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Abstract: Control of invasive vertebrate pests is likely to be needed in perpetuity unless their pest status changes or they are completely eradicated, both of which seem unlikely at present. This emphasises the need for pest managers to adopt long-term strategies that are both ecologically sound and cost-effective. We suggest that a strategy for simultaneous management of multiple sympatric species of pests is preferable to a single-species approach. While present strategy involves periodic control over entire areas to achieve management aims, modelling suggests that a strategy of localised elimination followed by perimeter control offers significant cost-savings in the long term. We are therefore researching three aspects of this strategy: (1) the further refinement of aerial baiting by identifying principal causes of individual pest survival, (2 the optimal deployment of control devices around the perimeter following localised elimination, and (3) the development of an efficient pest detection device to enable targeted elimination of survivors.

Key Words: 1080, aerial baiting, invasive species, pest control strategy, pest detection, possum, ship rat.

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INTRODUCTION

In New Zealand, four introduced, invasive, small mammals (the brushtail possum, *Trichosurus vulpecula*; the ship rat, *Rattus rattus*; the house mouse, *Mus musculus*; and the stoat, *Mustela erminea*) are now virtually ubiquitous. All four are seen as conservation pests because of their adverse impacts on native flora and fauna (Morgan and Hickling 2000, Innes 2005, King and Murphy 2005, Wilson et al. 2006) and possums have also become a major wildlife reservoir of bovine tuberculosis (Tb, Coleman and Caley 2000). Although these pest species have tended to be managed individually in the past, there is an increasing focus in New Zealand (and elsewhere) on managing whole ecosystems (Innes and Barker 1999), which requires integrated management of all important threats simultaneously. This automatically favours a multi-species approach to pest control (Morgan 1993) both to save money and to minimise unwanted ecological side-effects of single-species control, such as the potential for a major increase in rat numbers and impact after possum control (Sweetapple et al. 2006) or increased predation of native birds by stoats when single-species control of ship rats removed their primary prey (Murphy and Bradfield 1992).

Although these species can all be eradicated from islands or securely fenced areas, it is not currently technically feasible and economically affordable to eradicate them from large unfenced areas of the New Zealand mainland. That is because eliminating the last few pests is usually prohibitively expensive and that large expense has been considered pointless when there is a high certainty of reinvasion from adjacent unmanaged areas. Pest managers have therefore been forced to adopt a strategy of sustained control in perpetuity, with pest densities kept below some low (but not zero) threshold, below which their impacts are considered tolerable. If, however, pest numbers can affordably be reduced to zero, and if immigration can be prevented, a new strategic possibility of local elimination emerges (Morgan et al. 2006). This new strategy is, in essence, sustained control at zero density, and has three requirements: (1) an ability to cheaply reduce initially high pest densities to near zero (initial knockdown), (2) an ability to cheaply prevent all or most reinvasion (perimeter control), and (3) an ability to cost-effectively locate and eliminate the few survivors and immigrants (mop up).

In New Zealand, broad-scale pest control often involves aerial poisoning of densely forested montane areas, and is most well developed for possum control, although increasingly the same tools are being used for other pests.

Table 1. Aerial and ground control operations monitored since 2000 in which very low or nil survival was recorded using the residual trap catch index (RTCI, the percentage of trap-nights in which a possum was caught, NPCA 2004). Pre-control trap catch indices are typically in the range 10–60%. (Morgan et al. 2006.)

Operation	Area (ha)	Trap-nights	RTCI %
a) Aerial operations			
Bideford – July 2000	2,907	660	0.0
Tongariro – September 2001	19,980	1,020	0.1
Kahutara – March 2003	910	450	0.0
Titiraupenga – July 2003	10,150	600	0.0
Waikaremoana – July 2004	9,219	1,170	0.1
Kahutara – September 2004	1,337	630	0.1
Hauhangaroa – September 2005	82,876	15,358	<0.1
b) Ground operations			
Hopkins – July 2003	1,500	2,700	0.0
Matea – July 2003	14,787	2,550	0.2
North Taupo – July 2003	2,164	1,740	0.2
Hochstetter – September 2003	450	420	0.0
Bideford – November 2003	1,188	690	0.0
Te Wharau – April 2004	1,224	600	0.0
Kahutara – 2004	2,988	2,250	0.0
Holdsworth – 2004	1,185	1,800	0.0
Raetea – 2004	920	600	0.0
Matea – 2004	2,799	1,800	0.2

For possums, monitoring of recent control operations indicates that the first requirement of local elimination can sometimes now be met (Table 1).These outcomes prompted us first to explore whether the benefits of these highly successful knockdowns could be extended through perimeter control (Morgan et al. 2006).

We modelled the long-run cost of possum control over 60 years under four scenarios: sustained area-wide repeated control achieving either (1) a 95% reduction or (2) total knockdown (i.e. 100% reduction); sustained area-wide repeated total knockdown complemented by perimeter control reducing immigration by (3) 50% or (4) 80%.

We arbitrarily set a threshold of 1 possum/ha, which equates to an RTCI of about 5-10%, as a trigger for repeating area-wide control. Where the cost of total knockdown is similar to that of 95% control, as can be the case with aerial poisoning, the total-knockdown scenario will obviously be more cost-effective. More importantly, the model predicted that total knockdown combined with perimeter control was a more cost-effective control strategy under most scenarios than a conventional 95% control strategy even when the costs of total knockdown were up to twice as high as for the 95% control. Adding to the predicted cost savings, average possum densities would be lower under the total-knockdown scenarios, so the conservation and Tb control benefits would likely be greater.

This paper reports progress in research that has since been initiated to increase the feasibility of local elimination as a strategy not only for possums but for ships rats, house mice and stoats as well. In line with the three requirements above, we aim to:

- Increase the consistency with which pests can be knocked down to near-zero densities in a single aerial poisoning operation. Aerial control techniques have been greatly improved over the last 40 years (Morgan 2004), but while some operations are highly successful, failures still occur, so our focus is to better determine why some pests still survive.

- Determine the most cost-effective tools and tactics needed to reliably and substantially reduce immigration rates. The aim is to design low-cost perimeter control systems through bioeconomic modelling, using field data on rates of immigration and encounter with control devices when different device spacings are used.
- Development and field testing of highly sensitive but ultra-low-cost multi-species monitoring devices and systems for determining where survivors and invaders are, so that highly targeted mop-up control can be used to affordably eliminate them.

REFINING AERIAL POISONING AS A MULTI-SPECIES TOTAL-KNOCKDOWN TOOL

Pests may survive aerial poisoning because they do not encounter any toxic bait at all, or because they encounter toxic bait but it does not contain a lethal dose, or because they encounter toxic bait but choose not to eat a lethal dosage. Research and operational experience have led to the development of sophisticated and systematic GPS-guided bait delivery that largely eliminates the first of these risks (Morgan 2004). Pre-feeding with non-toxic bait a few days or weeks before the sowing of toxic bait has been shown to increase possum kills (Coleman et al. 2007), and sowing rate and sowing pattern obviously affect the rate at which pests encounter bait.

In 2006, we conducted a major field experiment to determine the relative effects of sowing rate (1, 2 or 5 kg of 1080-laden [sodium monoflouroacetate] diced carrot bait per hectare), sowing pattern (single direction versus cross-hatched sowing), and pre-feeding (nil, once, or twice) on the survival of possums, ships rats, and house mice. The set of 18 unique combinations of the various treatments was replicated twice in different locations a month apart, with each treatment applied to 100 ha of forest. Changes in pest abundance were monitored using changes in the rates at which pests interfered with multi-species monitoring devices, the ChewTrack Card (CTCs, described in detail below). We used 100 devices per 100-ha block to monitor interference over approximately two weeks just before and again immediately after poisoning. For the first replicate, there was no consistent effect of sowing pattern on survival, but where all of the toxic bait was sown in a single direction, a generalised linear model showed significant variation in kill for both possums ($P = 0.03$) and rats ($P = 0.046$). Pre-feeding significantly increased the kill of both possums ($P = 0.01$) and rats ($P = 0.003$) (Figure 1) and two pre-feeds appeared to be consistently more effective than one (Figure 1). Increased sowing rate resulted in a smaller, but still marginally significant ($P = 0.06$) increase in possum kill, but there was no significant effect on rats ($P = 0.36$). The second replicate appeared to show broadly similar effects of pre-feeding and sowing rate on kill, but joint statistical analysis was precluded by technical problems in the monitoring of that replicate.

The results from the first replicate, coupled with similar findings elsewhere (Coleman et al. 2007), indicate that multiple exposure to non-toxic bait is usually needed to overcome the reason(s) for possum and rat survival. In a subsequent survey of two of the blocks in early 2007, we found that surviving possums and rats still readily consumed 54% of 200 non-toxic cereal baits, but only 8% of carrot baits presented simultaneously. This near-total aversion to carrot bait implies that most, if not all, possums and rats had encountered bait during the earlier experiment and consumed some of it. Concurrent trials with penned possums indicated that only a single previous exposure to non-toxic bait any time in the preceding two months was sufficient to overcome cautious feeding effects (G. Nugent unpublished data), so we infer that the improvement resulting from a second pre-feed is, instead, a result of some change in encounter rate. Taken together, these data suggest most of the possums that survived the pre-feed treatments in the field trial did so because their first encounter with toxic bait was with a sub-lethal quantity, and that they consumed all or most of this bait, but did not find another bait before the onset of toxicosis and loss of appetite that typically occurs within 30–60 minutes of 1080 ingestion. Although efforts are made to ensure that all baits sown contain a lethal dose of toxin, fragmentation of baits can occur during their passage through sowing machinery or on impact with the forest canopy and ground, and bait size can be reduced by partial consumption by other individual pests.

DESIGNING A COST-EFFECTIVE PERIMETER CONTROL SYSTEM

We envisage that reducing pest invasion will involve placement of pest control devices such as long-life toxic baits or kill traps at some optimal

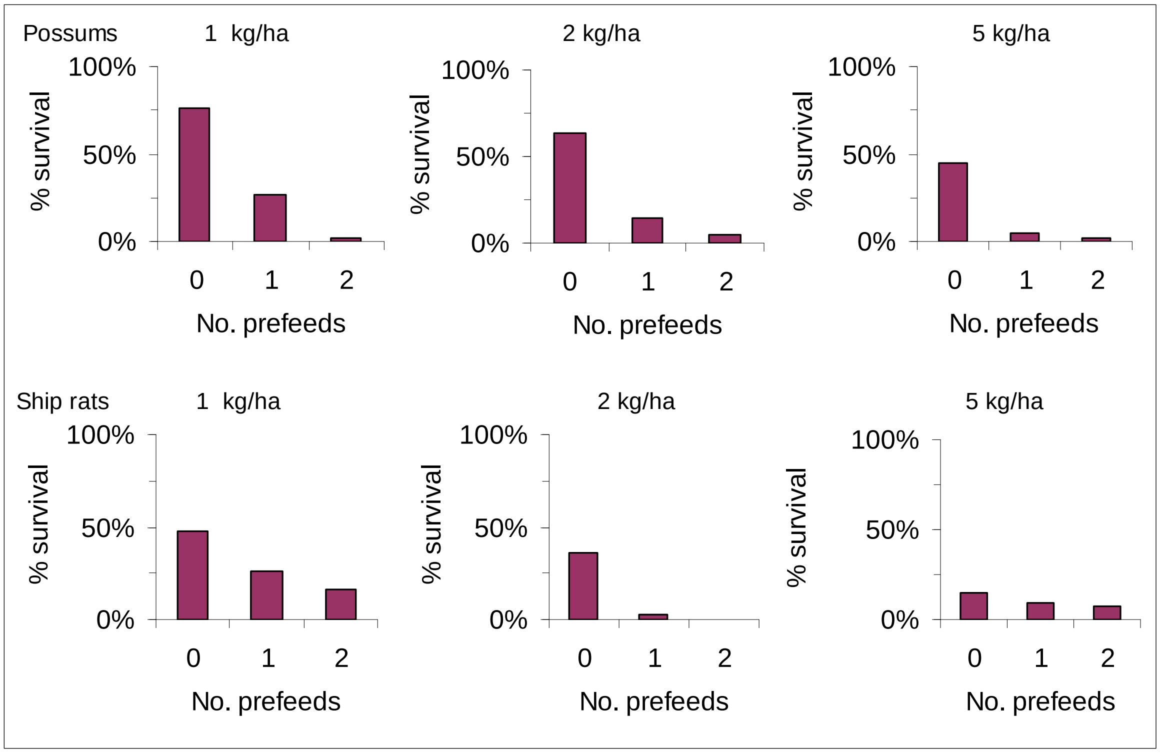

Figure 1. Relative measure of survival of possum and ship rat populations after aerial application of 1080-laden (0.15%) carrot baits at different sowing rates per hectare and with different numbers of non-toxic pre-feeds. The bait type sowing rate for pre-feeding treatments was the same as for the toxic treatments. The index of relative survival was estimated from changes in the Poisson-transformed detection rates partially adjusted for pre- and post-control differences in detectability.

spacing along parallel transects located near the perimeter of the management area. Identifying the most cost-efficient system for reducing invasion rates requires not only information on the cost of each device and the cost of deploying and maintaining them, but also understanding the complex interplay between device-spacing along transects, the number of transects, the spacing between transects, and their combined effect on the proportion on invader animals killed.

We have simulated these interacting influences on the proportion on invader animals killed (PIK), assuming that, even when devices are placed very close together, some dispersing pests will simply walk straight through a transect because they happened not to be hungry at the time. We also assumed that PIK would decline as the spacing was increased, and used a Weibull curve to provide an intuitively reasonable representation of that effect for a single transect, and calculated a cumulative joint probability for multiple transects (Figure 2a). The costs of perimeter control were then estimated using assumed values for the various activities involved in achieving specified levels of control (e.g., bait materials, time spent deploying baits, time spent walking between bait plots and lines, etc., Figure 2b). The particular scenario modelled in Figure 2 suggests that for a device capable of killing only 60% of invader animals when deployed at saturation levels (i.e., less than a few metres apart) approximately 80% of invader animals could be killed at the same cost using 2, 3, 4 or 5 transects. Killing an even higher percentage is predicted to require at lest three transects. Field research is now underway to paramaterise these models for possums and rats, with the major aims being to determine the "saturation" PIK for a single transect, and the shape of the curve describing how PIK declines with increasing distance between

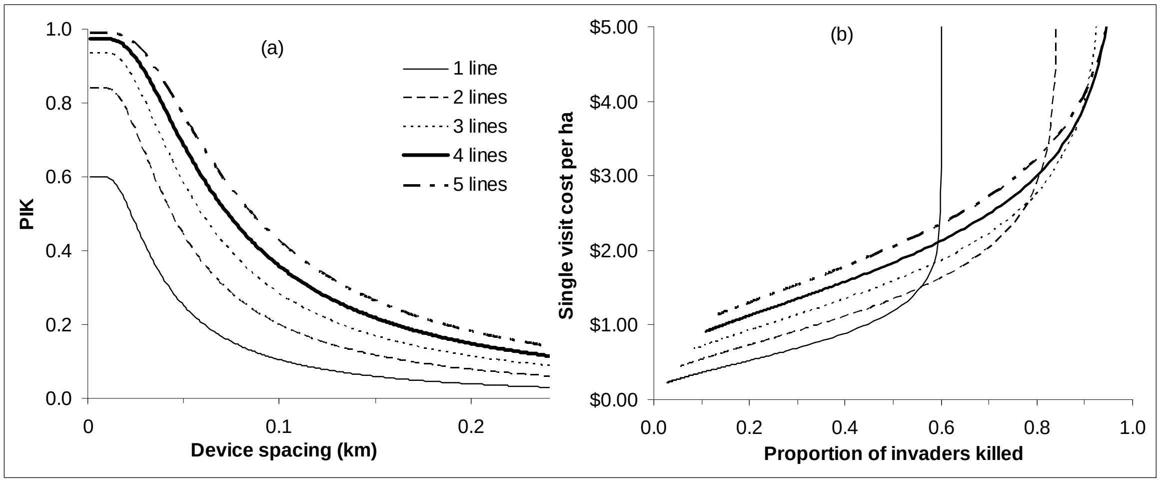

Figure 2. (a) Theoretical proportion of pests killed by control devices arranged at different spacings along 1-5 lines, and (b) the estimated associated costs.

devices. Using bioeconomic models, we will then be able to design cost-effective long-term strategies for perimeter control.

DEVELOPMENT OF AN EFFICIENT MULTI-SPECIES DETECTION DEVICE FOR TARGETED MOP UP

At present, possum populations are monitored mainly using leg-hold traps, following a nationally standardised protocol (NPCA 2004), whereas rats and house mice (and stoats to some extent) are monitored by either snap-traps or tracking tunnels (King 1983, Brown et al. 1996). The possum-trap-catch method is relatively expensive because the traps have to be checked each day and the resulting index is insensitive, and therefore imprecise, at low density (Thomas et al. 2003). For all four species, the traps or tracking tunnels are bulky, limiting the numbers that can be deployed by one person in a day. To overcome some of these disadvantages, a variety of light-weight interference devices have been developed (NPCA 2005). These can be deployed in large numbers and can be left unchecked to accumulate interference data over multiple nights or even weeks or months, increasing sensitivity in terms of probability of recording a detection per observer-visit. We have adapted that principle in developing a small low-cost light-weight multi-species interference device, the 'ChewTrack Card', that we initially hoped would record interference rates for all four of the small mammal invasive species we are interested in.

The CTC consists of plasticised card (Coreboard) folded and nailed to trees with bait forced into the channel openings along the sides of the card and also placed inside the fold (Figure 3). In addition, tracking ink is applied as shown, so animals can be identified by both the bite marks and tracks they leave. Although still in development, CTCs have now been used both to monitor pest population reductions (as reported above) and to map the distribution of isolated survivors. Thus far, detection rates for stoats have been very low compared with those typically recorded using traps (King 1983, Murphy et al. 1999), suggesting CTC interference is a poor index of stoat abundance. In contrast, detection rates for possums and rodents are far higher (Table 2). In one field trial in which house mouse snap-back trapping and CTC surveys were conducted simultaneously, we recorded mouse trapping rates of 2.6% while the CTC interference rates were 47%. CTCs appear likely to be useful for identifying any generalist omnivore species, as we have also incidentally detected hedgehogs (*Erinaceus europaeus*, Table 2).

The efficiency of the devices is best illustrated by possum data from the Hauhungaroa Range, central North Island, which also highlights how we envisage the tool being used to target mop-up control. In that area, 82,900 ha was aerially poisoned in winter 2005 in an intensive high-cost

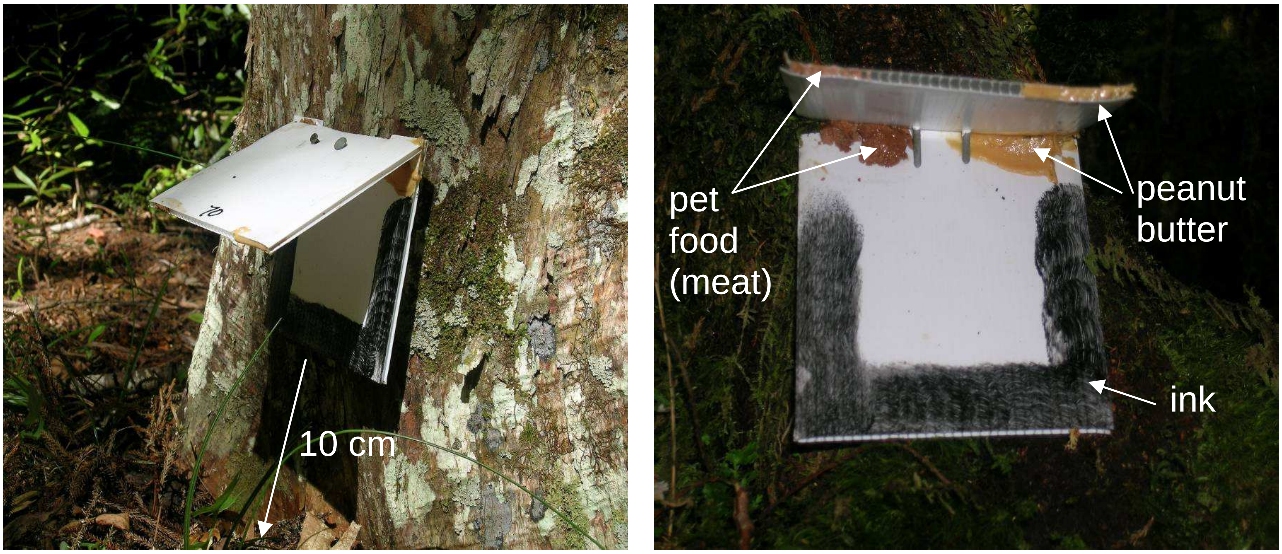

Figure 3. ChewTrack Card design, showing (a) side view, and (b) the location of tracking ink.and bait (peanut butter for possums and rodents, meat paste for rodents, stoats and other carnivores).

Table 2. Small mammals detected during post-control trapping surveys in the Hauhangaroa Range, September 2005 to March 2006. The possum-specific trapping survey was conducted immediately after aerial poisoning and involved the setting and checking for three consecutive days of 88 randomly located lines of 10 traps spaced 20 m apart. The CTC survey involved setting 3070 CTCs 50 m apart along continuous transects systematically spaced 1 km part and checking them one week later.

	Trap	CTC				
	Possum	Possum	Rat	Mouse	Stoat	Hedgehog
Detections	1	28[1]	2025	1351	8	73
% detections per device-day	0.04	0.13	9.42	6.29	0.04	0.34
% detections per field-day	0.006	0.275	19.853	13.245	0.078	0.716

[1] Number of foci of possum detection, each focus comprised up to three consecutive chewed cards.

operation specifically designed to deliver near-total knockdown. That goal was successfully achieved (Table 1), and we have subsequently mapped pest survival and recovery in part of the area using CTCs.

Operational monitoring of that part of the area comprised 880 leg-hold traps set (and checked daily for 3 days) along 18 km of transect. This required 176 days of field effort and detected a single possum (i.e., 0.0004 captures per trap-night). In contrast, we deployed 3,070 chew cards along 153 km of transect and checked them a week later. This required just 102 days and detected at least 28 possums (i.e., 0.0013 detections per CTC night). More importantly, the CTCs were 46 times more efficient in terms of the number of possum detections per field day. The CTC surveys were conducted several months after the trapping survey, so some of this greater sensitivity is likely to reflect an increase in possum detectability, which is known to increase two- or three-fold with increasing time since poisoning (Forsyth et al. 2003), but the difference in detections per day is far greater than that, so we are confident the efficiency gain is real.

Both the trapping and CTC surveys confirm extremely low numbers of survivors. A mean distance between capture and recapture of about 160 m has been recorded elsewhere in the Hauhungaroa Range (Morgan et al. 2007), so the 153 km of CTC transects monitored equates roughly to 2,500 ha of possum range surveyed. Subsequent trapping has indicated there was usually just one possum at each focus of CTC detections, suggesting that there was likely to be only one female per 150-200 ha. Possum home ranges are typically only a few hectares and females produce only one or two young per year, so we assume reaggregation of males and females into reproductive clusters will result in isolated foci of survivors that gradually increase in numbers. One concept for mop-up control is therefore to conduct annual CTC surveys along transects spaced 1 km apart, with transect location shifted laterally by 0.25 km each year. Over a 4-year cycle, this should identify the location of almost all of the low-number isolated reproductive foci of possums and enable them to very efficiently and cost-effectively targeted, perhaps simply by placement of long-life toxic baits (Morgan 2005) at the few possum detection sites when the CTCs are checked.

CONCLUSION

Local elimination of invasive, small mammals now appears to be technically feasible as a new strategy for pest control in large unfenced mainland areas of New Zealand, at least for slow-breeding possums. This achievability mainly reflects the sustained incremental improvement in aerial poisoning over several decades to the point where possum populations can now sometimes be reduced to small numbers of geographically isolated foci. Provided those foci can be located cheaply, this enables highly-targeted mop-up control of only a small fraction of the area, rather than the blanket whole-area coverage that is currently the norm for repeat control. Transforming the concept into reality will require greater consistency in the achievement of near-total knockdown, and further development and refinement of the perimeter-control and mop-up tools outlined in this paper, but we see no major or fundamental obstacles to achieving that result.

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