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RESEARCH

Effects of aerial 1080 operations on deer populations in New Zealand

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Abstract: Aerially distributed baits containing sodium fluoroacetate (1080) are used in New Zealand for small-mammal pest control over an average of about 600 000 ha each year. This can also kill non-target species, including deer. This incidental mortality of deer generates antipathy to 1080 amongst many hunters, adding to the broader opposition to aerial 1080. Hunter opposition to 1080 baiting has also prompted the development of deer-repellent 1080 bait formulations. Historical estimates of deer mortality varied widely but were sometimes high. However, a recent study showed no adverse impact of 1080 on red deer sighting rates in one area and suggested that modern baiting protocols and frequency may have reduced the risk to deer. Here we provide a broader review of deer mortality observed in 26 aerial 1080 operations (or part operations) conducted since 1999. The estimated mortality of deer ranged from 0% to 100%. Overall, 42%, 38% and 20% of operations were classed as having low (0 to 33%), moderate (34 to 66%) or high (67 to 100%) impacts on deer populations, respectively. Adult males were found dead less often than adult females and all other age/sex classes, suggesting that by-kill risk might sometimes be inversely related to body size. Lower sowing rates (0.25–1.5 kg ha^{-1}) more often resulted in low deer by-kill than higher sowing rates (2.0–3.1 kg ha^{-1}), but there was no indication that using larger (12 g) rather than smaller (6 g) baits increased deer mortality. There was some indication that mortality may be lower where 1080 operation had been repeated within 5 years, possibly because of learned bait aversion in survivors of previous operations. The determinants of incidental mortality of deer are complex and somewhat unpredictable, and some deer are likely to be killed in most if not all operations, irrespective of the baiting strategy. We recommend formally planned experiments (rather than gathering often informal observations as summarised here) to assess whether deer mortality is significantly reduced when low sowing rates and/or short-interval repeat baiting is used, and (if so) whether this jeopardises efficacy in possum and rat control.

Keywords: aerial baiting, compound 1080, deer, mortality, hunting

Introduction

Aerial baiting with sodium fluoroacetate (1080) in cereal baits is a common small-mammal pest control practice in New Zealand. Currently, it is the most cost and time efficient way—Department of Conservation operations average $33 ha^{-1} (DOC 2018)— to achieve large reductions (generally over 90% reductions for the target species, Elliott & Kemp 2016), over large and topographically difficult areas (PCE 2011; Forsyth et al. 2018). Ground control methods typically have variable costs per hectare depending on the intensity with which they are applied, they rarely achieve equivalent reductions across the suite of pest species targeted by aerial baiting and are limited to areas accessible on foot. Users are required to report all aerial baiting operations to the Environmental Protection Authority (EPA), and their annual reports show an average of about 600 000 ha have been treated annually between 2008 and 2018. The Department of Conservation (DOC) has baited 107 000–645 000 ha yr^{-1}, mostly in their 'Battle for Our Birds' (now called Tiakina Ngā Manu) campaigns. These operations are

usually conducted in mast years in beech forests, primarily to target ship rats (*Rattus rattus*) and brushtail possums (*Trichosurus vulpecula*), with mice (*Mus musculus*) and stoats (*Mustela erminea*) as a desirable additional kill (Elliott & Kemp 2016). OSPRI has baited 239 000–427 000 ha yr^{-1} (EPA 2019), aiming to reduce possum density in order to locally eradicate bovine TB, but with the largely incidental mortality (by-kill) of other small mammalian predators seen as a conservation benefit (Warburton & Livingstone 2015). Regional councils and private landowners also conduct smaller aerial 1080 operations often targeting rabbits (*Oryctolagus cuniculus*) or Bennett's wallabies (*Macropus rufogriseus*) (EPA 2019).

Efforts to find alternatives to aerial 1080 baiting have not yet succeeded in delivering a tool that can be effective, practical and affordable at landscape scales. Therefore, the use of aerially-sown 1080 baits remains the most cost-effective tool for landscape-scale control of these key introduced mammals and disease vectors (PCE 2011). However, 1080 is toxic to most animals, so incidental poisoning of non-target species has long been an issue. Managers aim to minimise the risks

to non-target native species, and this is generally successful (Veltman & Westbrooke 2011), at least in the sense of ensuring that the benefits of increased recruitment of native species as a result of reduced predation outweighs any immediate losses from the baiting (e.g. Kemp et al. 2018). Arguably, there has been less concern about the killing of non-target species such as introduced birds (Morriss et al. 2016) and larger introduced mammals, including deer (Nugent et al. 2001; Veltman & Parkes 2002).

Much of the area subjected to aerial 1080 baiting is occupied by deer (mostly red deer *Cervus elaphus*), and any mortality of deer creates antipathy amongst recreational and commercial hunters, some of whom are vociferous in public campaigns against the use of 1080 (Green & Rohan 2011; Hansford 2016). The ongoing use of 1080 requires political approval to continue in the face of active opposition by some citizens and widespread unease by others because of animal welfare concerns (SPCA 2019). Therefore, objective assessment of the risks (e.g. the range of adverse consequences), and avoidance or mitigation of these where needed and possible, is required if the socio-political licence to aerially-sow 1080 bait is to be retained. In line with this, deer mortality was measured several times in the late 1900s and found to vary widely (5–93%, with about 50% being the modal level for red deer) (Nugent et al. 2001; Veltman & Parkes 2002).

The sometimes high by-kill of deer prompted efforts in the early 2000s to reduce hunter antipathy to aerial 1080 by successfully developing and testing a deer repellent for 1080 cereal baits by an aerial-1080 contractor (Epro Ltd) and New Zealand's TB management agency (then AHB/TBfreeNZ, now OSPRI) (Morriss et al. 2006). However, the addition of the Epro deer repellent, to both the non-toxic pre-feed and toxic baits, adds about \$6–8 ha^{-1} (about 15%) to the direct costs of aerial 1080 baiting (Morriss 2007). The higher cost has resulted in deer repellent bait being used mainly in areas of greatest concern to hunters, mostly on private land and to a lesser extent on public conservation land where deer are officially largely regarded as conservation pests.

In addition, best practice for aerial 1080 baiting for possums has changed since the 1990s, with a shift away from the use of diced carrot as bait to the almost universal use of cereal bait containing 0.15% w/w 1080. Cereal baits are usually lured with cinnamon to attract possums and deter birds (Hickling 1997). Current best practice also uses non-toxic pre-feeding to increase bait uptake by the target species, and sowing rates have reduced by an order of magnitude (from 15–45 to < 3 kg ha^{-1}; Nugent et al. 2011). Recent trials have also assessed the control efficacy of cluster or strip sowing bait rather than the usual broadcast baiting (Nugent & Morriss 2010; Nugent et al. 2012a; Nugent et al. 2012b). All these modifications could potentially influence the risk to deer, either positively or negatively.

There have been only three published estimates of deer incidental mortality since broad changes in baiting practice took effect, all using different methods to assess the mortality (see Appendix S1 in Supplementary Materials). an estimated two-thirds of fallow deer (*Dama dama*) were killed in a 2001 operation in the Blue Mountains, Otago (Nugent & Yockney 2004). In contrast a study showed no statistically measurable effect of aerial 1080 baiting on red deer sighting rates after three separate operations near Abbey Rocks and Moeraki in South Westland (Malham et al. 2019). Between those estimates, Forsyth et al. (2013) reported that non-repellent 1080-baiting in two central North Island operations (one using carrot bait, the other using cereal) had a negative effect of deer faecal pellet counts.

Malham et al. (2019) conclude that their findings should alleviate concerns amongst recreational hunters that current best practice aerial 1080 operations necessarily compromise recreational hunting of red deer – at least in the beech–podocarp forests of South Westland they studied. Here we review and summarise all available observations and/or estimates of deer by-kill using cereal 1080 bait since 1999 to determine the extent to which that conclusion can be generalised.

Data sources and methods

In addition to the published studies, we located 22 other records of deer mortality following aerial 1080 baiting using 6 or 12 g cereal baits with low sowing rates (≤ 3.1 kg ha^{-1}, mostly 1–2 kg ha^{-1}), including four records providing separate estimates when different aerial baiting treatments were used (i.e. aggregated baiting by cluster or strip-sowing versus standard broadcast sowing; Nugent et al. 2012a). The operations or parts of operations included in our analyses are summarised in Appendix S1 and S2 in the Supplementary Materials. All 1080 operations since 2008 are recorded as operational reports in the Environmental Protection Agency's 1080 website (EPA 2019). More detailed information was collated in many of these operations than is noted in the EPA reports (see Appendix S1) and summarised in management reports, most of which involved at least one of the authors of this paper, and were produced by Manaaki Whenua – Landcare Research (MWLR) for OSPRI as part of their efforts to eliminate TB from possums and other wildlife. The MWLR reports were internally peer-reviewed by MWLR, and also by OSPRI, the client. The reports are publicly available in the MWLR datastore (https://datastore.landcareresearch.co.nz/) via the digital object identifier (doi) links in the reference list.

The mortality estimates summarised here were derived from a diverse variety of data sources (Appendices S1 and S2). These include (1) direct assessment of the mortality of radio-collared deer; (2) before-and-after comparisons of indices of deer abundance (faecal pellet counts, live deer counts by observers or using trail cameras, and footprint counts); (3) counts of deer carcasses during deliberate searches within a mark–recapture framework or incidentally during other monitoring; (4) comparison of post-1080 deer sightings between poisoned and unpoisoned areas. Not all the records or reports provided a quantitative estimate of deer mortality. For these, we subjectively assigned a mortality class (see below) using data on sightings of live and dead deer, indices of deer abundance such as footprint sightings or faecal pellet counts, hunting success data, and any other background data on likely deer densities in the area. We acknowledge that the weakest of these assignments are no more than expert guesses. Given the wide differences in rigour with which mortality was assessed, we pragmatically classified the estimates of deer by-kill into just three broad classes: low (< 33%), moderate (34–66%) or high (67–100%).

The annual intrinsic rate of increase of red deer is about 35% (exponential rate $r = 0.3$), the average of several published studies (Forsyth et al. 2010). The actual rate of increase of recovering deer populations will usually be less than this and may be reduced by any ongoing harvest by hunters or increased by reinvasion. A population increasing at $r = 0.3$ will double every 2.3 years. Therefore, in relation to our low-moderate-

high classification, a population subject to low mortality rates would be expected to recover to previous levels by reproduction within 0 to 2 years, and from moderate mortality within 2 to 4 years, but it would probably require 5 or more years to recover from a high mortality rate.

To explore which operational or other factors might affect incidental mortality of deer, we used contingency tables to compare the number of operations in each mortality class between two and three broad categories of most of the operational variables. This analysis is exploratory as we did not have enough studies to include more than one or two factors of possible interest in a single analysis, cf. the analysis on possum mortality done by Veltman and Pinder (2001).

Results

Proportions of deer killed

The estimates and assessment of mortality indicate that the effect of modern cereal 1080 baiting operations on deer populations is highly variable, ranging from low or no detectable effect in 11 cases, moderate effects in 10 cases, and high effects in five cases (Tables 1 and 2). The three highest-impact case studies (an estimated 88% killed at Molesworth in 2017, 90–95% killed at Timaru Creek in 2018, and 100%

killed in the Upper Awatere in 2019) were also the most recent (i.e. most modern). For Molesworth in 2017, the high mortality estimate based on dead deer seen (Pinney 2019) is supported by the large difference in the rate at which live deer were seen during post-1080 aerial surveys in the poisoned area (0.2 deer km^{-2} searched; total area searched = 118 km^2) and in a similar unpoisoned area nearby (1.7 deer km^{-2} searched; total area searched = 100 km^2) (Morriss et al. 2018).

Susceptibility by species, size, age and sex

In some operations, larger individuals (adult males) were strongly under-represented relative to smaller individuals (all other age/sex classes) and relative to the smaller adult female class alone. As we do not know the actual age/sex distributions of the various populations, we cannot determine how much of the under-representation of adult males can be attributed to poisoning. However, the effect was most marked in the Blue Mountains 2001 operation, where only three adult males were found dead compared to 16 adult females and 34 younger deer (Nugent & Yockney 2004). In contrast, in the Timaru Creek 2018 operation, where mortality was high, the relative reduction in visits to camera sites by adult males was almost as high as for other age/sex classes (see Appendix S3 in Supplementary Information). From the overall all-operations-pooled data, there was only weak support for the hypothesis

Table 1. Numbers and sex ratios by age class (adultM: adultF – yearlingM: YearlingF – fawnM: FawnF) of dead deer found in incidental and/or deliberate carcass searches after aerial 1080 baiting (NR = not reported). For the deliberate searches only, the area searched and resulting carcass density estimates are shown where reported (NA = not applicable). Lastly, any quantitative estimates of % by-kill are shown, along with mortality class assigned in this study. The data sources are listed in Table S2. The two operations reported by Forsyth et al. (2013) are not included because one of the operations summarised used carrot bait.

Operation name	No. dead deer found post-baiting[1]	Sex ratios of dead deer by age class[2]	Area searched for carcasses (ha)	Density of dead deer (carcasses km^2)	Estimated % mortality	Mortality class assigned
Orongorongo	1		NA		54	Moderate
Wainuiomata	1		NA		5	Low
Blue Mountains	54 (53)	3:16–5:7–11:12	358	2–39	c. 66	High
Waianakarua	(8)	1:12–2:1–1:1	47	12.2	NR	High
Waipunga	13 (13)	1:4–2:4–0:0	1446	2.4–3.9	NR	Moderate
Caples 2006	1 (1)		c. 950	0.1	NR	Low
Caples 2009	0		c. 100		0	Low
Lake McRae: broadcast	5		NA		NR	Moderate
Lake McRae: cluster sowing	24		NA		NR	Moderate
Isolated Hill: broadcast	8		NA		NR	Moderate
Isolated Hill: cluster sowing	3		NA		NR	Moderate
Waitutu	7		2000	>0.3	7–14	Low
Tihoi 3B: broadcast	10 (5)	3:2–2:0–1:1	326	2.9	<33	Low
Hauhungaroa AS3: strip sown	22 (9)	4:5–3:2–3:4	326	6.9	>33	Moderate
Hauhungaroa 2013: broadcast	12 (1)	4:6–2:0–0:0	NA		NR	Moderate
Hauhungaroa 2013: strip sown	11 (1)	1:4–7:1–0:0	NA		NR	Moderate
Lower Dart	3		c. 1300	0.2	NR	Low
Dart/Routeburn	0		400		NR	Low
Dart/Routeburn	4	1:2–0:1–0:0	c. 50	1.28	c. 50	Moderate
Abbey Rocks – Windbag 2011	NR		NA		0	Low
Abbey Rocks 2014	NR		NA		0	Low
Moeraki 2013	NR		NA		0	Low
Hauhungaroa: Tihoi 2016	46 (24)	9:13–7:5–4:7	29 x 89	?	18	Low
Molesworth 2017	92		29,800		88	High
Timaru Creek 2018	10	1:2–0:0–0:0	NA		90–95	High
Upper Awatere 2019	30	6:9–1:0–1:3			100	High

[1]The total number of dead deer found, with those found in deliberate searches in brackets.
[2]Sex and age were not always recorded, so the total can be less than in column 4, while the total for Waianakarua includes the sex and age of 10 carcasses found in part of the area baited with carrot at 2 kg ha^{-1}.

Table 2. Comparison of effects of species, season, baiting frequency, bait size, sowing rate, and age/sex class on deer mortality from aerial 1080 baiting. The percentages are percentages of the row totals across the three by-kill classes for category of operations. The outcome of a log-linear analyses of the 2 × 2 × 3 contingency table for baits per hectare are reported in the results test.

	Number of operations in mortality class			
	High	Moderate	Low	Fishers exact test *(p)*
Deer species				
Red deer	4 (20%)	9 (45%)	7 (35%)	
Fallow and white-tailed deer	1 (17%)	1 (17%)	4 (67%)	0.43
Season				
Winter	4 (33%)	4 (33%)	4 (33%)	
Spring	1 (8%)	6 (46%)	6 (46%)	0.31
Operation repeat time (years)				
2–5 years	0 (0%)	3 (33%)	6 (67%)	
>5 years	5 (29%)	7 (41%)	5 (29%)	0.12
Bait size				
6 g	3 (18%)	6 (35%)	8 (47%)	
12 g	2 (22%)	4 (44%)	3 (33%)	0.76
Sowing rate				
≤1.5 kg ha^{-1}	0 (0%)	6 (46%)	7 (54%)	
>1.5 kg ha^{-1}	5 (38%)	4 (31%)	4 (31%)	0.05
Baits per hectare (sowing rate × bait size)				
≤1.5 kg ha-1 and 6 g baits	0 (0%)	4 (40%)	6 (60%)	
≤1.5 kg ha-1 and 12 g baits	0 (0%)	2 (67%)	1 (33%)	
>1.5 kg ha-1 and 6 g baits	3 (42%)	2 (29%)	2 (29%)	
>1.5 kg ha-1 and 12 g baits	2 (33%)	2 (33%)	2 (33%)	NA
	Number of deer in mortality class			
	High	Moderate	Low	
Deer body size				
Largest (adult males)	11 (33%)	10 (30%)	12 (36%)	
Smaller (all others)	84 (49%)	44 (26%)	42 (25%)	0.19
Size ratio (proportion large)	0.12	0.19	0.22	
Adult sex ratio				
Adult males	11 (33%)	10 (30%)	12 (36%)	
Adult females	39 (53%)	20 (27%)	15 (20%)	0.11
Sex ratio (proportion male)	0.22	0.33	0.44	

that under-representation of adult males was more marked when overall mortality was high (Table 2). Despite the indication that mortality is sometimes lower for large individuals, we could detect no difference in mortality between red deer and the two smaller deer species: fallow and white-tailed (*Odocoileus virginianus*) (Table 2).

Season, pre-feeding, and sowing method

There was no indication of any seasonal effect on deer mortality (Table 2). There was also no indication that familiarisation of deer with cereal bait (through non-toxic pre-feeding) was a major cause of increased deer mortality, as in all three operations that were not pre-fed, mortality was classed as moderate rather than low (Table 1).

Despite expectations that aggregated baiting would increase local bait density and therefore deer mortality (Meenken & Sweetapple 2000; Nugent et al. 2012a), the four trials in which broadcast and aggregated baiting were compared (Lake McRae, Isolated Hill, Tihoi-Hauhungaroa, and Hauhungaroa 2013), showed similar outcomes (three moderate and one low mortality operation for each method), albeit based on low sample sizes.

Previous exposure to 1080, sowing rate and bait size

We hypothesised that most deer that survive aerial 1080 baiting will have encountered bait, will have been sub-lethally poisoned, and will then have developed a learned aversion to cereal bait (as has been demonstrated for possums and rats). If so, mortality would tend to be lowest in recently poisoned areas and highest in areas never previously poisoned. The data are overall not strongly consistent with this (Table 2; $P = 0.12$), but we note that all five examples of high mortality were recorded in areas either never previously poisoned (four) or at least not for nine years (one).

Bait size by itself did not appear to have any strong direct effect on deer mortality ($P = 0.76$), whereas there was an indication that mortality was often higher when sowing rates of > 1.5 kg ha^{-1} were used ($P = 0.05$) (Table 2). Segregating operations by both bait size and sowing rate (2 × 3 × 2 contingency table; Table 2) indicated strong support for an effect of sowing rate (log-linear analysis, $P = 0.02$). Most notably, all five operations resulting in high mortality used sowing rates > 1.5kg ha^{-1}. However, there was again little support in that two-factor analysis for a bait size effect or other interactions (all P-values > 0.20). A parallel comparison

of the effect of the time since the previous 1080 baiting in conjunction with sowing rate was not possible because there were no operations with a > 1.5 kg ha^{-1} sowing rate in areas that had been poisoned within the previous 5 years.

Discussion

The estimates of deer mortality we summarise vary greatly in robustness. Apart from a single observation based on the mortality of radio-collared deer coupled with identification of 1080 in killed deer, the estimates are all indirect. They were mostly based on either a comparison of indices (faecal pellet counts, live deer counts by observers or using trail cameras, or footprint counts) or on counts of deer carcasses found during planned searches or from incidental observations during other monitoring (sometimes in conjunction with measurement of one of the other indices). Some estimates of mortality were derived from comparison with other 1080 treatments (usually application of a deer repellent) in which deer mortality was assessed as low or (less often) sometimes with a non-treatment area. There are weaknesses in 'design' of most, if not all, of the observations in terms of robust assessment of non-treatment effects and lack of replication. We therefore acknowledge again that the estimates should be viewed as informed guesses, with some being well-informed and other not. Our results and the discussion below are therefore based on the assumption or caveat that the estimates are not consistently biased high or low.

Whether a deer is at risk when exposed to 1080 baits probably depends firstly on whether the bait is palatable to deer, in both absolute (i.e. will deer eat the bait when hungry?) and relative (i.e. will deer eat the bait when other highly palatable food is abundant?) terms. Previous research indicates that RS5 cereal bait is highly palatable to well-fed captive deer (Morriss 2007). Consistent with that, the high incidental mortality of deer in the 2017 Molesworth possum control operation in spring, when high-quality spring growth was plentiful, indicates that most of the deer there must have eaten enough baits to obtain a lethal dose, despite the presence of high-quality natural food. In addition, most deer populations are held below carrying capacity by some combination of commercial and recreational hunting (Nugent et al. 2001) so are unlikely to be starving. We therefore infer that relative palatability is probably not a major determinant of deer by-kill.

Instead, the main risk appears to lie in how quickly a deer can find and eat multiple baits. For example, the LD$_{50}$ of 1080 for red deer is about 0.5 mg kg^{-1} (Rammell & Fleming 1978) which appears to be similar to that of other ungulates (P. Fisher, unpubl. data) although there are no published LD$_{50}$ estimates for fallow or white-tailed deer. Therefore, an average female red deer weighing 75 kg would have to eat about five 6 g baits (or 2.5 12-g baits) with 0.15% 1080 to have a 50% chance of dying. An average male weighing 100 kg would have to eat about seven 6 g baits or 3.5 12-g baits. Because 1080 is a fast-acting toxin, animals typically begin to feel ill and stop feeding not long after eating the first bait – symptoms appear in other better-studied mammals between about 0.5 and 2.5 hours after ingestion (Eason et al. 1994). This sets the time window in which the multiple baits required to kill an individual deer (at least the number to kill half of the animals) must be found and consumed.

Whether a deer can find and eat enough baits to obtain a lethal dose obviously depends firstly on the combination of sowing rate and bait size (1 kg ha^{-1} provides 167 6-g baits per hectare, or 83 12-g baits per hectare). Because deer have home ranges of hundreds or thousands of hectares (Nugent & Fraser 2005), it seems certain all deer within a baited area will encounter bait and will do so on the day that bait is sown. However, several other factors will also influence risk. Firstly, deer are obviously likely to take longer to find bait in areas where ground cover is dense. Consistent with that, Nugent and Yockney (2004) showed that the density of dead deer was lowest in Blue Mountain blocks where ground cover was most dense. Another risk is that other diurnal species (particularly rats) could rapidly reduce bait density—by eating or caching it (Morriss et al. 2012)—and we note that six of the seven operations conducted in beech forest during mast years (i.e. when rodent densities were high; Elliott & Kemp 2016) resulted in low incidental mortality of deer. Susceptibility to 1080 appears to vary with season in possums (Veltman & Pinder 2001), but we found no evidence of that for deer. Since all but one of the operations were outside the annual rut, March to May, depending on the species (Nugent 2005; Nugent & Asher 2005; Nugent & Fraser 2005), the apparently lower mortality of adult males in some operations cannot be due to the anorexia exhibited by stags during their rut. Rather, it may reflect the influence of size on deer susceptibility: larger-bodied deer may be more likely to survive because they must find more baits within the pre-toxicosis window to be killed than would smaller bodied deer. The very low number of adult stags found dead in the Blue Mountains in 2001 (Nugent & Yockney 2004) and a predominance of adult stags amongst survivors of the 2017 Molesworth operation (Morriss et al. 2018) is consistent with this, although adult males appeared to be as severely impacted as other age-sex classes in the Timaru Creek operation (Appendix S2). Another potential risk factor is non-toxic pre-feeding which increases bait acceptance by (and therefore mortality of) possums (Warburton et al. 2010) and rabbits (Nugent et al. 2012c), but there were too few not-prefed operations to usefully test this for deer.

There is something of a dichotomy in bait size between 1080 operations primarily targeting possums for TB eradication and those primarily targeting rats for bird conservation: the former tend to use 12-g baits in an effort to ensure that every bait encountered delivers a lethal dose for possums, whereas the latter tend to use 6-g baits (which are easily big enough to kill rats) in order to increase the number of individually lethal baits available for rats (Brown et al. 2015). The absence of a bait-size effect signal in our analysis, suggests that for any given sowing rate, the lower dose of 1080 in each small bait is largely or completely offset by the greater number of such baits available relative to when larger baits are used.

If animals are sub-lethally poisoned with 1080, they are likely to develop a learned aversion to the bait. This has been shown for possums (Hickling 1994; Ross et al. 2000), rats (Nugent et al. 2019) and rabbits (Fraser 1985), so we assume it is highly likely to also hold for deer. Therefore, we believe that a large majority of deer that survive 1080 operations will have encountered and eaten a sub-lethal amount of toxic bait so are likely to be bait averse. If so, a simple deer population model with annual male and female survival of 72% and 82%, respectively (which produces an age structure like those for large samples of hunter-killed deer; Nugent et al. 2001) suggests that 62%, 48%, 38% and 31% of deer in such a population could be 1080 survivors at timepoints two, three, four and five years after the 1080 baiting, respectively. If those survivors remain bait averse for at least 3–5 years, the by-kill of deer would probably be reduced if 1080 baiting was repeated within

five years, as has become increasingly common since rats have become a major target in DOC operations (EPA 2019). The inference of low mortality for deer for the Abbey Rocks / Moeraki and Hauhungaroa–Tihoi operations are consistent with this prediction.

The apparent increase in deer encounters and sightings in the first year after the 1080 baiting and the subsequent decline over the following two years reported by Malham et al. (2019) is interesting. Their models take seasonal variation into account, removing it as a possible cause of the initial increase. One explanation is that deer often become less wary and more detectable if hunting is stopped (Forsyth et al. 2010), so it is possible that the post-baiting increase they report might reflect deer becoming less wary of ground-based observers during the cautionary period of four months put in place to stop hunters from taking venison from areas subjected to 1080 baiting (MPI 2019). Malham et al. (2019) argue that this is unlikely given the localised nature of recreational hunting in their study area. They suggest, instead, the possibility that lethal or sub-lethal poisoning may disrupt the social organisation of the population in ways that somehow make the deer less wary. We suggest this would be more plausible if there had actually been some low or even moderate level of mortality that resulted in the break-up of the family groups in which deer in New Zealand forests typically reside (Nugent et al. 2001) creating a greater number of smaller groups (including 'groups' of single individuals) resulting in an increased encounter rate. The Hauhungaroa–Tihoi 2016 operation possibly provides an example of how that could occur: we found clear evidence of some mortality (in the form of 46 carcasses), and the weekly sighting rate recorded on trail cameras accordingly declined by over half immediately after the 1080 baiting, but then increased 2–3 months later to levels that were much the same as before baiting.

Whether deer mortality due to aerial 1080 baiting is a 'good' or 'bad' outcome depends largely on whether people see deer as a pest or a resource. Most hunters see incidental mortality of deer as undesirable, whereas people who see deer as a threat to native habitats and biodiversity may not be concerned that they are killed as non-targets during pest control. Deer occur across about 48% of New Zealand (13 million ha) (Fraser et al. 2000), so the area subject to aerial 1080 baiting annually equates to about 5% of the total deer range. Most (81%) of our estimates of deer mortality were low or moderate, suggesting that deer mortality is likely to be well below 50% on average. If so, the annual reduction in the national deer population caused by 1080 is likely to be $< 2\%$ yr^{-1}. With a few exceptions, most deer populations in New Zealand have been held well below carrying capacity by hunting for many decades (Nugent et al. 2001), so the annual recruitment rate (and therefore the annual harvest rate) is likely to often approach the maximum reproductive rate of increase for deer of about 35% yr^{-1} (Table 1 in Forsyth et al. 2010). If so, that suggests that 1080 operations will commonly have only short-term (0–3 years) effect on local deer densities, and the cumulative effect of a $<2\%$ yr^{-1} reduction will probably be well below 5%. It also suggests that the numbers of deer killed during 1080 operations are small relative to the national hunter harvests. Those harvests are not well quantified, but recreational hunters may harvest up to about 80 000 deer yr^{-1} (Woods & Kerr 2010) and commercial helicopter-based hunters have taken 16 000–29 000 deer annually since 2008 (Ministry of Primary Industries, unpubl. data).

For those who view deer as conservation pests, a question is whether the incidental mortality of deer during 1080 operations provides useful conservation benefits. Our data show that although such operations sometimes reduce deer density greatly, most do not. Further, for the few operations that do substantially reduce deer density, maintaining those reduced densities by repeating the aerial 1080 baiting at short intervals may fail as Malham et al. (2019) show repeat baiting did not reduce deer sighting rates. We conclude that reducing deer densities to the low levels often required to substantially ameliorate their unwanted impacts (Nugent et al. 2001) may occasionally be an outcome of 1080 baiting but unless the baiting is repeated the populations will soon recover. But if the baiting is repeated the mortality of deer appears to often be minor, so deer mortality from 1080 baiting alone appears unlikely to produce sustained conservation outcomes.

The overall opposition to the use of 1080 in New Zealand includes concerns about animal welfare in lethally and sub lethally poisoned animals (Green & Rohan 2011). For non-target species such as deer it is unclear whether reducing risk by minimising their chance of finding and eating enough baits would reduce deer suffering, given that that might results in a greater number of survivors possibly suffering (from sub-lethal poisoning) for longer. Reduction of such welfare effects is likely to require the use of deer-repellent bait.

The observations and estimates summarised here suggest that, for broadcast baiting at least, use of low sowing rates of 1.0 kg ha^{-1} or less should reduce the risk of a high mortality of deer. Repeat baiting within 5 years may further reduce that risk. Based largely on logic, and some anecdotal observations, we suggest that the ease with which multiple baits can be quickly found by deer may also sometimes be an important risk factor. In summary, the inference by Malham et al. (2019) that modern repeat aerial 1080 baiting may not greatly affect deer or deer hunting has some support from our analysis; nevertheless, we found wide and still somewhat unpredictable variation in deer mortality even using modern baiting approaches. There is good evidence that deer repellent bait can be used to reduce deer mortality (Morriss 2007). However, that adds to the cost of baiting, so deer repellent bait tends to be used mainly in areas where hunter or landowner interest in deer is particularly high. Deer mortality can still be moderate or high even when repellent bait is used (Morriss & Nugent 2018; Morriss et al. 2019), so consistently reducing deer mortality to low levels (where that is deemed desirable) is likely to require finding ways to avoid high kills when non repellent bait is used.

A key research question is to determine whether a reduction in deer mortality could be achieved by lowering sowing rates or by shortening the interval between repeat baitings (or by some combination of those). Because those effects are somewhat confounded in current operational practices, addressing this question will require a formal programme of experimental research using a fully balanced and replicated design (rather than the collection of mostly incidental observations as in this review). If sowing rate is the major determinant of deer mortality, a key question will be whether the low sowing rates required to minimise deer mortality jeopardise efficacy in possum and rat control.

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Supplementary Material

Additional supporting information may be found in the online version of this article:

Appendix S1. Study site descriptions and design of assessments of deer mortality in 26 operations using aerial 1080 in cereal baits.

Appendix S2. Operational protocols for aerial 1080 baiting projects using cereal RS5 (short field-life) or Wanganui No. 7 (W 7) (longer field-life) baits.

Appendix S3. Numbers of photographs of live red deer, by sex-age class, recorded at camera traps over 3 months immediately before and 3 months immediately after aerial 1080 baiting, Timaru Creek, 2018.

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