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## RESEARCH

# Dual aerial 1080 baiting operation removes predators at a large spatial scale

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**Abstract:** As New Zealand attempts to become predator free by 2050, transitioning aerial 1080 (sodium fluoroacetate) operations from predator control to complete predator removal has become an important research objective. Aerial 1080 operations may not remove every last target animal, but they may be able to remove a very high proportion (> 0.99). We trialled a modified [dual] aerial 1080 operation for the removal of brushtail possums (*Trichosurus vulpecula*), ship rats (*Rattus rattus*), and stoats (*Mustela erminea*) at large spatial scale. Our trial involved two toxin applications (TA#1 & TA#2), each preceded by two applications of non-toxic pre-feed bait. Different types of cereal baits and lures were used for each toxin application. Camera traps (*n* = 142; 200–1431 m asl) were used to detect the target species and to incidentally observe house mouse (*Mus musculus*), birds, and ungulates across the study area. The operation had no significant impact on the number of cameras detecting most birds and ungulate species; however, house mouse, blackbird (*Turdus merula*), and red deer (*Cervus elaphus*) were detected on significantly fewer cameras after TA#1 than before. Numbers of cameras that detected target species were significantly reduced for all three target species after TA#1, and significantly reduced again for possums after TA#2, when no stoats were detected on cameras and a small number of cameras detected rats. Mean relative abundance estimates based on camera trap indices (proportion of camera trap days that target species were detected) showed the operation appears to have removed over 99% of ship rats, stoats, and possums.

**Keywords:** Wildlife management, sodium fluoroacetate (1080), camera traps, invasive species

## Introduction

New Zealand is a hotspot for endemic biodiversity (Myers et al. 2000), and many native vertebrate species are vulnerable to predation from invasive mammals (Byrom et al. 2016; Elliott & Kemp 2016). In 2016, the New Zealand government announced a goal to be predator free by 2050. Since then, there has been an increased focus on the complete removal of brushtail possums (*Trichosurus vulpecula*), ship rats, Norway rats, and pacific rats / kiore (*Rattus rattus*, *R. norvegicus*, *and R. exulans*), and mustelids (*Mustela furo*, *M. nivalis*, *M. erminea*) throughout New Zealand (Russell et al. 2015a).

Aerial baiting with sodium fluoroacetate (1080) is used over parts of New Zealand's forested landscape for suppressing populations of possums and ship rats (Eason et al. 2011; Kemp et al. 2019; Nugent et al. 2019) for the benefit of native biodiversity, and for reducing the incidence of bovine tuberculosis (TB) in possums that may infect cattle (Warburton & Livingstone 2015). These operations also remove stoats through secondary poisoning (Dilks et al. 2020; Murphy et al. 1999).

Modern large-scale aerial 1080 operations for predator suppression typically consist of one non-toxic pre-feed application followed by one toxic application (Dilks et al. 2020). However, some possums and rats survive aerial 1080 operations for reasons such as plentiful natural food (Elliott & Kemp 2016), not encountering a toxic bait, or not eating bait quickly enough to ingest a lethal dose before the onset of sublethal toxicosis (Graham Nugent et al. 2019). As the focus shifts towards local elimination and eventual eradication of ship rats, possums, and stoats rather than ongoing suppression (Russell et al. 2015), modified aerial baiting techniques have been trialled. These have involved increased sowing rates, multiple pre-feeds, and multiple toxin applications of differently-lured baits in a single season (Bell 2017; Nugent et al. 2019). Pre-feed applications significantly reduce the incidence of bait shyness in possums (Ross et al. 2000). Dual toxin applications implemented a few months apart have shown potential for the local elimination of ship rats ( Nugent et al. 2019). Compound 1080 is an acute toxin, meaning the onset of toxic symptoms is rapid and any sub-lethal dose is likely to result in aversion (Ross et al. 2000; Morgan et al. 2002; Nugent et al. 2019). There may always be survivors of predator removal operations, despite multiple pre-feeds and high sowing rates of toxic bait used in these modified operations (Graham Nugent et al. 2019). However, switching lures and cereal bait types can reduce bait shyness in captive possums (Moss et al. 1998; O'Connor & Matthews 1999).

This study evaluates a highly modified aerial 1080 operation consisting of two toxin applications (with higher

sowing rates than is now usual) in a single season, each with two non-toxic pre-feeds, for the removal of possums, ship rats, and stoats at large scale. This contrasts with the usual approach in modern aerial 1080 baiting in which a single sowing of 1080 bait is preceded by a single prefeed. We used camera traps primarily, as well as chew cards (Sweetapple & Nugent 2011) to estimate relative abundance of target species before and after the operation. We recorded incidental camera trap footage of non-target species (house mice *Mus musculus*, birds, and ungulates) across the site, and compared numbers of cameras with detections for each species before and after each toxin application.

## Methods

### Study area

The Perth River Valley study area (43.2616° S, 170.3590° E) spans approximately 10 000 ha in the wider Whataroa valley in South Westland, New Zealand. The Whataroa and Perth valleys have been subject to cyclical aerial 1080 operations for possum control since 1997, with the most recent in 2015 (Stephens & Grunner, unpubl. report). The Perth Valley has been identified as a priority site in the Department of Conservation's (DOC) ecosystems prioritisation programme (Brown & Urlich 2005). A primary reason we selected this study area was its natural barriers to slow target species reinvasion. The study area lies between two substantial rivers: the Perth River and the Barlow River. These rivers join to form its western boundary, with the Bettison Stream at the southern boundary. The main divide of the Southern Alps forms the northern and eastern boundary, with the highest point at 2543 m above sea level. Vegetation in the study area consists mostly of indigenous forest, including southern rātā (*Metrosideros umbellata*), rimu (*Dacrydium cupressinum*), and kāmahi (*Weinmannia racemosa*) from 200 m to 1100 m asl. Below the treeline are makomako (*Aristotelia serrata*), kōtukutuku (*Fuchsia excorticata*), horoeka (*Pseudopanax crassifolius*), Hall's tōtara (*Podocarpus hallii*), māhoe (*Melicytus ramiflorus*), patē (*Schefflera digitata*), and haumakaroa (*Raukaua simplex*) (Stephens & Grunner 2016). Above the treeline, vegetation is primarily snow tussock (wī kura; *Chionochloa* spp.) grassland and herb fields up to approximately 1800 m asl. Above this elevation are glaciers and bare rock.

In 2019, forests and alpine grasslands experienced a heavy mast, a periodic event defined by synchronous heavy seed production (Norton & Kelly 1988). This ecological condition was confirmed by reports of unusually high levels of fruit and seed fall throughout forests in New Zealand (Department of Conservation 2019). In South Westland, rimu and snow tussock were expected to mast in autumn 2019, consistent with previous mast seeding events (Rees et al. 2002; Harper 2005). Sampling of rimu in the study area confirmed that it was masting in 2019. The aerial operation in the current study was intended for 2018 (a non-mast year), but heavy and prolonged snow fall forced postponement to 2019.

### Treatment

Toxin applications were separated by 3.5 months. Each toxin application was preceded by two non-toxic pre-feed applications. All cereal bait was manufactured by Orillion (Wanganui, New Zealand). Toxic baits were dyed green, in accordance with regulations to protect field workers and minimise interaction by birds (Moss et al. 1998; Weser & Ross 2013). Pre-feed baits were also dyed green as part of ongoing kea (*Nestor notabilis*) risk mitigation work (Nichols et al. 2020; Nichols & Bell 2019). Deer repellent was not included in baits as the risk of attracting kea was assumed to be high, and any changes to the baits would interfere with bait aversion training of kea (Nichols & Bell 2019). In toxin application 1 (TA#1), the total area treated was 8659 ha and up to an elevation of 1800 m asl, to ensure all vegetated areas (predator habitat) were treated. In toxin application 2 (TA#2), the total area treated was 6130 ha, and up to an elevation of 1200 m asl (above the treeline to ensure rats were exposed, but below the high alpine in accordance with the detection history of predators at the site, Table 2). Permission was granted by the Medical Officer of Health (Community and Public Health, a division of the Canterbury District Health Board), and DOC, to aerially sow bait to the river edge and around public huts, thus removing any exclusion zones from the treatment area. Hut rainwater collection was disconnected, and roofs cleared of bait before reconnection, as part of the conditions of this permission.

All bait was aerially distributed by underslung buckets flown by GPS-guided helicopters. All baits (pre-feed and toxic) in TA#1 were Wanganui #7 (W#7) double orange-lured 6 g cereal pellets (Table 1). Pre-feed baits were sown with a 10% sowing overlap for both pre-feed applications making 2 kg ha$^{-1}$ on the ground (all bait quantities that follow are ground coverage). Toxic baits containing 0.15% 1080 were sown at 4 kg ha$^{-1}$, with a 50% sowing overlap (Table 1). All baits (pre-feed and toxic) in TA#2 were RS5 double cinnamon-lured 6 g cereal pellets (Table 1). In TA#2, pre-feed baits were sown at 1 kg ha$^{-1}$, with a 10% sowing overlap for both pre-feed applications, and toxic baits containing 0.15% 1080 were sown at 2 kg ha$^{-1}$, with a 50% sowing overlap (Table 1). The reduction in bait quantity for TA#2 and its pre-feeds was in recognition that, with many fewer predators present, home ranges may increase (Margetts et al. 2020). Caching of baits by predators during prefeed would be undesirable if it meant that toxic baits were not consumed. One kg ha$^{-1}$ was near the lower limit of effective bucket operation.

Several other changes were made from a standard suppression operation to maximise the chances of exposing all animals to toxic bait, adapting methods used in offshore island eradication and previous experience (Bell et al. 2019). Helicopter contractors were paid by time rather than area or bait volume. A conservative view was taken of the nominal bucket broadcasting swathe width, which resulted in a reduction from 200 m to 180 m for several buckets. Swathe separation was thus 162 m for 10% overlap and 90 m for 50% overlap. Pilots were requested to keep speed as constant as possible and required to re-sow any lines with a speed greater than 10% of average. Drift of bait in the air was a consideration in planning. The relative isolation of the study area meant that no bait exclusion zones were required, allowing bait spread outside the target boundary and guaranteeing spread up to the edges of the block.

The area was divided into blocks of 500–2000 ha and the swathe direction specified for each block to approximately follow terrain contours, so that pilots would stay as close as possible to the minimum effective distance above the terrain or canopy. A target windspeed of 5 km h$^{-1}$ sustained (10 km hr$^{-1}$ gust) was used in planning, but in practice most days that had suitable forecasts, for 48 hours without rain following, had low wind on the day. The schedule of blocks and sow lines through the day was rearranged to take advantage of low

**Table 1.** Timeline and overview of each toxin application and detection network deployment in the Perth River Valley, South Westland, in 2019. All cereal bait was aerially deployed. Camera trap surveys were continuous throughout the operation. Asterisks indicate the first date chew cards were deployed, as not all could be deployed on the same day.

| Operation and detection | Dates (2019) | Deployment specifications | Notes |
|---|---|---|---|
| Camera traps | Pre operation; 22 February—12 April | $n = 142$; 700 m × 500 m spacing | Camera traps were serviced continuously throughout 2019. |
| **Toxin application 1:** Wanganui #7, double orange-lured | | | |
| Pre-feed 1 | 19 March | 6 g pellets 2 kg ha$^{-1}$ | |
| Pre-feed 2 | 3 April | 6 g pellets 2 kg ha$^{-1}$ | |
| 1080 baiting | 13–14 April | 6 g pellets 4 kg ha$^{-1}$ | |
| Possum collared ($n = 1$) | 23 May | GPS collar | Adult female within the treatment area. Captured, collared, and released 39 days after toxin application 1 |
| Chew cards | *7 June | $n = 3000$; 700 × 20 m spacing | Deployed 7.5 weeks before toxin application 2 |
| **Toxin application 2:** RS5, double cinnamon-lured | | | |
| Pre-feed 1 | 18 June | 6 g pellets 1 kg ha$^{-1}$ | |
| Pre-feed 2 | 24 June | 6 g pellets 1 kg ha$^{-1}$ | |
| 1080 baiting | 22–23 July | 6 g pellets 2 kg ha$^{-1}$ | |
| **Post-toxin application 2 detection** | | | |
| Chew cards Camera traps | 24 July—9 September | | Both detection networks ran continuously through October 30. Analysis completed through first 7 weeks after TA#2 |

**Table 2.** Percentage of camera traps that detected the target species at different altitudes in the study area pre-toxin application #1. Perth River Valley, February–April 2019.

| Camera Altitude (m asl) | Number of Cameras | Ship Rat (%) | Possum (%) | Stoat (%) |
|---|---|---|---|---|
| 200–400 | 15 | 100 | 100 | 46 |
| 400–600 | 35 | 94 | 100 | 43 |
| 600–800 | 29 | 86 | 100 | 62 |
| 800–1000 | 30 | 53 | 96 | 50 |
| 1000–1200 | 25 | 36 | 96 | 32 |
| 1200–1431 | 8 | 0 | 100 | 13 |
| **Total camera network** | **142** | 69 | 99 | 45 |

wind speed where possible. Bait remaining at the end of each operation was sown (1) along any narrow valleys perpendicular to swathe direction, (2) on steep slopes with vegetation, and (3) on the low-altitude podocarp forest considered the most favourable habitat for target species. Animal ethics committee approval (Lincoln University AEC-2016-28) was obtained to live-capture (cage trap) and attach GPS collars (Sirtrack Ltd; model: LiteTrack 30) to any surviving possums detected at any point post-aerial toxin deployment.

**Camera traps**

Relative abundance calculated from camera trap detections is often used to assess the results of predator control operations (Bengsen 2014; Dilks et al. 2020; Glen et al. 2014; Glen & Peace 2020; Nugent et al. 2019). As such, cameras were not expected to record every individual of each target species. However, we aimed to distribute cameras across all potential target species' habitats. We used a network of 142 camera traps (Browning Dark Ops 6HD-940, Prometheus Group,

Birmingham, Alabama) with 500-m spacing between devices on cut tracks, at elevations ranging from 200−1431 m asl (Fig. 1; Table 1). Cameras were deployed on all accessible main tracks (continuous along inside perimeter of study area) and interior tracks (these intersect with main tracks and extend inwards towards the core of the study area) spaced approximately 500 m apart (Fig. 1).

All cameras were mounted on trees (or steel fence posts as required above the treeline) with the base of each camera 45 ± 10 cm from the ground. Cameras were set to take a series of three photos per trigger, with a delay of 5 seconds (the minimum possible time delay) between triggers. Cameras were lured with Best Food's™ egg mayonnaise dispensed from automated lure dispensers, known as MotoLures (ZIP 2019a), at a rate of 0.25 ml three times per day. MotoLures were mounted on trees (or steel fence posts as required above the treeline) 1.5 m directly in front of the camera's field of view to increase the chance of small mammals being detected (Glen et al. 2013).

Camera surveys were conducted for seven weeks before and after TA#1 and for 7 weeks before and after TA#2 (Table 1). Importantly, the risk of confounded results from possible reinvasion by dispersing animals (particularly stoats and possums), and breeding rats was expected to increase after the seven weeks of surveys following TA#2 (Byrom et al. 2015; King & McMillan 1982).

**Chew cards**

For detection of rats and possums, we attempted to increase spatial coverage by adding chew cards (Sweetapple & Nugent 2011) (*n* = 3000) at approximately 20-m spacing on all accessible main tracks and interior lines. Chew cards, which are rectangles of corrugated plastic (Corflute) (Waters et al., 2017), were lured with Pic's™ peanut butter and deployed in addition to the camera traps. Chew cards were deployed before and after TA#2 only (Table 1), and were replaced every 21 days on average.
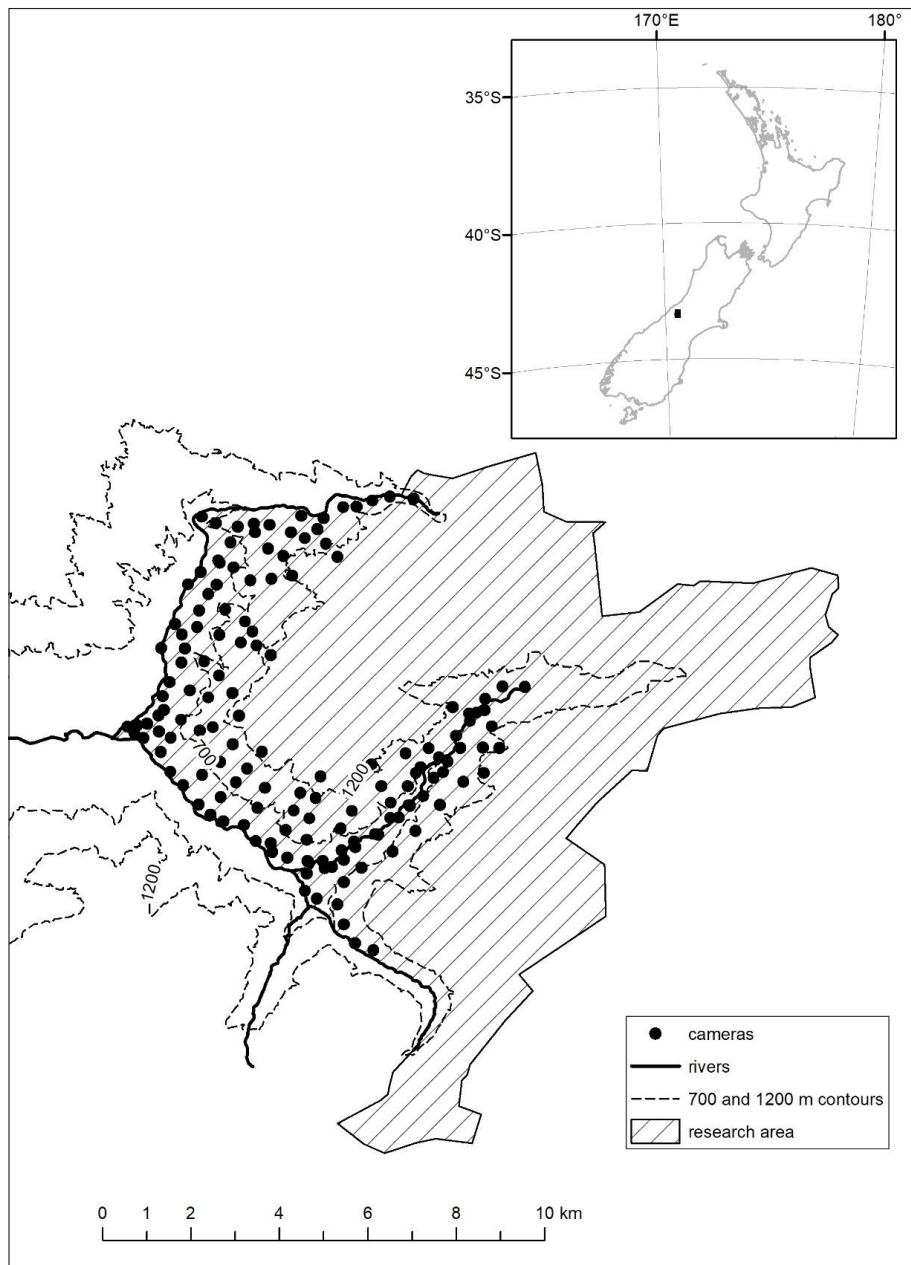


**Figure 1.** The Perth River Valley camera trap network in 2019. Cameras were spaced approximately 500 m apart, at 200–1431 m asl.

## Analysis

We used camera traps to estimate an index of relative abundance for each of the three target species (Rovero & Marshall 2009). Detections for each target and non-target species monitored were recorded as '1' or '0' per 24-hr period, taken from noon to noon for nocturnal species such as rats and possums, and midnight to midnight for stoats, birds, and ungulates.

The proportion of camera-trap days with a detection $p$ was amalgamated by week for the seven weeks before and after each toxin application.

The proportion $p$ was further averaged across each seven-week period before and after each toxin application to produce a single value before $p_0$, and a single value after each toxin application $p_1$. We calculated a linear index of animal density λ, by a Poisson transformation (Hone 1988):

$$\lambda = -\ln(1-p) \tag{1}$$

Two-tailed Fisher's exact tests of the odds ratio (Sokal & Rohlf 1981):

$$\theta = p_1(1-p_0)/(p_0(1-p_1)) \tag{2}$$

were used to test whether there was a difference in the number of cameras detecting a species before and after each toxin application. Results with $P < 0.05$ were deemed statistically significant. We used this test for both target and non-target species. Occupancy modelling was not deemed appropriate for this study as sample sizes of detections were very small after each toxin application.

## Results

### Camera traps

All three target species were seen on camera traps pre-operation (Table 2). Possums and stoats were detected on cameras up to 1431 m asl, while no rats were detected on cameras above 1160 m asl. Of the total camera network available during pre-operation surveys, rats were seen on 69% of cameras, possums on 99% of cameras, and stoats on 45% of cameras.

The non-target species recorded on cameras were house mice, birds, and ungulates. Bird species included song thrush (*Turdus philomelos*), blackbird, South Island tomtit (ngirungiru, *Petroica macrocephala*), New Zealand fantail (pīwakawaka, *Rhipidura fuliginosa*), bellbird (korimako, *Anthornis melanura*), silvereye (tauhou, *Zosterops lateralis*), and South Island robin (kakaruwai, *Petroica australis*). Ungulates recorded on cameras included Himalayan tahr (*Hemitragus jemlahicus*), chamois (*Rupicapra rupicapra*), and red deer.

### Target species

The proportion of camera trap days that detected species before and after each toxin application can be found in Figs 2a, b, and c. Mean relative abundance, shown as the proportion $p$ further averaged across seven-week periods to produce a single value
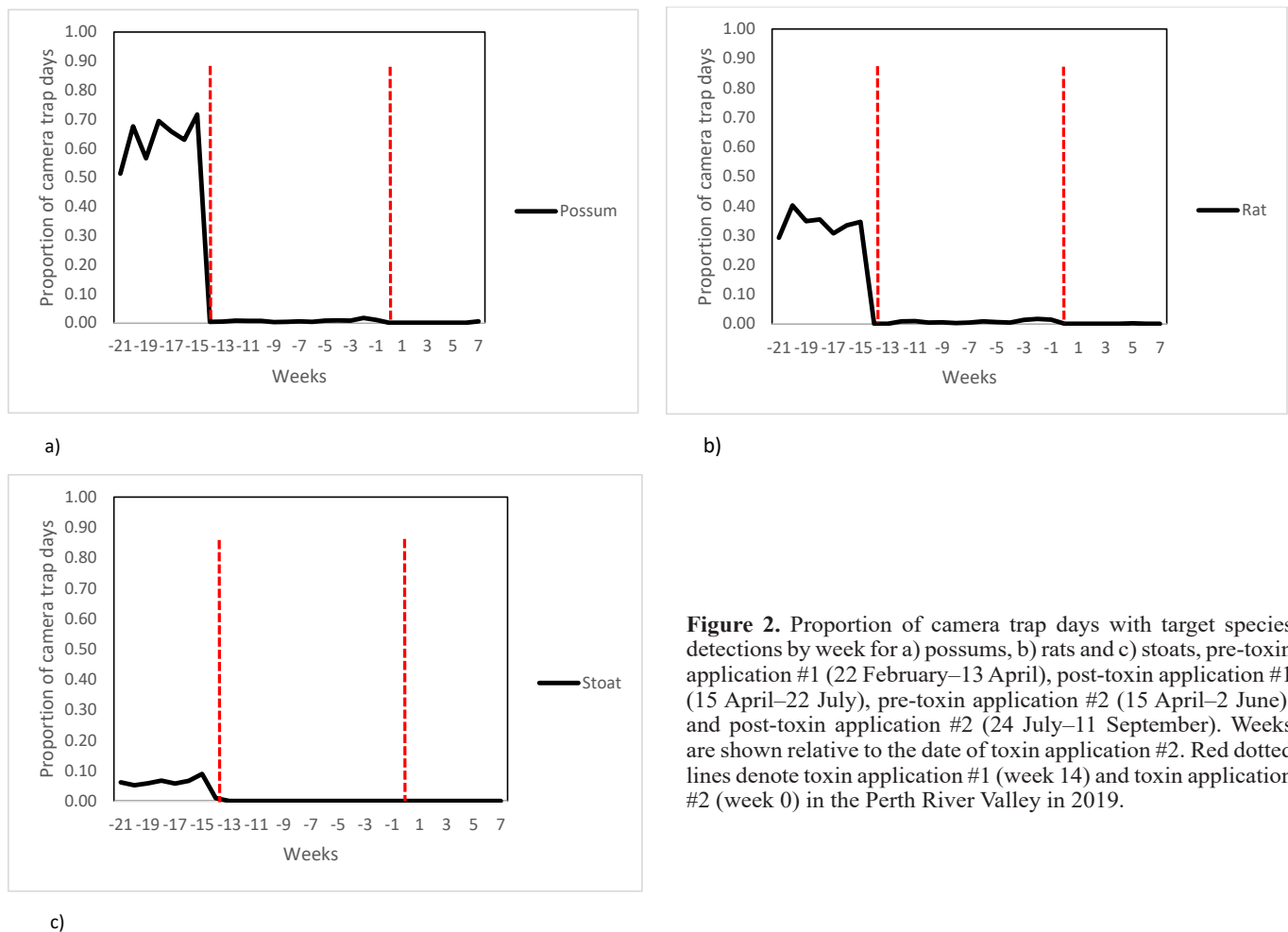


a)



b)



c)

**Figure 2.** Proportion of camera trap days with target species detections by week for a) possums, b) rats and c) stoats, pre-toxin application #1 (22 February–13 April), post-toxin application #1 (15 April–22 July), pre-toxin application #2 (15 April–2 June), and post-toxin application #2 (24 July–11 September). Weeks are shown relative to the date of toxin application #2. Red dotted lines denote toxin application #1 (week 14) and toxin application #2 (week 0) in the Perth River Valley in 2019.

before each toxin application, $p_0$, and a single value after each toxin application, $p_1$, and the linear index of animal density $\lambda$ ($\pm$ SE) can be found in Table 3. TA#1 reduced detections (based on the linear index $\lambda$) of possums and rats each by 99%, and 98% for stoats. TA#2 reduced detections of possums by a further 93%, and rats by 99%. No stoats were detected after the first week post-TA#1.

Possums, rats, and stoats all showed a significant reduction in the number of cameras with detections after TA#1 (Fisher's exact test, $P < 0.01$, Table 4). Cameras detecting possums were significantly reduced again after TA#2 ($P < 0.01$), and again, no stoats were detected before or after TA#2. The number of cameras detecting rats did not differ significantly before and after TA#2 ($P = 0.06$); however, sample sizes for this test were small ($n = 9$ cameras before TA#2, and $n = 2$ cameras after TA#2).

One possum that presumably survived TA#1, an adult female, was live-captured and fitted with a GPS collar 39 days after the TA#1 (Table 1). This individual was recorded on two camera traps on the same line (500 m apart), nine days after capture. It then visited each of these cameras on at least two of the next three days. This individual was then not seen again for nearly a month, before appearing on the same two cameras regularly for the next three weeks. Its GPS-collar was detected in mortality mode seven days after TA#2.

**Chew cards**

Prior to TA#2, possums were detected on four chew cards, and rats on 18. After TA#2, neither possums nor rats were detected on chew cards. Chew cards were not lured for stoat detection, and no stoat chew-marks were found.

**Non-target species**

Camera detections of mice decreased to zero in the first week following TA#1, and remained so for the following seven weeks (Table 4). Mice were detected again pre-TA#2, and although camera detections of mice decreased to zero in the first week following TA#2, they were detected again two weeks later. Blackbirds were detected on significantly fewer cameras post TA#1, while the number of cameras that detected silvereye increased dramatically after TA#1 (Table 4). Silvereye showed interest in the chew cards and the egg mayonnaise lure at camera trap sites. The ungulate species tahr and chamois showed little change in camera detections throughout the operation, but red deer were detected on significantly fewer cameras following TA#1 than before (Table 4).

**Table 3.** Proportion $p$ of camera trap days with target species detections, and corresponding linear index of animal density ($\lambda \pm$ SE, based on a Poisson transformation of $p$), averaged for the seven weeks before and after each toxin application in the Perth River Valley in 2019.

| Species | Proportion of camera trap days | | | | Animal density index | | | |
|---|---|---|---|---|---|---|---|---|
| | Before TA#1 ($p_0$) | After TA#1 ($p_1$) | Before TA#2 ($p_0$) | After TA#2 ($p_1$) | Before TA#1 ($\lambda_0$) | After TA#1 ($\lambda_1$) | Before toxin 2 ($\lambda_0$) | After toxin 2 ($\lambda_1$) |
| Possum | 0.64 | 0.004 | 0.008 | 0.001 | $1.03 \pm 0.07$ | $0.004 \pm 0.001$ | $0.008 \pm 0.002$ | $0.001 \pm 0.001$ |
| Rat | 0.34 | 0.004 | 0.009 | 0.000 | $0.42 \pm 0.02$ | $0.004 \pm 0.001$ | $0.009 \pm 0.002$ | $0.000 \pm 0.00$ |
| Stoat | 0.064 | 0.001 | 0.000 | 0.000 | $0.07 \pm 0.005$ | $0.001 \pm 0.00$ | 0 | 0 |

**Table 4.** Number of cameras that detected each species (target and non-target), pre- toxin application #1, post-toxin application #1, pre-toxin application #2, and post-toxin application #2 in the Perth River Valley in 2019. Two-tailed Fisher's exact test $P$-values show the results of statistical comparison of detections of each species before and after each toxin application. Asterisks denote significant values.

| Species | Pre TA#1 | Post TA#1 | Fisher exact test $P$-value | Pre TA#2 | Post TA#2 | Fisher exact test $P$-value |
|---|---|---|---|---|---|---|
| Possum | 140 | 8 | < 0.01* | 17 | 4 | < 0.01* |
| Rat | 98 | 4 | < 0.01* | 9 | 2 | 0.06 |
| Stoat | 64 | 9 | < 0.01* | 0 | 0 | NA |
| Mouse | 22 | 0 | < 0.01* | 3 | 3 | 1 |
| Song thrush | 17 | 9 | 0.2 | 10 | 10 | 1 |
| Blackbird | 49 | 15 | < 0.01* | 16 | 16 | 1 |
| South Island tomtit (Ngirungiru) | 38 | 26 | 0.1 | 27 | 21 | 0.4 |
| Fantail (Pīwakawaka) | 7 | 5 | 0.7 | 4 | 6 | 0.8 |
| Bellbird (Korimako) | 4 | 5 | 1 | 2 | 6 | 0.3 |
| Silvereye (Tauhou) | 2 | 4 | 0.7 | 81 | 90 | 0.3 |
| South Island robin (Kakaruwai) | 14 | 9 | 0.4 | 7 | 3 | 0.3 |
| Tahr | 16 | 25 | 0.2 | 12 | 17 | 0.4 |
| Chamois | 40 | 47 | 0.4 | 23 | 19 | 0.6 |
| Red deer | 24 | 5 | < 0.01* | 0 | 1 | 1 |

## Discussion

This study provides the first large-scale demonstration that dual application of 1080 bait during a 3.5-month period can reduce possum and rat numbers to near zero levels. The operation reduced our index of relative abundance by over 99% for possums, rats and stoats. The number of cameras that detected possums was significantly reduced further after the second toxin application (TA#2) compared with the first (TA#1), and stoats were no longer detected. These reductions from very low levels after TA#1 to even lower levels after TA#2 are consistent with the prediction by Nugent et al. (2019) that rats surviving a first 1080 baiting could be killed by a second baiting (following a second pre-feeding). Importantly, the further reduction in possum abundance indicates that repeat application of a second cereal bait type (RS5 vs W#7) can be effective for that species, which was not observed by Nugent et al. (2019).

It is likely that most, if not all, of the animals detected after TA#2 were resident survivors. Small-scale field trials suggest that rivers may be an obstacle at least to immediate reinvasion by most possums and rats, particularly in non-dispersal periods (Cook et al. 2021; ZIP 2019b). In contrast, rats detected on cameras after the dual 1080 field trial in Nugent et al. (2019) were found at the edges of the treatment blocks (no natural barriers), on a similar timeline (4–6 weeks), and assumed to be re-invaders. Distinguishing survivors and re-invaders after a removal operation is not possible with un-marked individuals and without genetic material for comparison (King et al. 2011; Russell et al. 2010). Throughout this study, we assumed few animals resided above the tussock-line (> 1600 m asl at the Perth Valley site). We are most certain of this limit for ship rats (Christie et al. 2009; Christie et al. 2017; O'Donnell et al. 2017); however, possums and stoats may be present at high elevations (Cowan 2005; King & Murphy 2005).

The degree to which rivers, mountain passes, and other natural features are barriers to movement of all three species requires further research. Stoats can swim across fast-flowing rivers (Murphy & Dowding 1994), but we detected no reinvasion by stoats during the post-operation survey period. Future research around the use of natural barriers may become increasingly important as projects aiming to achieve predator-free sites seek to maintain them following complete predator removal.

Chew cards in this study consistently detected fewer rats and possums than camera traps. As chew cards were deployed on the same tracks as cameras, there was always a chew card within a camera's field of view. Both possums and rats were occasionally seen to ignore these chew cards in favour of the MotoLures dispensing egg mayonnaise. One hypothesis is that the egg mayonnaise was simply more attractive than the peanut butter. Another hypothesis, based on the findings of Nugent et al. (2019), suggests MotoLures dispensing egg mayonnaise were simply more familiar to the surviving individuals than the chew cards with peanut butter. Although Nugent et al. (2019) also reported relatively low detections of rats by peanut butter chew cards, they were surprised by the upsurge in detections of possums when chew cards were refreshed. The deployment of chew cards differed in Nugent et al. (2019) as they were available to animals pre-operation. In contrast, chew cards in the current study were not deployed until prior to TA#2, because the number of chew cards required for 20-m spacing on all tracks across the site (*n* = 3000) made this device too labour-intensive for use in pre-operational monitoring. Our assumption

was that having chew cards available to survivors a few weeks before TA#2 would overcome any potential neophobia (Burge et al. 2017; Nugent et al. 2019). Surviving animals would have been much more familiar with the MotoLures, however, most of which were available continuously for nine months prior to the operation (ZIP 2018).

Field staff members reported unusually high levels of fruit and seed fall throughout the forest, with rimu in particular (Norton & Kelly 1988), and snow tussock at higher elevations in autumn 2019, consistent with a mast seeding event (Harper 2005; Rees et al. 2002). Where abundant natural food resources are available, the relative attractiveness of cereal bait pellets may be reduced (Elliott & Kemp 2016; Keitt et al. 2015). For this reason, the length of time between TA#1 and TA#2 was extended to 14 weeks (from an initially planned 4–6 weeks), in an attempt to avoid the period of highest natural food availability. Despite the delay, there seeds and fruit were abundant throughout the study area, which may have reduced the efficacy of the operation, particularly for rats. However, the additional time between toxin applications allowed changes to be made to the size of the treatment area in TA#2, based on camera detections. With few camera detections of target species after TA#1, and no detections above 1200 m, the treatment area was reduced.

The toxin applications reduced incidental camera detections of some non-target species. Mouse detections were significantly reduced after TA#1, but not after TA#2. There was no significant reduction in numbers of cameras that detected most bird and ungulate species after either toxin application. However, the number of cameras that detected blackbirds and red deer was significantly reduced after TA#1, but not TA#2 (with very small sample sizes for statistical tests after TA#2). Blackbirds are be affected by aerial 1080 operations (Morriss et al. 2016; Van Vianen et al. 2018), as are red deer with variable results (Malham et al. 2019; Nugent & Fraser 2005; Graham Nugent et al. 2019). We could not use deer repellent in conjunction with kea risk mitigation strategies, and although historical impacts of 1080 operations on deer have been highly variable, impacts can increase with higher rates of sowing (Morriss et al. 2020).

Although non-target species were seen on fewer cameras than target species, occupancy (site-use) does not equal abundance (Russell et al. 2015b). Low numbers of camera detections during the surveys and a lack of non-treatment sites for comparison, make it difficult to draw conclusions about the abundance of non-target species (Veltman & Westbrooke 2011). In future operations, calibrating camera trap detections to monitoring methods such as faecal counts for ungulates (Forsyth et al. 2007) and five-minute bird counts (Greene et al. 2013), would be useful to better interpret results from incidental camera data.

Overall, the modified 1080 operation appears to have removed a high proportion of possums and rats (and possibly all stoats) from the Perth River Valley study area. Modern aerial 1080 operations often have high kill rates (Dilks et al. 2020; Elliott & Kemp 2016). However, as operations move from focussing on suppression to local elimination and eradication, modifications for complete removal such as using two toxin applications may become more common (Bell 2017; Nugent et al. 2019). The full operation (including research and development costs and goods-and-services tax) was $155 ha$^{-1}$. We expect this cost to drop to $133 ha$^{-1}$ once the research and development costs are removed. Although the operation did not remove every resident individual possum and rat, the

reduction in camera trap detections was very high, suggesting that few animals remained and hence their removal using other methods might be feasible. Within each toxin operation and associated pre-feeds it is not possible to assess which of the modifications to a typical suppression operation (i.e. 2 kg ha$^{-1}$ rather than 1 kg ha$^{-1}$ for TA#1, 50% block overlaps, care taken over constant speed, minimisation of altitude), had the most success, without performing manipulative experiments. However, our results suggest that transitioning from predator control operations to complete removal using modified baiting techniques coupled with targeted mop-up of survivors, is a feasible initial step towards elimination and then eradication of predators in forested locations on mainland New Zealand (Bell et al. 2019; Murphy et al. 2019).

Large-scale, mainland eradication of multiple predators requires a suite of tools and techniques, including both ground-based and aerial methods. Refinements to aerial 1080 operations, as well as optimal deployment methods for detection devices, are necessary. In addition, further research into technologies and strategies for effective mop up of survivors, particularly those that may be averse to cereal baits (Nugent et al. 2020), is ongoing and necessary for the overall goal of New Zealand becoming predator free by 2050.

## Author contributions

MN, HN, and NM designed the study. MN and NM analysed the results. MN, HN, and NM wrote the manuscript.

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