at low densities (Gillies and Brady 2018), although the study did not investigate detectability at densities analogous to a rat incursion. Similarly, baited wax tags had the highest detection rates for Brown Rats at another mainland site in New Zealand, but the differences between a wide variety of techniques were not significant (Pickerell et al. 2014). Baited chew-track cards, that detected rats by both recording footprints and bite marks, showed “weak evidence” of detecting more rats at low densities than baited tracking tunnels on mainland New Zealand (Sweetapple and Nugent 2011) although, this study did not explore detections at densities analogous to an individual rat. Baited tracking tunnels were found to be more effective than baited kill traps at detecting rats at low densities on mainland New Zealand because tracking tunnels continued to detect rats when no more were being killed in traps (Christie et al. 2015). Surveying for chew marks on seed coatings was a new technique for detecting rats that was trialled in comparison to kill traps, tracking tunnels and detection dogs. However, chewed seed coatings were found to be less effective than the other three techniques at detecting rats on 14 islands and a mainland site in New Zealand (Wilmshurst and Carpenter 2020). Baited chew cards were used to successfully detect remaining rats after initial eradication efforts on a small (125 ha) temperate island off Australia, which then lead to the successful eradication of the remaining rats (Robinson and Dick 2020), although this approach was not compared to other techniques.

Jarrad et al. (2011) used expert elicitation to estimate the probability of detecting rats with 11 different surveillance techniques in parts of a large (23,400 ha) tropical island off Australia and the expert consensus was that the three most effective techniques for detecting individual rats were structured surveys by biologists (detection probability [σ] = 0.9), baited remotely-activated cameras and Scentinel® traps (both σ = 0.8). Baited chew cards and baited tracking tunnels were estimated to have a moderate probability of detecting rats (σ = 0.5) whereas other techniques (baited hair traps, unstructured surveys by biologists, engaged workers, passive workers, unbaited tracking tunnels and baited cage traps) were considered to have a low probability of detecting rats ($\sigma \leq 0.2$). However, these were estimates only and have not generally been supported by subsequent field studies, which have shown that baited chew cards were more effective at detecting rats than baited motion-sensored cameras (Nottingham et al. 2021) and baited tracking tunnels (Sweetapple and Nugent 2011). Unfortunately, we could find no evidence that Scentinel® traps, essentially tracking tunnels that dispense bait and have a camera and weighbridge within them (King et al. 2007), had been used as surveillance devices but Jarrad et al. (2011) indicate that they may have value in detecting rats at low densities.

Improving detectability

While the surveillance device has a fundamental effect on the probability of detecting rats at low densities, there are also methods than can improve the detectability of rats on any given device. The most obvious method is to bait the surveillance device and it has been shown that baiting tracking tunnels and motion-sensored cameras increased detectability by 363% compared to unbaited tunnels and cameras at a mainland site in New Zealand (Anton et al. 2018). Hence, surveillance devices are invariably baited, with the type of bait used usually dependent on the frequency with which devices are monitored. For locations that are monitored infrequently, usually remote or uninhabited islands, an effective bait to detect rats in exposed situations on a small (207 ha) tropical island in the West Indies was found to be Klerat® wax blocks that contain brodifacoum and chocolate polyurethane blocks (Bell and Daltry 2014).

Another aspect of improved detectability of rats is an improved knowledge of habitats used by rats with eradication techniques providing some insights into how rats might be effectively detected in those habitats. Studies have recently shown that rats occur commonly in mangroves on tropical islands (Harper et al. 2015; Russell et al. 2011) and remotely-activated cameras have been used to monitor wax bait “bolas” installed in the canopy of mangroves (Ringler et al. 2021). Similarly, studies in impenetrable intertidal thickets also attached wax bait “bolas”, in addition to elevated poison bait stations, to the canopy of *Pemphis* shrubs on a moderately sized (710 ha) tropical island (Siers et al. 2018). This innovative study also installed floating poison bait stations in intertidal areas lacking vegetation with all bait types monitored by visual inspection. Overall, these studies indicate that surveillance of rats in mangroves and other intertidal areas is potentially feasible with motion-sensored cameras or baited wax tags and that bait stations could also be installed as part of any surveillance program.

One review explored whether pheromones could be used to attract rats to baits and kill traps. It found that pheromones did appear to act as an attractant, but were less effective than bait in attracting rats (Clapperton et al. 2017). However, applying the scent of a dominant apex predator elicited curiosity in rats and increased detections when used (Garvey et al. 2017). These studies suggest that pheromones, either of rats or apex predators, could potentially be used to increase rat detection in locations where the use of long-lasting baits were unfeasible. However, the utilisation of pheromones as a lure could potentially decrease the efficacy of detection dogs as a surveillance method, although no study has yet investigated this issue. Another innovative laboratory study explored whether adding fluorescent dyes to bait could help increase the detectability of rats. It found that the dyes were incorporated into rat faeces and this made the faeces fluorescent and highly visible (Frankova et al. 2015), indicating that this method could increase the ability of detecting individuals rats by locating rat faeces. Live rats and rat urine were also found to attract rats and increase their detectability on mainland New Zealand, although the study did not evaluate whether this led to greater detectability than using baits (Gsell et al. 2014). However, an earlier study on mainland New Zealand found that the use of live rats as lures did increase trapping rates, and that the increase was greater than with bait, although the total number of animals trapped did not differ significantly between bait and live rat lures (Shapira et al. 2013).

Other studies have focused not on the surveillance method but on the spatial location of surveillance devices. Studies of experimentally released rats that mimicked invading individuals on island and mainland New Zealand showed that they rapidly increase their movements and home range after a few days (Innes et al. 2011; Russell et al. 2010). These results suggest that surveillance devices should be placed within 100 m of potential incursion sites for early detection, but also widely across the area of concern to detect individuals as they start to wander widely after a few days. Models of detectability have been shown to be positively related to rainfall in both the Marianas Islands and New Zealand (Adams et al. 2011; Christie et al 2015), suggesting that after heavy rain events may be an appropriate time to check surveillance devices.

A recent study modelled the optimal device spacing for detecting and, consequently, confirming rat eradication (Mackenzie et al. 2022). Rats in urban New Zealand were radio-tagged to estimate the probability of a rat encountering a device (non-toxic bait stations, chew cards and wax tags) and then interacting with it. This information was then used to model the optimal device spacing to maximise rat detection. It found that the mean nightly probability of an individual encountering a device was 0.38, whereas the probability of interacting with the encountered device was 0.34. Modelling showed that a surveillance network of 3.25 chew chards ha^{-1} or 3.75 wax tags ha^{-1} deployed for 14 nights would be required to confidently confirm the absence of rats. The density could be halved if the surveillance network was deployed for 28 nights. However, the authors emphasised that this study only explored detection probabilities in urban habitats and, hence, different spacing may be required in different habitats where detection probabilities were higher or lower than in their study (Mackenzie et al. 2022). The approach used in this study could be used to model detection probabilities and device densities for a range of devices, rat species and habitats and could be an important tool in developing effective surveillance networks.

Surveillance theory

There have also been significant recent improvements in surveillance theory, which has led to models that help identify the best allocation of biosecurity resources between quarantine, surveillance and response (Moore et al. 2010; Rout et al. 2014, 2011). These have all used preventing incursions on Barrow Island off Western Australia as the model system, but have identified the variables that need to be considered when developing a surveillance program and can be applied to surveillance programs anywhere globally. More recent iterations of these models are able to account for the uneven probability of incursions across the area of interest and suggest surveillance strategies that maximise detections (Berec et al. 2015) and how these strategies might be modified through time as more information becomes available (Rout et al. 2017). Rapid Eradication Assessment (REA) is another recent tools that was originally designed to estimate the probability of successful eradications on tropical Mexican islands (Russell et al. 2017a; Samaniego-Herrera et al. 2013) but, given that it can account for differing detection probabilities both spatially and between surveillance devices, the tool has great potential to inform surveillance programs elsewhere (Kim et al. 2020). Overall, these recent models have the potential to significantly improve the efficacy of surveillance programs and, with incremental improvements, this potential is likely to increase in the future.

Non-target fauna

One major issue for surveillance programs aiming to detect rats at low densities can be interference with surveillance devices by other fauna. While this is undesirable for poison bait stations because it can potentially lead to rodenticide leaching into ecosystems and secondarily poisoning other fauna, it is primarily undesirable from a surveillance viewpoint if fauna consume poison or trigger lethal traps, leaving the devices unable to detect or kill rats. Interference from other fauna appears to be particularly acute on tropical islands. While land crabs have long been recognised as being attracted to rat bait stations (e.g. Cuthbert et al. 2012; Griffiths et al. 2011; Pott et al. 2015), other studies have found that a wide range of lizard and invertebrates, as well as crabs, can also interfere with surveillance devices (Bell and Daltry 2014). Unfortunately, methods to design surveillance devices impervious to interference from crabs and other fauna have not been the focus of study, though some designs exist (Rauzon 2007). Resolution of interference issues often involves moving surveillance devices (Bell and Daltry 2014). Interference can also be an issue on temperate islands and some studies in New Zealand have found that tracking tunnels can rapidly become saturated by non-target species, precluding their ability to subsequently detect rats (Russell et al. 2009; Yiu et al. 2022).

One study found that applying a vertical PVC tube to non-toxic bait stations reduces access to bait stations by a native rat (Zewe et al. 2014) on the temperate mainland and islands off Australia, which has implications for the design of surveillance devices in the presence of native rats. One species that is especially problematic for rat detection is the house mouse (*Mus musculus*). Given their similarity to rats, most current surveillance devices for rats are susceptible to interference from mice (e.g. Burge et al. 2017; Sweetapple and Nugent 2011). However, mice in the absence of rats can have devastating effects on island ecosystems (Carter et al. 2023; Angel et al. 2009; Simberloff 2009) and mouse populations have been shown to increase after the removal of rats (Harper and Cabrera 2010; Ruscoe et al. 2011). Hence, it is likely that future eradications on islands where both rats and mice are present will target both groups (Bell and Daltry 2014). However, if mice are still present after rat eradication, some studies have focused on designing surveillance devices that can detect, and potentially kill, rats in the presence of mice, using rat-specific poisons such as norbormide (Roskowski 1965). Further work has focused on improving the palatability of baits containing norbormide to increase uptake, with implications for detecting rats at low densities (Campbell et al. 2015). Work is ongoing on developing self-resetting devices called Spitfire traps that squirt a lethal dose of poison onto the fur of a rat, with the rat ingesting the poison during grooming, with the device only triggered when a rat is detected (Blackie et al. 2014). A24 traps are also tailored to target primarily rats (https://goodnature.co.nz/collections/a24-rat-stoat-trap-kits) and can be effective in the presence of mice, though without modifications such as an excluder device they have the potential to kill or maim non-target wildlife (Crampton et al. 2022; Kreuser et al. 2022). Lastly, motion-sensored cameras are a detection method that have reliably detected rats in the presence of other fauna on mainland New Zealand and a large (10,100 ha) temperate island off Australia (Anton et al. 2018; Rendall et al. 2014).

Although there has been considerable recent work into methods to reduce interference from other fauna, this research has focused almost exclusively on reducing interference at bait stations rather than surveillance devices. From this research we can conclude that A24 traps and cameras are surveillance devices that can reliably detect rats in the presence of other fauna and rat-specific poisons could be used in surveillance devices in the future, potentially including Spitfire traps. However, it would be desirable for future research to focus specifically on the issues that influence the efficacy of surveillance devices for rats in the presence of interference from other fauna, as this remains a neglected issue.

Inhabited islands

The challenges of eradicating rats from inhabited islands are well documented (Glen et al. 2013; Oppel et al. 2011). While the focus of challenges on inhabited islands has been on eradication, many of the same issues are relevant for surveillance programs on inhabited islands as well. However, the successful eradication of rats from some inhabited islands shows that the challenges of surveillance and biosecurity on inhabited islands can be overcome. On inhabited islands, one of the main issues involves the provision of poison around human settlements and farms and the potential poisoning of pets or livestock. This has often been overcome by using surveillance methods that involve non-lethal detection of rats, with poison then used, and broadcast by hand, when rats were detected. On the Isles of Scilly in the United Kingdom, surveillance methods involved motion-sensored cameras, tracking tunnels and non-lethal materials attractive to rats that would clearly show teeth marks (e.g., chocolate, peanut, or coconut flavoured wax, candles and soap). These monitoring stations were checked monthly and only when signs of rats were detected was poison placed around the station to kill the rat (Bell et al. 2019a). Similarly, non-lethal baited traps and wax-tags were used to detect re-invading rats in sub-Antarctic South Georgia, with poison only used if rats were detected (Martin and Richardson 2019; Richardson and Croxall 2019). The recent development of re-setting traps that are lethal but do not contain poison, such as A24 traps, or the use of detection dogs, should further improve the ability to detect re-invading rats on inhabited islands. Furthermore, surveillance and detection of rats at low densities can be improved by the permanent presence of people that can check surveillance devices frequently and replace baits, or stations in the case of interference or depletion from other fauna, as well as detect direct or indirect signs of rats. However, numerous other factors, such as regulations, legislation, policies, agreements with landholders and social attitudes towards different surveillance methods all need to be addressed before the deployment of surveillance devices (Oppel et al. 2011; Pearson et al. 2019). Clearly, effective surveillance and detection of re-invading rats on inhabited islands will involve the cooperation and participation of local people, which can be challenging to secure, although methods to achieve this collaboration are continually improving (Capizzi 2020; Glen et al. 2013; Oppel et al. 2011; Pearson et al. 2019).

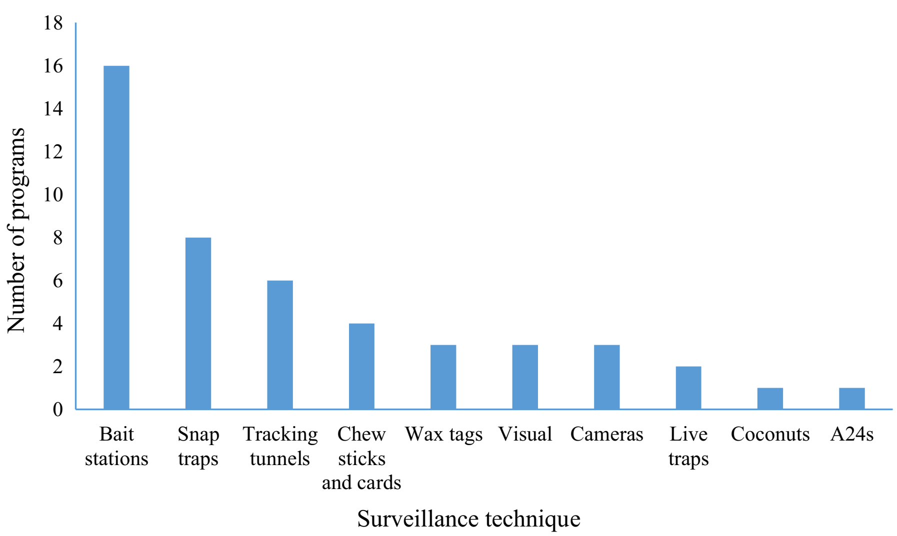
Rat species

Little attention has been paid to how the different ecology of the three species of invasive rat might influence their detectability by different surveillance devices and whether surveillance programs might need to be modified for different invasive rat species. There is, however, some evidence that A24 traps are less effective at detecting Pacific Rats than Black Rats (Shiels et al. 2022), although whether other surveillance devices differ in their ability to detect rats at low densities in unknown. Furthermore, rat behaviour is known to influence the efficacy of control devices (Clapperton 2006), but this issue has not been well-investigated in relation to surveillance devices. It is apparent that the three invasive species of rats typically prefer different habitats (Bramley 2014; Harper et al. 2005), consume different foods (Grant-Hoffman and Barboza 2010) and have different levels of arboreality (Foster et al. 2011; Key and Woods 1996). Brown Rats are also known to be more neophobic than the other species (Clapperton 2006). Re-invading individuals range more widely than resident rats and may display unusual behaviour, so these differences between species may be less relevant for surveillance programs. Exploring whether different surveillance programs work most effectively for particular rat species is a potentially important area for future research.

Surveillance programs

Most surveillance programs to date on islands post-eradication have used a variety of surveillance techniques to maximise rat detections, often placed together in rat motels (Table 1). Published

Fig. 2 The number of surveillance programs using each of the ten surveillance devices identified in the 21 surveillance programs for which information was available



surveillance programs used between one and six surveillance devices, with the average number of devices used being 2.24. Bait stations were the most common surveillance device with snap traps, tracking tunnels and chew sticks and cards also commonly used (Fig. 2). Given their efficacy in detecting rats at low densities, it is surprising that motion-sensored cameras have not been used more widely (Fig. 2). Quite possibly their up-front cost, the need to re-battery them regularly, and the labour in processing images, has precluded their widespread uptake, although their previously unquantified efficacy compared with existing devices may also be a factor. Despite their efficacy in detecting rats (Glen et al. 2018; Gsell et al. 2010), trained dogs also do not appear to have been widely used in surveillance programs, at least outside New Zealand (Kim et al. 2020). The skills required to train dogs, the cost of training and maintaining dogs (Bassett et al. 2016) and the preference for detection dogs to have the same human handler to maintain efficiency (Jamieson et al. 2018) are presumably a significant barrier to their widespread adoption as a surveillance tool, particularly in developing countries. While we acknowledge that the studies in Table 1 likely represent only a small proportion of surveillance programs, with many surveillance programs not publishing their results or publishing them in the grey literature (see Bassett et al. 2016), we believe they provide a useful overview of key methods and developments.

An innovative new approach to keep mainland New Zealand landscapes free of rats uses the remove and protect model, which entails complete removal of predators from an area and then protection against reinvasion. Preventing reinvasion of sites where predator-proof fences cannot be installed in a way that is cost-effective and feasible at large scales involves the use of surveillance devices at low densities of which the aim is not to detect individuals, as on rat-free islands, but prevent a population from being established. This model aims to be able to detect at least one of the first generation (estimated to be ~ 11 individuals) within a 100 day window, which is considered the length of time required for rats to give birth to a second generation (Bell et al. 2019b). This approach, based on recent trials, would involve surveillance devices at a density of only one per 20 ha and trials are being run on devices that are automated to provide near real-time updates on the triggering of traps using long range radio technology, as this can transmit reliably over large distances in rugged or forested terrain (Jones et al. 2015). Detection of rats surviving for a 7-week period post-baiting in a mainland area of New Zealand was achieved with a grid of motion-sensored cameras at a density of one per 35 ha and this proved sufficient to detect rats occurring at low densities post-baiting (Nichols et al. 2021).

There has also been the development of modelling and planning approaches that enable empirical decisions to be made about the allocation of resources to surveillance and the design of surveillance programs. Modelling allocation of resources between quarantine and surveillance using a Markov decision process found that preventing rats becoming established on Barrow Island, Australia was optimised by investing in surveillance at specific locations rather than quarantine (Moore et al. 2010). Similarly, modelling allocation of resources between quarantine, surveillance and response using a partially observable Markov decision process in the same system found that rat establishment was best prevented with a combination of surveillance and response (Rout et al. 2014), although the investment in surveillance increased as the impact of a localised incursion increased. Given that even a single rat can do significant damage to biodiversity (see e.g. Dowding and O'Connor 2013), these two models emphasise the importance of an effective surveillance program in preventing the establishment of rat populations. Further models have been developed that enable a surveillance program to be designed where the spatial location and density of surveillance devices can ensure the absence of rats is real to a pre-specified level of confidence. These models have been used to design rat surveillance program for Great Mercury Island, New Zealand (Kim et al. 2020) and Barrow Island, Australia (Jarrad et al. 2011), although they do not appear to have been widely incorporated into the design of surveillance programs elsewhere.

Limitations of generalisations

Although the detection of rats at low densities and its relevance to surveillance programs is a growing field and has been subject to considerable recent study, there are still some issues that limit the generalisation of these studies more broadly. The first is the preponderance of studies from New Zealand and the lack of studies from other regions. New Zealand has many unique features, such as the lack of native non-volant mammals and largely endemic bird fauna that cautions against extrapolating conclusions about rat detectability and surveillance from New Zealand to other parts of the globe, particularly as interference from other fauna is likely to differ from New Zealand. Similarly, there are a preponderance of studies on Black Rats and a noticeable paucity of studies on Pacific Rats. Given the difference in ecology between the three invasive rats species, conclusions about rat detectability and surveillance based on Black Rats may not apply to Pacific Rats or the more terrestrial Brown Rats.

Another issue that makes generalisations about detecting rats at low densities difficult, is the lack of published studies of long-term, or permanent, surveillance programs as part of a biosecurity plan. The reason for this are unclear but likely relate to either: (1) no surveillance program was implemented due to financial or logistical constraints; (2) islands that were targeted for eradication were isolated and so quarantine was the biosecurity methods employed, not surveillance; or (3) surveillance was implemented but the results were not published and made available, likely in many cases because no rats were detected. It is likely that all three reasons contribute to the lack of published studies on surveillance programs, but this highlights the importance of publishing the methodology and results from such programs. Currently, the lack of published studies is hampering our ability to identify optimal surveillance methods, the factors that influence the success of those methods and how we would adapt and modify methods in response to those factors.

Future directions

Our ability to detect rats at low densities has evolved and improved considerably over the past 15 years since the earlier reviews of Dilks and Towns (2002) and Russell et al. (2008a). This has occurred both through increasing detectability by existing technologies, such as tracking tunnels, and the adoption of new technologies, such as motion-sensored cameras. Likewise, the efficiency of surveillance programs with almost certainly improve in the future, both by improving the efficiency of existing surveillance devices and incorporating new ones. Improving the efficiency of surveillance programs could be achieved either through improving detectability in individual surveillance devices, or by improving cost-efficiencies so that more devices can be deployed or with lower maintenance within a surveillance program. Future research could focus on methods of improving detectability, such as increasing the attractiveness of devices, the use of baits and/or lures (such as pheromones), or improving device design to reduce avoidance by rats, which would increase the ability of devices to detect rats at low densities. The use of drones with multi-spectral and/or infra-red cameras flown along pre-programmed night flights are one area that may improve our future ability to detect rats (Campbell et al. 2015), as is the use of environmental DNA (Browett et al. 2020), which is now coming into widespread use. Although the efficacy of environmental DNA as a surveillance tool for detecting rats at low density has not been investigated, it has been shown to be more effective at detecting the presence of small mammals then motion-sensored cameras (Leempoel et al. 2020; Lyet et al. 2021), themselves an effective method of detecting rat at low density, which suggests it could potentially be a very effective surveillance method. Additionally, Spitfire traps have been recently prototyped in New Zealand to control invasive mammals (Blackie et al. 2016; Murphy et al. 2018). While they have not been trialled on rats, they also have the potential to increase detectability and decrease reinvasion probability. The development of rat-specific toxins is also an important area for future research as it would greatly improve our ability to eradicate rats and develop effective surveillance programs that minimise the risk of rat reinvasion on inhabited islands (Campbell et al. 2015).

Future improvements in the cost efficiency of devices are an equally important area for future research. The development of automated devices that are able provide real-time information on the presence of rats using, for example, long-range radio technology would reduce costs by precluding the need to undertake regular checks of devices (Bell et al. 2019b; Jones et al. 2015). This automated technology could be developed to send a remote signal when a device, such as a A24 or snap trap, is triggered or it could enable images from motion-sensored cameras to be downloaded and reviewed remotely. Artificial intelligence is also becoming an increasingly important tool in processing the large volume of pictures generated and will have an important role in rapid identification of rats on camera images (e.g. Tabak et al. 2020).

Another potential area for future research should aim to quantify rat detectability for a range of surveillance devices and the factors that influence that detectability. Detectability for any given device is likely to vary depending on the rat species, habitat, season and other animals present, among a range of factors (e.g. Adams et al. 2011; Burge et al. 2017; Yiu et al. 2022). Recent modelling innovations have enabled the density and spatial distribution of surveillance devices required to detect a rat to pre-specified confidence level to be determined (Jarrad et al. 2011; Kim et al. 2020) if the detectability with a given device is known. These innovations have not been widely used and adopted in designing surveillance programs, yet quantifying variations in detectability would enable these tools to optimise the range and spatial locations of devices used in surveillance programs in the future. Overall, improved cost efficiency will help in the uptake and maintenance of efficient surveillance programs, particularly in developing countries that often lack strong government logistical and financial support. This will be critical to future conservation efforts because developing countries are typically where the maintenance of rat-free areas or suppression of rat populations will give the greatest conservation benefits (Holmes et al. 2019; Jones et al. 2016).

Conclusions

Given that even a single rat can do significant damage to biodiversity (Dowding and O'Connor 2013), effective surveillance programs need to maximise their probability of detecting rats at low densities, preferably even a single rat. Although detecting rats at low density, let alone a single rat, is extremely challenging, advances over the past 15 years, since the last review of surveillance techniques (Russell et al. 2008b), have significantly improved our ability to detect rats. Motion-sensored cameras and rodent detection dogs are two techniques developed recently that have greatly improved our ability to detect rats at low density (e.g. Gsell et al. 2010; Rendall et al. 2014), with cameras consistently showing an ability to detect rats at lower densities than other techniques. Rodent detection dogs are also able to reliably detect even individual rats although there are challenges to their widespread adoption, particularly in developing countries, due to the cost and skills required for their training and maintenance (Bassett et al. 2016). However, it needs to be acknowledged that both these techniques only detect rats, rather than eliminate them, and so these detection methods need to be combined with control methods to maintain the suppression or eradication of rats. Furthermore, no one technique is optimal, and a combination of techniques is more likely to detect rats at low densities than any single technique. Our ability to detect rats at low densities using existing techniques has further improved due to a better understanding of optimal baits and techniques to place surveillance devices in challenging habitats, such as mangroves and intertidal thickets (Ringler et al. 2021; Siers et al. 2018). Lastly, the development of models that can identify not only the optimal allocation to quarantine, surveillance and response but also the optimal choice and spatial location of surveillance devices has further improved our ability to detect rats at low densities (Berec et al. 2015; Kim et al. 2020; Moore et al. 2010).

However, there is still much that needs to be done to better understand how to detect rats at low density. How we vary surveillance programs to detect different rat species, between different island types (e.g., tropical vs. temperate, inhabited vs uninhabited) or in the presence of different types of interfering fauna (e.g. crabs vs mice) remains to be better elucidated. Future surveillance programs are likely to incorporate both improvements to current methods and new methods and devices that will be developed in the future. Spitfire and A24 traps that kill rats multiple times before needing reloading, drones with multispectral and/or infra-red cameras, rat specific poisons and long-range radio technology that provide real-time information on rat detections are all ideas that are currently in development for deployment in surveillance programs (Campbell et al. 2015; Gronwald and Russell 2021; Jones et al. 2015).

There have been numerous improvements over the past 15 years in our ability with to detect rats at low densities and several emerging technologies that should lead to improvements in the future. Currently, a combination of motion-sensored cameras, rodent detection dogs and bait stations appear to provide the best opportunities to detect rats at low densities, particularly if employed with models that identify the optimal location and density of surveillance devices. However, drones with multi-spectral and/or infra-red cameras and eDNA both show considerable promise at detecting rats at low densities, even individual rats post-eradication, and it is likely these techniques will be more widely incorporated into surveillance programs in the future. Given the significant negative effects on invasive rats on a wide range of species, the future of many species depends on our ability to develop effective surveillance programs that can detect rats at low density. This will maximise our ability to ensure important areas for biodiversity continue to suppress rats at low densities or remain rat-free and protect the (often considerable) investment involved in rat suppression and eradication.

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Declarations

Conflict of interest There are no conflict of interest to declare.

References

Adams AAY, Stanford JW, Wiewel AS et al (2011) Modelling detectability of kiore (*Rattus exulans*) on Aguiguan, Mariana Islands, to inform possible eradication and monitoring efforts. N Z J Ecol 35:145–152

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? Biol Invasions 11:1743–1754

Anton V, Hartley S, Wittmer HU (2018) Evaluation of remote cameras for monitoring multiple invasive mammals in New Zealand. N Z J Ecol 42:74–79

Aplin KP, Suzuki H, Chinen AA et al (2011) Multiple geographic origins of commensalism and complex dispersal history of black rats. PLoS ONE 6:e26357

Bagasra A, Nathan HW, Mitchell MS et al (2016) Tracking invasive rat movements with a systemic biomarker. N Z J Ecol 40:267–272

Barrett S, Whittle P, Mengersen K et al (2010) Biosecurity threats: the design of surveillance systems, based on power and risk. Environ Ecol Stat 17:503–519

Bassett IE, Cook J, Buchanan F et al (2016) Treasure islands: biosecurity in the Hauraki Gulf marine park. N Z J Ecol 40:250–266

Bell EA, Daltry JC (2014) Dog Island restoration project: two-year assessment following the eradication of black rats (*Rattus rattus*) from Dog Island, Anguilla. Wildlife Management International Ltd and Fauna & Flora International, Cambridge, p 54

Bell EA, Challenger S (2018) Technical report on the final check following the eradication of black rats Rattus rattus from Redonda, Antigua and Barbuda, June-July 2018. Report from Wildlife Management International Ltd and Fauna & Flora International to the Redonda Restoration Programme, St John's, Antigua and Barbuda

Bell E, Floyd K, Boyle D et al (2019a) The Isles of Scilly seabird restoration project: the eradication of brown rats (*Rattus norvegicus*) from the inhabited islands of St Agnes and Gugh, Isles of Scilly. In: Veitch CR, Clout MN, Martin AR, Russell JC and West CJ (eds) Island invasives: scaling up to meet the challenge. IUCN Occasional Paper SSC No. 62, Gland, pp 88–94

Bell P, Nathan H, Mulgan N (2019b) 'Island' eradication within large landscapes: the remove and protect model. In: Veitch CR, Clout MN, Martin AR, Russell JC and West CJ (eds) Island invasives: scaling up to meet the challenge. IUCN Occasional Paper SSC No. 62, Gland, pp 604–610

Berec L, Kean JM, Epanchin-Niell R et al (2015) Designing efficient surveys: spatial arrangement of sample points for detection of invasive species. Biol Invasions 17:445–459

Blackie HM, Mackay JWB, Allen WJ et al (2014) Innovative developments for long-term mammalian pest control. Pest Manag Sci 70:345–351

Blackie H, Mackay J, Barrett B et al (2016) A novel device for controlling brushtail possums (*Trichosurus vulpecula*). N Z J Ecol 40:60–64

Bourgeois K, Ouni R, Pascal M, Dromzée S, Fourcy D, Abiadh A (2013) Dramatic increase in the Zembretta Yelkouan shearwater breeding population following ship rat eradication spurs interest in managing a 1500-year old invasion. Biol Invasions 15:475–482. https://doi.org/10.1007/s10530-013-0419-x

Bramley GN (2014) Habitat use by kiore (*Rattus exulans*) and Norway rats (*R. norvegicus*) on Kapiti Island, New Zealand. N Z J Ecol 38:64–75

Browett SS, O'Meara DB, McDevitt AD (2020) Genetic tools in the management of invasive mammals: recent trends and future perspectives. Mammal Rev 50:200–210

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

Campbell KJ, Beek J, Eason CT et al (2015) The next generation of rodent eradications: innovative technologies and tools to improve species specificity and increase their feasibility on islands. Biol Conserv 185:47–58

Capizzi D (2020) A review of mammal eradications on Mediterranean islands. Mammal Rev 50:124–135

Capizzi D, Bertolino S, Mortelliti A (2014) Rating the rat: Global patterns and research priorities in impacts and management of rodent pests. Mammal Rev 44:148–162

Carey PW (2019) Simultaneous rat, mouse and rabbit eradication on Bense and Little Bense Islands, Falkland Islands. In: Veitch CR, Clout MN, Martin AR, Russell JC and West CJ (eds) Island invasives: scaling up to meet the challenge. IUCN Occasional Paper SSC No. 62, Gland, pp 108-113

Carrion V, Donlan CJ, Campbell KJ et al (2011) Archipelago-wide island restoration in the galápagos islands: reducing costs of invasive mammal eradication programs and reinvasion risk. PLoS ONE 6:e18835

Carter RS, Lohr CA, Burbidge AH et al (2023) Eaten out of house and home: local extinction of Abrolhos painted button-quail *Turnix varius scintillans* due to invasive mice, herbivores and rainfall decline. Biol Invasions 25:1119–1132

Christie JE, Mackenzie DI, Greene TC et al (2015) Using passive detection devices to monitor occupancy of ship rats (*Rattus rattus*) in New Zealand temperate rainforest. N Z J Ecol 39:79–86

Clapperton BK (2006) A review of the current knowledge of rodent behaviour in relation to control devices. Sci Conserv 263:1–55

Clapperton BK, Murphy EC, Razzaq HAA (2017) Mammalian pheromones—new opportunities for improved predator control in New Zealand. Sci Conserv 330:1–53

Crampton LH, Reeves MK, Bogardus T et al (2022) Modifications to prevent non-target lethality of Goodnature A24 rat traps—effects on rodent kill rates. Manag Biol Invasions 13:513–533

Cuthbert RJ, Brooke MDL, Torr N (2012) Overcoming hermit-crab interference during rodent-baiting operations: a case study from Henderson Island, South Pacific. Wildl Res 39:70–77

Dilks P, Towns D (2002) Developing tools to detect and respond to rodent invasions of islands: workshop report and recommendations. Department of Conservation, Wellington, p 19

Dilks P, Sjoberg T, Murphy EC (2020) Effectiveness of aerial 1080 for control of mammal pests in the blue mountains, New Zealand. N Z J Ecol 44:1–7

Doherty TS, Glen AS, Nimmo DG et al (2016) Invasive predators and global biodiversity loss. Proc Natl Acad Sci USA 113:11261–11265

Donlan CJ, Wilcox C (2007) Complexities of costing eradications. Anim Conserv 10:154–156

Dowding JE, O'Connor SM (2013) Reducing the risk of extinction of a globally threatened shorebird: translocations of the shore plover (*Thinornis novaeseelandiae*), 1990–2012. Notornis 60:70–84

Duron Q, Shiels AB, Vidal E (2017) Control of invasive rats on islands and priorities for future action. Conserv Biol 31:761–771

Foster S, King C, Patty B et al (2011) Tree-climbing capabilities of Norway and ship rats. N Z J Zool 38:285–296

Frankova M, Eliasova BK, Rodl P et al (2015) Monitoring of *Rattus norvegicus* based on non-toxic bait containing encapsulated fluorescent dye: laboratory and semi-field validation study. J Stored Prod Res 64:103–108

Garvey PM, Glen AS, Clout MN et al (2017) Exploiting interspecific olfactory communication to monitor predators. Ecol Appl 27:389–402

Gillies C, Brady M (2018) Trialling monitoring methods for feral cats, ferrets and rodents in the Whangamarino wetland. N Z J Zool 45:192–212

Glen AS, Atkinson R, Campbell KJ et al (2013) Eradicating multiple invasive species on inhabited islands: the next big step in island restoration? Biol Invasions 15:2589–2603

Glen AS, Russell JC, Veltman CJ et al (2018) I smell a rat! Estimating effective sweep width for searches using wildlife-detector dogs. Wildl Res 45:500–504

Grant-Hoffman MN, Barboza PS (2010) Herbivory in invasive rats: criteria for food selection. Biol Invasions 12:805–825

Griffiths R, Miller A, Climo G (2011) Addressing the impact of land crabs on rodent eradications on Islands. Pac Conserv Biol 17:347–353

Griffiths R, Cranwell S, Derand D et al (2019) Multi island, multi invasive species eradication in French Polynesia demonstrates economies of scale. In: Veitch CR, Clout MN, Martin AR, Russell JC and West CJ (eds) Island invasives: scaling up to meet the challenge. IUCN Occasional Paper SSC No. 62, Gland, pp 611–617

Gronwald M, Russell JC (2021) Measuring rat relative abundance using camera traps and digital strike counters for Goodnature A24 self-resetting traps. N Z J Ecol 45:1–7

Gronwald M, Russell JC (2022) Behaviour of invasive ship rats, *Rattus rattus*, around Goodnature A24 self-resetting traps. Manag Biol Invasions 13:479–493

Gsell A, Innes J, De Monchy P et al (2010) The success of using trained dogs to locate sparse rodents in pest-free sanctuaries. Wildl Res 37:39–46

Gsell AC, Seabrook-Davison MNH, Brunton DH (2014) Are wild rodents attracted to lure laboratory rats? Pac Conserv Biol 20:108–115

Harper GA, Bunbury N (2015) Invasive rats on tropical islands: their population biology and impacts on native species. Glob Ecol Conserv 3:607–627

Harper GA, Cabrera LF (2010) Response of mice (*Mus musculus*) to the removal of black rats (*Rattus rattus*) in arid forest on Santa Cruz Island, Galápagos. Biol Invasions 12:1449–1452

Harper GA, Dickinson KJM, Seddon PJ (2005) Habitat use by three rat species (*Rattus* spp.) on Stewart Island/Rakiura, New Zealand. N Z J Ecol 29:251–260

Harper GA, van Dinther M, Russell JC et al (2015) The response of black rats (*Rattus rattus*) to evergreen and seasonally arid habitats: informing eradication planning on a tropical island. Biol Conserv 185:66–74

Harper GA, Carr P, Pitman H (2019) Eradicating black rats from the Chagos – working towards the whole archipelago. In: Veitch CR, Clout MN, Martin AR, Russell JC and West CJ (eds) Island invasives: scaling up to meet the challenge. IUCN Occasional Paper SSC No. 62, Gland, pp 26–30

Holmes ND, Campbell KJ, Keitt BS et al (2015) Reporting costs for invasive vertebrate eradications. Biol Invasions 17:2913–2925

Holmes ND, Spatz DR, Oppel S et al (2019) Globally important islands where eradicating invasive mammals will benefit highly threatened vertebrates. PLoS ONE 14:e0212128

Houston DM (2002) Eradicating rats from Maninita Island, Vava'u, Kingdom of Tonga. Unpublished report prepared for the Tonga Visitors Bureau, Ministry of Land, Survey and Natural Resources, Department of Environment, Kingdom of Tonga

Innes J, Watts C, Fitzgerald NL et al (2011) Behaviour of invader ship rats experimentally released behind a pest-proof fence, Maungatautari, New Zealand. In: Veitch CR, Clout MN, Towns DR (eds) Occasional papers of the IUCN species survival commission. IUCN, Gland and Auckland, pp 437–440

Jamieson LTJ, Baxter GS, Murray PJ (2018) You are not my handler! impact of changing handlers on dogs' behaviours and detection performance. Animals 8:176

Jarrad FC, Barrett S, Murray J et al (2011) Improved design method for biosecurity surveillance and early detection of non-indigenous rats. N Z J Ecol 35:132–144

Jones HP, Tershy BR, Zavaleta ES et al (2008) Severity of the effects of invasive rats on seabirds: a global review. Conserv Biol 22:16–26

Jones C, Warburton B, Carver J et al (2015) Potential applications of wireless sensor networks for wildlife trapping and monitoring programs. Wildl Soc Bull 39:341–348

Jones HP, Holmes ND, Butchart SHM et al (2016) Invasive mammal eradication on islands results in substantial conservation gains. Proc Natl Acad Sci USA 113:4033–4038

Keitt B, Griffiths R, Boudjelas S et al (2015) Best practice guidelines for rat eradication on tropical islands. Biol Conserv 185:17–26

Key GE, Woods RD (1996) Spool-and-line studies on the behavioural ecology off rats (*Rattus* spp.) in the Galapagos Islands. Can J Zool 74:733–737

Kim JHK, Corson P, Mulgan N et al (2020) Rapid eradication assessment (REA): a tool for pest absence confirmation. Wildl Res 47:128–136

King CM, McDonald RM, Martin RD et al (2007) Long-term automated monitoring of the distribution of small carnivores. Wildl Res 34:140–148

Kreuser AM, Shiels AB, Lepczyk CA et al (2022) Bird and rat carcass persistence in a Hawaiian rainforest managed for rodents using Goodnature A24 self-resetting traps. Manag Biol Invasions 13:494–512

Leempoel K, Hebert T, Hadly EA (2020) A comparison of eDNA to camera trapping for assessment of terrestrial mammal diversity. Proc R Soc B BiolSci. https://doi.org/10.1098/rspb.2019.2353

Lyet A, Pellissier L, Valentini A et al (2021) eDNA sampled from stream networks correlates with camera trap detection rates of terrestrial mammals. Sci Rep 11:11362

Mackenzie HR, Latham MC, Anderson DP et al (2022) Detection parameters for managing invasive rats in urban environments. Sci Rep 12:16520

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

Matisoo-Smith E, Robins J (2009) Mitochondrial DNA evidence for the spread of Pacific rats through Oceania. Biol Invasions 11:1521–1527

Meier GG, Varnham K (2004) Rat eradication as part of a green turtle (Chelonia mydas) conservation programme in Indonesia. Marine Turtle Newsletter 106:11–12

McCreless EE, Huff DD, Croll DA et al (2016) Past and estimated future impact of invasive alien mammals on insular threatened vertebrate populations. Nat Commun 7:12488

Millett JE, Accouche W, van de Crommenacker J et al (2019) Conservation gains and missed opportunities 15 years after rodent eradications in the Seychelles. In: Veitch C R, Clout M N, Martin A R, Russell J C and West C J (eds) Island invasives: scaling up to meet the challenge. IUCN Occasional Paper SSC No. 62, Gland, pp 580–587

Moore JL, Rout TM, Hauser CE et al (2010) Protecting islands from pest invasion: optimal allocation of biosecurity resources between quarantine and surveillance. Biol Conserv 143:1068–1078

Mulder CPH, Grant-Hoffman MN, Towns DR et al (2009) Direct and indirect effects of rats: Does rat eradication restore ecosystem functioning of New Zealand seabird islands? Biol Invasions 11:1671–1688

Murphy E, Sjoberg T, Dilks P et al (2018) A new toxin delivery device for stoats—results from a pilot field trial. N Z J Zool 45:184–191

Nichols M, Nathan H, Mulgan N (2021) Dual aerial 1080 baiting operation removes predators at a large spatial scale. N Z J Ecol 45:1–10

Nottingham CM, Glen AS, Stanley MC (2021) Relative efficacy of chew card and camera trap indices for use in hedgehog and rat monitoring. N Z J Zool 48:1–15

Oppel S, Beaven BM, Bolton M et al (2011) Eradication of invasive mammals on islands inhabited by humans and domestic animals. Conserv Biol 25:232–240

Orueta JF, Aranda Y, Gomez T et al (2005) Successful eradication of invasive rodents from a small island through pulsed baiting inside covered stations. Biol Invasions 7:141–147. https://doi.org/10.1007/s10530-004-9644-7

Owens B (2017) The big cull. Nature 541:148–150
Pascal M, Lorvelec O, Bretagnolle V et al (2008) Improving the breeding success of a colonial seabird: a cost-benefit comparison of the eradication and control of its rat predator. Endanger Species Res 4:267–276
Pearson J, St Pierre P, Lock L et al (2019) Working with the local community to eradicate rats on an inhabited island: securing the seabird heritage of the Isles of Scilly. In: Veitch CR, Clout MN, Martin AR, Russell JC and West CJ (eds) Island invasives: scaling up to meet the challenge. IUCN Occasional Paper SSC No. 62, Gland, pp 670–678
Pickerell GA, O'Donnell CFJ, Wilson DJ et al (2014) How can we detect introduced mammalian predators in non-forest habitats? A comparison of techniques. N Z J Ecol 38:86–102
Pott M, Wegmann AS, Griffiths R et al (2015) Improving the odds: assessing bait availability before rodent eradications to aid in selecting bait application rates. Biol Conserv 185:27–35
Puth LM, Post DM (2005) Studying invasion: Have we missed the boat? Ecol Lett 8:715–721
Radley PM, Davis RA, Doherty T (2021) Impacts of invasive rats and tourism on a threatened island bird: The Palau Micronesian Scrubfowl. Bird Conserv Int 31:206–218
Rauzon MJ (2007) Island restoration: exploring the past, anticipating the future. Mar Ornithol 35:97–107
Rendall AR, Sutherland DR, Cooke R et al (2014) Camera trapping: a contemporary approach to monitoring invasive rodents in high conservation priority ecosystems. PLoS ONE 9:e86592
Richardson MG, Croxall JP (2019) Achieving post-eradication biosecurity on South Georgia. In: Veitch CR, Clout MN, Martin AR, Russell JC and West CJ (eds) Island invasives: scaling up to meet the challenge. IUCN Occasional Paper SSC No. 62, Gland, pp 489–493
Ringler D, Guillerault N, Baumann M et al (2021) Rodenticide baiting black rats (*Rattus rattus*) in mangrove habitats. Wildl Res 48:554–560
Robinson S, Dick W (2020) Black rats eradicated from Big Green Island in Bass Strait, Tasmania. Pap Proc R Soc Tasman 154:3745
Roskowski AP (1965) The pharmacological properties of Norbormide, a selective rat toxicant. J Pharmacol Exp Ther 149:288–299
Rout TM, Moore JL, Possingham HP et al (2011) Allocating biosecurity resources between preventing, detecting, and eradicating island invasions. Ecol Econ 71:54–62
Rout TM, Moore JL, McCarthy MA (2014) Prevent, search or destroy? A partially observable model for invasive species management. J Appl Ecol 51:804–813
Rout TM, Hauser CE, McCarthy MA et al (2017) Adaptive management improves decisions about where to search for invasive species. Biol Conserv 212:249–255
Ruffino L, Krebs E, Passetti A et al (2015) Eradications as scientific experiments: progress in simultaneous eradications of two major invasive taxa from a Mediterranean island. Pest Manag Sci 71(2):189–198. https://doi.org/10.1002/ps.2015.71.issue-210.1002/ps.3786
Ruscoe WA, Ramsey DSL, Pech RP et al (2011) Unexpected consequences of control: competitive vs. predator release in a four-species assemblage of invasive mammals. Ecol Lett 14:1035–1042
Russell JC, Broome KG (2016) Fifty years of rodent eradications in New Zealand: another decade of advances. N Z J Ecol 40:197–204
Russell JC, Towns DR, Anderson SH et al (2005) Intercepting the first rat ashore. Nature 437:1107
Russell JC, Beaven BM, MacKay JWB et al (2008a) Testing island biosecurity systems for invasive rats. Wildl Res 35:215–221
Russell JC, Towns DR, Clout MN (2008b) Review of rat invasion biology. Science for conservation. New Zealand Department of Conservation, Wellington
Russell JC, Hasler N, Klette R et al (2009) Automatic track recognition of footprints for identifying cryptic species. Ecology 90:2007–2013
Russell JC, McMorland AJC, MacKay JWB (2010) Exploratory behaviour of colonizing rats in novel environments. Anim Behav 79:159–164
Russell JC, Ringler D, Trombini A et al (2011) The island syndrome and population dynamics of introduced rats. Oecologia 167:667–676
Russell JC, Clout MN, Towns DR (2007) Early detection and eradication of invading rats. In: Witmer GW, Pitt WC, Fagerstone KA (eds) Managing vertebrate invasive species: procedings of an international symposium. Fort Collins, National Wildlife Research Center, pp 268–272
Russell JC, Binnie HR, Oh J et al (2017a) Optimizing confirmation of invasive species eradication with rapid eradication assessment. J Appl Ecol 54:160–169
Russell JC, Meyer JY, Holmes ND et al (2017b) Invasive alien species on islands: impacts, distribution, interactions and management. Environ Conserv 44:359–370
Samaniego-Herrera A, Anderson DP, Parkes JP et al (2013) Rapid assessment of rat eradication after aerial baiting. J Appl Ecol 50:1415–1421
Shapira I, Shanas U, Raubenheimer D et al (2013) Laboratory rats as trap lures for invasive Norway rats: field trial and recommendations. N Z J Ecol 37:240–245
Shiels AB, Bogardus T, Rohrer J et al (2019) Effectiveness of snap and A24-automated traps and broadcast anticoagulant bait in suppressing commensal rodents in Hawaii. Hum Wildl Interact 13:226–237
Shiels AB, Bogardus T, Crampton LH et al (2022) An introduction to a special issue and review of the effectiveness of Goodnature A24 self-resetting rat traps. Manag Biol Invasions 13:466–478
Siers SR, Berentsen AR, McAuliffe TW et al (2018) Rodenticide application strategies for intertidal rat habitats. Wildl Res 45:82–91
Simberloff D (2009) Rats are not the only introduced rodents producing ecosystem impacts on islands. Biol Invasions 11:1735–1742
Smart WA, Collier N, Rolland V (2021) Non-native rats detected on uninhabited southern Grenadine islands with seabird colonies. Ecol Evol 11:4172–4181
Spatz DR, Zilliacus KM, Holmes ND et al (2017) Globally threatened vertebrates on islands with invasive species. Sci Adv 3:e1603080

Spatz DR, Holmes ND, Will DJ et al (2022) The global contribution of invasive vertebrate eradication as a key island restoration tool. Sci Rep 12:13391

Springer K (2016) Methodology and challenges of a complex multi-species eradication in the sub-Antarctic and immediate effects of invasive species removal. N Z J Ecol 40:273–278

Sweetapple P, Nugent G (2011) Chew-track-cards: a multiple-species small mammal detection device. N Z J Ecol 35:153–162

Tabak MA, Norouzzadeh MS, Wolfson DW et al (2020) Improving the accessibility and transferability of machine learning algorithms for identification of animals in camera trap images: MLWIC2. Ecol Evol 10:10374–10383

Thoresen JJ, Towns D, Leuzinger S et al (2017) Invasive rodents have multiple indirect effects on seabird island invertebrate food web structure. Ecol Appl 27:1190–1198

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

Veitch CR (2002a) Eradication of Norway rats (Rattus norvegicus) and house mouse (Mus musculus) from Browns Island (Motukorea), Hauraki Gulf, New Zealand. In: Veitch CR, Clout MN (eds) Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK, pp 350–352

Veitch CR (2002b) Eradication of Pacific rats (Rattus exulans) from Tiritiri Matangi Island, Hauraki Gulf, New Zealand. In: Veitch CR, Clout MN (eds) Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK, pp 360–364

Will DJ, Swinnerton K, Silander S, Keitt B et al (2019) Applying lessons learnt from tropical rodent eradications: a second attempt to remove invasive rats from Desecheo National Wildlife Refuge, Puerto Rico. In: Veitch CR, Clout MN, Martin AR, Russell JC and West CJ (eds) Island invasives: scaling up to meet the challenge. IUCN Occasional Paper SSC No. 62, Gland, pp. 154-161

Wilmshurst JM, Carpenter JK (2020) Rodent detection and monitoring for conservation on islands: gnawed seeds provide reliable indicator of rodent presence. N Z J Ecol 44:1–9

Witmer GW, Boyd F, Hillis-Starr Z (2007) The successful eradication of introduced roof rats (Rattus rattus) from Buck Island using diphacinone, followed by an irruption of house mice (Mus musculus). Wildlife Research 34:108–115

Yiu SW, Gronwald M, Russell JC (2022) Reliable detection of low-density Pacific rats by using camera trapping. Wildl Res 50:398–411

Zewe F, Meek P, Ford H et al (2014) A vertical bait station for black rats (*Rattus rattus*) that reduces bait take by a sympatric native rodent. Aust Mammal 36:67–73