Efficacy of bird repellents at deterring North Island robins (*Petroica australis longipes*) and tomtits (*P. macrocephala toitoi*) from baits

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Abstract: North Island robins (*Petroica australis longipes*) and tomtits (*P. macrocephala toitoi*) are at risk of being poisoned during pest control operations in New Zealand. Robins are deterred from feeding on diets containing primary repellents (e.g. blue colour, d-pulegone) and secondary repellents (e.g. illness-inducing materials such as anthraquinone, which induce taste aversions). We tested, with wild robins, primary and secondary repellents surface-coated onto dough baits, over 4 days on Tiritiri Matangi Island. In comparison with green-coloured cinnamon-scented control baits, robins averaged at least 71% fewer pecks at blue-coloured, anthraquinone (0.09% wt/wt) baits with or without cinnamon oil (commonly used as a bird repellent) and 0.045% wt/wt anthraquinone baits with cinnamon oil or d-pulegone. There were no significant differences in pecking rates among the repellent formulations. Pecking rates at baits containing 0.09% anthraquinone were almost nil by Day 4.

The efficacy of 0.09% anthraquinone at protecting tomtits from poisoning was tested in a commercial aerial possum control operation at Whareorino Forest using carrot baits. Prefeed (2 kg ha^{-1}) and toxic baits (3 kg ha^{-1}; 1080 at 0.12% wt/wt) were coated with anthraquinone (at 0.57 and 0.45 mg per kilogram of carrot, respectively), blue dye and an orange-flavoured lure and laid over an area of 1400 ha. Tomtit abundance, measured using sightings of territorial males along transects before and after the control operation, increased significantly more in the bird-repellent-treated block than in an adjacent block receiving the standard prefeed and green dye plus orange-lured toxic carrot baits. Possum catch rates declined further in the 'Repellent' block than in the 'No Repellent' block, but the field trial requires replication in a more effective possum poisoning operation. These trials have demonstrated the efficacy of repeatedly presented bird repellent formulations combining an illness-inducing agent, an unattractive colour and a distinctive flavour for protecting ground-feeding New Zealand forest birds from poisoning during mammalian pest control.

Keywords: anthraquinone; colour; d-pulegone; feeding behaviour; non-target impact; pest control; survival

Introduction

Forest birds are vulnerable to poisoning from eating toxic baits containing 1080 (sodium monofluoroacetate) used in control operations against pest mammals, primarily brushtail possums (*Trichosurus vulpecula*) and ship rats (*Rattus rattus*) (Veltman & Westbrooke 2011). The North Island robin (*Petroica australis longipes*) and the North Island tomtit (*P. macrocephala toitoi*) ('robin' and 'tomtit' hereafter) are small, territorial, and predominately insectivorous forest-dwelling New Zealand passerines (Heather & Robertson 1996). Because they often feed on the ground (Powlesland 1981), both species are particularly at risk of poisoning (Spurr & Powlesland 1997; Knegtmans & Powlesland 1999; Powlesland et al. 1999, 2000), especially if there are small fragments of toxic bait chaff (Spurr 2000).

Minimising sowing rates, removing small bait fragments, using green dye, and adding cinnamon oil are methods currently used to reduce the acceptability of bait to birds (Spurr 2000). There is still, however, a measurable impact on tomtit populations from control operations that use carrot baits (Westbrooke & Powlesland 2005), and robins will readily peck at cinnamon-flavoured, green carrot or cereal baits (Spurr & Powlesland 1997; Day 2003). Other potential methods for reducing bait acceptability include the use of blue as the bait colour (Hartley et al. 1999; Day & Matthews 1999) or the chemical cinnamamide (Spurr & Porter 1998). However, colour has only a temporary or mild deterrent effect when used alone (Bryant et al. 1984; Hartley et al. 2000; Day 2003; Clapperton et al. 2012). In contrast, Spurr and Porter (1998) found that cinnamamide deterred weka (*Gallirallus australis*) and kea (*Nestor notabilis*), but noted that it would add substantially to the cost of control operations.

Olfactory (e.g. d-pulegone), flavour and visual cues (such as colour) that immediately deter animals are referred to as primary repellents. By contrast, anthraquinone acts as an illness-inducing agent through conditioned taste aversion (Avery 2003) and it has been shown to be effective against a range of bird species (Avery et al. 1997; Dolbeer et al. 1998; Werner et al. 2009, 2011; Day et al. 2012). Such agents are called secondary repellents; the animal learns to associate the gastrointestinal discomfort with the sensory cue.

Combinations of primary and secondary repellents and/or cues that make these repellents more detectable and memorable are likely to work more effectively than single repellents (Mason & Reidinger 1983; Greig-Smith & Rowney 1987; Avery 1997; Avery & Mason 1997). While a more distinctive colour (e.g. red or yellow) might in principle be likely to provide the most discriminable cue for the development of taste aversion to anthraquinone (Avery 1997), the use of other, inherently repellent colours has the advantage of providing additional protection while a taste aversion is being established (Clapperton et al. 2012). Free-ranging sparrows (*Passer domesticus*) are deterred more by the combination of blue colour and anthraquinone than by blue colour alone or anthraquinone alone (Clapperton et al. 2012). Robins have been shown to peck less at coloured baits containing anthraquinone and a combination of anthraquinone and d-pulegone than coloured baits containing cinnamon oil (Day 2003; Day et al. 2003). The anthraquinone/d-pulegone combination has also been shown to deter kea from green-coloured cereal-based 1080 baits (Orr-Walker et al. 2012).

Materials such as cinnamon oil, orange or other flavourings (so-called lures) are added to pest baits to mask the smell and taste of toxins (e.g. 1080) to the targeted pests (e.g. possums; Morgan 1990) as well as for their potential bird repellency. Thus, repellents need to be effective in the presence of a mixture of materials added to baits. The aim of the first part of this study was to compare the efficacy of various combinations of primary and secondary repellents (anthraquinone, d-pulegone and cinnamon oil) in deterring feeding by robins. Some effective repellents (e.g. d-pulegone) may be prohibitively expensive to use in commercial pest control operations (Nelms & Avery 1997), so a secondary aim was to determine if another more-cost-effective primary repellent (blue coloration) would prove to be effective. Direct observation of individuals interacting with baits is an effective method for assessing feeding deterrence in robins (Day et al. 2003), but not tomtits. An alternative procedure is required, therefore, to determine repellency effectiveness with tomtits. Assessing the impacts on tomtit populations following commercial pest control operations could provide an effective alternative. Bird repellents would not be useful if they deterred the targeted pest species from eating baits. We have shown in previous captive and field studies that carrot baits treated with anthraquinone alone, or in combination with d-pulegone are palatable to possums and rats (Matthews et al. 1999, 2005; T. Day & B.K. Clapperton unpubl. data). The use of bird repellents in an actual pest control operation also allowed us to assess the acceptance of the baits to possums, by monitoring changes in possum numbers. Accordingly, additional aims were to determine the effects of the use of bird repellents on tomtits and possums during a commercial pest control field operation.

Methods

Study sites and species

Wild adult and juvenile robins ($n = 67$) living on Tiritiri Matangi Island (36°36’ S, 174°53’ E, Hauraki Gulf, New Zealand) were used as subjects for the first trial. This 220-ha island is a wildlife sanctuary, 25 km north of Auckland. The robins lived in gently sloping valleys of remnant and regenerating native forest up to c. 60 m a.s.l. Many of the robins had been conditioned to approach humans to receive natural foods (mealworms), and it is unknown whether this training would increase or decrease the birds’ propensity to eat repellent-treated baits. They had all been colour-banded for individual identification as part of other studies (Armstrong et al. 2000; Armstrong & Ewen 2002). The juveniles were independent of the adults at the time of the current study in March 2004. Only eight of the adult robins had been used in previous bird repellent trials on the island (Day 2003; Day et al. 2003) and they were randomly assigned to treatments. No birds had been exposed to repellents since 2002. Statistical analysis of the data showed that prior exposure to repellent-treated baits was not a significant factor in robin responses in this experiment (Student $t = 2.06$, d.f. = 24, $P = 0.171$, experienced vs naïve adult birds).

A population of wild adult male tomtits was the subject of the second trial, which was carried out as part of a pest control operation at Whareorino Forest (38°25′ S 174°44′ E), western King Country, North Island, New Zealand, in spring of 2004. Whareorino Forest is a 20 000-ha tract of lowland coastal podocarp–hardwood forest (Fig. 1) situated south-west of Te Kuiti. Only male tomtits were chosen because the method takes advantage of the territorial habits of male tomtits (i.e. territorial calling, territory defence behaviours, increasing conspicuousness and consistency in behaviour) (Westbrooke et al. 2003). The study area comprised c. 2400 ha on the western edge of this forest. The topography is dominated by narrow ridges with rocky outcrops and limestone bluffs, with

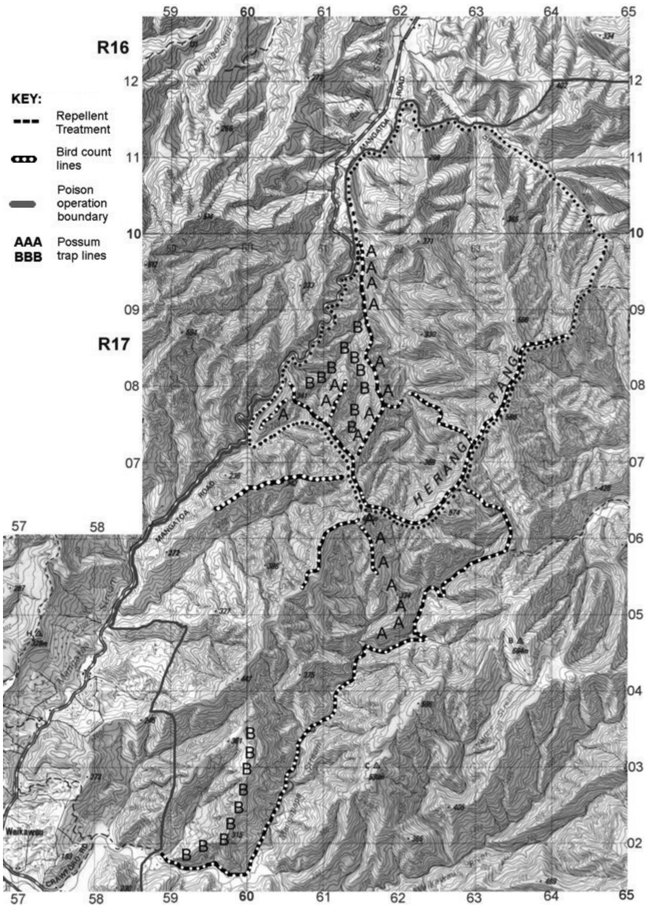

Figure 1. Whareorino Forest study site map (NZMS 260 R16/ R17), showing tomtit monitoring lines, possum trap lines, and boundaries of the Repellent block and the poison operation. Grid squares are 1 × 1 km.

Table 1. Bait type and bird repellent treatments nominally applied to the baits in (a) the Tiritiri Matangi bait trial and (b) the Whareorino field trial. Toxic baits contained 1080 at a nominal loading of 0.12% wt/wt.

	Bait type	Treatment components
(a) Tiritiri Matangi bait trial		
AQ0.09	Dough	Blue dye (0.01%) + anthraquinone (0.09%)
AQ0.09C	Dough	Blue dye (0.01%) + anthraquinone (0.09%) + cinnamon (0.03%)
AQ0.045C	Dough	Blue dye (0.01%) + anthraquinone (0.045%) + cinnamon (0.03%)
AQ0.045DP	Dough	Blue dye (0.01%) + anthraquinone (0.045%) + d-pulegone (0.05%)
GC	Dough	Green dye (0.01%) + cinnamon (0.03%)
(b) Whareorino field trial		
Prefeed ‘Repellent’	Carrot	Blue dye (100 g $tonne^{-1}$) + anthraquinone (0.9 L $tonne^{-1}$)
Prefeed ‘No repellent’	Carrot	Orange lure (1 L $tonne^{-1}$) undyed
Toxic ‘Repellent’	Carrot	Blue dye (100 g $tonne^{-1}$) + anthraquinone (0.9 L $tonne^{-1}$)
Toxic ‘No repellent’	Carrot	Green dye (100 g $tonne^{-1}$) + orange lure (1 L $tonne^{-1}$)

steep, deeply incised stream gullies. None of the birds was individually identifiable, or had any previous experience with bird-repellent-treated baits. There had been no pest control operations conducted in Whareorino Forest for 4 years prior to this trial.

Tiritiri Matangi Island bait trial

Test materials

The test baits were 5-mm pieces of non-toxic, baked flour dough, coloured, and surface-coated with bird repellent as described by Day et al. (2003). The bird repellent formulations were solutions of water with blue dye (royal blue permanent colour powder H6406, International Flavours and Fragrances, Auckland, NZ) and anthraquinone (in the form of Avex™ active ingredient 43% 9,10-anthraquinone, Loveland Industries Inc., USA) at two different concentrations (0.09%, 0.045%) with or without either cinnamon oil (Bush Boake Allen, Auckland, NZ) or d-pulegone (Aldrich Chemicals Co. Inc., USA). The control bait solution contained green dye (Special Green V200A dye, Bayer NZ, Auckland, NZ), and cinnamon oil as a positive control for the accepted industry standard bait formulation used to deter birds (Day & Matthews 1999). The baits were soaked in one of these solutions until all the liquid (10% wt/wt of the bait) was absorbed. The formulations and final concentrations of all four bird repellent treatments and the control baits are given in Table 1. The baits were air-dried before storage in airtight containers until they were used.

Robin behavioural observations and analyses

We used test procedures similar to those of Day et al. (2003). We cleared leaf litter from a test arena (c. 0.5 × 0.5 m) in each robin territory, and placed a teaspoonful (8–12 baits) of one type of bait into the centre of the arena. The robins were attracted to the site by the presence of the observer and, if necessary, by the observer tapping lightly on a plastic container or throwing twigs into the arena. We used colour video cameras with spoken commentary and direct observations to record the investigatory and feeding behaviour of each robin. The test period began when the robin had approached within 5 m of the test arena and continued for 30 min. We noted the number of times the robin pecked and made contact with the bait. If a robin removed a bait from the arena we noted the subsequent fate of the bait (eaten or dropped) where possible. The procedure was repeated in each robin’s territory on each of 4 days. Most trials were run on consecutive days, but, in 11 cases, there were 2 days between trials. Not all the birds responded on all of the 4 days, Seventeen birds responded on all four days, 21 on 3 days, 13 on 2 days, and 16 on only 1 day. The treatments were randomly assigned to the individual robins, irrespective of sex and age, as this information was not available for all of the birds. We used data from all observable birds because Day et al. (2003) found no differences in pecking rates to green-dyed dough baits containing anthraquinone and d-pulegone of male vs female robins or naïve birds vs birds that had previously encountered bird-repellent-treated baits. Four observers were used, with the same observer monitoring the same birds over the 4 days. To ensure we minimised observer biases, each observer tested similar numbers of the different bait types, and two observers reviewed the video recordings, including a subset of 10 videos that they both reviewed, after receiving training on how to standardise the protocol.

The data on numbers of pecks made per bait were analysed, with bird fitted as a random factor and treatment and time and their interaction as fixed factors, using a generalised linear mixed model with a Poisson distribution and a log link, in the GenStat 5.4 statistical package, allowing for extra-Poisson variation and meeting the required assumptions of dispersion.

Whareorino Forest field trial

Application of bird repellent and 1080

The pest control operation comprised two phases: in the first, non-toxic prefeed carrot baits were applied aerially by helicopter to the whole study area; in the second, toxic carrot baits containing 1080 with or without a repellent were applied aerially to ‘Repellent’ and ‘No Repellent’ areas, respectively. The non-toxic baits (mean weight 12 g) were broadcast at 2 kg ha^{-1} on 27 September 2004 over the 1416-ha Repellent treatment block, and on 28 September 2004 over the remaining 18 584 ha of forest, which included the 1000-ha No Repellent control block (Fig. 1). The helicopter flew 200 m over the ridgeline to create a 200-m buffer between the operational boundary and the monitored areas. Twenty-one days later, toxic carrot baits (at a nominal 0.12% wt/wt 1080 loading but see below) were applied at 3 kg ha^{-1}. On the No Repellent block, the treatment conformed to normal operational procedures (i.e. non-toxic baits were undyed, orange-lured (but not orange-coloured) carrot, and the toxic carrot bait was dyed green (Special Green V200A dye, Bayer NZ, Auckland, NZ) with orange lure). On the Repellent block, both the non-toxic and toxic baits were coated with a bird repellent formulation consisting of dark blue dye (Bayer Blue AEN, Bayer NZ, Auckland, NZ) and anthraquinone (as Avex™ active ingredient 43% 9,10-anthraquinone), as well as containing the orange-flavoured lure. This repellent/dye/lure/water or 1080 solution (at the concentrations listed in Table 1) was sprayed onto the cut carrot as it moved up the auger. Twenty-three millimetres of rain fell on the night before the poison drop, but only a few light showers fell in the subsequent 3 days (C. Speedy, Epro, pers. comm., 26 November 2004).

Three or four samples of five pieces of carrot baits were collected from both the prefeed and toxic drops – immediately before and immediately after they had been dropped by helicopter – and sent to Landcare Research, Lincoln, for assaying for anthraquinone and 1080 where appropriate.

Possum monitoring

To determine whether or not the bird repellent had an effect on acceptance of the baits by the target pest, possum capture rates before and after poisoning were monitored using leghold traps. Twenty-six lines of 10 traps were established in both the Repellent and No Repellent blocks. The traps were spaced at 20-m intervals. The lines were at least 200 m apart and followed the same ridges used for some of the tomtit monitoring lines (see below). They were set for three nights and baited with plain white flour and icing sugar. The pre-poisoning monitoring was undertaken taken between 30 August and 15 September 2004. The post-poisoning monitoring of the possum population (with the traps moved 200 m from their previous sites) was conducted in February 2005. Trap-catch rates were calculated as the number of target animals caught per 100 trap-nights. Changes in catch rates adjusted for all sprung traps (Nelson & Clark 1973) and escapees (National Possum Control Agencies 2004) were compared between the Repellent and No Repellent blocks, using the Fisher exact test for 2×2 tables on the paired pre- and post-poisoning data.

Tomtit monitoring and analysis

Tomtit monitoring was conducted using procedures similar to those outlined by Westbrooke et al. (2003) and Westbrooke and Powlesland (2005), which involved noting the number of resident males seen or heard within 40 m of either side of transect lines. Forty transects were established in each of the Repellent and No Repellent blocks (Fig. 1). It was not safe or practical to place transects randomly across the landscape, but rather we utilised ridgelines and existing networks of formed tracks that sampled similar mature hardwood forest habitats in each of the two study areas. Although there were more lines along a river in the No Repellent block, those in the Repellent block also sidled or crossed small streams. Each transect was 250 m in length, and the end of one transect was 100 m from the start of the next. Where transects were parallel, the gap between transects was a minimum of 200 m, to ensure that no tomtit territory was crossed by more than one transect. Male tomtit density in nearby blocks of Whareorino Forest during a similar time frame to our study was estimated to be less than 0.8 per hectare (Spurr et al. 2012).

To overcome the potential confounding by migration of tomtits between the No Repellent and Repellent areas, count lines were positioned, at minimum, 200 m from the operational boundaries and a 200-m buffer was applied on the south and east sides of the main dividing ridge between the two areas, creating a minimum 400-m gap between transect lines in the No Repellent and Repellent areas (Fig. 1). Distance measurements were obtained using hip-chain cotton. Along each transect, the start and finish points and 50-m intervals were marked using plastic track markers and each point was numbered. A grid reference of the start or finish point on each transect was recorded using a Garmin 12XL GPS (Global Positioning System).

Tomtits were counted along all transects three times before the control operation and three times after the operation by two experienced observers. Each transect count took 8–10 min. The pre-poison counts were conducted at variable (weather-dependent) intervals between 18 August and 18 September 2004. Post-poison counts took place from 27 October to 5 November 2004, beginning 9 days after the toxic baits were broadcast. Observations were made when the weather was dry and relatively calm. Most counts were conducted between 0800 and 1400 hours, or between 1600 and 2000 hours, the times when tomtits are most vocal (K. Oates, pers. obs.).

Any territorial male tomtit seen or heard singing within 40 m of a transect was counted while the observer walked along each transect. It is possible that some of the high-pitched repeated calls of distant males may have actually been closer females, but the main territorial song of the male is loud and clear (Heather & Robertson 1996). Each bird's perpendicular distance from the line was estimated, and its position relative to the 50-m-interval markers was recorded. Ten lines were counted in both the treatment and control areas on each day. Observers alternated which transects they counted each day, to minimise the impact of observer bias.

The counts were combined to provide single estimates of numbers of territorial male tomtits per block per time period (pre- and post-poisoning). The counts were derived by plotting all recorded locations of tomtits on a 260 Series topographical map, scale 1:50 000, and allowing a territorial width of 100 m (Westbrooke et al. 2003). Changes in numbers of birds (post- minus pre-poisoning) were calculated and compared for the Repellent and No Repellent blocks, using analysis of variance (ANOVA) with transect line as the unit of replication. Tests revealed no evidence of heterogeneity or skewness. If a bird was detected close to the same location (i.e. within the same 100-m length of transect) during all three of the pre-poison counts, we assumed that it was the same individual being counted, as resident male tomtits occupy territories year-round (Michaux 2009). If two or more tomtits were allocated to the same space, it was because they were seen (positively identified). If only heard, it was conservatively assumed to be one bird. Accordingly, the significance of the loss of these individual birds between the pre- and post-poison counts was assessed using a one-tailed Fisher exact 2×2 test.

Results

Tiritiri Matangi Island bait trial

Significant differences in mean numbers of pecks were detected between the five bait types averaged across test days (Wald statistic = 5.98, 4 d.f., $P = 0.039$). The green cinnamon baits with no bird repellent had the greatest mean 30-min peck rate per bird per day (17.39 ± 7.14 SEM). The bird repellent treatments did not differ significantly from each other, with wide variability in the responses of individual birds. The mean peck rate was 1.51 (±0.61) for 0.09% anthraquinone, 3.71 (±1.27) for 0.09% anthraquinone + cinnamon, 4.87 (±1.87)

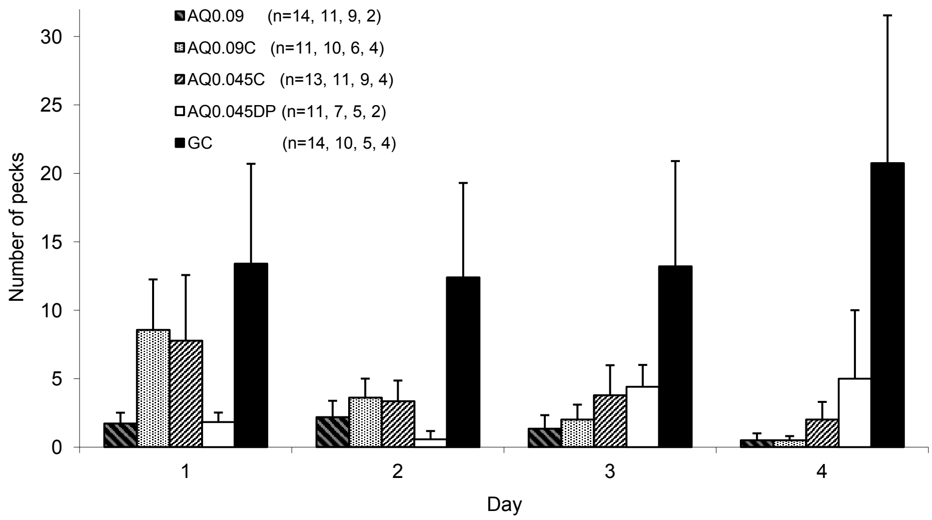

Figure 2. Pecking responses of North Island robins (*Petroica australis longipes*) at dough baits coated with blue dye + 0.09% anthraquinone (AQ0.09), blue dye + 0.09% anthraquinone + 0.03% cinnamon (AQ0.09C), blue dye + 0.045% anthraquinone + 0.03% cinnamon (AQ0.045C), blue dye + 0.045% anthraquinone + 0.05% d-pulegone (AQ0.045DP), or green dye + 0.03% cinnamon (GC) over the 4-day test period. Data are presented as average number of pecks per trial (+SEM). They exclude four birds that never entered the test arenas. Sample sizes are given for each test day.

Table 2. Concentrations of anthraquinone (mg kg^{-1} carrot) actually detected on bait samples and calculated percentage of Avex^{TM} on the bird-repellent-treated carrot during the 1080-carrot operation at Whareorino Forest.

Application	Collection site	Anthraquinone	AvexTM
Prefeed	Before sowing	0.57	0.13%
	After sowing	0.19	0.04%
Toxic	Before sowing	0.45	0.11%
	After sowing	0.13	0.03%

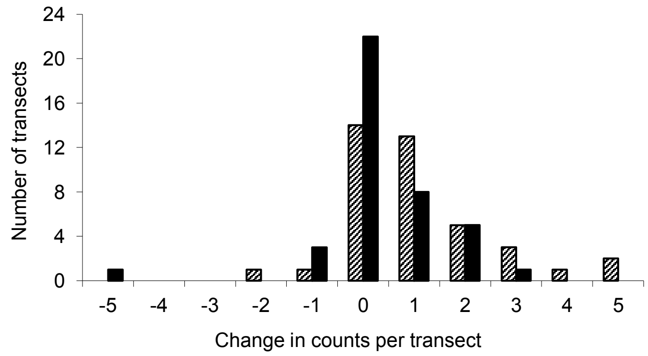

Figure 3. Changes in numbers of tomtits (*Petroica macrocephala toitoi*) recorded on each of the 40 transect lines before and after poisoning in both Repellent (grey columns) and No Repellent (black columns) blocks.

for 0.045% anthraquinone + cinnamon, and 1.95 (±0.73) for 0.045% anthraquinone + d-pulegone. There was a significant treatment×day interaction (Wald statistic = 27.75, 12 d.f., $P = 0.012$. Mean numbers of pecks at baits containing 0.09% anthraquinone were low throughout the trial. Pecks at 0.09% anthraquinone + cinnamon were almost zero by Day 4, and pecks at 0.045% anthraquinone + cinnamon also reduced over time. By contrast, pecking rates at the control baits and at 0.045% anthraquinone + d-pulegone increased over time (Fig. 2).

Whareorino Forest field trial

Repellent and toxin assessments

Before sowing, the assayed concentration of anthraquinone on the carrot was considerably lower than expected from Avex^{TM} applied at a nominal 0.2% rate (Table 2). After aerial application, the anthraquinone levels were even less than expected.

Before sowing, the carrot baits contained an average 1080 concentration of 0.072% and 0.094% by weight in the No Repellent and Repellent toxic drops, respectively. Carrot that was collected from the ground from the Repellent block after the operation contained 0.05% 1080.

Possum monitoring

Before poisoning, possum catch rates averaged 18.6% (SEM = 2.71%) in the Repellent block and 11.8% (±2.3%) in the No Repellent block. In February after the poison operation, catch rates had fallen to 5.6% (±1.2%) in the Repellent block and 9.7% (±1.2%) in the No Repellent block. A significantly higher percentage of the trap lines in the Repellent block (73%) than the No Repellent block (42%) showed a reduction in catch rates ($P = 0.029$).

Tomtit monitoring

While there was little change in the numbers of male tomtits counted on most transects in both Repellent and No Repellent blocks, significantly more transects in the Repellent block recorded an increase in birds counted after the control operation ($F_{1,78} = 6.029$; $P = 0.016$) (Fig. 3). There was an average of 2.50 tomtits recorded before poisoning in the Repellent block, rising to 3.58 after poisoning, an increase of 1.075 (SEM = 0.233), compared with 2.53 per transect in the No Repellent block before the poison operation and 2.85 afterwards, an increase of 0.325 (0.197). Removing the results from the river-side lines in the No Repellent block, to avoid confounding effects of different habitats, reduced the average increase in that block to 0.187 (0.390).

In the No Repellent block, 7.9% of the individual birds known to be occupying territories before poisoning were missing afterwards (8 out of 101, 95% confidence interval = 3.5–15.0%), not statistically significant (Fisher's exact test: $P = 0.22$) from the 3% decline in the Repellent block (3 out of 100, 95% CI = 0.6–8.5%).

Discussion

Tiritiri Matangi bait trial

This study supports the value of combining primary and secondary repellents to deter robins from feeding on baits, which has been demonstrated in previous trials (Day 2003; Day et al. 2003). We cannot rule out the possibility that the repellent baits were more effective simply because they were a different colour from the control baits, as robins are known to peck less at blue than at green baits (Hartley et al. 1999). However, the tendency for the robins to reduce their pecking rates at the baits containing the higher concentration of anthraquinone supports the findings of Clapperton et al. (2012), who showed that neither blue nor green colour on its own remained as effective as a combination of anthraquinone and blue colour. The blue colour appears to be important both for its role as a primary deterrent and as a salient cue for inducing taste aversion to anthraquinone. While blue would be the best bait colour for deterring robins, other bird species show different colour preferences. For example kea consumed less green-dyed cake than blue-dyed cake (Weser & Ross 2013).

The addition of cinnamon, commonly used in mammalian poison baits to mask the flavour of 1080, did not detract from the efficacy of the anthraquinone-based repellent. The fact that birds initially pecked at cinnamon-lured baits shows the importance of pre-baiting with non-toxic baits to allow time for the birds to test the baits and develop a learned taste aversion. Pre-baiting is already common practice in pest control operations in New Zealand, as it has been demonstrated to minimise bait shyness in possums (Moss et al. 1998; Ross et al. 2000; Nugent et al. 2011).

The combination of anthraquinone and d-pulegone at lower rates than previously trialled produced as strong an initial repellency as the other treatments. While there was (non-significant) increased take over the last 2 days of the trial, this combination has proven to be equally repellent as 0.09% anthraquinone on blue wheat to free-ranging sparrows over 8 days (Clapperton et al. 2012). Concerns about the loss of the volatile d-pulegone from baits dictated our choice of 0.09% anthraquinone with no d-pulegone for the field operation at Whareorino. In other situations, where baits are hand laid, the combination of a lower concentration of anthraquinone plus d-pulegone may be a potent repellent (Clapperton et al. 2012). Incorporation of the repellents into cereal baits during manufacture, as used by Orr-Walker et al. (2012), might ensure better retention of the volatiles. Where cost is an important factor, the combination of blue colour, 0.045% anthraquinone and cinnamon may be adequate to protect robins.

Whareorino Forest field trial

Westbrooke and Powlesland (2005) suggested that pest control operations that use low sowing rates and large toxic baits have little impact on tomtit populations, and Greene et al. (2013) found that a 1080 operation using 0.15% loading on RS5 cereal baits spread at 2 kg ha^{-1} had no negative impact on tomtits in Waitutu Forest in Fiordland, New Zealand. Such baits were used in the operation in the present study, so minimal effect was expected on tomtit numbers. This proved to be the case. Nonetheless, there was a positive effect of the bird repellent on tomtit survival. The significantly larger increase in observed tomtits in the repellent-treated area after the operation suggests that the inclusion of the bird repellent in the baits helped to protect these birds, although this was not confirmed by our measures of disappearance of individual tomtits during the operation.

Previous studies using the territorial male count methodology found greater stability in tomtit numbers on transects before and after a poison operation than in the current study (Westbrooke et al. 2003). However, Spurr et al. (2012), working in the same forest and the same year as the current study, found that tomtit counts increased between September/October and November. They related this to tomtit calling rates. Our pre-poison counts were conducted in August and September, when temperatures were cool. The cooler temperatures before poisoning may have reduced the calling rate of male tomtits, although counts were only conducted on fine-weather days and territorial song and displays should have been intense at that time of year (Michaux 2009; Greene et al. 2013). Post-poison counts were carried out in October and early November, when temperatures were warmer and tomtits may have been more conspicuous, actively defending nests, mate feeding, or brood rearing. Tomtit song intensity peaks from November onwards (Michaux 2009), so the reduced post-poison counts in the No Repellent block may have underestimated the number of birds killed. Movement of tomtits towards observers can also lead to overestimation of abundance (Broekema & Overdyck 2012).

The positive result of the bird repellent on tomtit detection is not likely to have been the result of a lower exposure to 1080 in the Repellent block. In fact, if anything, the 1080 concentration was slightly higher in the Repellent than in the No Repellent block. The efficacy of the 1080 in the Repellent block was confirmed by the relative high possum kill in that block. Further, the trial design may have limited our ability to detect the full effect of the bird repellent in that some of the bird-monitoring lines were close to the boundary between the Repellent and No Repellent blocks. This may have allowed for some potential exposure of birds in the Repellent block to non-treated baits and vice versa. The two lines on the Repellent block where known birds disappeared were near these boundaries.

To be applied in mammalian pest control, bird repellents must not only deter birds but must also not interfere with the efficacy of the poison baits for killing the target pests. This was demonstrated in the current study, with fewer possums caught in the Repellent block after poisoning than in the No Repellent block, indicating that the poisoning operation was at least as effective if not more so where the bird repellent was used. This result confirms the findings of previous laboratory and field trials (T.D. Day and B.K. Clapperton, unpubl. data).

The field trial proved to be a difficult scenario in which to test the bird repellent. The loading of 1080 proved to be less than the nominal loading, and possum kills were relatively low. The concentrations of anthraquinone on the carrot baits both before and after sowing were considerably lower than the nominal loadings. This is the first time that the bird repellent has been added to the baits while it travelled through an auger and was subsequently distributed aerially. In previous trials on sparrows and robins, the anthraquinone was mixed with the baits in small plastic containers and distributed manually (Day et al. 2003, 2012; Matthews et al. 2005). Prior to the current study, baits had not been assayed for anthraquinone. It appears, from the anthraquinone concentration and the low concentration of 1080 on the baits in this trial, that the carrots did not receive a full coating of the field solution, or the materials were partially removed during sowing, or errors were made in preparation. Improved application techniques are needed to ensure that repellents and toxins remain on the baits.

The conclusions from our trial in a single forest block cannot be generalised to other situations without replication. To confirm our findings that the bird repellent enhanced tomtit survival, the trial needs to be repeated with better quality control of toxic bait and repellent application and, ideally, in areas where robins as well as tomtits could be monitored.

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