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RESEARCH

Developing a new resetting tool for controlling rats

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Abstract: A resetting toxin device (the "Spitfire") has been designed that delivers a toxic paste to a rat's ventral surface when it passes through a tunnel. The rat grooms off the paste and ingests the toxin. The system was assessed in cage trials and one field trial. The purpose of the cage trials was to investigate whether a range of toxins can be delivered by the Spitfire to rats (*Rattus rattus* and *R. norvegicus*), namely 0.55% sodium fluoroacetate (1080), 0.2% brodifacoum, 15% cholecalciferol, and 12.5% zinc phosphide. The trials with 1080, brodifacoum, and zinc phosphide were successful with > 85% of rats ingesting lethal doses. The trials with cholecalciferol were less successful with only 58% of rats dying. A one-month pilot field trial was undertaken using 1080 in the Spitfires. There was a knockdown in rat (and stoat *Mustela erminea*) abundance, establishing proof of concept for the Spitfire delivery system with this toxin. The long-term, effective control of introduced rats will require a range of toxins with different modes of action. The Spitfire could be a useful additional control tool for rats and is currently being re-engineered to be made more reliable.

Keywords: 1080, brodifacoum, cholecalciferol, Norway rat, ship rat, Spitfire, toxin, zinc phosphide

Introduction

Introduced rats (*Rattus* spp.) have established on about 90% of islands worldwide (Towns et al. 2006). This has resulted in a devastating impact on native wildlife through both predation and competition (Innes et al. 2010; Dueñas et al. 2021). Introduced rats continue to have a major impact on wildlife and sustained control, or eradication where possible, is needed to avoid further extinctions of native species (Doherty et al. 2016).

Rats are currently controlled using various techniques, including toxic baits, mechanical traps and barriers (Duron et al. 2016; Murphy et al. 2019). For the long-term control of rats, a range of tools with different modes of action will be required (Campbell et al. 2015). Resetting toxin devices (Spitfires) have been explored for the control of rats, stoats (*Mustela erminea*), and brushtail possums (*Trichosurus vulpecula*) in New Zealand (Murphy et al. 2014, 2018; Blackie et al. 2016). The Spitfire works by firing a paste containing a toxin onto the ventral surface of a pest and the device then re-sets. When the pests groom the paste from their fur, they ingest the toxin. The Spitfires for the different pest species use the same basic mechanism but have different housings and can use different toxins depending on the pest to be controlled. Each Spitfire is capable of approximately 100 doses and is fitted with a counter and a delay mechanism. A desirable key performance indicator for the Spitfires would be continued delivery of toxic paste for at least a year without being serviced.

The current study aimed to investigate whether four toxins, sodium fluoroacetate (1080), brodifacoum, cholecalciferol, and zinc phosphide, would be lethal to rats when delivered by the Spitfire in captive trials. The effectiveness of 1080 in a rat Spitfire was also tested in a pilot field trial; 1080 was developed in the 1940s in the USA as a rodenticide but is now principally used for the control of pests in New Zealand and Australia (Eason et al. 2011; Ross & Eason 2021). Brodifacoum is a very potent second-generation anticoagulant active against rats and has been used successfully in rodent eradication programmes on offshore islands to protect populations of threatened species (Towns & Broome 2003). Cholecalciferol (vitamin D_3) was developed in the 1980s as a rodenticide and is registered in New Zealand for the control of rodents and brushtail possums (Eason et al. 2010a). There are no long-term residue risks in sub-lethally exposed animals and there is a relatively low risk of secondary poisoning of dogs. Zinc phosphide has been used internationally as a vertebrate pest control tool for several decades and has a comparatively low risk of secondary poisoning and lack of environmental persistence (Eason et al. 2013).

Having a Spitfire which could use a range of toxins with different modes of action would increase control options and

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enable the use of Spitfires by farmers, community groups, as well as by professional operators.

Methods

Captive trials

The captive rat trials were conducted at the Johnstone Memorial Laboratory, Lincoln University, New Zealand. Wild-caught Norway (*Rattus norvegicus*) and ship rats (*R. rattus*) were housed individually in steel cages (48 × 30.5 × 20 cm). The rats were fed Western Animal Nutrition rodent pellets, seed mix and water *ad lib.* The rats were trialled individually in a 2.4 × 0.6 × 0.8 m test cage.

The Spitfires were designed to fit inside a DOC 200 single-set tunnel trap box (DOC n.d.) to limit access by non-target species. The boxes had the usual baffles, but contained no trap. Peanut butter was placed inside the DOC 200 box and the only way the rat had access to it was to go through the Spitfire tunnel. When the Spitfire was triggered, 800 mg of toxic paste was ejected onto the ventral surface of the rat; grooming behaviour and whether the paste was ingested or not were recorded.

Two Spitfire designs were trialled. The first model (S1) had a weight treadle to trigger the device and compressed CO_2 to propel the toxin once triggered; however, leakage of the CO_2 was a problem. The second model (S2) had a capacitance trigger and used liquid petroleum gas (LPG) as the propellant. Four toxins were trialled on rats: 0.55% 1080 in the S1 and S2 models, 0.2% brodifacoum, 15% cholecalciferol, and 12.5% zinc phosphide all in the S2 model. The concentrations of the toxins are higher than those used in registered baits to ensure that a lethal dose could be delivered in 800 mg of paste. We were also allowing for large Norway rats to be targeted as Norway rats weighing 480–500 g have been trapped on islands. Lethal doses for toxins are generally reported as an LD_{50} (the dose required to kill 50% of the test animals). We wanted a dose that would kill all, or almost all, of the ship and Norway rats trialled ($LD_{90–99}$) but there are very few such data available for most toxins. Values also can vary between studies. For brodifacoum, Littin et al. (2000) cite 0.5 mg kg^{-1} as an LD_{90} for Norway rats. Moussa (2005) reports an LD_{90} of 1.64 mg kg^{-1} for male rats and 2.7 mg kg^{-1} for female rats when fed on maize and wheat. Rats fed only on vegetables had a lower LD_{90} of 0.95 mg kg^{-1} for male rats and 1.25 mg kg^{-1} for females. If we assume an LD_{99} of 3 mg kg^{-1}, then a 500 g rat needs to eat 1.5 mg toxin. 0.02% brodifacoum paste was chosen as the 800 mg fired by the Spitfire would contain 1.6 mg brodifacoum.

Pilot field trial

The field trial was undertaken from October to December 2015 in predominantly mixed beech forest within the Rahu Scenic Reserve and Victoria Forest Park, Westland (between Reefton and Springs Junction). There were two study sites 2.5 km apart: a 36 ha non-treatment and 24 ha treatment site. A third Spitfire model (S3) was used in the field trial as the S2 model was found to be unsuitable for use in the field (Murphy et al. 2018). The S3 model used load cells to measure weight for the trigger and LPG as the propellant. Each Spitfire contained 100 g of 0.55% 1080 paste and was contained within a DOC 200 box that required a square-drive screwdriver to access. As the rat triggered the treadle within the tunnel an 800 mg dose of 0.55% 1080 toxin paste was sprayed onto the ventral surface of the rat. The toxin was then orally delivered when the rat groomed itself. The Spitfire only triggered for animals that weighed > 70 g, and the DOC 200 box with baffles was designed to exclude non-targets.

Forty-nine empty DOC 200 trap boxes were placed on a 7 × 7 100 m grid (36 ha) in the non-treatment site and 35 boxes on a 7 × 5 100 m grid (24 ha) in the treatment area. Twenty-five Ltl Acorn trail cameras (Model Ltl-5210A, 940 nm infrared, Ltl Acorn Outdoors) were installed at every second box in the non-treatment site, and 18 cameras were installed on the treatment site. These monitored rat activity and recorded target and non-target interactions with the boxes. The cameras recorded 20–30 s video clips when triggered.

The DOC 200 boxes were baited with c. 30 g peanut butter in both the treatment and non-treatment areas on 28–29 October 2015. The Spitfires were placed inside the boxes on the treatment site on 19 November 2015. At that time, all boxes at both sites were rebaited using fresh peanut butter, and batteries and memory cards were changed on all the cameras. The Spitfires and trail cameras were serviced and re-baited on 1–2 December 2015, and were removed on 15–16 December 2015, approximately one month after deployment.

Tracking tunnel lines were also used in both the treatment and non-treatment areas to monitor the effectiveness of the Spitfires at reducing rat abundance. There were three lines within the treatment area and four in the non-treatment area. Each line had 5 tunnels 50 m apart, and lines were 200 m apart. The tracking tunnels were baited with peanut butter and ran for one night on 18 November 2015 (pre-monitoring) and on 16 December 2015 (post-monitoring).

For each camera station, we recorded whether a visit took place by a particular species during each 24 hr period (i.e. a presence/absence response). A 'visit' is defined as the presence of an animal (one or more video clips recorded within a 24-hr day); animals did not have to enter the tunnel during a visit. To compare the detection of rats and stoats at camera stations, we recorded whether a species was sighted at a camera station within each 24 hr period over a 12 day survey before Spitfire deployment (first survey: 28 October–8 November), and for two 12 day surveys during deployment (second survey: 19–30 November and third survey: 1–12 December).

To analyse the camera data, we used a generalised linear mixed model (GLMM) with a binomial error distribution and logit link to estimate the detection probability for each of the three 12 day survey periods. This estimate was then back-transformed (± 95% CI), indicating the probability that a rat or stoat was detected per camera per day for each survey period. For this modelling, the survey period was specified as a fixed effect, and the day and camera station were specified as random effects (Bengsen et al. 2014). Model validity was checked by visually examining residual plots and assessing dispersion parameters (Bolker et al. 2009). To test for significance between survey periods appropriate linear contrasts were set up and tested, controlling for multiple comparisons (Cichini et al. 2011). All the computations were done with the R version 4.2.0 software (R Development Core Team 2015). For GLMMs, the lme4 package (Bates & Maechler 2015) was used, and for multiple comparisons, the multcomp package (Hothorn et al. 2015) was used.

The percentage reduction in activity for the tracking tunnels (pre- vs post-treatment) was also estimated for rats. Following the calculation of the treatment site percentage reduction, changes in the non-treatment site were used to adjust the

percentage reduction estimate, enabling the estimation of the mean percentage change directly attributable to the treatment (i.e. the addition of the Spitfire device). For example, if rat numbers decreased in the non-treatment site (pre- vs post), then some of the estimated percentage reduction in the treatment site resulted from natural variations in animal numbers. This adjustment was conducted using equations detailed in Hix et al. (2012), and both values (adjusted and non-adjusted) are reported below.

Results

Captive trials

All rats that entered a Spitfire and were sprayed with toxic pastes groomed themselves. After grooming, no paste was observed on the fur, although the fur was dyed green where it had been sprayed. All Norway rats and 14 of 15 ship rats ingested a lethal dose of 1080 (Table 1). The one ship rat that survived may not have received a full dose of the toxin due to the S1 model malfunctioning. Trials on the last 6 ship rats with 1080 were undertaken using the S2 model and all died. Trials with 0.2% brodifacoum paste in the Spitfire were successful, with all rats of both species ingesting a lethal dose. The 12.5% zinc phosphide was moderately successful on Norway rats and achieved 100% mortality with ship rats. Of 12 ship rats trialled with 15% cholecalciferol, only 7 died. It was not possible to formulate a more concentrated paste that could be fired by the device, so no further trials with cholecalciferol were undertaken with either ship or Norway rats. Time to death ranged from 4.5 hours to almost 2 days for 1080 but most rats died overnight. Time to death was 5–13 days for brodifacoum and 6–14 days for cholecalciferol. Ship rats died more quickly with zinc phosphide than did Norway rats; time to death was between 3–7 hours for ship rats, and between 6–32 hours for Norway rats, but most died overnight.

Pilot field trial

A total of 23 of 25 cameras on the non-treatment site and 12 of 18 cameras on the treatment site were working over the entire study period. No species other than rats (most, if not all, ship rats) and stoats were recorded entering the boxes. Weka (*Gallirallus australis*) and South Island robins (*Petroica australis*) were commonly recorded on the cameras. Song thrushes (*Turdus philomelos*), blackbirds (*T. merula*), and chaffinches (*Fringilla coelebs*) were recorded less commonly, hopping on the boxes, feeding nearby, or flying past. One mouse was recorded and it did not enter the box. There was no indication that any species other than rats and stoats triggered the Spitfires.

On the first service, each Spitfire was found to have fired between 0–6 times, with a total of 44 fires. Of the 35 Spitfires, 16 had run out of propellant when checked and this was replaced. On the second service, there were 0–10 fires for each Spitfire and a total of 57 fires, but 25 of the Spitfires were no longer working, mostly due to gas leakage. Overall, there was a total of 101 fires for the trial.

For rats at the non-treatment site, there was a non-significant change in the detection probability in the second ($Z = 0.098$, $P = 0.995$) and third surveys ($Z = 1.366$, $P = 0.359$) when compared with the first survey estimate (Figure 1a). At the treatment site, there was a non-significant change in the second survey compared to the pre-control detection probability from the first survey ($Z = 1.945$, $P = 0.126$), but there was a significant reduction in the third survey ($Z = 4.275$, $P < 0.001$) (Figure 1b).

The tracking tunnels estimated an 80.0% (± 18.3 SE) reduction in rat activity at the treatment site (33% tunnels tracked by rats before the Spitfires to 7% tracked after), with a corrected reduction estimate of 86.2% when considering changes at the non-treatment site (55% tracked before to 80% after).

For stoats at the non-treatment site, there was a marginal non-significant decrease in the detection probability in the second survey ($Z = 2.309$, $P = 0.055$), becoming significant in the third survey ($Z = 4.088$, $P < 0.001$) when compared with the first survey (Figure 1c). At the treatment site, the pre-control detection probability from the first survey significantly reduced in the second survey ($Z = 6.506$, $P < 0.001$) and further after the third survey ($Z = 4.975$, $P < 0.001$) (Figure 1d).

Discussion

The captive rat trials confirmed that rats will groom lethal levels of a range of toxins from their fur and the field trial indicated that the Spitfires did reduce rat and stoat abundance. The grooming response has been utilised previously to deliver a lethal dose to mammal pests (Gibson 1982; Morris et al. 1983; Murphy 2018; Moseby et al. 2020). The technique has obvious advantages in situations where animals may not readily consume bait because of an abundance of alternative food or bait shyness. When food is abundant, social lures could also be used to attract rats and stoats into the Spitfires (Clapperton et al. 2017). The Spitfire has been designed to

Table 1. Captive ship and Norway rats tested in the Spitfire with 0.55% 1080, 0.2% brodifacoum, 15% cholecalciferol, and 12.5% zinc phosphide.

Toxin	Species	Number	Weights (g)	Died (%)
1080 (0.55%)	Ship	15	105–184	93.3
	Norway	15	141–401	100
Brodifacoum (0.2%)	Ship	15	76–181	100
	Norway	8	110–325	100
Cholecalciferol (15%)	Ship	12	121–209	58.3
Zinc phosphide (12.5%)	Ship	17	96–197	100
	Norway	20	111–415	85

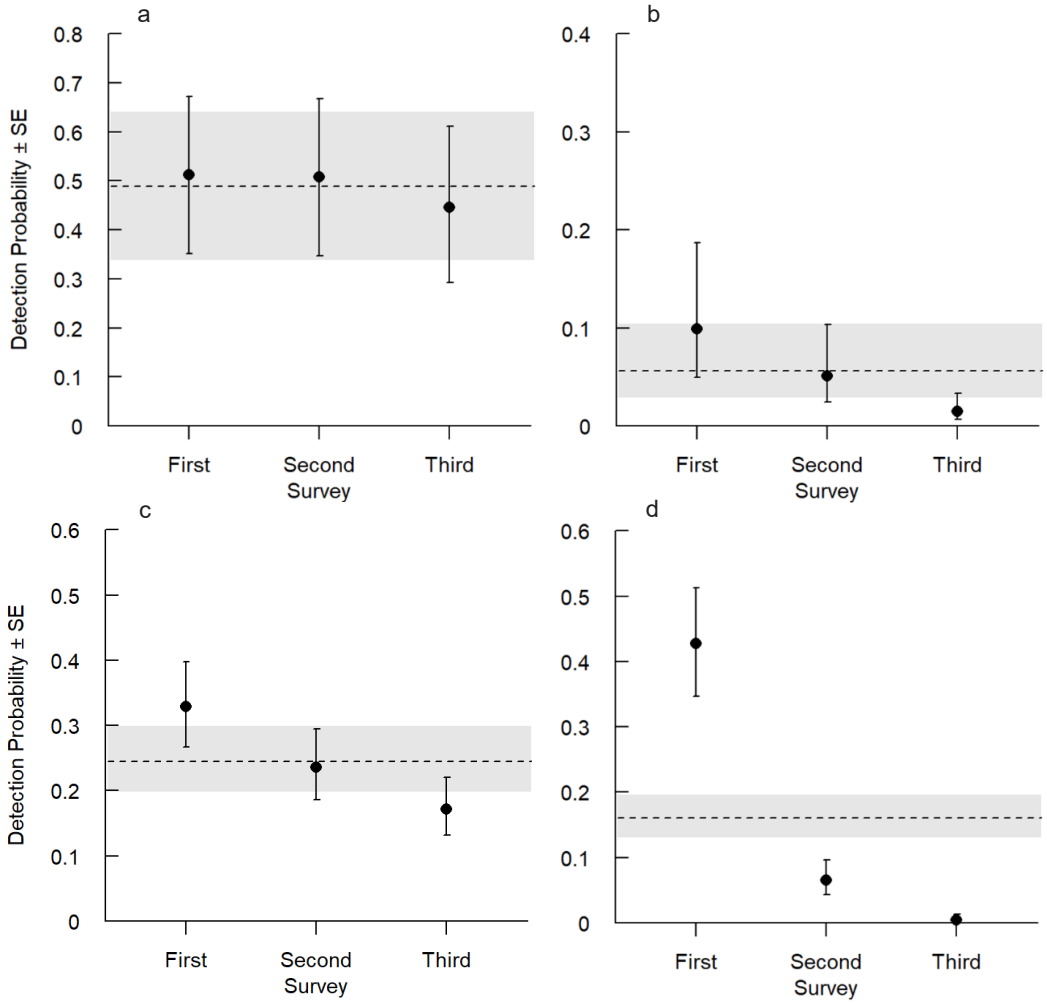

Figure 1. Detection probability estimates per 24 hr period calculated from 12 day camera trap surveys for rats and stoats (a) detection probability for rats in the non-treatment area, (b) detection probability for rats in the treatment area, (c) detection probability for stoats in the non-treatment area, and (d) detection probability for stoats in the treatment area. The dashed line represents the expected value across the three surveys, and the shaded area represents the 95% confidence interval. Survey 1 was 28 October–8 November 2015, Survey 2 was 19–30 November 2015 and Survey 3 was 1–12 December 2015. Spitfires were deployed in the treatment area for Surveys 2 and 3.

deliver a measured amount of toxin to a pest, thus providing a high probability that a lethal dose is ingested. The consistency of the paste and the force at which the propellant sprays it also ensures it does not leak out of the delivery system and is less likely to contaminate the environment when compared with conventional baits. Secondary poisoning could be a risk however, depending on the toxin used.

In New Zealand, a controlled substance licence (CSL) is required to handle 1080. While a Spitfire containing 1080 would be a useful tool for professional pest-control operators, the ability to use toxins that do not require a CSL (such as cholecalciferol and brodifacoum) would be of particular benefit to community groups, farmers, and other users. The disadvantage of brodifacoum is that it is very persistent (Eason et al. 2010b); however, the toxin would be more contained when delivered in the Spitfire system and not so readily available to non-target species. Zinc phosphide could be useful for control of ship rats and an advantage would be that it would not cause secondary poisoning. Cholecalciferol was not effective in our captive trials, but it may be useful to trial a mixture of diphacinone and cholecalciferol in the future, as it is more potent and has lower environmental persistence than brodifacoum (Eason et al. 2020). Norbormide, a rat-specific toxin (Campbell et al. 2015), would also be a good option.

Stoats also appeared to be controlled by the 1080 Spitfire, this could have been both from primary and secondary poisoning. Stoats were seen entering the Spitfires and the dose would have been sufficient to be lethal. Potter et al. (2006) found that 1 g baits containing 0.1% 1080 were lethal to stoats, so 800 mg of 0.55% 1080 should have been sufficient to be lethal, even if they only ingested half the dose. Stoats could also have died from secondary poisoning. Stoats are known to be killed after 1080 control operations from eating poisoned rodents (Murphy et al. 1999; Dilks et al. 2020). Stoat detection also declined in the non-treatment area. The treatment and non-treatment sites were only 2.5 km apart and stoats in the non-treatment site could have been affected by the Spitfires; stoat home range lengths varied from 0.9–6.6 km in a Fiordland study (Murphy & Dowding 1994).

The cage trials and the field trial reported in this paper have demonstrated proof of concept for the rat Spitfire. This device has the potential for use in urban, agricultural, and

conservation settings if appropriate toxins are chosen for these different scenarios. The Spitfires are being re-engineeered to be made more reliable and trials will be undertaken in 2023 with the rat Spitfire (https://www.envicotech.co.nz/spitfire-devices). The device will have an automatic lure dispenser and use mechanical pressure to fire the same amount of toxin so the results from this trial are still relevant. The advantage of the Spitfire for conservation of endangered species will be realised if it can be made to function reliably for a year or more without being serviced.

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Data and code availability

The data from this article are available from the authors.

Author contributions

CE & DM for the device concept. DM organised the construction of the Spitfires and preparation of the toxic pastes. EM designed the study & led the captive trials. TA & TS led the field trial. JR & EM analysed the results. EM wrote the manuscript.

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