Delivery of toxic bait in clusters: a modified technique for aerial poisoning of small mammal pests

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Abstract: Sowing 1080 baits for vertebrate pest control in clusters, rather than evenly, could potentially reduce toxin use. We developed a new technique for aerial delivery of 1080 baits in clusters and, in a set of four trials, compared its efficacy in controlling pests against conventional aerial broadcast baiting. In an initial trial where non-toxic prefeeding was not used (Molesworth Station, North Canterbury) we confirmed that aerial delivery of bait clusters is technically feasible and operationally practical. The reductions in possum activity indices achieved with cluster sowing (98.4%) were similar to those achieved with broadcasting sowing (97.8%), despite using 60% less 1080 bait (1 kg ha^{-1}). Comparable efficacy against possums was also recorded in the Landsborough Valley, Westland, where aligned prefeeding and an even lower sowing rate of toxic bait were used (0.25 kg ha^{-1}). In a third trial (Isolated Hill, Marlborough) the same cluster-sowing approach resulted in large reductions in possum and rat activity indices, but the possum reductions were more spatially variable than with broadcast baiting. At Maruia, Westland, near-total reductions in possum and rat activity were recorded with both broadcast and cluster sowing, even when there was a longer than usual interval (>30 days) between the aligned prefeeding and cluster baiting, and even when a wide (150 m) helicopter-flight-path spacing was used to reduce the cluster sowing rate of toxic bait to just 0.17 kg ha^{-1} (92% lower than the broadcast sowing rate used). These trials suggest that cluster baiting at lower-than-usual sowing rates could lower operational costs, and substantially reduce toxin usage, while maintaining high control efficacy against rats and possums in most cases. Reduced use of toxin might go some way to allaying public concerns over 1080 usage. Further operational testing is required to refine aerial cluster baiting and to identify the optimal balance between lowering costs and toxin use yet consistently achieving high control efficacy.

Keywords: 1080; aerial baiting; cluster sowing; possum; reduced toxin use

Introduction

The colonisation of New Zealand by humans and 32 other species of mammals in the last 700–800 years has caused major ecological transformations, some of which are considered desirable but many of which are not (King 2005). Of those established in the wild, the Australian brushtail possum (*Trichosurus vulpecula*) has had some of the most varied and pervasive impacts, and it remains a major agricultural and conservation pest. Possums are widespread and reach higher densities than in their homeland, competing with livestock, causing damage to plantation forests, and spreading disease (with their role as primary hosts of bovine tuberculosis (TB) particularly important); possums also cause major changes in native forest composition, and prey on native birds and invertebrates (Cowan 2005). Lethal control of possums has therefore been implemented over millions of hectares, using traps or toxins, to mitigate their unwanted effects. Aerial application of baits containing the toxin sodium fluoroacetate ('1080') is a key control tool in large forested and/or remote areas. In 2010, 438 000 ha of country were subjected to aerial 1080 baiting for pest control, receiving, on average, 2.9 g of 1080 per hectare (EPA 2010). New Zealand is globally unique in using an acute non-specific mammalian toxin in this way. That is possible primarily because, bats and seals aside, all the wild terrestrial mammals present are introduced species that are regarded as undesirable pests (King 2005). In other countries, aerial 1080 baiting is considered to pose too great a non-target risk to the valued native mammals typically present.

Lethal control has been demonstrably successful in lowering possum populations (Warburton et al. 2009a), to levels that reduce their adverse effects on foliar cover and mortality of native trees (Sweetapple et al. 2002a; Gormley et al. 2012), native bird populations (Innes et al. 2010), and the levels of bovine TB in domestic cattle (Caley et al. 1999). The conservation successes, in particular, prompted a recent governmental review to conclude that there was an urgent need to expand the use of 1080 to prevent further declines in indigenous biodiversity (Parliamentary Commissioner for the Environment 2011). However, the unwanted impacts of possums and other introduced pests occur at scales far larger than can be addressed with the available funding and current cost of control techniques (Walker et al. 2012). In addition there are major ecological complexities, in that possum control alone can result in increases in ship rat (*Rattus rattus*) densities (Ruscoe et al. 2011) with adverse consequences for native invertebrates (Ruscoe et al. 2013). There is therefore an ongoing need to reduce the costs of all forms of possum control, to enable both wider and more frequent control. Possum control with 1080 is not without some public opposition, often strongest in relation to aerial 1080 baiting, viewed by some as an 'indiscriminate' control method (Green & Rohan 2012). Accordingly, the need is for new or improved techniques that reduce both the cost of control and the amount of toxin used without sacrificing control efficacy. We document here the development and field testing of a new technique for aerial 1080 baiting aimed at helping fulfil that need.

Although aerial 1080 baiting has been used primarily for possum control, it is increasingly also used to protect native birds from ship rats (Innes et al. 1995) and to reduce rabbit (*Oryctolagus cuniculus*) impacts on pastoral production (Nugent et al. 2011a). Here, we focus on its use for possum control or for simultaneous combined control of possums and rats. Current practice involves sowing cereal baits containing 0.15% 1080 or, less often, carrot baits containing 0.08% 1080 (NPCA 2004; EPA 2010). The area targeted for control is usually first prefed, i.e. baited with non-toxic bait. Prefeeding increases the pest mortality (Coleman et al. 2007; Nugent et al. 2011a) by increasing the likelihood that pests will actively search for, encounter and accept baits (Warburton et al. 2009b). One to several weeks after prefeeding, toxic 1080 baits are sown more-or-less evenly over the area using helicopter-slung buckets fitted with a spinner to 'broadcast' bait both along and between parallel flight lines spaced 100–280 m apart. Sowing rates of 2 kg of toxic bait per hectare are the norm, although rates as low as 1 kg ha^{-1} or as high as 5 kg ha^{-1} can be used depending on possum density.

Current sowing rates for possums are, on average, about 80% lower than in the past, when rates as high as 32 kg ha^{-1} were sometimes used (Morgan 2004; Veltman & Westbrooke 2011). Despite that major reduction in cost and toxin use, there is still potential to further reduce sowing rates by sowing the baits in small clusters instead of evenly (Nugent et al. 2012a). Using a hand-laying approach to sow 1080 bait in clusters at an overall rate of just 0.4 kg ha^{-1}, we recently reported reductions in possum and rat abundance similar to those using conventional broadcasting at 2 kg ha^{-1} (Nugent et al. 2012a). However, hand-laying of bait is labour intensive and expensive, and is not a practical or safe option in many steep or otherwise inaccessible areas, thus necessitating some form of aerial delivery to become operational.

The proposition of aerially delivering bait in clusters within narrow strips under the flight path, leaving large unbaited areas between adjacent strips, is arguably a return to the original approach used in aerial poisoning. Aerial delivery of poison bait was first undertaken in New Zealand (and possibly globally) in the late 1940s (McLean 1966) and for the next 40 years was mostly undertaken using fixed wing aircraft to sow bait in strips. However, Morgan (1994, 2004) showed there were often large gaps, up to 400 m in width, between baited areas, and that poor bait coverage was linked to low control efficacy. That prompted a switch to uniform broadcast baiting (using GPS-guided helicopters) where a spinner under the sowing bucket would spread bait laterally across a far wider swath than previously, and where the flight-path spacing was typically set at the same width as the baited swath, aiming to deliver 100% coverage and thereby ensure that all pests encountered bait. That paradigm has become accepted practice for most aerial baiting systems, despite knowledge that possums and rats have home ranges that are at least many tens and usually hundreds of metres across (Cowan 2005; Innes 2005), and so all animals can be put at risk without baiting the whole area. In fact, where poison bait is delivered in de facto 'clusters' (i.e. inside bait stations) for possums and rats in New Zealand, such devices are usually spaced 100–150 m apart (Thomas 1994).

We have therefore developed an aerial baiting system capable of delivering bait in clusters at controlled spacings. This paper documents an evolutionary series of four trials testing the efficacy of this 'aerial cluster-sowing' technique. In these trials, we compare the reductions in various indices of possum and/or rat abundance achieved using the new technique with that achieved using some variant of broadcast sowing. The first trial used a cluster baiting rate of 1 kg ha^{-1}, 60% lower than the broadcast-baiting protocol with which it was compared. In subsequent trials the cluster baiting rate was reduced to 0.25 kg ha^{-1}, and in the final trial, as low as 0.17 kg ha^{-1} (>90% lower than the broadcast rate in that trial).

Materials and methods

Study sites

All four trials comparing cluster and broadcast sowing were conducted as part of large-scale operations undertaken to meet agency pest management goals. These operations were conducted by the Animal Health Board (AHB) to reduce the threat of bovine TB posed by possums or by the Department of Conservation (DOC) for conservation purposes. All operations used RS5 cereal pellets (Animal Control Products, Wanganui, NZ) as possum bait, containing 0.15% 1080 in the case of toxic baiting.

All four study sites were in mountainous parts of the South Island of New Zealand, and included one largely unforested area (Molesworth Station) and three areas of more-or-less continuous native forest on conservation land (Landsborough Valley, Isolated Hill, and Maruia Valley; Fig. 1 and Table 1).

Molesworth Station (MS): This area in northern Canterbury lies approximately 60 km east of the main alpine divide. The

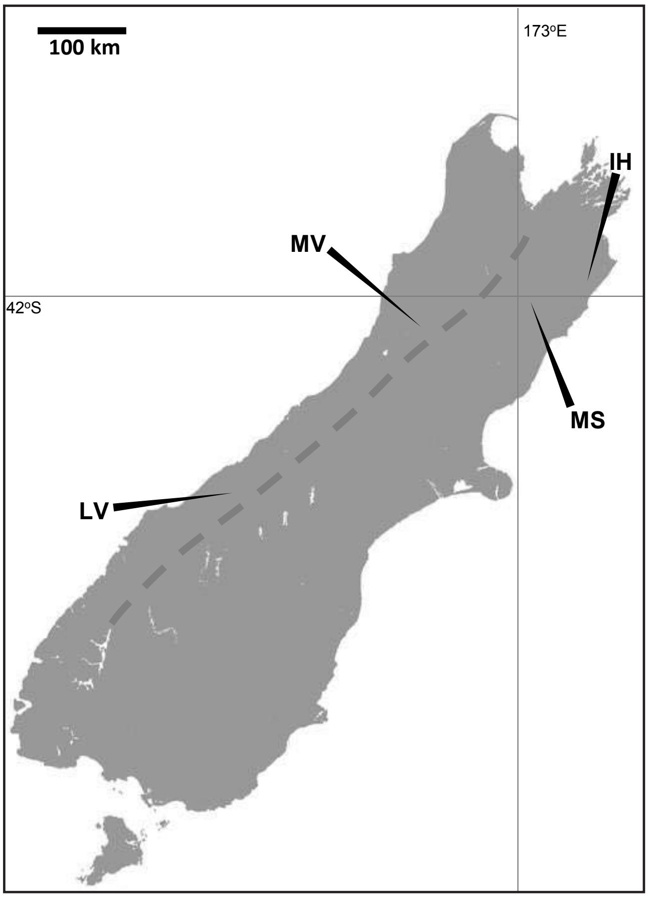

Figure 1. Image map of the South Island of New Zealand, indicating locations of the four study sites in relation to the alpine divide (represented by the grey dashed line). MS = Molesworth Station (2008), LV = Landsborough Valley (2009), IH = Isolated Hill (2009), MV = Maruia Valley (2010).

Table 1. Summary of study site characteristics, bait treatments and flight-path-spacing (FPS) regimes used for aerial 1080 baiting at four New Zealand study sites, 2008–2010

Site, date	Site characteristics	Pre-feed used	Broadcast treatment; FPS	Cluster sowing treatment, FPS
Molesworth Station, spring 2008	Semi-arid, sparsely-vegetated (c. 800 mm rain p.a.); montane (700–1200 m elevation)	No*	8-g 1080 cereal pellets sown at 2.5 kg ha^{-1}; 130-m FPS (single 7870-ha block)	8-g 1080 cereal pellets sown at 1.0 kg ha^{-1}; 130-m FPS (single 4300-ha block)*
Landsborough Valley, summer 2009	Wet beech forest valley hillside (c. 4000 mm rain p.a.); variable altitude (100–1900 m elevation)	Yes, at 1.0 kg ha^{-1}	12-g 1080 cereal pellets sown at 3 kg ha^{-1}; 100-m FPS (two blocks 301 and 455 ha, both below 700 m elevation)	6-g 1080 cereal pellets sown at 0.25 kg ha^{-1}; 100-m FPS (two blocks 301 and 455 ha, both below 700 m elevation)
Isolated Hill, spring 2009	Mixed canopy forest with moderately low rainfall (c. 1000 mm rain p.a.); variable altitude (200–1000 m elevation)	Yes, at 1.0 kg ha^{-1} (broadcast) or 0.5 kg ha^{-1} (cluster)	6-g 1080 cereal pellets sown at 3 kg ha^{-1}; 140-m FPS (two blocks 483 and 730 ha)	6-g 1080 cereal pellets sown at 0.25 kg ha^{-1}; 100-m FPS (two blocks 648 and 736 ha)
Maruia Valley, winter 2010	Beech forest with moderately high rainfall (c. 2000 mm rain p.a.); variable altitude (400–1300 m elevation)	Yes, at 1.0 kg ha^{-1} (broadcast) or at a variable rate (cluster; *see text*)	12-g 1080 cereal pellets sown at 2 kg ha^{-1}; 100-m FPS (four 110-ha blocks)	6-g 1080 cereal pellets sown at various rates using variable FPS, 12 110-ha blocks (*see main text & Table 2 for explanation of treatments*)

*In addition, a smaller block (760 ha) received the same cluster-sowing treatment but this block had received non-toxic bait as prefeed.

area is largely unforested scrubby farmland, rising from rough grasslands in the valley floor through thorny shrubland to a tussocky or rocky alpine zone. The area had no recent history of possum control but previous surveys by Byrom et al. (2008) indicated that the unmanaged 'pre-control' possum population was likely to be at low density – about 5–10% Trap Catch Index (TCI) (NPCA 2011) equating to an approximate density of 0.9–1.9 possums ha^{-1}. The 1080 baiting operation was conducted in spring 2008, over an area of 28 000 ha on the north-western side of the Clarence River, and aimed to reduce TB levels in possums.

Landsborough Valley (*LV*): This area in South Westland lies approximately 30 km west of the Main Divide. The area controlled comprises 3685 ha of a steep north-west-facing valley side with mostly complete forest cover dominated by a mixture of silver beech (*Nothofagus menziesii*) and podocarp species, with an understorey comprised largely of dense waist-high crown fern (*Blechnum discolor*). It had been aerially poisoned previously, so pre-control possum density was low; a TCI of 7.5 ± 4.2% 15 months prior to this study (G. Scott, DOC South Westland, pers. comm.). The aerial 1080 baiting operation was conducted by DOC in early 2009 to reduce possum (and rat and stoat *Mustela erminea*) numbers for biodiversity protection.

Isolated Hill (*IH*): This area in Marlborough lies approximately 130 km east of the Main Divide. The site comprises 2597 ha of steep limestone country with vegetation predominantly consisting of mixed low-canopy beech–seral forest. The area had been aerially poisoned several times previously (with 1% residual TCI recorded following the most recent 1080 carrot aerial baiting in 2001; M. Brennan, DOC Marlborough, pers. comm.). In late October 2009, aerial 1080 baiting was jointly undertaken by AHB and DOC for TB management and biodiversity protection, respectively.

Maruia Valley (MV): This area in north Westland lies approximately 20 km west of the Main Divide. The terrain is steep, mostly east-facing forest dominated by beech (*Nothofagus* spp.), with a mostly open understorey. The area had not been aerially poisoned previously. Before control, possum density was high with a TCI of 27 ± 7% recorded in part of the area 8 months before the poisoning operation (R. Blankenstein, Vector Control Services, pers. comm.). In mid-2010, the AHB conducted aerial 1080 baiting for TB management over 23 000 ha on the west side of the Maruia River.

Cluster-sowing technology

Conventional broadcast sowing of bait uses buckets slung under helicopters, with high-speed spinners under a gravity-fed outlet at the bottom of the bucket to dissipate bait laterally in every direction. To deliver bait aerially in clusters, we modified a 700-kg-capacity bucket originally developed to allow reliable broadcasting of bait at lower-than-usual sowing rates (SowLow bucket; Morgan et al. 1997; Morgan 2004). A paddle-wheel mechanism (used to regulate bait flow) was altered and the broadcast spinner was replaced with a timed gate mechanism that released bait at regular intervals with minimal lateral momentum. This bucket, developed by Landcare Research and Amuri Helicopters, was used in the MS, LV, and IH trials.

To calibrate the cluster-release interval against sowing rate and characterise cluster size, searches were conducted for bait after cluster sowing on several occasions. At a flying speed of c. 85 kph and flying low over flat farmland, the Landcare Research – Amuri Helicopters bucket delivered clusters of about 50 baits with a mean cluster length and width of 8 × 5 m, but at c. 100 kph and flying slightly higher, mean cluster size increased to 18 × 22 m on a gentle grassland slope. In the first trial (described below), flying much higher but also at c. 100 kph, a mean cluster size of 26 × 20 m was recorded on valley flats, and 30 × 31 m on steep valley sides.

For the fourth trial below, we developed (in conjunction with Helicopters Otago) a new 250-kg-capacity sowing bucket designed specifically for cluster sowing using a lightweight, low-cost helicopter. This used a different, proprietary cluster release system, with a GPS-controlled cluster-release mechanism that delivered clusters at the required distances apart regardless of the speed at which the helicopter was flown. When flown at 100 kph, at 100 m above ground, on both hill and flat pasture this bucket produced bait clusters of c. 12 × 8 m (unpubl. data).

Broadcast- and cluster-sowing treatments in each trial

Although each trial compared cluster and broadcast sowing, the protocols for each differed between trials, partly because we wanted to test ever-greater reductions in cluster sowing rates, and partly because the trials were undertaken as part of agency operations with whatever variant of conventional broadcast sowing was preferred by the agency in control of the operation. The sequence of trials was as follows.

Trial 1 (MS). One main study block received conventional broadcast sowing, while another received experimental cluster sowing along parallel GPS-guided flight paths (Table 1); neither block had received prefeed. In addition, a single smaller block was prefed (using broadcast sowing at 1 kg ha^{-1} of non-toxic bait) and then cluster sown as for the main cluster-sown block.

In the subsequent three cluster-sowing trials, we explored a number of different cluster sowing protocols but, for simplicity, present only the results from the main cluster-sowing protocol common to all three trials. This protocol used a broadcast bucket with a greatly reduced spinner speed to sow non-toxic prefeed in narrow swaths 40–60 m wide (strip sowing), and to then cluster-sow toxic bait along exactly the same flight paths (i.e. in all cluster-sowing treatments the prefeed and toxic baited areas were spatially aligned, whereas with broadcast baiting no effort is made to align flight paths in this way).

Trial 2 (LV): Two study blocks were treated 'conventionally' with a broadcast prefeed followed by broadcast toxic baiting (Table 1); in addition, two experimental trial blocks were prefed by strip sowing followed by deployment of toxic bait by aligned cluster sowing.

Trial 3 (IH): As for the LV trial, two 'conventional' broadcast blocks received prefeed followed by toxic baits by broadcast; while two experimental trial blocks received strip-sown prefeed followed by cluster-sown toxic bait (Table 1).

Trial 4 (MV): This trial compared outcomes across 16 study blocks of c. 110 ha each (Table 1). Four randomly selected blocks were treated as replicate treatment areas using 'conventional broadcast' baiting, with a single broadcast prefeed followed 26 days later by toxic bait via broadcast. The remaining 12 blocks were all cluster-sown, with aligned strip-sown prefeed, using 2-g baits as prefeed and 6-g toxic baits. Based on a 3×3 treatment design, nine combinations of three different flight path spacings (FPS = 100, 125, and 150 m) and three different intervals between prefeed and toxic baiting (5, 14, and 30 days) were examined in a matrix fashion. For the different flight- path spacings, the same prefeed and toxic baiting rates were used along each flight path, so the overall prefeed and toxic baiting rates were lower at the widest spacing, i.e. 0.5 kg and 0.25 kg ha^{-1} respectively at 100-m FPS, 0.4kg and 0.20 kg ha^{-1} at 125-m FPS, and 0.33 kg and 0.17 kg ha^{-1} at 150-m FPS.

Measuring possum and rat control outcomes

To determine the relative effect of the different treatments on the numbers of possums and rats, we measured the rate at which each species 'interfered' with various monitoring devices. The four trials were each monitored somewhat differently, depending on the size of the study blocks, the information needs of the management agencies conducting the operation, and the evolution during the trial of the protocols for using chewcards as our main index of possum abundance; this latter device comprises a new monitoring technique that was being developed in parallel with these studies (Sweetapple & Nugent 2011). Chewcards (CCs) are corrugated plastic cards baited (with peanut butter, icing sugar, and ground lucerne) to attract mammals, and the percentage of CCs with bite marks is used as an index of animal activity that we assumed to be positively correlated with animal abundance (possum and rat bite marks are easily distinguished using this method; Sweetapple & Nugent 2011). In all four trials, CCs were established in lines or grids before aerial 1080 baiting, checked after a predetermined interval to provide an index of pre-control abundance, rebaited, and checked again following control to obtain indices of post-control abundance; unless otherwise stated, pest interference with CCs was assessed over the same time interval for the pre-control measure and the post-control measure, in order to ensure bias associated with different monitoring lengths was not introduced.

In the first trial (MS) alternative interference devices (WaxTags®; Thomas et al. 2003) were used for pest monitoring in parallel with CCs; these function in a similar role to CCs, but are less palatable to pest mammals. WaxTag® devices (WTs) and CCs were set c. 10 m apart as pairs, with each WTCC pairing spaced c. 50 m apart along transects of c. 1 km distributed semi-randomly through the accessible parts of study areas. A composite WaxTag®–Chewcard Index (WTCCI) was calculated from the percentage of device pairs with CC and/ or WT interference (bite marks).

In the LV, IH, and MV trials, only CCs were used. At LV and IH, these were spaced at 40-m intervals along four 1-km-long transects established in each of the four blocks in both trials. For the MV trial, where the study blocks were much smaller, 6×6 grids of 36 CCs spaced 100 m apart were established in the central core of each block, with the edges of each grid at least 250 m from the block boundary. A Chewcard Index (CCI) was calculated as the percentage of cards on which bite marks were recorded. The WTCCIs and CCIs were Poisson-transformed prior to analysis, on the assumption that would increase the linearity of the index as a measure of abundance, as has been reported previously (Nugent et al. 2012a).

For the first three trials, some ancillary data on control outcomes were available from the operational monitoring undertaken by the management agencies. For possums only, post-control abundance was assessed by measuring the Residual TCI (RTCI) (NPCA 2011). In the two large MS study blocks, 58 trap lines were used, while at the LV and IH sites 6 and 10 trap lines, respectively, were monitored in each of the four blocks per trial.

Statistical analyses

Reductions in possum activity were estimated by regressing the transformed post-control index of possum activity against the pre-control value for the same transect, with the regression forced through the origin on the assumption that when possums are absent, both pre- and post-control indices must be zero. Trap Catch and Chewcard Index data were then compared between different treatment groups, using ANOVA models, having first ascertained that the data were amenable to parametric analysis. For the MS trial, RTCIs were calculated for each trap line and were compared between treatments using 2×2 between-subjects factorial ANOVA; for the LV and IH trials, statistical comparisons of differences in reductions in CCIs and in RTCIs were made using a linear mixed-effects ANOVA (Pinheiro et al. 2009). All analyses were undertaken in the R Statistical Computing Environment, version 2.13.0 (R Development Core Team 2010).

Results

Effect of aerial cluster sowing on operational efficacy

*Trial 1 (*MS*):* A 2005 survey covering much of the Molesworth Station study area recorded an average TCI for the then-uncontrolled possum population of 5–10% (Byrom et al. 2008). Compared to that, the RTCI values recorded after control were low in both the broadcast (not prefed) block (0.42%; 95% CIs 0–0.92%, $n = 35$ trap lines) and the cluster (not prefed) block (0.75%; 95% CIs 0.2–1.20%, $n = 23$). The difference between these two blocks was not statistically significant ($P = 0.40$).

For the small prefed cluster block, RTCI was 0% ($n = 10$). Although consistent with evidence that prefeeding results in a subsequent greater uptake of 1080 bait (and hence a greater kill-rate; Coleman et al. 2007), the difference between the unprefed and prefed cluster blocks was not significant ($P = 0.24$).

As a result of operational delays, the interference indices of possum abundance (WTCCIs) were measured over c. 50 days before control compared with c. 11 days after control. The changes in the index are therefore likely to misrepresent the actual reduction in possum activity (due to differing time intervals for the interference device measures before and after control), but can still be used to compare reductions in relative terms. The relative reductions in the Poisson-transformed WTCCIs (as estimated by regression through the origin) were 97.8% in the broadcast-sown block and 98.4% in the cluster-sown block (Fig. 2). The difference was not statistically significant ($P = 0.29$). No rats were detected before or after control in this trial.

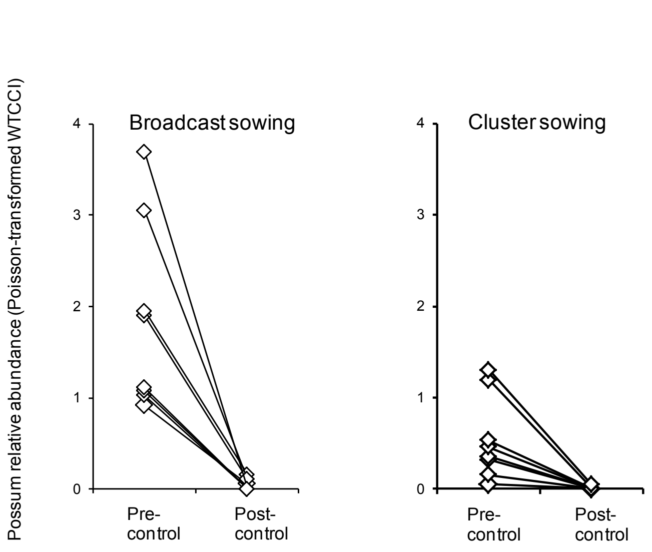

Figure 2. Relative reductions in possum activity indices, as assessed by pre- *vs* post-operation changes in WaxTag®/Chewcard Indices (WTCCI), following either broadcast or cluster sowing at the Molesworth Station study site, northern Canterbury. Lines denote the degree of decline in pest activity between pre- and post-control points. Both sets of operations were conducted in the absence of prefeeding of non-toxic bait.

Trials 2 & 3: In the Landsborough Valley (LV) trial, an average relative reduction in Poisson-transformed possum CCI of 89.6% was recorded across the two broadcast-sown blocks, compared with 86.7% for the two cluster-sown blocks (Fig. 3a). The difference was not statistically significant ($P = 0.23$).

In the Isolated Hill (IH) trial, the equivalent figures were 87.2% and 73.3%, respectively (Fig. 3b). Visual inspection of Fig. 3b indicates that the lower mean reduction for cluster sowing reflected moderate rather than high reductions on three of the eight lines in the two cluster-sown blocks. Despite the greater difference between these means, the overall difference was again not statistically significant ($P = 0.43$). However, the Trap Catch Indices of post-control possum abundance also suggested better control with broadcast sowing (mean RTCI = 0.8 ± 0.6%), than with cluster sowing (4.2 ± 0.6%), a difference that approached significance ($P = 0.06$).

In the LV trial, pre-control rat abundance was low (with only 14 rat detections on 198 CCs in the broadcast blocks and 5 on 201 CCs in the cluster blocks), and no rats were detected after control, appearing to indicate high efficacy regardless of sowing method. In the IH trial, pre-control rat abundance was overall moderate but variable, with rats detected on all 16 transects. After poisoning, rats were detected on just four transects, three in the two cluster-sown blocks and one in one of the broadcast-sown blocks, with mean relative reductions of 94.2% in the broadcast blocks and 84.7% in the cluster blocks (Fig. 4); the difference between these reduction values was not statistically significant ($P = 0.355$, Student's *t*-test).

Trial 4: Before control, possum and rat abundance indices in the Maruia Valley (MV) trial were variable but overall moderate. Control efficacy was high for both species, regardless of sowing method, flight-path spacing (and interdependent sowing rate), or prefeed interval (Table 2). No possums were detected after control in 11 blocks, while only two CCs were bitten in the remaining block. Likewise rats were detected in a single block, with just a single CC bitten in the cluster block with the longest prefeed interval and the widest FPS (and consequently the lowest sowing rate). There were too few post-control data for either species to warrant statistical comparison in relation to sowing method.

Discussion

Ecologically, we aimed to find a cheaper, yet equally effective, method for using aerial poisoning to periodically reduce the density of two introduced pests to levels at which their unwanted impacts on ecosystem processes or disease transmission were negligible. Our goal was to deliver toxic bait in small clusters containing a high density of baits, so that possums or rats encountering bait for the first time were likely to encounter another soon after, yet avoiding the need to apply that high density everywhere.

This set of trials has demonstrated it is technically and operationally feasible to sow poison baits aerially in clusters.

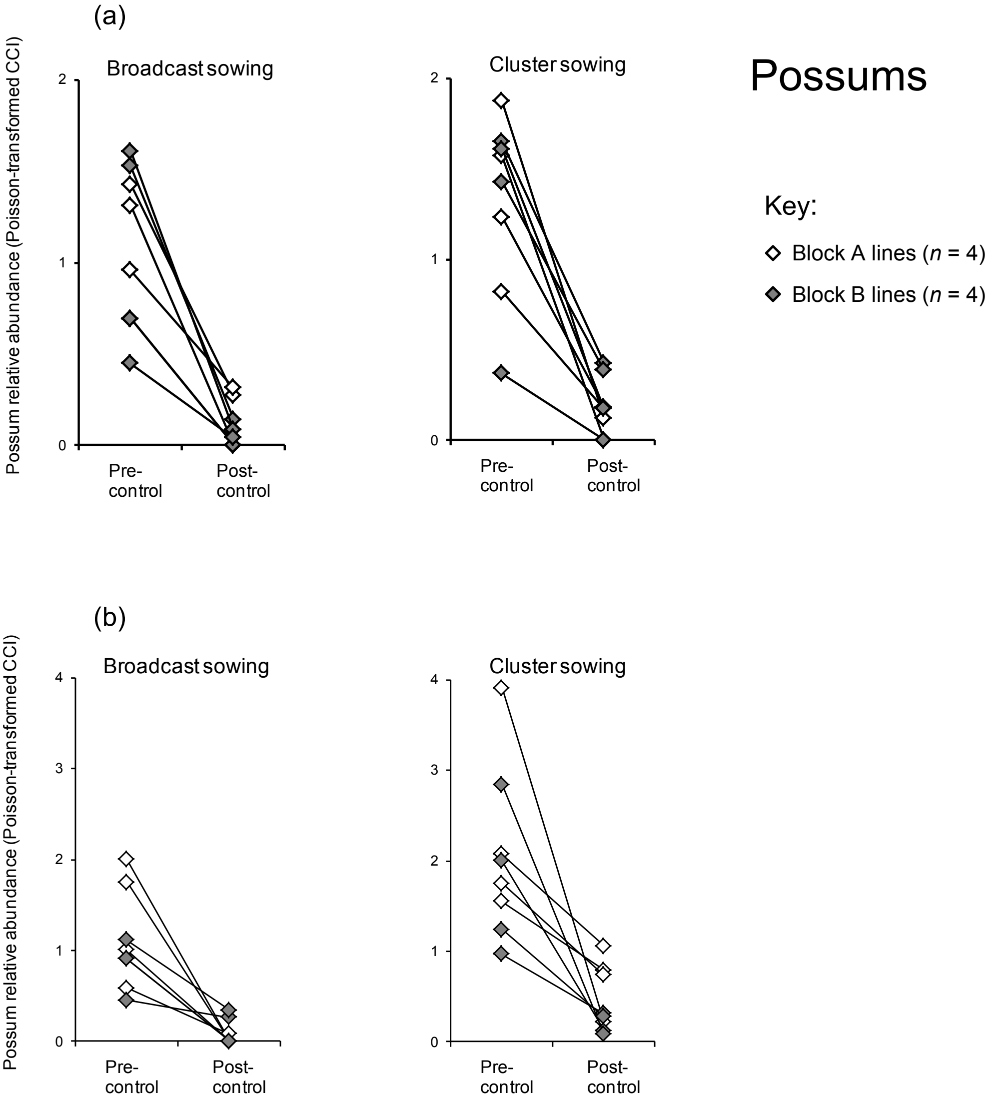

Figure 3. Relative reduction in indices of possum abundance, as assessed by pre- vs post-operation changes in Chewcard Indices, following either broadcast or cluster sowing of 1080 baits in (a) wet rainforest habitat in the Landsborough Valley, Westland, and (b) dry mixed forest at Isolated Hill, Marlborough. Two blocks (A, B) were poisoned with each sowing method, both following prefeeding. In the LV trial the pre-control indices were measured over c. 15 days before control and c. 20 days after control, while in the IH trial the pre- and post-control indices were both measured over 7 days. Lines denote the degree of decline in pest activity between pre- and post-control points.

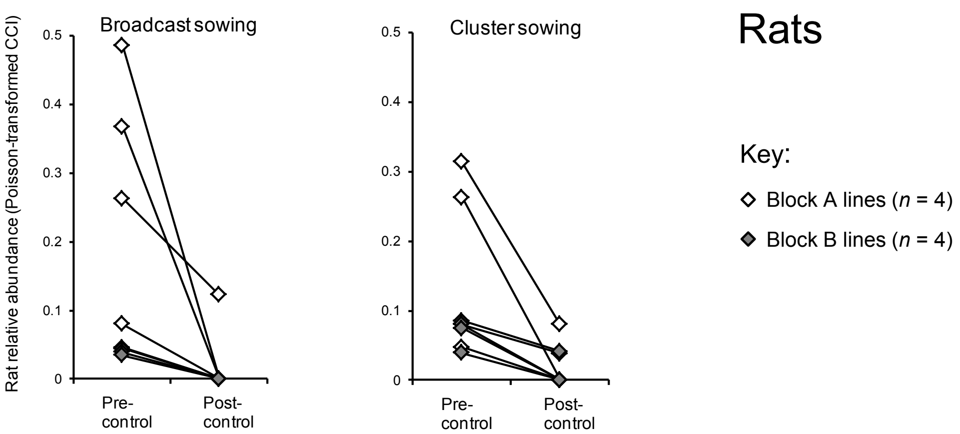

Figure 4. Relative reduction in indices of rat abundance, as assessed by pre- vs post-operation changes in Chewcard Indices (CCI), following either broadcast or cluster sowing of 1080 baits in dry mixed forest at Isolated Hill, Marlborough. Two blocks (A, B) were poisoned with each sowing method. The pre- and post-control indices were both measured over 7 days.

Table 2. Pre- and post-control 7-day Chewcard Indices (CCIs) of possum and rat abundance, and the percentage reduction in Poisson-transformed CCIs, for each of 12 110-ha blocks in the Maruia Valley, north Westland. The sowing method, flight-path spacing (FPS), and interval in days between prefeeding and toxic baiting (PFI) are shown, with each sub-trial listed separately.

Sowing method	Prefeed/ toxic sowing rates (kg ha^{-1})	FPS / PFI	Possums Pre-control CCI (%)	Post-control CCI (%)	% reduction	Rats Pre-control CCI (%)	Post-control CCI (%)	% reduction
Cluster	0.50/0.25	100 m / 5 d	65.7	0.0	100	62.9	0.0	100
Cluster	0.40/0.20	125 m / 5 d	65.7	0.0	100	42.9	0.0	100
Cluster	0.33/0.17	150 m / 5 d	66.7	0.0	100	80.6	0.0	100
Cluster	0.50/0.25	100 m / 14 d	47.2	0.0	100	27.8	0.0	100
Cluster	0.40/0.20	125 m / 14 d	54.3	5.6	93	37.1	0.0	100
Cluster	0.33/0.17	150 m / 14 d	33.3	0.0	100	38.9	0.0	100
Cluster	0.50/0.25	100 m / 30 d	17.1	0.0	100	48.6	0.0	100
Cluster	0.40/0.20	125 m / 30 d	28.1	0.0	100	37.5	0.0	100
Cluster	0.33/0.17	150 m / 30 d	36.1	0.0	100	22.2	2.8	89
Broadcast	1.00/2.00	100 m / 26 d	67.6	0.0	100	41.2	0.0	100
Broadcast	1.00/2.00	100 m / 26 d	61.1	0.0	100	27.8	0.0	100
Broadcast	1.00/2.00	100 m / 26 d	77.8	0.0	100	19.4	0.0	100
Broadcast	1.00/2.00	100 m / 26 d	8.3	0.0	100	11.1	0.0	100

The technical innovation needed to achieve that was not especially complex, with the two helicopter companies involved developing different engineering solutions. The sowing bucket used for the first three trials was developed by simple modifications to a bucket previously designed to deliver bait at a consistent, well-controlled rate, particularly at low sowing rates of a few kilograms per hectare (Morgan et al. 1997). The bucket used in the final MV trial was purpose built, at a cost about two to three times the usual cost of a sowing bucket. Now that the design has been tested, and GPS control and mapping software developed and made commercially available, the cost of any future bucket should be comparable with that of a conventional broadcast bucket.

In a previous study (Nugent et al. 2012a) we showed that aggregating 1080 cereal bait into hand-laid clusters, spaced c. 12.5 m apart along transects spaced c. 100 m apart, resulted in possum and rat control efficacy as high as that attained with conventional (aerial) broadcast baiting. Here we show that similar results can be attained when clusters of bait are delivered aerially. The final trial (MV), in particular, indicated that under what appears to have been highly favourable circumstances, near total reductions of moderate numbers of both possums and rats are achievable even when there are gaps of up to 130 m between baited areas and up to 150 m between flight lines. That implies most, if not all, possums and rats were ranging over these distances. Intuitively, we conclude from this and the earlier study that leaving unbaited areas up to 100 m wide does not greatly reduce the probability that a possum or rat will encounter a toxic bait soon after it is sown. If home ranges were, for simplicity, assumed to be more or less circular this would require that most possums and rats must range over an area > 3 ha during the period bait is available. If not, a proportion of animals with smaller ranges would not encounter a bait cluster. However, the mean home range of possums in forest is typically < 2 ha (Cowan 2005) and even smaller range sizes have been reported for rats (Hooker & Innes 1995). That suggests the possibility that some possums and rats were somehow 'drawn out' of their usual home ranges, perhaps by the way in which prefeed was applied; with a 100-m flight-path spacing, the 40–60 m swath width used for prefeed will have left unbaited strips of only about 50 m wide on average, ensuring that any possum or rat with a circular range >0.2 per hectare should have encountered prefeed. As shown by Warburton et al. (2009b), that could have then encouraged them to shift activity centres toward the flight path, where most prefeed baits will have been, increasing the likelihood of them finding clusters of toxic baits sown along the flight paths a few days later.

The finding that most possums and rats can be killed even when there are 100-m-wide unbaited areas has implications not only for flight-path spacing for cluster or strip sowing, but also for broadcast sowing. For broadcast sowing, it suggests that the FPS could be set up to 100 m wider than the width of bait swath that the bucket is able to deliver. As broadcast swath widths are typically 100–150 m wide (Nugent et al. 2011b), this suggests that the FPS could be increased to 200–250 m, substantially reducing the amount of flying and bait required. At first sight, this suggestion is at odds with earlier evidence that poor bait coverage can be linked to low control efficacy (Morgan 1994, 2004). However, the earlier work identified a high frequency of very large gaps, up to 400 m in width, between baited areas – gaps far larger than the smallest home range lengths of forest-dwelling possums and rats, as noted above. Our results indicate that the historical operational response (which was to switch to GPS-guided helicopter-based broadcast sowing to ensure total coverage) could be seen as overcompensation that ignored the ability of animals to move modest distances (i.e. within the confines of their home ranges) to where bait was sown. Our approach here, instead, would allow a return to the use of low-cost fixed-wing aircraft (but with the key improvement of GPS-guidance).

Overall results from the set of four trials reported here suggest that on most occasions any difference in efficacy between broadcast and cluster baiting will be small. In three of the four trials (MS, LV, MV) there appeared to be very little difference between broadcast and cluster sowing, but at IH the three outcome measures recorded (possum CCI reduction, possum RTCI, and rat CCI reduction) were all lower for cluster than broadcast sowing. We do not know what caused the difference in efficacy between the sowing methods within the IH trial, or the causes of the variation (for both methods) between the trials. With regard to the latter, however, we note that the greatest possum reductions were achieved in the MS and MV areas where possums had not previously been aerially poisoned with 1080, and the smallest reductions were at IH where they had been aerially poisoned three times previously. If a long history of aerial 1080 poisoning somehow contributes to possums being more difficult to poison, possibly due to the development of bait shyness as a result of previous exposure to sublethal amounts of bait (Ogilvie et al. 2000) and if that effect is exacerbated using cluster sowing, multiple prefeeds of non-toxic bait may be a solution, as prefeeding twice appears to result in better kills (Coleman et al. 2007; Nugent et al. 2012a). The IH results could be taken to imply that efficacy of cluster sowing is more variable than for conventional broadcast sowing, although, given that there are occasionally still also control failures with conventional broadcast sowing (Coleman et al. 2007; Nugent et al. 2012a), a large number of trials would be needed to confirm that. As a caveat, we note that the indices of activity we measure are not the end goal of possum and rat management, but rather a more proximate measure of operational success. A more ecologically relevant measure of success in outcome would be to observe, for example, similar levels of tree canopy recovery, or native bird population increase, when using either of the two poison-bait sowing methods. Even if the differences were small, the possibly greater variability in immediate control outcomes might equate to much less satisfactory ultimate outcomes. A 95% kill of fast-breeding rats with cluster sowing, for example, might provide only a few months of protection for native bird breeding, whereas a 98% kill with broadcast sowing could provide protection for a year or more.

Aerial 1080 baiting can also kill mice and stoats as well rats and possums, and in these studies the chewcards we used to assess possum and rat reductions were also sometimes bitten by those species. For stoats, data were too sparse to warrant statistical analysis; no stoats at all were detected before or after poisoning at MS or IH, but at the MV and LV sites there was a total of 14 detections before 1080 (7 each in cluster and broadcast blocks) and none after. The latter result suggests that cluster sowing also results in high stoat kills, as previously recorded for broadcast 1080 (Murphy et al. 1999). For mice, there were many more detections, but the data are difficult to interpret because of uncertainty of our accuracy in correctly identifying mouse bite marks, indications that mouse bite marks were often obscured by possum and rat interference, and indications of behavioural responses of mice to rat removal. We have therefore not analysed these data formally, but the indices recorded sometimes increased immediately after poisoning (LV/IH) suggesting both that there had been an increase in mouse detectability and that a substantial but unknown proportion of mice had survived. In contrast, at MV, mouse CCIs in the cluster-sown blocks declined overall from 55.8% before poisoning to 1.5% afterward, and in the broadcast blocks from 66.9% to 0.7%, suggesting a high kill was achieved there with both methods. The reasons for this apparently wide variation in mouse outcomes are not known.

The large number of toxic baits sown per hectare during conventional broadcast baiting (usually in excess of 150 baits ha^{-1}, and historically much higher) results in many times more lethal doses of 1080 than is needed to kill the relatively small number of possums and rats present (usually <10 per hectare) (Nugent et al. 2012a). We have previously hypothesised that such ‘overbaiting’ is required because not all individual baits contain a lethal dose of 1080, making it essential that animals encounter multiple baits in a short period before they begin to develop sublethal toxicosis as a result of the first ingestion of toxin (Nugent et al. 2012b). That requires a minimum bait density, and with broadcast sowing, the aim is to achieve the target bait density over the whole area. The present results suggest it is sufficient to deliver that bait density in just a small percentage of the area, provided the distance between bait clusters remains less than the smallest home range diameter of the target pests.

Overall, the demonstration that near total reductions of previously unmanaged populations of possums and rats can be achieved using as little as 0.33 kg ha^{-1} of prefeed and just 0.17 kg ha^{-1} of toxic 1080 bait indicates considerable potential for reducing cost. A simple costing model incorporating bait purchase and transport costs (and also helicopter positioning, reloading and application times) suggests that the direct flying and bait costs of aerial 1080 baiting operations could be reduced by up to 90%. Incorporating ‘fixed costs’ (planning, acquisition of consents, water quality monitoring, etc.) suggests the overall operational costs could be reduced by up to 60% for large operations. That would either produce significant savings or allow for a far greater area to be controlled with a fixed budget. Alternatively, it could make more frequent control of rats at landscape scale more feasible and affordable. Unlike possums, which have a comparatively low rate of annual increase (c. 30–45% p.a.; Efford 2001), rat populations can recover quickly after control (Innes et al. 1995; Sweetapple et al. 2002b; Sweetapple & Nugent 2007), so individual operations usually provide only limited respite for the native animals they prey upon. Biennial cluster sowing operations might therefore be one way of affordably providing more sustained protection for native animals, although such an approach carries its own risk, in that rat populations could become resistant to control by developing a learned aversion to 1080, as has been shown for laboratory rats (Nachman & Hartley 1975) and mice (*Mus musculus*; Fisher et al. 2009). These trials indicate that despite the major historical reductions in 1080 sowing rates over the last 10–20 years (Morgan 2004; Veltman & Westbrooke 2011) there remains potential to not only reduce costs but also to greatly reduce the amount of 1080 toxin used per hectare during operations, simply by leaving much of the area unbaited. We have argued that this is also likely to be true in other aerial baiting contexts, such as rabbit control (Nugent et al. 2012b) or for the use of anticoagulant toxins during attempts to eradicate small mammals from islands.

Best practice for the broadcasting technique that is currently the predominant approach in aerial baiting has evolved through two decades of extensive research, review, and operational refinement. Our ability to match the efficacy of that technique in the first-ever use of aerial cluster sowing in the MS trial (and also in two of three subsequent trials where we deliberately aimed to test the limits in reducing sowing rates) suggests that the new technique, or the principles that underpin the approach, has/have the potential to drive several further refinements in aerial baiting generally. First, a key hypothesis underpinning use of bait clusters is that high local bait densities are needed because not all baits currently sown are individually lethal (Nugent et al. 2011b, 2012b). If so, then simply ensuring that each bait is lethal could reduce the need for high bait density with both broadcast and cluster sowing. Second, although we focus here on using bait clusters (to maximise sowing-rate reduction) the same principles would apply to bait sown in narrow strips, which as noted above would allow a return to the use of low-cost fixed-wing aircraft (but with the key improvement of GPS-guidance). Third, as noted above, our demonstration that leaving narrow gaps of up to 130 m between baited areas does not greatly diminish control efficacy could allow use of wider flight-path spacing in broadcast baiting. However, we suggest a conservative approach in implementation of this final point (i.e. beginning with 50-m gaps between baited swaths), since strip-sowing trials subsequent to these studies have since indicated that operational results can be more variable than with standard broadcasting (unpubl. data). The need now, not just for cluster sowing but for all forms of aerial baiting, is to identify the optimal balance between lowering costs and toxin use yet consistently achieve high control efficacy.

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