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RESEARCH

Attempting local elimination of possums (and rats) using dual aerial 1080 baiting

Graham Nugent*, Grant A. Morriss and Bruce Warburton

Manaaki Whenua – Landcare Research, PO Box 69040, Lincoln 7640, New Zealand
*Author for correspondence (Email: nugentg@landcareresearch.co.nz)

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Abstract: New Zealand aims to eradicate possums (*Trichosurus vulpecula*) and ship rats (*Rattus rattus*) nationally by 2050. This aim will require more effective tactics for locally eliminating these pests. Therefore, we explored whether possums and rats could be eliminated from large areas using pre-feeding and two applications of sodium fluoroacetate (1080) bait spaced a few months apart. The specific key question we investigated was whether any bait aversion learned by possums or rats that survived the first application of 1080 cereal bait would be overcome by a second application. A two-stage field trial was undertaken in 2016 and 2017, using 100-ha forested study blocks near New Creek, Westland. In the first stage, eight blocks were aerially baited with 1080 after being aerially pre-fed twice, once, or not at all. The relative abundance of rats fell to zero immediately after the baiting in all four blocks that were pre-fed, but lesser reductions in the four blocks not pre-fed. The survivors in the non-pre-fed blocks appeared to be universally and strongly bait averse. In the second stage, the non-pre-fed blocks were then aerially pre-fed twice and 1080-baited (by hand laying) with a bait type that differed slightly in appearance and smell from the original. Based on trail camera visitation rates and chew card interference, the relative abundance of rats fell to zero or close to it in the second group of four blocks, whereas possum activity indices increased markedly after an initial one week dip. The increase in possum activity was attributed to the peanut bait used in the chew cards attracting possums to monitoring sites. We conclude that dual application of 1080 using a similar bait in a single operation has the potential to locally eliminate rats from large areas, and that with further development involving use of two very different bait types and/or different pre-feeding sequencing, could potentially achieve the same for possums.

Key words: 1080, bait aversion, eradication, possum, pre-feeding, *Rattus rattus*, ship rat, *Trichosurus vulpecula*

Introduction

In 2016, New Zealand adopted two ambitious pest eradication goals. The agricultural sector and government committed to eradicating bovine tuberculosis (TB) from wildlife and livestock nationally by 2055 through a programme managed by OSPRI (OSPRI 2017; Crews & Nugent 2018), while the conservation community and government aimed to eradicate three widespread ‘predators’ from the country by 2050, a goal now championed by Predator Free 2050 Ltd (PF2050 2016). Both goals would be more achievable if introduced possums (*Trichosurus vulpecula*; the main wildlife host of TB (Nugent et al. 2015) and one of the targeted PF2050 pests) could be quickly and affordably eliminated, especially from large areas of native forest where their numbers tend to be greatest (Forsyth et al. 2018).

Such large-scale local elimination is already achievable using aerial baiting and an anticoagulant toxin (brodifacoum) with a long latent period. The largest example from the main islands of New Zealand is the elimination of possums (and other pests) from the fenced 3400 ha Maungatautari Sanctuary (Speedy et al. 2007). However, the persistence of this toxin in non-target species (Eason et al. 2002) has led to its use being restricted on public conservation lands. The only other aerially deliverable toxin currently available is sodium fluoroacetate (1080). It is already widely used to suppress possum and/or ship rat (*Rattus rattus*) densities in remote forest and/or mountain areas (Brown et al. 2015; Warburton & Livingstone 2015). However, 1080 is a comparatively fast-acting toxin (time-to-onset of loss of appetite and subsequent sickness is typically 40–70 minutes for possums depending on dose; Henderson et al. 1999) so at least a few possums usually survive 1080 baiting, either because they do not encounter bait at all, or (more usually nowadays) because they do not eat enough bait quickly enough to ingest a lethal dose before the onset of sub-lethal toxicosis. Substantial research in the late 1990s (Morgan et al. 1996; Moss et al. 1998; O'Connor & Matthews 1999; Ogilvie et al. 2000; Ross et al. 2000) showed that such sub-lethal poisoning often resulted in a strong and long-lasting (>2 years) aversion to the bait used to poison them, and that this learned aversion was not easily overcome. The risk of sub-lethal poisoning can be reduced by ensuring (i) all individual baits contain at least one lethal dose of 1080 (Latham et al. 2017); (ii) baits do not fragment during sowing (Nugent et al. 2010); (iii) bait density is high enough for every possum to quickly encounter multiple baits (Nugent et al. 2012; Nugent

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& Morriss 2013); and (iv) possums are familiar with the bait being used as a result of one or two previous exposures to non-toxic baits (pre-feeds) (Coleman et al. 2007; Nugent et al. 2009, 2011). A large-bait/multiple-pre-feed/high-sowing-rate solution is almost always highly effective but is inevitably expensive (Coleman et al. 2007) and there is always some chance of possum survival; for example, when a dominant possum displaces a subordinate possum from a partly eaten bait (as has been observed with trail cameras; S. Hough, Landcare Research, unpubl. data, 2011), potentially resulting in the sub-lethal poisoning of both possums.

Because some possums usually survive, aerial 1080 poisoning operations are typically repeated some years later. However, if a total kill of possums could be achieved in a single operation involving two applications of toxic 1080 bait just a few months apart (dual baiting), there could be far less need to repeat operations in order to guarantee local eradication of TB (simply because a 100% kill would result in instantaneous eradication of TB from resident possums). It would avoid any need for the expensive post-control possum TB surveillance usually required to verify TB eradication, and so could potentially enable treated areas to be declared free of TB in possums after just one 1080 operation (Nugent et al. 2017) rather than the usual three operations spaced ~4–6 years apart (Warburton & Livingstone 2015). Such an outcome would speed up progress towards national TB freedom.

If dual 1080 baiting can deliver total kills of possums, and if re-invasion can be prevented by perimeter control (Morgan et al. 2006), it would also help make PF2050 goals of national eradication much more feasible with current tools. That possibility is currently being developed and tested at large scales by ZIP (Zero Invasive Predators) with their '1080-to-Zero' dual 1080 concept (ZIP 2018). In conjunction with that large-scale initiative, we investigated a key question that crucially determines whether the concept of dual 1080 baiting might be a useful approach in achieving 100% kills of possums.

Although the funding (and therefore the focus) of this research relates primarily to possums, we also extended the investigation to cover ship rats, another of the predators targeted for eradication by 2050 (PF2050 2016) and also targeted in the ZIP initiative. Rats can be eliminated from large areas using aerial baiting (e.g. Maungatautari; Speedy et al. 2007) but that has always relied on use of anticoagulants such as brodifacoum and, to our knowledge, has never been achieved via 1080 baiting. The specific targeting of rats with 1080 did not begin until the 1990s, much later than for possums, so the body of research investigating the efficacy of 1080 for rat control is smaller than for possums. There are some similarities (most notably an even greater need for pre-feeding than for possums; Innes et al. 1995; Brown et al. 2015; Elliot & Kemp 2016), but also differences (most notably, wide variation in control efficacy possibly related to seasonal timing and/or rat density; Elliot & Kemp 2015).

In undertaking this research, we assumed that there will always be a risk of some possums and/or rats surviving a single 1080 baiting even if large robust baits, multiple pre-feeds, and high sowing rates are used. Therefore, we focussed on whether most survivors of a first 1080 baiting would be killed by a second application of 1080 bait a few months later. Specifically, we field-tested the hypothesis that repeated pre-feeding of a recently poisoned area with a non-toxic bait would reverse any learned bait aversion induced by the first toxic 1080 baiting so that most survivors would then accept subsequent 1080 baits. If not, the second baiting would not be worthwhile. Building on the large body of previous research into the nature and longevity of learned toxic-bait aversion, and the factors affecting it, we tested this hypothesis in small-scale (100 ha) field trials conducted in 2016 and 2017. The study was not designed to directly assess whether using 1080 twice could eliminate possums and rats, but rather to field test the crucial sub-question of whether survivors of a first baiting could be killed by a second baiting soon after. Although we were constrained (by aerial poisoning consent processes) to using a second bait that differed slightly from the initial bait, we show that the approach has promise, especially for rats and potentially for possums. We also report (see Supplementary Material) some incidental data indicating the effects of hand-laid1080 baiting on some non-target mammal and bird species.

Materials and methods

Study site and treatments

The main study was conducted between June 2016 and May 2017 in eight 100-ha study blocks in a forested area near New Creek (41.806S, 171.945E) on the West Coast of New Zealand's South Island (see Appendix S1 in Supplementary Material). The area has high annual rainfall (1.6–2.3 m p.a), and the main study blocks were all in mixed-canopy forest dominated by beech species (*Nothofagus/Fucospora* spp.) and with ground cover usually dominated by crown fern (*Blechnum discolor*). Possum densities in such forests are typically moderate to low (~1–3 per ha; Clout & Gaze 1984; Coleman 1988), while ship rats are usually also present but in highly variable numbers (Innes 2005). The trial blocks were selected to cover areas of similar terrain and topography (and therefore forest) that were within practical walking distance from a road. Some were contiguous with other study blocks on one side, or were separated by up to ~1 km.

We used a two-stage design. In the first stage, we aimed to create populations of 1080-bait-shy survivors (possums and rats) by implementing three levels of non-toxic pre-feeding: no pre-feed in four study blocks, and one or two pre-feeds in each of two study blocks followed by aerial 1080 poisoning in all eight blocks (Table 1). The once- and twice-pre-fed blocks resulted in too few survivors post-1080 baiting to usefully explore the effectiveness of a second 1080 baiting. Therefore, the second stage aimed to determine whether survivors in the four study blocks that were not pre-fed could be killed using twice-aerially pre-feeding before a second application of 1080 bait.

The bait type used for the first stage was cinnamon-lured RS5 cereal pellets (Orillion, Whanganui, New Zealand). Non-toxic pre-feeding was conducted in late winter 2016 using either 2 g or 6–8 g baits (Table 1) aerially broadcast at 1 kg ha^{-1} along flight paths 120 or 200 m apart. As part of the main OSPRI operation, pre-feeding was conducted 3 weeks after the first pre-feed (in the two twice pre-fed blocks only) and 12–13 days before 1080-baiting (Fig. 1). Toxic green-dyed 12 g bait of the same type containing 0.15% w/w 1080 was then aerially broadcast over the whole 92 000 ha area at the rate of 2.0 kg ha^{-1}.

In the second stage, the RS5 baits used were modified by surface-coating them with a proprietary deer repellent (Epro Deer Repellent (EDR); Speedy 2005) that changed the appearance and smell of the bait. Previous research (Morriss 2007) has shown that EDR-coated bait reduces incidental deer kill without adversely affecting possum or rat kill in

Table 1. Overview of treatments and timeline of monitoring activities in eight 100-ha blocks at New Creek, West Coast. All pre-feeds were aerially broadcast. FPS = flight path spacing. In Stage 1, the second pre-feed and the 1080 baiting were conducted as part of a much larger TB-possum-control operation. The ticks indicate when the various activities were undertaken in each block.

	Approx. dates	Treatment: Non-pre-feed	Treatment: One pre-feed	Treatment: Two pre-feed	Notes
Stage 1					
Number of 100-ha blocks		4	2	2	
7-night CCI deploy & check	Jun 16	✓	✓	✓	
Deploy long interval CCI	Jun 16	✓	✓	✓	
Radio-collar possums	Jul 16	✓	✓	✓	
First pre-feed	Aug 16			2 g RS5 1 kg ha^{-1}	Aerial broadcast, 100 m FPS
Second pre-feed	Sep 16		6 g RS5 1 kg ha^{-1}	6 g RS5 1 kg ha^{-1}	Aerial broadcast, 200 m FPS
1080 baiting	Sep 16	12 g RS5 2 kg ha^{-1}	12 g RS5 2 kg ha^{-1}	12 g RS5 2 kg ha^{-1}	Aerial broadcast, 220 m FPS
Check long interval CCI	Oct 16	✓	✓	✓	
7-night CCI deploy & check	Oct 16	✓	✓	✓	
Deploy long interval CCI	Oct 16	✓	✓	✓	
Assess %kill radio collars	Oct 16	✓	✓	✓	
Bait acceptance trials	Nov 16	✓			+ non-treatment site
Stage 2					
Deploy trail cameras	Nov 16	✓			
First pre-feed	Early Feb 17	2 g EDR-RS5 1 kg ha^{-1}			Aerial broadcast, 100 m FPS
Second pre-feed	Mid Feb 17	2 g EDR-RS5 1 kg ha^{-1}			Aerial broadcast, 100 m FPS
1080 baiting	Late Feb 17	12 g EDR RS5 0.75 kg ha^{-1}			Hand laid, 100 m transect spacing
Check long interval CCI	Mar 17	✓			
7-night CCI deploy & check	Mar 17	✓			
Deploy long interval CCI	Mar 17	✓			
Recover trail cameras	May 17	✓			
Check long interval CCI	May 17	✓			

a measurable way. The four study blocks with adequate numbers of surviving possums and rats were re-poisoned with EDR-coated 1080 bait in early 2017 (160 days after the first operation), after first being pre-fed twice (at 20–23 days and 7–10 days before the toxic baiting) with non-toxic 2 g EDR-coated baits aerially broadcast at 1 kg ha^{-1} (Table 1). The toxic green-dyed 12 g EDR-coated bait was delivered by hand (rather than aerially) at about 0.75 kg ha^{-1}, along parallel transects spaced 100 m apart. In two of the blocks, ground staff aimed to simulate aerial delivery by flinging baits up to about 10 m laterally from the transects, so that each individual bait was at least somewhat separated from any other. In the other two blocks, baits were hand placed in clusters of four every 5 m (Nugent et al. 2012; Nugent & Morriss 2013) in an effort to ensure that every possum encounter with 1080 bait was with a lethal dose of 1080 (something not always guaranteed with individual baits).

Assessment of the relative abundance of possums and rats

Relative abundance of possums and rats was assessed using peanut-butter-lured chew cards (Sweetapple & Nugent 2011). The percentage of cards bitten by possums or rats during each period was determined for each block, and the resulting Chew Card Index (CCI) was used as a measure of relative abundance. Within each block, chew cards were spaced at 100 m intervals along eight parallel 800 m long transects spaced about 100 m apart (i.e. 64 chew cards per block). Chew cards were deployed continuously for about 9 months with six assessment periods (Table 1): three standard '7-night' (CCI_7) assessment periods (the first before the first 1080 baiting, the second soon after the first 1080 baiting, and a third soon after the second 1080 baiting). Between each of these 7-night assessments, and after the third, replacement cards were left in place for much longer assessment periods of varying lengths (CCI_{long}; 56–155 days).

Chew cards were removed, checked, and scored at the end of each assessment period, and, except for the final assessment, replaced immediately with a fresh card. Differences in the CCI were compared using contingency tables.

Direct assessment of possum kill

In the first stage, we assessed the likely number of possum survivors in each block by measuring the survival of possums fitted with radio collars before the first 1080 baiting. In the centre of each block, 64 leg-hold traps were set at each of

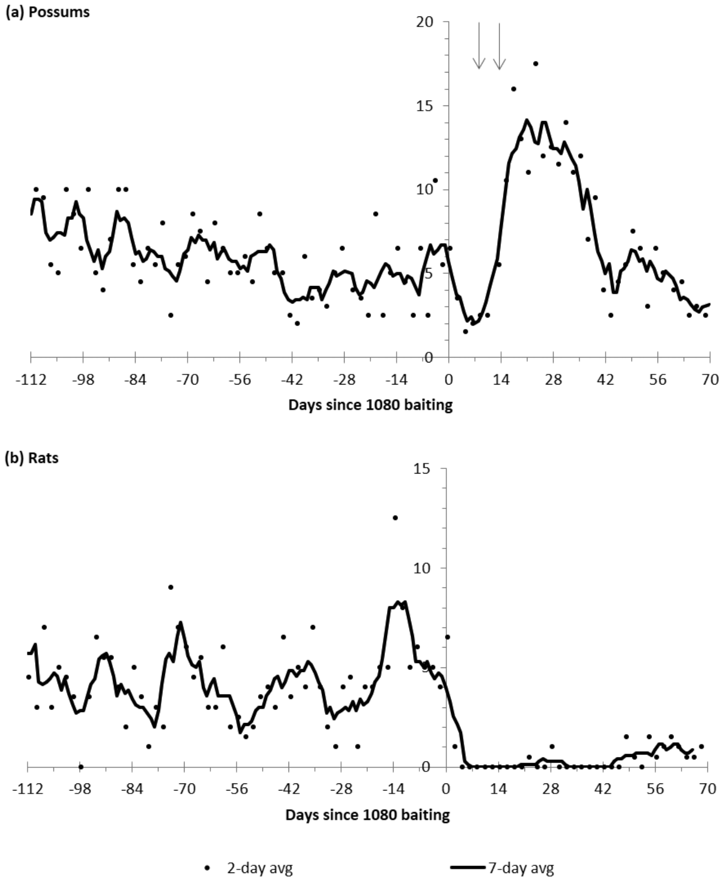

Figure 1. Variation in the average number of visits by (a) possums and (b) rats to 69 trail camera sites, with a chew card also deployed at each site. The data depicted are the average number of visits for every 2-day period (points), and the 7-day running average for each date (lines). The arrows in (a) show the two occasions when fresh chew cards were deployed, replacing (on the first of these occasions) cards that had been in place for about 155 days. The first 2-day data point after baiting represents the first 2 nights after baiting.

the chew cards sites described above and set for 3–6 nights in mid-winter 2016. Captured adult possums were sedated by intramuscular injection of Zoletil at 5 mg kg^{-1} of possum weight (Morgan et al. 2012), fitted with VHF radio collars with motion-cessation (mortality mode) signalling and time-since-death functionality (Sirtrack Ltd, Havelock North, New Zealand) and then released at the capture site. Radio-tagged possums were located aerially c. 1.5 months before the first 1080 baiting. Ground-based telemetry searches were conducted 1–2 weeks after the 1080 baiting, and a further aerial check was conducted one week later. In total, 196 possums were radio-collared, ten of which were never relocated. A further 23 moved out of the study blocks, died or slipped their collars before the initial 1080 baiting. The efficacy of control (possum % kill) in each block was assessed from the numbers of radio-collared possums confirmed still alive in each block 3 weeks after the 1080 baiting compared to the number confirmed from the radio-tracking data to still be alive and present in the poisoned areas at the time of the 1080 baiting.

Assessment of bait aversion by possums and rats

To assess the nature and severity of learned bait aversion in the survivors of the initial 1080 baiting, a bait acceptance trial was conducted in the four non-pre-fed blocks in November 2016 about 6–8 weeks after the 1080 baiting. Bait acceptance was also assessed in an area of similar forest type and terrain about 15 km away that had not been recently pre-fed or poisoned.

In the four non-pre-fed poisoned blocks, bait acceptance stations were established at all 41 chew card sites (2–20 per block) where possums had been detected during the 7-night CCI assessment conducted immediately after the first 1080 baiting. At each bait acceptance site, five non-toxic baits, each of a different type and each weighing about 12 g, were nailed in a cluster arrangement a few centimetres apart (in random arrangements) to a tree under a plastic rain guard. The bait types (all undyed) used were:

- cinnamon-lured RS5 cereal pellets (used in the first 1080 baiting)
- cinnamon-lured RS5 cereal pellets coated with EDR (used in the second 1080 baiting)
- orange-lured RS5 cereal pellets
- orange-lured cereal pellets produced by a different pest bait manufacturer (Connovation Ltd, Auckland, New Zealand)
- diced carrot chunks (without additional odour or coatings).

We considered that this array of baits could potentially indicate whether the anticipated learned aversion in survivors could be overcome simply by changing the smell (to orange RS5), or the smell and appearance of the bait type (to EDR-coated RS5), or by switching to a different cereal matrix (to Connovation) or to a non-cereal bait (to carrot). One or two trail cameras at each bait acceptance site were used to monitor possum, rat, and other species behaviour over 4 consecutive nights. For possums, the observed behaviours were classified as nil (no close approach to the baits); approach; sniff or contact but no bait consumption; and consumed (in three classes: less than a quarter, more than a quarter but less than three-quarters, most or all of the bait material). Notes were taken on which baits were consumed. In addition, the percentage of each bait type remaining was subjectively assessed after the 4 nights.

For the unpoisoned area, in March 2017, 20 similar bait acceptance stations were established at 100-m spacing and monitored as above for 2 nights. Although this assessment of acceptance was (for logistical and staffing reasons) conducted in a different season to the assessment in the poisoned area, we do not consider that will have greatly affected results as all of the baits have been developed to be highly attractive to possums.

Trail camera monitoring of possum and rat activity

In the second stage, 69 motion-sensing trail cameras were deployed at chew card sites at the four poisoned blocks at approximately 200 × 200 m spacing, using the chew card transects. The cameras remained in place between November 2016 and May 2017 (i.e. from 16 weeks before the second 1080 baiting until about 12 weeks afterwards).

The date-and-time-stamped images obtained were categorised according to species present (including species other than rats and possums), and the number of different individuals present during each visit was recorded; a visit was defined as any sequence of images of an individual or individuals of a particular species that all looked the same and which had no gap of more than 5 minutes between successive images. During the second 1080 baiting operation, single EDR-coated toxic baits were deliberately placed at the camera sites in an effort to further assess the behavioural responses of possums and rats to toxic bait.

Results

Stage 1: Effect of double, single or no pre-feed on possum and rat abundance

In the four blocks that were pre-fed once or twice before the first 1080 baiting, all radio-collared possums were killed and there were 100% reductions in the possum CCI_7 (Table 2). High kill rates and large CCI_7 reductions were also recorded in the four blocks non-pre-fed. However, at least one radio-collared possum remained alive in two of these blocks and some residual possum chew card activity was detected, with CCI_7 >3% in all four blocks (resulting in an overall average CCI_7 reduction in possum activity of 90% for the not pre-fed blocks; Table 2). The pattern was similar with long-interval CCIs: for the 93-day period mostly before the first 1080 baiting (but including about a week after), almost every card was bitten by possums in every block (CCI_{long} average 99.1%), whereas for the 156 days mostly between the two 1080 baiting events, the CCI_{long} averaged just 1.7% in the four pre-fed blocks compared to 55.7% in the four non-pre-fed blocks.

For rats, the pre-poisoning (winter 2016) CCI_7 were low, ranging from 0.0% to 20.3% (Table 2). As with possums, the CCI_7 fell to zero immediately after the first 1080 baiting in all four blocks that were pre-fed, but in the non-pre-feed blocks there were only modest reductions, averaging 57.1% across all four blocks. The long-interval CCI was also low initially, with the CCI_{long} for the 93-day interval mostly before 1080-baiting (and mostly in late winter) averaging just 10.8% in the pre-fed blocks (range 0.0–23.8%) and decreasing to zero in three of those blocks for the 156 days mostly between the 1080 baiting events (but increasing from 1.6% to 12.5% in the fourth block). For the four non-pre-fed blocks, CCI_{long} averaged 13.4% (range 1.6–31.1%) before the first baiting but 40.0% (range 9.4–65.1%) between the baiting events.

Stage 1: Effect of non-pre-fed 1080 on bait acceptance by possums and rats

In the area that was not poisoned with 1080, over 2 nights, trail cameras recorded possum visits to 17 of the 20 bait acceptance sites, with 52 visits occurring when at least some bait was still present. Possums approached, investigated, or fed on the baits during 60% of these 52 visits, and during the two-thirds of visits in which they at least approached the bait station, they ate most or all of the bait still available (Table 3).

In contrast, in the four non-pre-fed poisoned blocks after the first 1080 baiting, possums visited 15 of the 41 bait acceptance stations, with 49 visits recorded over 4 nights. In three quarters of the visits, possums did not show any discernible response to the bait station. In visits when they did approach and even sniff or contact one or more of the baits, possums

Table 2. Survival of radio-collared possums and reductions in a 7-night Chew Card Index (CCI_7) of the relative abundance of possums and rats after the Stage 1 initial 1080 baiting in four pairs of New Creek area study blocks in September 2016, with each pair of blocks subject to one of three different pre-feeding regimes. The percent kill and % reduction CCI figures are the averages for each pair of blocks.

		Possums						Rats		
		No. of radio-collared possums			CCI			CCI		
Blocks	*Pre-feed treatment applied*	Alive before poison	Killed by poison	Percent kill (95% CI)	Before poison	After poison	% reduction in activity	Before poison	After poison	% reduction in activity
1, 2	No pre-feed	25	24	98%	88.7%	3.1%	97.0%	17.7%	10.9%	40.7%
		13	13	(80–100%)	88.7%	9.4%		-	-	
3, 4	No pre-feed	27	27	98%	100.0%	31.7%	83.0%	15.0%	7.9%	73.6%
		23	22	(88–100%)	57.1%	20.3%		1.6	0%	
5, 6	Single pre-feed	20	20	100%	95.3%	0%	100%	6.3%	0%	100%
		14	14	(88–100%)	70.3%	0%		3.1%	0%	
7, 8	Dual pre-feed	20	20	100%	88.0%	0%	100%	20.3%	0%	100%
		21	21	(89–100%)	78.1%	0%		0%	0%	

Table 3. Comparison of possum behaviours at bait-acceptance sites comprised of five different bait types nailed a few centimetres apart on tree trunks under a plastic rain guard. Data are the number of separate possum visits (i.e. groups of images separated in time by >5 mins) recorded by trail cameras over either 4 nights in the non-pre-fed poisoned areas at New Creek or over 2 nights in a nearby area not poisoned at Stockton. In the area not poisoned, possum visits at times when no bait was available are excluded. It is not known how many different possums were involved in the visits recorded.

	Area not poisoned		Poisoned area	
Closest interaction recorded during visit	No. of visits	% of visits	No. of visits	% of visits
Nil	21	40.4%	36	73.5%
Approach	4	7.7%	7	14.3%
Sniff/contact	3	5.8%	4	8.2%
Nibble (no discernible consumption)	3	5.8%	1	2.0%
Discernible consumption <25%	1	1.9%	1	2.0%
Discernible consumption 25–75%	2	3.8%	0	0.0%
Discernible consumption 76–100%	18	34.6%	0	0.0%
All	**52**	**100.0%**	**49**	**100.0%**

appeared to feed on only two occasions and ate very small amounts of bait (Table 3). The difference in the percentage of visits when baits were at least approached was significant (60% not poisoned v. 27% poisoned; 2 × 2 Contingency table $P<0.001$), as was the difference in the percentage of times when possums ate more than 25% of bait available during a visit when they approached the bait (64% not poisoned v. 0% poisoned; $P<0.001$). These data collectively confirmed that the possums surviving the first 1080 baiting were highly averse to all the five bait types presented.

Rat behaviours were not analysed in similar detail because they did not always trigger the cameras, so the outcomes of visits were not always clear. In addition, the images collected often had insufficient clarity to confidently judge the amount of particular bait eaten during a possum or rat visit.

However, all bait types were clearly highly palatable to both possums and rats in the area not poisoned with 1080. The orange-lured Connovation baits were completely eaten at all the 17 (of 20) sites visited by possums and the 19 sites visited by rats. For the two EDR-coated RS5 baits, bait was left uneaten at one site, while for cinnamon-RS5 bait, a partly eaten bait was left at one site. In contrast to the cereal bait types, some or all the carrot bait was left uneaten at three of the possum-visited sites and five of the rat-visited sites.

In contrast, in the poisoned area, possums alone visited eight stations, rats alone visited three, and rats and possums both visited a further seven. They did not eat all of any of the bait types at any station, but half of one EDR-coated orange RS5 was eaten at two sites visited by both species, and bait was 'sampled' (<10% eaten) at 1–4 sites for each of the other four bait types. These results indicate that at about 6 weeks after 1080 baiting most of the possums and rats present in the non-pre-fed poisoned blocks were strongly averse to any of the five bait types in the acceptance trials (at least when the baits were presented simultaneously for 4 nights).

Stage 2: Effect of second 1080 baiting on possums, rat, and non-target activity

Chew card monitoring provided no indication of a reduction in possum abundance from the second twice-pre-fed 1080 baiting, as the possum CCI_7 recorded immediately after averaged 42.2% across the four blocks, more than double the average CCI_7 of 16.1% after the first baiting (Table 1). The CCI_{long} averaged 55.7% over 8–9 weeks after the second baiting, compared with 56.9% for about 5 months before.

There was some evidence of a reduction from the trail camera data, as the number of possum visits to camera sites reduced by more than half in the week immediately after the second baiting. However, visitation rates then increased to much higher than previous levels before gradually declining to slightly lower than pre-second-baiting levels (Fig. 2a).

Despite the upsurge in possum visits, we are confident that at least some possums were killed, if only some or all of the nearly independent juvenile possums that were likely to have been fully dependent backriders at the time of the first 1080 baiting. In total, 68 camera visits by mother-juvenile pairs were recorded before the second baiting but just two afterward, with both of those being at the same camera close to the time of baiting. In the second of those two visits (2 nights after 1080 baiting), the juvenile was photographed eating 1080 bait but was then not photographed again, whereas its radio-collared mother was, so we presume the juvenile was killed.

The rat CCI_7 recorded immediately after the second baiting was zero in all four blocks. The CCI_{long} over the following 8 weeks was 0.0% in three blocks and 1.6% in the other (four block average 0.4%). The number of rat visits to camera sites declined to zero within 5 days of the baiting, and remained at zero for almost 3 weeks. There were also no rat visits recorded in the 4–6 week period after the second baiting. Most (5/7) of the camera sites visited by rats after the baiting were those closest to the edges of the baited areas, suggesting that the rats may have been re-invaders rather than survivors.

The incidental data on camera-site visitation rates by non-target species after twice-pre-fed hand-laid 1080 baiting (see Appendix S2) indicated increased activity 1–4 weeks after the baiting for mice (*Mus musculus*), weka (*Galliralus australis*) and robins (*Petroica australis*). There were no large reductions in visit rates of tomtits (*Petroica macrocephala*) and kiwi (*Apteryx haastii*), but visits by blackbirds (*Turdus merula*) and thrushes (*Turdus philomelos*) were less frequent.

Discussion

Initial 1080-baiting: efficacy and induction of learned bait aversion

The control outcomes of the stage one setup phase of this study re-confirms the well-documented benefits of pre-feeding for achievement of high kills of possums (Coleman et al. 2007; Nugent et al. 2011) and, even more so, of rats (Innes et al. 1995). These findings are already incorporated into operational best-practice guidelines (Brown et al. 2015). Control efficacy did not differ significantly between the once- and twice-pre-fed blocks after the first 1080 baiting, but that may simply reflect insufficient sampling effort to distinguish between a high kill and a very high kill, as pre-feeding once does not always result in near total kills of rats (Elliott & Kemp 2016) or possums (Coleman et al. 2007).

The total reductions in CCI and total kill of radio-collared possums in the pre-fed blocks (Table 1) suggest that all or almost all possums in those blocks encountered and ate 1080 bait. That implies that all or nearly all possums and rats in the non-pre-fed blocks will have also encountered bait and eaten at least some of it, yet some survived, implying sub-lethal poisoning as a result of their consuming too little bait was the major contributor to their survival. Consistent with that, we were able to demonstrate that survivors of both species were universally strongly bait averse, not only to the bait type used in the first baiting but also to the other three cereal-based bait types and also to carrot bait of similar size, at least when all bait types were presented together on a single occasion. We are unable to assess from this study whether the bait aversion was related to specific food characteristics (appearance, smell, taste, or texture) or to some generalised learned neophobia. An exception appeared to be nearly independent juvenile possums that were still associating with their mothers, which were responsible for the only observed consumption (albeit modest) by possums, and the only photographed evidence of a possum eating a 1080 bait during the second baiting. That suggests that such juveniles did not eat any 1080 bait during the first baiting even though their mothers did.

Our evidence for near-universal learned aversion in surviving rats is not as robust as for possums due to poor detection and resolution of images of rats and baits on motion-sensing cameras. However, in a recent (2018) video monitoring trial of bait acceptance by wild ship rats in a high-density population not subject to pest control since 2016, the rats typically ate all 29 pairs of 12 g RS5 baits they encountered within 1–2 nights of bait deployment (G. Morriss, unpubl. data). Therefore, our observation that almost all baits at the 19 sites visited by rats in the poisoned blocks remained completely untouched after 4 nights is a strong indication of learned aversion. The bait acceptance trials were undertaken about 8 weeks after the first 1080 baiting. The high degree of aversion demonstrated by rats at that time implies that most of the animals present then were survivors rather than post first baiting immigrants.

Efficacy of rapid-repeat dual 1080 baiting

The second twice-pre-fed 1080 baiting may have killed only a few of the adult possums that survived the first baiting. This contrasts with a previous study showing only 9% of captive possums that had been extensively pre-fed for seven consecutive days then sub-lethally poisoned were subsequently classed as being averse to the same 1080-bait (Moss et al. 1998). That suggests that our second baiting would probably have been more effective if it had been practical to monitor outcomes from the Stage 1 treatments that were pre-fed on two occasions, but that possibility was precluded by there being too few Stage 1 survivors for those treatments. However, a key point is that even with multiple exposures to non-toxic pre-feed, Moss et al. (1998) showed that some survivors were bait averse and this study suggests that such survivors cannot be easily killed with a repeated sowing of the same bait type. Our results are consistent with another study (Ross et al. 2000) showing that post-feeding (i.e. offering possums a non-toxic cereal bait after they had been sub-lethally poisoned with it) resulted in only 30% mortality of caged possums subsequently offered the same toxic bait (and 0% mortality in those not post-fed). In contrast to the adults, at least some juveniles that survived the first 1080 baiting (possibly because they were not actually exposed to the 1080 bait) were killed, indicating that a pre-fed second 1080 baiting can be expected to kill some component of the surviving population, but that seems unlikely to be considered cost-effective.

In contrast to possums, rat reductions from the second 1080 baiting were almost total, with very few camera-site visits for most of the 6 weeks after baiting. The few visits during and after that time were mostly close to the periphery of the poisoned areas, suggesting they were most likely to be invaders. While some of the rats killed will have been born after the first 1080 baiting, the acceptance trial at 5–6 weeks later showed most of the population then were bait-averse survivors that we expect will have survived until the second baiting. If so, pre-feeding twice largely, or possibly completely, overcame any learned bait-specific aversion or induced generalised neophobia in surviving rats. That success may have been partly facilitated by the change to EDR-coated bait. However, rats did not eat EDR-coated bait in the bait acceptance trial. Excluding the possibility that that EDR avoidance could reflect collective avoidance of all five bait types at each acceptance station (because of the presence of the cinnamon RS5 bait type they were poisoned with) that suggests that numerous encounters with non-toxic bait are likely to be required to fully overcome learned aversion in rats. That suggestion is supported by the extensive literature that indicates that the number of exposures to a novel food is a key factor in overcoming neophobia, not only in rats but in many other species (see recent reviews; Birch & Anzman-Frasca 2011; Modlinska & Stryjek 2016).

Continued acceptance of a markedly different bait

The upsurge in possum visits to camera sites beginning one week after the second baiting seems likely to reflect an attraction to the new chew cards deployed at that time, or, more specifically, to the fresh peanut butter they contained. The visitation rate remained high for about 3 weeks after chew card deployment, in line with previous research showing a sustained impact of localised pre-feeding on possum foraging behaviour and in attracting possums to the pre-feed site (Warburton et al. 2010). The extent of the response seems remarkable, given the limited food reward provided by a very modest amount of peanut butter in each card (3–5 g), suggesting that peanut butter was more attractive than the alternative natural foods available.

The willingness of possums that had survived not just one but two 1080-baitings to accept peanut butter was unexpected. One explanation is that peanut butter may simply be a far more attractive bait than the other bait types tested. Alternatively, the aversion to those other bait types may be at least partly related to their broad similarity in size, shape, and (at least for the cereal bait types) texture. It has long been known that some species, such as rats, tend to avoid new objects as well as new foods (Cowan 1977; Inglis et al. 1996). If so, a more radical change in bait types between baiting events may have been more effective for possums than the modest change in this study, as suggested previously (Morgan & Hickling 2000). Ross et al. (2000) found that changing from cereal pellet bait to a gel bait resulted in 64% mortality of possums that had previously been sub-lethally poisoned by 1080-cereal pellet bait.

A third explanation is that possums accepted peanut butter but not the other bait types because they had already been exposed to it (i.e. pre-fed) twice before and twice immediately after the first 1080 baiting with no ill effects, and so continued to accept it. If so, dual 1080 baiting with two bait types could be conducted by pre-feeding with both bait types before the first 1080 baiting.

Implications

Our results imply that rapid-repeat dual 1080 baiting does have the potential to locally eliminate rats. If our first 1080 baiting had been pre-fed even just once, very few rats would have remained to be killed and previous research with possums suggests that as pre-fed survivors they would perhaps have been less strongly bait averse than those not pre-fed (Ross et al. 2000). We speculate that using only one pre-feed instead of two between the two toxic batings may have been enough.

In contrast, local elimination of possums appears unlikely to be achievable using dual 1080 baiting if some possums survive the first baiting with a learned bait aversion and if the second bait type is not sufficiently different from the first. Therefore, the best option currently available for achieving local elimination of possums with 1080 baiting appears to be multiple pre-feeds (Nugent et al. 2011) and a single sowing of 1080 bait at high sowing rates (2–5 kg ha^{-1}) using large (>10 g) individually-lethal baits (Latham et al. 2017). However, our results and previous findings (Ross et al. 2000) indicate that bait-averse possums may be able to be poisoned if a very different bait type is used for the second 1080 baiting. A peanut-butter-based bait would be one option (or use of baits even more attractive than peanut butter; Jackson et al. 2016). As no bait type other than cereal is currently registered for aerial 1080 baiting, the second baiting might initially need to be conducted (as in this trial) with aerial pre-feeding, but hand-laying of the alternative 1080 bait type, which already has been demonstrated to be effective at operational scales (Morgan et al. 2015). Another avenue of potential research could focus on determining whether pre-feed sequencing (e.g. pre-feeding with two different bait types ahead of the first 1080 baiting) can overcome the broad learned aversion exhibited by surviving possums after a first 1080 baiting.

Overall, we conclude that dual application of 1080, with both applications preceded by non-toxic pre-feeding using the same bait no more than a few months apart, has the potential to locally eliminate rats from large areas, and that, with further development involving the use of two very different bait types and/or different pre-feed sequencing, it could potentially achieve the same for possums.

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Consents and approvals

This project was conducted as an experimental component of a large-scale poison-control operation (for TB vector control) conducted by OSPRI over 92 000 ha in the West Coast region of the South Island during the spring of 2016 (September–November) (https://www.ospri.co.nz/assets/Uploads/Documents/New-Creek-West-Coast-Tasman-aerial-operation-July-2016.pdf). Consents and approvals for this aerial broadcast-delivery operation are listed in the Environmental Protection Agency report for this OSPRI operation; and were extended for hand-delivery of poison bait by Community & Public Health (West Coast) approval no. 16/984/GRYPH/CB and by Department of Conservation approval no. 2850656, both granted to Manaaki Whenua – Landcare Research. Additionally, approval to trap, sedate, and attach radio-collars to possums, and to conduct experiments involving poison application to animals (possums and rats) for research purposes, was granted by Manaaki Whenua – Landcare Research Animal Ethics Committee approval number 16/05/02.

References

Birch LL, Anzman-Frasca S 2011. Promoting children's healthy eating in obesogenic environments: lessons learned from the rat. Physiology & Behavior 104: 641–645.

Brown K, Elliott G, Innes J, Kemp J 2015. Ship rat, stoat and possum control on mainland New Zealand. An overview of techniques, successes and challenges. Wellington, Department of Conservation.

Clout M, Gaze P 1984. Brushtail possums (*Trichosurus vulpecula* Kerr) in a New Zealand beech (*Nothofagus*) forest. New Zealand Journal of Ecology 7: 147–155.

Coleman J 1988. Distribution, prevalence, and epidemiology of bovine tuberculosis in brushtail possums, *Trichosurus vulpecula*, in the Hohonu Range, New Zealand. Wildlife Research 15: 651–663.

Coleman J, Fraser K, Nugent G 2007. Costs and benefits of pre-feeding for possum control. New Zealand Journal of Zoology 34: 185–193.

Cowan P 1977. Neophobia and neophilia: new-object and new-place reactions of three Rattus species. Journal of Comparative and Physiological Psychology 91: 63.

Crews K, Nugent G 2018. Proving freedom from TB: the

pathway to eradication. DairyNZ Technical Series 38: 11–13.
Eason CT, Murphy EC, Wright GR, Spurr EB 2002. Assessment of risks of brodifacoum to non-target birds and mammals in New Zealand. Ecotoxicology 11: 35–48.
Elliott G, Kemp J 2016. Large-scale pest control in New Zealand beech forests. Ecological Management & Restoration 17: 200–209.
Forsyth DM, Ramsey DS, Perry M, McKay M, Wright EF 2018. Control history, longitude and multiple abiotic and biotic variables predict the abundances of invasive brushtail possums in New Zealand forests. Biological Invasions 20: 2209–2225.
Henderson RJ, Frampton CM, Morgan DR, Hickling GJ 1999. The efficacy of baits containing 1080 for control of brushtail possums. The Journal of Wildlife Management 68: 1138–1151.
Inglis I, Shepherd D, Smith P, Haynes PJ, Bull DS, Cowan DP, Whitehead D 1996. Foraging behaviour of wild rats (*Rattus norvegicus*) towards new foods and bait containers. Applied Animal Behaviour Science 47: 175–190.
Innes J 2005. Ship rat. In: King CM ed. The handbook of New Zealand mammals. Melbourne, Oxford University Press. Pp. 187–203.
Innes J, Warburton B, Williams D, Speed H, Bradfield P 1995. Large-scale poisoning of ship rats (*Rattus rattus*) in indigenous forests of the North Island, New Zealand. New Zealand Journal of Ecology 19: 5–17.
Jackson M, Hartley S, Linklater W 2016. Better food-based baits and lures for invasive rats *Rattus* spp. and the brushtail possum *Trichosurus vulpecula*: a bioassay on wild, free-ranging animals. Journal of Pest Science 89: 479–488.
Latham A, Gormley A, Thomson C, Latham M, Whitford J, Nugent G 2017. Optimal size of cereal pellet baits for aerial control of possums: a field study (OSPRI Project R-10756). Landcare Research Contract Report LC2893 (unpubl.). Lincoln, New Zealand, Landcare Research. 32 p.
Modlinska K, Stryjek R 2016. Food neophobia in wild rats (*Rattus norvegicus*) inhabiting a changeable environment—a field study. PloS one 11: e0156741.
Morgan D, Hickling G 2000. Techniques used for poisoning possums. In: Montague T ed. The brushtail possum: biology, impact and management of an introduced marsupial. Lincoln, New Zealand, Manaaki Whenua Press. Pp. 143–153.
Morgan D, Morriss G, Hickling G 1996. Induced 1080 bait-shyness in captive brushtail possums and implications for management. Wildlife Research 23: 207–211.
Morgan D, Nugent G, Warburton B 2006. Benefits and feasibility of local elimination of possum populations. Wildlife Research 33: 605–614.
Morgan D, Scobie S, Arthur D 2012. Evaluation of Zoletil and other injectable anaesthetics for field sedation of brushtail possums (*Trichosurus vulpecula*). Animal Welfare-The UFAW Journal 21: 457.
Morgan D, Warburton B, Nugent G 2015. Aerial prefeeding followed by ground based toxic baiting for more efficient and acceptable poisoning of invasive small mammalian pests. PloS one 10: e0134032.
Morriss GA 2007. EPRO deer repellent baits for possum control: review of development and use 2001–2007. Landcare Research Contract Report LC0607/147 (unpubl.). Lincoln, New Zealand, Landcare Research. 20 p.
Moss ZN, O'Connor CE, Hickling GJ 1998. Implications of prefeeding for the development of bait aversions in brushtail possums (*Trichosurus vulpecula*). Wildlife Research 25: 133–138.
Nugent G, Morriss GA 2013. Delivery of toxic bait in clusters: a modified technique for aerial poisoning of small mammal pests. New Zealand Journal of Ecology: 246–255.
Nugent G, Turner J, Warburton B 2009. Sustained recall of bait acceptability in captive brushtail possums (*Trichosurus vulpecula*). New Zealand Journal of Zoology 36: 473–478.
Nugent G, Morgan D, Clayton R, Warburton B 2010. Improving the efficacy of aerial poisoning of brushtail possums (*Trichosurus vulpecula*) through reduced fragmentation of bait. International Journal of Pest Management 57: 51–59.
Nugent G, Warburton B, Thomson C, Sweetapple P, Ruscoe WA 2011. Effect of prefeeding, sowing rate and sowing pattern on efficacy of aerial 1080 poisoning of small-mammal pests in New Zealand. Wildlife Research 38: 249–259.
Nugent G, Warburton B, Thomson C, Cross ML, Coleman MC 2012. Bait aggregation to reduce cost and toxin use in aerial 1080 baiting of small mammal pests in New Zealand. Pest Management Science 68: 1374–1379.
Nugent G, Buddle B, Knowles G 2015. Epidemiology and control of *Mycobacterium bovis* infection in brushtail possums (*Trichosurus vulpecula*), the primary wildlife host of bovine tuberculosis in New Zealand. New Zealand Veterinary Journal 63: 28–41.
Nugent G, Sweetapple P, Yockney I, Morriss G 2017. TB freedom in the Hauhungaroa Range: a large-scale test of a new surveillance approach. Landcare Research Contract Report LC2842 (unpubl.). Lincoln, New Zealand, Landcare Research. 49 p.
O'Connor C, Matthews L 1999. 1080-induced bait aversions in wild possums: influence of bait characteristics and prevalence. Wildlife Research 26: 375–381.
Ogilvie S, Thomas M, Morriss G, Morgan D, Eason C 2000. Investigation of sodium monofluoroacetate (1080) bait shyness in wild brushtail possum (*Trichosurus vulpecula*) populations. International Journal of Pest Management 46: 77–80.
OSPRI 2017. Annual report 2016/2017. OSPRI New Zealand. 104 p.
PF2050 2016. About us. http://pf2050.co.nz/about-us/ (accessed 10 August 2018).
Ross J, Hickling G, Morgan D, Eason C 2000. The role of non-toxic prefeed and postfeed in the development and maintenance of 1080 bait shyness in captive brushtail possums. Wildlife Research 27: 69–74.
Speedy C 2005. Field trials and operational results of a deer repellent for 1080 possum baits. New Zealand Journal of Forestry 50: 27.
Speedy C, Day T, Innes J 2007. Pest eradication technology-the critical partner to pest exclusion technology: the Maungatautari experience. In: Witmer GW, Pitt WC, Fagerstone KA eds. Managing vertebrate invasive species: proceedings of an international symposium. Fort Collins, CO, USA. USDA/APHIS/WS, National Wildlife Research Center. Pp. 115–126.
Sweetapple P, Nugent G 2011. Chew-track-cards: a multiple-species small mammal detection device. New Zealand Journal of Ecology 35: 153–162.
Warburton B, Livingstone P 2015. Managing and eradicating wildlife tuberculosis in New Zealand. New Zealand Veterinary Journal 63: 77–88.
Warburton B, Clayton R, Nugent G, Graham G, Forrester G 2010. Effect of prefeeding on foraging patterns of brushtail

possums (*Trichosurus vulpecula*) about prefeed transects. Wildlife Research 36: 659–665.

ZIP 2018. 1080 to Zero: A modified technique for the complete removal of possums and rats. http://zip.org.nz/findings/2017/11/1080-to-zero-a-modified-technique-for-the-complete-removal-of-possums-and-rats (accessed 10 August 2018).

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Supplementary material

Additional supporting information may be found in the supplementary material file for this article:

Appendix S1. Map of the study area.

Appendix S2. Non-target effects of pre-fed hand-laid 1080 baiting with EDR-coated RS5 cereal bait.

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