Forest bird mortality and baiting practices in New Zealand aerial 1080 operations from 1986 to 2009

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Abstract: We collated 48 surveys of individually banded birds or birds fitted with radio transmitters that were checked before and after 1080 poison (sodium fluoroacetate) baits were aerially distributed to control brushtail possums (*Trichosurus vulpecula*) in New Zealand forests. The surveys were associated with 34 pest control operations from 1986 to 2009 and covered 13 native bird species, of which four were kiwi (*Apteryx* spp.). Sample sizes ranged from 1 to 46 birds (median 15). In 12 cases a sample of 1 to 42 birds (median 13) was surveyed in an untreated area at the same time. In total, 748 birds were checked before and after operations and 48 birds disappeared or were found dead. In non-treatment areas, 193 birds were checked and four died. Surveys of kiwi, whio (*Hymenolaimus malacorhynchos*), kaka (*Nestor meridionalis*) and kokako (*Callaeas cinerea*) were grouped for meta-analyses. The 95% pooled upper confidence bounds for the point estimate of zero mortality were each less than 4% for kiwi, kaka and kokako indicating only a small risk of mortality during 1080 pest control operations. Prefeeding with non-toxic baits increased from 22% (1998–1999) to 79% (2007–2008) in 322 operations on public conservation lands but was used in only 9 (26%) of the operations during which individually marked birds were monitored. We caution that failure to observe bird deaths in small samples may lead to weak inference about zero mortality across a population, most surveys in the review did not involve prefeeding, and that 11 native bird species for which deaths were reported after 1080 operations have not been studied.

Keywords: brushtail possum; meta-analysis; non-target mortality; poison baits; sodium fluoroacetate; *Trichosurus vulpecula*

Introduction

When vertebrate pesticides such as sodium fluoroactetate (1080) or brodifacoum are distributed in baits from aircraft to control brushtail possums (*Trichosurus vulpecula*) and ship rats (*Rattus rattus*) in New Zealand forests, there is a risk of poisoning birds. Corpses of 19 native bird species have been recovered after aerial baiting with 1080 since it began in 1956 (Spurr, 2000). Moreporks (*Ninox novaeseelandiae*), weka (*Gallirallus australis*), kākā (*Nestor meridionalis*), kokakō (*Callaeas cinerea*) and robins (*Petroica australis*) died when Kapiti Island was sown with brodifacoum baits to eradicate rats (Empson & Miskelly 1999) and saddlebacks (*Philesturnus carunculatus rufusater*) were killed when brodifacoum was used on Mokoia Island (Davidson & Armstrong 2002). In considering impacts on birds, the decision to proceed with an aerial poison operation must balance the possible mortality of birds from ingestion of poison baits against the ongoing risk of low recruitment and low adult female survival in bird populations depredated by possums, ship rats and stoats (*Mustela erminea*) (Innes & Barker 1999; Davidson & Armstrong 2002). On offshore islands, such as the Kapiti Island and Mokoia Island examples, bird deaths caused by a single application of a vertebrate pesticide to eradicate invasive mammals may be rapidly offset by improved reproduction of survivors in the newly-predator-free habitat (Empson & Miskelly 1999). However, at mainland sites the immigration of pests and consequent need for repeated applications of pesticides might reduce population viability of some bird species from the cumulative effect of a series of even small-scale mortality events.

An analysis of aerial 1080 baiting for brushtail possum control at mainland sites in the 1994–1999 period showed an average possum mortality of 87.9% (SD 10.0, $n = 48$; Veltman & Pinder 2001). Since then, prior baiting with non-toxic baits (called 'prefeeding') has been adopted by many pest control operators and possum mortality exceeds 90% (Coleman et al. 2007). The mechanism by which prefeeding increases possum mortality has been shown to be an increase in bait consumption and change in foraging behaviour patterns (Warburton et al. 2009). Ship rat populations at some sites recover rapidly from very low densities after 1080 poison operations, to reach densities (indexed by kill-trapping) higher than existed in the presence of possums before control was carried out (Sweetapple & Nugent 2007). These studies raise questions of whether incidental bird mortality also increases when prefeeding is used and whether demographic responses in the years after poisoning are suppressed by ship rat predation. If the answer is yes to both questions, perverse outcomes can be predicted from repeated use of aerial 1080 baiting at conservation sites on the mainland.

To address these questions, data are required on bird mortality as well as operational specifications and on bird population dynamics in ensuing years. This paper is concerned with bird deaths during poison operations in relation to how baits are presented. Ongoing studies of bird population dynamics at poisoned mainland sites exist for kokakō (Flux & Innes, 2001), kiwi (*Apteryx* spp.; Holzapfel et al. 2008) and kākā (Moorhouse et al. 2003) and were started but not continued for kereru (*Hemiphaga novaeseelandiae*) and kākā (Powlesland et al. 2003), but have yet to be reported for passerines.

Possible procedures for quantifying bird disappearance rates over the course of a poisoning operation were listed by Spurr and Powlesland (1997) as five-minute call counts; checks for occupants of known territories or nest sites; roll-calls of banded birds trained to approach observers; and post-operation searches for banded birds or birds fitted with radio-transmitter devices. Since then, mark–resighting procedures have been used to quantify changes in saddleback density (Davidson & Armstrong 2002) and a procedure for quantifying counts of territorial singing males in tomtit (*Petroica macrocephala toitoi*) populations along transects has been developed (Westbrooke et al. 2003). Given that five-minute call counts can detect only large changes in abundance (Spurr & Powlesland 1997) and that territory transect counts and distance sampling have so far been reported only on one species (Westbrooke et al. 2003; Westbrooke & Powlesland 2005), we concentrated on surveys in which birds were individually colour-banded or were carrying radio transmitters at sites treated with aerial 1080 baiting.

We collated published and unpublished bird surveys, and where necessary retrieved details of the aerial 1080 operations to which they were exposed. We used a database of pest control reports maintained by the Department of Conservation from 1998 to characterise baiting practices such as bait type, toxin concentration, sowing rates and use of prefeeding. In this way, we were able to review knowledge of bird death rates in relation to how 1080 is presented when it is aerially broadcast in mainland forests.

Methods

Bird surveys

Surveys of colour-banded birds or birds fitted with radio transmitters were found by searching the literature, tracking down cited but unpublished reports, and contacting Department of Conservation rangers and scientists for information about surveys that were not previously documented.

For each case we recorded the year and aerial 1080 operational information (Table 1). We determined the number of marked birds alive at the time of poisoning and the number known to be still alive during a census in the days or up to 3 weeks after a poison operation (the time interval varied between cases). The difference was taken to be the number of birds killed in the operation, and when birds wore radio transmitters this was confirmed by assays of tissues recovered from the corpses. Where papers or reports lacked the required detail, we contacted authors for clarification.

Estimating confidence intervals

The difference between the number of birds alive before and after each poison operation gave a point estimate of mortality for each survey. We estimated the upper confidence bounds based on a binomial model, using an 'exact' approach. Clopper-Pearson estimates provide a $100 \times (1–\alpha)$% upper confidence bound for the event rate, simplifying to $1–\alpha^{1/n}$ where there was no observed mortality. When $\alpha = 0.05$ and $n > 15$, this upper confidence bound is very well approximated by $3/(n + 1)$, a calculation known as the 'Rule of Three', especially in medical statistics (Jovanovic & Levy 1997). We present the Clopper-Pearson estimates for the upper bound of 95% confidence intervals. In the case of zero observed mortality, this corresponds to a 95% upper confidence bound as the confidence interval is one-sided, being already bounded below by zero, while for cases with observed mortality the interval is two-sided and it corresponds to a 97.5% upper confidence bound.

Meta-analyses for cases when no birds died

Standard meta-analysis tools do not allow estimation when there is no variation between the surveys. To carry out a meta-analysis for species subject to several surveys in which no birds had died, we derived a result specific to zero observed mortality in multiple surveys. We show in the Appendix that when no event occurs in any of several groups, each with a possibly different binomial rate, the standard upper confidence calculated as if there were one group provides an upper confidence bound for the weighted mean binomial rate across these groups (where weighting is by the sample size in each group). This allows an interpretable result for the pooled mean without assuming that the rate of mortality is the same for all the surveys in the pool. For example, as shown in Table 2, the interval for kiwi mortality is 0–1.5%, which is equivalent to a 95% confidence interval for weighted mean kiwi survival across these surveys of 98.5% to 100%.

Aerial 1080 operations 1998–2008

To learn how 1080 was presented during aerial baiting operations we searched a Department of Conservation database for reports of aerial 1080 poisoning operations conducted between 1998 (when the database begins) and June 2008 (a verification step for later operations had not been completed when we ran our analyses). From each report we obtained data on bait type and weight, 1080 concentration, bait sowing rate and whether prefeeding with non-toxic baits had been used (Table 1). By grouping reports into business years (1 July to 30 June), we were able to look for changes in baiting practices.

Results

Bird deaths observed during surveys

We found 47 surveys of individually banded birds or birds fitted with radio transmitters before 1080 poison baits were aerially distributed and one survey in which baits were broadcast by hand to simulate aerial distribution (Table 1). The surveys were associated with 34 pest control operations from 1986 to 2009, of which 20 were conducted before or during 1998 (Table 1). We note that 13 of the surveys had not been previously published (Table 1).

There were surveys for 13 species, of which four were kiwi (Table 1) and all were native. Sample sizes ranged from 1 to 46 birds (median 15) and in 12 cases a sample of 1–42 birds (median 13) was surveyed in an untreated area for comparison (Table 1). In total, 748 birds were checked before and after poison operations and 48 birds were found dead or disappeared before the post-operation census. In non-treatment areas, 193 birds were checked and four died (Table 1).

Meta-analyses of multiple surveys in which no birds died

We grouped surveys of kiwi (four species) and of kākā (two subspecies) for meta-analysis, reasoning that foraging modes (and hence exposure risk) were the same for related

Table 1. Surveys of banded or radio-wearing native birds before and after aerial distribution of 1080 baits for possum or ship rat control in New Zealand forests. Month 1 refers to January. RS5, W7 and Mapua refer to baits manufactured from cereal. Exact binomial 95% upper confidence limits on an estimate of zero mortality are shown for all surveys in which no birds died. The code 'nd' is used when we could not find information for a cell. ! signifies one case in which baits were spread by hand to mimic aerial distribution. [abc] same superscript signifies same operation. Sources are listed below. Pestlink refers to a Department of Conservation database.

Species	Year	Site	Operational specifications						Bird survey				Upper bound (as percentage) of 95% confidence interval	Information source*
			Month	Prefed	Bait type	Mass (g)	1080 ($g\ kg^{-1}$)	Sowing rate ($kg\ ha^{-1}$)	Treatment		Non-Treatment			
									Sample size	No. died	Sample size	No. died		
Apteryx haastii (great spotted kiwi)	1994[a]	Saxon River, North-West Nelson	8	No	RS5	6	1.5	5	9	0	-	-	28.3	39, 40
	1994	Karamea, West Coast	12	No	W7	6	1.5	5	7	0	-	-	34.8	34
	2009[i]	Hawdon Valley, Arthur's Pass National Park	9	Yes	RS5	6	1.5	2	20	0	-	-	13.9	2
Apteryx australis 'Haast'	2001	Hindley, Westland	5	No	W7	12	1.5	3	19	0	-	-	14.6	4, 17
Apteryx rowi (Okarito kiwi)	1998	Okarito, West Coast	11	No	W7	6	1.5	3	46	0	-	-	6.3	8, 31
Apteryx mantelli (NI brown kiwi)	1990	Waipoua, Northland	9	No	W7	6	0.8	5	5	0	-	-	45.1	31, 34
	1995	Tongariro Forest, Tongariro National Park	6	Yes	Carrot	nd	0.8	10	2	0	-	-	77.6	33, 34
	1995	Rewarewa, Northland	5	No	W7	6	1.5	3[!]	22	0	-	-	12.7	15, 30, 31
	2001[b]	Tongariro Forest, Tongariro National Park	9	Yes	W7	12	1.5	3	24	0	-	-	11.7	5, 6, 13, 28
	2006	Tongariro Forest, Tongariro National Park	9	Yes	W7	12	0.8	4	45	0	-	-	6.4	9, 13
Hymenolaimus malacorhynchos (whio)	1994[c]	Waihaha, Pureora Forest Park	7-8	Yes	carrot	nd	1.5	15	19	0	-	-	14.6	34
	2008	Oparara, West Coast	11	Yes	W7	12	1.5	3	15	0	-	-	18.1	1, 11, 29, 32
Gallirallus australis australis (weka)	1994[a]	Saxon River, North-West Nelson	8	No	RS5	6	1.5	5	7	0	-	-	34.8	39, 40
	1994[h]	Tennyson Inlet, Marlborough Sounds	8	No	RS5	6	1.5	5	17	1	-	-	28.7	39, 40
	1994	Rotomanu, West Coast	nd	No	W7	6	1.5	5	8	0	-	-	31.2	34
	2000	Copland Valley, Westland National Park	6	No	RS5	8	1.5	3	10	0	-	-	25.9	7, 38
	2008	Turiwhate, Central Westland	8	Yes	Carrot	nd	1.5	5	28	1	-	-	18.3	32, 37
Hemiphaga novaeseelandiae (NZ pigeon)	2000[d]	Whirinaki Forest Park	5	Yes	Carrot	6–9	0.8	10	15	0	11	1	18.1	27
Nestor meridionalis septentrionalis (NI kākā)	1994[c]	Waihaha, Pureora Forest Park	7-8	Yes	Carrot	nd	0.8	15	21	0	-	-	13.3	18, 19
	2000[d]	Whirinaki Forest Park	5	Yes	Carrot	6–9	0.8	10	17	0	20	0	16.2	27
	2001	Waipapa, Pureora Forest Park	10	Yes	W7	12	1.5	2	20	0	-	-	13.9	27, 36

Species	Year	Site	Operational specifications: Month	Prefed	Bait type	Mass (g)	1080 (g kg^{-1})	Sowing rate (kg ha^{-1})	Bird survey: Treatment		Non-Treatment		Upper bound (as percentage) of 95% confidence interval	Information source*
									Sample size	No. died	Sample size	No. died		
	2008	Waipapa, Pureora Forest Park	6	Yes	W7	12	1.5	1.5	10	0	-	-	25.9	12, 22, 36
Nestor meridionalis meridionalis (SI kākā)	1998	Windbag Valley, West Coast	6	No	W7	6	1.5	3	15	0	-	-	18.1	14, 27
Nestor notabilis (kea)	2008	Arawhata, Mt Aspiring National Park	1	No	W7	12	1.5	4	10	0	-	-	25.9	21
	2008	Franz Josef, Westland National Park	5	Yes	W7	12	1.5	2.5	17	7	-	-	67.1	21
	2009	Mt Arthur, Kahurangi National Park	6	Yes	RS5	12	1.5	2	13	0	7	0	20.6	21
	2009[i]	Hawdon Valley, Arthurs's Pass National Park	9	Yes	RS5	12	1.5	2	10	0	3	0	25.9	21
Ninox novaeseelandiae (morepork)	1994[a]	Saxon River, North-West Nelson	8	No	RS5	6	1.5	5	6	0	-	-	39.3	39, 40
	1994[h]	Tennyson Inlet, Marlborough Sounds	8	No	RS5	6	1.5	5	1	0	-	-	95.0	39, 40
	1996[e]	Tahae, Pureora Forest Park	9	Yes	Carrot	nd	0.8	15	6	1	1	0	64.1	23
	1998[f]	Long Ridge, Pureora Forest Park	8	No	W7	6	0.8	5	3	0	3	0	63.2	25, 36
Petroica macrocephala toitoi (NI tomtit)	1996[e]	Tahae, Pureora Forest Park	9	Yes	Carrot	nd	0.8	15	2	2	-	-	100.0	23
	1997[g]	Waimanoa, Pureora Forest Park	8	Yes	Carrot	nd	0.8	10	14	11	9	0	95.3	26
	1998[f]	Long Ridge, Pureora Forest Park	8	No	W7	6	0.8	5	14	0	16	0	19.3	26
	2001[b]	Tongariro Forest, Tongariro National Park	9	Yes	W7	12	1.5	3	15	1	15	0	31.9	41
Petroica australis australis (SI robin)	1994[a]	Saxon River, North-West Nelson	8	No	RS5	6	1.5	5	2	0	-	-	77.6	39
Petroica australis longipes (NI robin)	1996[e]	Tahae, Pureora Forest Park	9	Yes	Carrot	nd	0.8	15	22	12	24	0	75.6	24
	1997[g]	Waimanoa, Pureora Forest Park	8	Yes	Carrot	nd	0.8	10	31	3	42	1	25.8	24
	1998[f]	Long Ridge, Pureora Forest Park	8	No	W7	6	0.8	5	17	0	42	2	16.2	25, 36
	1998	Pokeka, Wanganui National Park	3	No	W7	6	1.5	5	35	9	-	-	43.3	3, 10, 35
Callaeas cinerea (kokakō)	1986	Meyer's Farm, Pureora	6	No	W7	6	0.8	8–10	5	0	-	-	45.1	16, 20, 36
	1986	Pureora Forest Park	7	No	Mapua	nd	1.5	10–12	9	0	-	-	28.3	16, 20, 36

Species	Year	Site	Operational specifications						Bird survey				Upper bound (as percentage) of 95% confidence interval	Information source*
			Month	Prefed	Bait type	Mass (g)	1080 ($g\ kg^{-1}$)	Sowing rate ($kg\ ha^{-1}$)	Treatment		Non-Treatment			
									Sample size	No. died	Sample size	No. died		
	1986	Tunawaea, Waikato	7	No	Mapua	nd	1.5	10–12	11	0	-	-	23.8	15, 16, 20, 36
	1990	Mapara; King Country	9	No	W7	6	0.8	8	5	0	-	-	45.1	15, 16
	1991	Mapara, King Country	10	No	W7	6	0.8	8	20	0	-	-	13.9	15, 16
	1992	Mapara, King Country	10	No	W7	6	0.8	8	37	0	-	-	7.8	15, 16
	1994	Rotoehu	10	nd	W7	6	1.5	2	26	0	-	-	10.9	16, 20
	2001	Mapara, King Country	10	Yes	W7	12	1.5	2	16	0	-	-	17.1	16

* 1, M. Abel, pers. comm.; 2, M. Ambrose, pers. comm.; 3, J. Campbell, pers. comm.; 4, DOC Pestlink 0203SWS25; 5, DOC Pestlink 0203TUR03; 6, DOC Pestlink 0203RUA06; 7, DOC Pestlink 0203SWS22; 8, DOC Pestlink 0304FZJ06; 9, DOC Pestlink 0708RUA01; 10, DOC Pestlink 0203WHA04; 11, DOC Pestlink 0809BUL14; 12, DOC Pestlink 0910MPT06; 13, N. Etheridge, pers. comm.; 14, T. Farrell, pers. comm.; 15, I. Flux, pers. comm.; 16, Flux & Innes 2001; 17, N. Freer, pers. comm.; 18, T. Greene, pers. comm.; 19, Greene 1998; 20, J. Innes, pers. comm.; 21, J. Kemp, pers. comm.; 22, R. Powlesland, pers. comm.; 23, Powlesland et al. 1998; 24, Powlesland et al. 1999a; 25, Powlesland et al. 1999b; 26, Powlesland et al. 2000; 27, Powlesland et al. 2003; 28, N. Poutu, pers. comm.; 29, G. Quinn, pers. comm.; 30, Robertson et al. 1999; 31, H. Robertson, pers. comm.; 32, T. Shaw, pers. comm.; 33, C. Speedy, pers. comm.; 34, Spurr & Powlesland 1997; 35, D. Stronge, pers. comm.; 36, A. Styche, pers. comm.; 37, van Klink 2008 (unpubl.); 38, van Klink & Tansell 2003; 39, Walker, K. 1997; 40, K. Walker, pers comm.; 41, Westbrooke et al. 2003.

taxa. The other bird species for which no disappearances or deaths were reported in multiple surveys were kokakō and whio (*Hymenolaimus malacorhynchos*). The 95% pooled confidence bounds for an estimate of zero mortality for these groups of surveys are shown in Table 2.

Aerial 1080 operations on public conservation lands

There were 322 aerial 1080 baiting operations from 1998 to 2008 carried out on public conservation lands, mainly using cereal baits with a toxin loading of 1.5 g kg^{-1} (Table 3). There was widespread adoption over time of 12-g baits, and prefeeding with non-toxic baits was carried out for the majority of operations by 2008 (Table 3).

Discussion

The surveys we reviewed encompassed eight of the 19 native bird species that have been found dead after aerial 1080 poison operations and none of the 13 exotic species killed in operations (Spurr 2000). Thus the poisoning risk has not been quantified for individuals of 11 other native bird species that have been known to die, of which two (rifleman *Acanthisitta chloris,* pipit *Anthus novaeseelandiae*) are classified as at risk – declining (Miskelly et al. 2008).

Only 12 (25%) surveys included a control and we could not ascertain the independence of some surveys, such as the repeated observations of kokakō at Mapara and North Island brown kiwi (*Apteryx mantelli*) at Tongariro. Some of the banded birds in those surveys were tracked through consecutive 1080 operations (J. Innes, pers. comm.; I. Flux, pers. comm.). 'Beyond BACI' designs for detecting environmental impacts on populations against a background of natural variability have been available for most of the period of the surveys we reviewed (Underwood 1992, 1994), yet no survey took advantage of the inferential improvements available from multiple controls and random allocation of the treatment. In an alternative approach, Armstrong et al. (2001) used model selection procedures on a time series of resightings of hihi (*Notiomystis cincta*) before and after brodifacoum was broadcast over Mokoia Island in 1996 to find support for 'a negligible increase in mortality' due to the pest control operation. These epistemological developments apparently did not influence the survey work we have reviewed.

While there were no bird deaths observed in 38 of the surveys, small sample sizes meant we could not rule out rates of death greater than 20% in 21 (55%) of those cases. It is possible that workers focused on detecting high kill rates, for which the small sample sizes used were appropriate. Alternatively, it is also possible that the need for larger samples was not understood by non-experts before publication of Choquenot & Ruscoe (1999) and Spurr & Powlesland (2000), by which time 28 of the surveys we reviewed had been completed. The fact that most birds survived in most of the surveys may have lulled managers of public conservation lands into believing there was negligible or no basis for concern, something also encountered in medicine (Hanley & Lippman-Hand 1983).

A strong case can be made for asserting that kiwi, kākā and kokakō have very low mortality risks when 1080 is broadcast. Conservation managers no longer report routinely on survival of individuals of these species through aerial 1080 operations and we relied on word of mouth to find the unpublished surveys we reviewed here. Notwithstanding the excellent survival of individuals of these species, we recommend continued reportage since there is strong public interest in the outcome.

Table 2. The 95% upper confidence bounds for grouped surveys of species in which no birds died.

Taxon	No. of surveys	Pooled sample size	Upper bound (as %) of 95% confidence interval
Kiwi (*Apteryx* spp.)	10	199	1.5
Whio (*Hymenolaimus malacorhynchos*)	2	34	8.4
Kākā (*Nestor* subsp.)	5	83	3.5
Kokakō (*Callaeas cinerea*)	8	129	2.3

Table 3. Characteristics of aerial 1080 baiting operations on public conservation lands.

		Treated area (ha)		Bait type		Percent 1080		Bait size (g)	Use of prefeed	Sowing rate (kg ha^{-1})	
Year	*n*	Total	Mean	Carrot	Cereal	0.08	0.15	Mode[1]	No. (%)	Range	Mean
1998–1999	23	104 449	8704	7	16	4	19	6	5 (22)	2–12	5.2
1999–2000	42	206 934	4812	9	33	3	39	6	9 (21)	2–15	4.8
2000–2001	28	206 408	14235	8	20	2	26	6, 12	8 (28)	2–8	3.6
2001–2002	27	141 772	5250	2	25	3	24	12	13 (48)	2–7	3.4
2002–2003	33	324 651	9837	3	30	1	32	12	15 (45)	2.5–25	4.2
2003–2004	34	301 546	8869	2	32	1	33	12	16 (47)	2–5	2.9
2004–2005	34	181 739	5345	11	23	2	32	12	19 (56)	2–8	3.3
2005–2006	33	360 636	10 928	9	24	3	30	12	28 (85)	2–5	3.7
2006–2007	29	201 050	6932	3	26	6	23	12	22 (76)	2–5	3.7
2007–2008	39	296 647	7606	0	39	1	38	12	31 (79)	1.5–9.3	3.3

[1]Data not recorded for all cases.

Comparison of Tables 1 and 3 shows that a total of 322 aerial 1080 baiting operations were conducted on public conservation lands in the 10-year period ending in June 2008 but banded or radio-carrying birds were observed during only 15 operations carried out from 1998 to the end of 2008. Furthermore, comparison of operational patterns in Tables 1 and 3 shows that information from surveys carried out before 1998 may not be relevant for modern aerial baiting operations. For example, prefeeding was used in only four cases in which birds were surveyed before 1998 and those involved carrot baits which were infrequently used by 2008. Baits of 12-g mass have become the most common option, whereas before 1998 baits usually weighed 6 g. By 2008, aerial baiting usually involved 12-g cereal baits with a toxic loading of 1.5 g kg^{-1} sown on average at 3 kg ha^{-1} following prefeeding, but only nine of the operations for which birds were surveyed in our sample involved these specifications. Not only has survey effort been small relative to the number of aerial baiting operations, it has not kept up with the evolution of operational practices for some species known to be at risk.

Improved bait quality and coverage (Eason et al. 2006) and declining sowing rates (Veltman & Pinder 2001; Table 3) may have reduced the potential risk of incidental poisoning. However, prefeeding increases the amount of bait consumed by possums (Warburton et al. 2009), raising the possibility it could similarly affect bird behaviour and increase the risk of poisoning them. Our review does not allow us to investigate this question any further. What is needed are more studies of birds at risk, at sites where prefeeding is used.

When high death rates were indicated from small samples of North Island tomtits (Powlesland et al. 2000), workers developed new sampling procedures in order to scale up the measurement effort and obtain better estimates (Westbrooke et al. 2003), which were then deployed in comparing mortality between carrot and cereal bait operations (Westbrooke & Powlesland 2005) and for comparing baits with and without deer repellent (Ross 2007 unpubl.). This type of two-step approach lets workers estimate mortality from a labour-intensive survey of a large sample of individually marked birds during a small number of poison operations before proceeding to population-level quantification of changes in abundance if kill rates of individually marked birds were shown to be high. We therefore do not advocate for endless banding or telemetry studies, but rather judicious use of intensive methods for data-poor species or for when baiting procedures change.

We also advocate for establishing long-term forest bird population monitoring at poisoned sites. This would meet the need for multiple controls when 1080 is applied at any one of the sites in the set (not all sites are treated in all years) and also permit quantitative statements about the sign and rate of change in population sizes, the measure that integrates non-target deaths and beneficial changes in survival and reproduction (Sibly & Hone 2002).

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Appendix

It was assumed we had m independent groups of Bernoulli trials, each with a fixed survival rate s_i, (i=1,2,…m) and each group with zero observed mortality in n trials. It is easiest to focus on survival rates and their lower bounds first. Consider the confidence set $S_\alpha \subseteq [0,1]^m$ of survival rates for the groups:

$$S_\alpha = \{\text{group survival rates: Pr(all in group samples survive)} \geq \alpha\}$$
$$= \{x_i : \text{Pr}(n_i \text{ survive out of } n_i \mid s_i = x_i) \geq \alpha\}$$
and as groups are independent
$$= \left\{ x_i : \prod_{i=1}^{m} x_i^{\,n_i} \geq \alpha \right\}$$
$$= \left\{ x_i : \left[\prod_{i=1}^{m} x_i^{\,n_i} \right]^{\frac{1}{N}} \geq \alpha^{\frac{1}{N}} \right\} \quad \text{where} \quad N = \sum_{i=1}^{m} n_i$$

Therefore the weighted geometric mean of the confidence set of survivals (weighted by the size of each group) for this set of groups has a lower bound $\alpha^{1/N}$ and, since the arithmetic mean ≥ the geometric mean, the weighted arithmetic mean of the confidence set also has $\alpha^{1/N}$ as a lower bound.

Hence, for homogeneous data, where we can take all the groups as having the same survival rate, $\alpha^{1/N}$ is a lower confidence bound for that rate. In the more general case, where each group may have a different survival rate, then the weighted mean (geometric, but also arithmetic) of these rates has $\alpha^{1/N}$ as a lower confidence bound.

Further, the weighed arithmetic mean of the mortality rates has $1–\alpha^{1/N}$ as an upper confidence bound (but this does not necessarily hold for the geometric mean of the mortality rates). If the surveys sampled the same number of birds, we could drop the ‘weighted’ condition on the means.