An assessment of the probability of secondary poisoning of forest insectivores following an aerial 1080 possum control operation

B. D. Lloyd[1] and S. M. McQueen[2]
[1]Science and Research, Department of Conservation, P.O. Box 10420, Wellington, New Zealand
[2]Otago Conservancy, Department of Conservation, P.O. Box 5244, Dunedin, New Zealand

Abstract: Assays for the toxin sodium monofluoroacetate (compound 1080) were undertaken on arthropods collected from toxic baits after a brushtail possum (*Trichosorus vulpecula*) control operation in *Nothofagus* forest in central North Island, New Zealand. The 1080 concentrations measured (mean 57 μg g^{-1}, max 130 μg g^{-1}) are considerably higher than those reported by other researchers who collected arthropods randomly after control operations. These data, together with published information on sensitivities to 1080, as well as diet and consumption rates, were used to calculate the median lethal doses of arthropods that have fed on 1080 baits for a number of vertebrate insectivores found in *Nothofagus* forest. The results indicate small insectivores that feed on, or close to, the ground (e.g., tomtit *Petroica macrocephala*, robin *P. australis*, hedge sparrow *Prunella modularis*, and the short-tailed bat *Mystacina tuberculata*) may be vulnerable to secondary poisoning. For instance, a tomtit will receive the median lethal dose of 1080 from 1.32 g (i.e., 14.7% of its daily food intake) of arthropods containing 57 μg g^{-1} of 1080. Because of their greater sensitivity to 1080 poisoning, bats are at much greater risk; a short-tailed bat will receive the median lethal dose of 1080 from as little as 0.04 g (0.7% of its daily food intake) of arthropods containing 57 μg g^{-1} of 1080.

Keywords: sodium monofluoroacetate; residue levels; arthropods; median lethal dose.

Introduction

The brushtail possum (*Trichosorus vulpecula* Kerr) was introduced into New Zealand from Australia at the end of the nineteenth century. It is now a serious pest throughout New Zealand, having detrimental impacts both on agriculture, through spreading tuberculosis and destroying crops, and on conservation values, through the destruction of natural biological communities (Department of Conservation, 1994; Livingston, 1994). Since the 1970s the principle method for control of possum numbers in forest areas has been poisoning using aerial broadcast carrot or grain-based baits impregnated with the toxin sodium monofluoroacetate (1080). The method was observed to cause mortality in non-target wildlife from early on in its use (Harrison, 1978). Since then considerable research effort has been expended in monitoring the severity of non-target mortality. The results of this effort, and similar work overseas, have been reviewed extensively (e.g., Spurr, 1979, 1991, 1994; McIlroy, 1992; Eisler, 1995; Spurr and Powlesland, 1997).

Poisoning of non-target species may be primary, by direct consumption of baits, or secondary, by consumption of animals that have fed on toxic baits. Secondary poisoning of carnivores and scavengers, is well documented (McIlroy and Gifford, 1992; Eisler, 1995; Gillies and Pierce, 1999; Murphy *et al*., 1999). The analogous process of secondary poisoning of insectivores mediated via arthropods has been suggested by a number of authors (Spurr, 1979; McIlroy, 1984; Hegdal *et al*., 1986; Notman, 1989; Lloyd, 1994), but has not been verified. (The term insectivore is used to describe animals that consume any terrestrial invertebrates, not just insects.) Although mortality of many insectivorous birds has been documented following the use of 1080 both in New Zealand (e.g., Harrison, 1978; Spurr, 1991; Powlesland *et al*., 1999), and overseas (Hegdal *et al*., 1986; McIlroy and Gifford, 1992), it has been assumed to be by primary poisoning (Spurr, 1991).

A wide range of invertebrate groups, particularly arthropods, have been reported as feeding on baits used in 1080 operations both in New Zealand (McIntyre, 1987; Notman, 1989; Hutcheson, 1989; Eason *et al*., 1993; Eisler, 1995) and overseas (Marsh, 1968; Eisler, 1995). Recent studies (Spurr and Drew, 1999; Sherley *et al*., 2000; S.M. McQueen and B.D. Lloyd, *unpubl*.) provide detailed evidence of leaf litter arthropods

feeding on the baits in indigenous New Zealand forests. The results of trials on the persistence of 1080 in arthropods led Eason *et al*. (1993) and Booth and Wickstrom (1999) to conclude that the risk of secondary poisoning of insectivorous birds is negligible.

This paper presents the concentrations of 1080 in forest arthropods collected after a possum control operation. These data are used to quantify the risk of secondary poisoning of a number of forest dwelling insectivores by calculating the lethal doses of arthropods that have fed on 1080 baits as a percentage of the insectivores' daily food consumption.

Methods

Study area

This study was undertaken within Karioi Rahui/ Sanctuary, in the south-east of Rangataua Conservation Area. The area is part of a 10 000 ha continuous tract of mature old growth *Nothofagus* forest on the southern slopes of Mt. Ruapehu, central North Island, New Zealand (39°26' S 175°32' E, 700-750 m a.s.l.). Forest canopy in the study area is dominated by *Nothofagus fusca* (Hook. f.), *N. menziesii* (Hook. f.), and *Dacrydium cupressinum* (Lamb.), but includes a variety of other podocarps and hardwoods.

Field methods

The work was undertaken during a large-scale possum control operation, by aerial broadcast of toxic 1080 baits on 30 August 1997. The toxic baits were Wanganui No. 7 pollard (i.e., grain based) baits from Pest Control Services, Wanganui, with a 0.15% toxic loading of 1080. The baits were dyed green and cinnamon lured. Individual bait mass ranged from 4-6 g. Baits were broadcast over a total of 2 500 ha, with sowing rates of 5 kg/ha for 1 200 ha and 3 kg/ha for 1 300 ha. The study was undertaken in the centre of the area sown at 5 kg/ ha.

Four parallel 150 m long transects were marked at right angles to an access track, using hip chain and compass. The transects were in pairs spaced more than 100 m apart with the individual transects in each pair 21 m apart. On the day of the aerial broadcast individual toxic baits were placed at 3 m intervals along all four transects (i.e., a total of 200 baits) to approximate the bait spacing for a 5 kg/ha sowing rate. The baits were taken from the batch used for the large-scale possum control operation. Any aerial broadcast baits seen on, or close to, transects were removed to maintain the local bait density close to 5 kg/ha. A small aluminium reflector (10 x 30 mm) was pinned to the ground, close to each bait. All baits were inspected during the two hours after dark on the first four nights after the aerial operation and then on the sixth and eighth night after the operation. A "Petzl" head-lamp fitted with a standard 0.22 amp light bulb was used to illuminate the baits during inspection. Each arthropod more than 4 mm long found on a bait was placed in a dry empty vial. The arthropods were identified using a reference collection, inspected for any bait particles adhering to them and then placed in a -20°C freezer within three hours of collection.

Arthropods were also collected from non-toxic baits to determine average body mass of taxa frequently found feeding on baits. These arthropods were collected in the study area some weeks after the aerial broadcast. They were stored in a -20°C freezer before being weighed on a Mettler bench balance with a 0.01 g resolution. Larger individuals were weighed separately, whereas individuals of smaller species were pooled and weighed together.

Twenty pitfall traps were placed at 15 m intervals along a transect line through the study area. Each trap consisted of a plastic cup (60 mm diameter and 70 mm deep) set into the ground and covered with a 150 mm diameter plastic plate raised *c*. 30 mm above the cup mouth. To prevent 1080 leaching out of the arthropods, the pitfall traps did not contain collection fluid. Arthropods were collected from the pitfall traps daily for the ten days after the aerial broadcast operation, identified using a reference collection, and then stored in a -20°C freezer.

A random sample of ten baits was taken from the batch of baits used for the control operation before broadcast. Further samples of ten baits were collected at random from within the operational area 5, 10, 17 and 32 days after broadcast. The baits were placed in individual plastic bags and stored in a -20°C freezer.

Rainfall was measured using a tipping bucket rain gauge (RGD-01 from Monitor Sensors) with values logged at ten-minute intervals on a Datataker 500 datalogger. The rain gauge was sited in open farmland approximately 9 km west of the study area. The study-area and the site with the rain gauge have similar aspects and are at the same altitude. Rainfall data from a number of sites around Mt. Ruapehu (Atkinson, 1981) indicates that the annual rainfall in the study area may be 15% lower than at the rain gauge.

Sodium monofluoroacetate (1080) concentrations

Concentrations of 1080 in baits and arthropod samples were measured by gas chromatography with flame ionisation detection (Hoogenboom and Rammell, 1987). The baits were assayed individually, but arthropods were pooled to provide sufficient material for assay. The limits of detection for the method were 5 $\mu g\ g^{-1}$ for the baits and 0.1 $\mu g\ g^{-1}$ for the arthropod

samples. The precision of the assays varied according to the 1080 concentrations present, but averaged 5% for baits and 15% for arthropod samples. Recovery rates were 100% for baits and 81% for arthropod samples.

The weighted mean 1080 concentration of the arthropod samples was calculated as

$$\bar{c}_w = \sum_{i=1}^{n}(m_i c_i) \Big/ \sum_{i=1}^{n}(m_i)$$

where n is the number of samples, m_i is the mass of sample i, and c_i is the 1080 concentration of sample i. The standard error of the weighted mean was calculated as $\sqrt{s^2/n}$ where s^2 is the variance calculated as.

$$\sum m_i (c_i - \bar{c}_w) \Big/ (n-1).$$

LD_{50} estimates of 1080 contaminated arthropods for forest insectivores

Seven species of vertebrate forest insectivores were considered vulnerable to secondary poisoning because they forage on, or close to, the ground, and consume a wide variety of arthropod species, including some that feed on baits (Daniel, 1976; Moeed and Fitzgerald, 1982; Arkins, 1996; Heather and Robertson, 1996). The seven species are: robin (*Petroica australis* Sparrman), tomtit (*P. macrocephala* Gmelin), hedge sparrow (*Prunella modularis* Hartert), kingfisher (*Halcyon sancta* Gmelin), blackbird (*Turdus merula* L.), morepork (*Ninox novaeseelandiae* Lesson), and the short-tailed bat (*Mystacina tuberculata* Gray).

Published median lethal dose (LD_{50}) estimates for 1080 were used to obtain best LD_{50} estimates for the seven species. McIlroy (1984) provides an LD_{50} estimate of 9.5 μg g^{-1} for the blackbird. There are no published LD_{50} estimates for the other six species, therefore mean estimates for related groups were used as the best available estimates. The value 6.85 μg g^{-1} was used for the five untested bird species. This is the mean LD_{50} for 31 species of non-Australian birds (579 individuals) from McIlroy (1986). LD_{50} values for Australian species were not included as some species have elevated tolerances to 1080 as a result of adaptation to foraging on 1080 bearing plants (McIlroy, 1986; Twigg *et al.*, 1988). Two values were used as estimates of the LD_{50} for the short-tailed bat. One value is 0.15 μg g^{-1}, the only published LD_{50} for any microbat, the American big brown bat (*Eptesicus fuscus* Beauvois) (Timm, 1983). The other value is 0.37 μg g^{-1}, the weighted mean LD_{50} for three groups of mammals comprising 50 species (1 297 individuals) obtained from McIlroy (1986). The three groups are: eutherian carnivores (0.19 μg g^{-1}, 13 species, 130 individuals), eutherian herbivores (0.40 μg g^{-1}, 7 species, 201 individuals) and non-Australian rodents (0.44 μg g^{-1}, 30 species, 966 individuals). The mass of arthropods containing LD_{50}s of 1080 was calculated for each of the seven vulnerable species. LD_{50} estimates of 1080-contaminated arthropods are for three different concentrations of 1080 that encompass a range of the reported values for 1080-contaminated arthropods after aerial possum control operations. The three concentrations are the mean and maximum concentrations found in this study (57 μg g^{-1} and 130 μg g^{-1}, respectively) and the mean 1080 concentration (12 μg g^{-1}) in tree weta collected two days after a 1080 operation (Eason *et al.*, 1993).

Daily food consumption was calculated for each of the seven species as FMR/ME (g per day), where FMR is field metabolic rate (kilojoules per day), and ME is the metabolisable energy in food (kilojoules per gram of dry matter) (Nagy, 1987). FMR estimates were calculated using the allometric equation $FMR = am^b$ (Nagy, 1987), where m is body mass (g), and a and b are parameter estimates. Values for the parameter estimates were $a = 8.88$ and $b = 0.749$ for passerine birds (Nagy, 1987), and $a = 4.63$ and $b = 0.762$ for eutherian mammals (not using torpor) (Nagy, 1994). Body mass estimates for the bird species are from Heather and Robertson (1996) and the body mass estimate for the short-tailed bat is from the authors' personal observations. ME estimates for arthropods are 18.7 kJ g^{-1}, when consumed by mammals, and 18.0 kJ g^{-1}, when consumed by birds (Nagy, 1987). The water content estimate for adult arthropods (67%) is the average of published values for ten species (Redford and Dorea, 1984; Barker *et al.*, 1998). The LD_{50}s of arthropods containing 1080 were then expressed as percentages of the estimated daily food consumption for each species.

Results

Arthropod collections and 1080 concentrations

Four of the 200 toxic baits on the transects went missing on the first two nights, presumably having been eaten by possums or rodents The rest of the baits remained in place and intact until the end of the eight day monitoring period. Seventy individual arthropods, from 20 taxa, were collected from toxic baits and 28 individuals, from 9 taxa, were collected in pitfall traps (Table1). The compositions of the arthropod collections taken from baits and pitfall traps were significantly different ($c^2 = 39.16$, d.f.=3, $P<0.001$). Samples from the baits contained mostly Insecta, while samples from pitfall traps contained mostly Malacostraca (Table 2).

The weighted mean 1080 concentration of the 8 samples of arthropods found feeding on toxic baits was 56.8 μg g^{-1} (S.E.=25.60 μg g^{-1}), the maximum sample

Table 1. The numbers of arthropods collected from toxic baits and pitfall traps during a 1080 operation in Rangataua Forest, August - September 1997, and the mean body masses of some forest arthropods found feeding on non-toxic baits.

Taxonomic group	Lowest taxonomic unit	No. of individuals Baits	Pitfalls	Body mass of individuals (g)
Cockroach (Blattaria)	Blattaria	2	0	
Weta (Orthoptera)	*Hemideina thoracica* White	1	0	4.7
	Gymnoplectron tuarti Richards	9	0	1.96
	Rhaphidophoridae	7	0	
	Neonotus sp.	1	0	
	Zealosandrus gracilis Salmon	2	0	
	Weta sp.	6	1	
Beetles & weevils (Coleoptera)	*Ctenognathus adamsi* Broun	2	1	
	Saphobius squamulosa Broun	11	0	0.01
	"weevil"	1	0	
Spiders (Araneae)	Araneae	2	2	
Harvestmen	*Nuncia* sp.	6	2	0.05
(Phalangidae)	*Pristobunus* sp.	5	0	
	Soerensenella rotara Phillips & Grimmet	1	0	0.06
	Pantopsalis sp.	1	0	
Millipedes (Diplopoda)	*Dimerogonus* sp.	3	0	0.59
	Icosidesmus sp.	1	2	0.15
	"grey millipedes"	0	2	
Centipedes (Chilopoda)	"orange centipedes"	4	1	
Slaters (Isopoda)	"slaters"	0	3	
Amphipod (Amphipoda)	Amphipods	5	14	
	Total No. of Arthropods	70	28	
	Total Mass of Arthropods	33.1 g	1.5 g	

Table 2. A comparison of the composition of arthropod collections from toxic baits and pitfall traps.

Taxonomic group	Baits	Pitfalls
Insecta (Insects)	42 (60%)	2 (7%)
Arachnida (Spiders & harvestmen)	15 (21%)	4 (14%)
Myriapoda (Millipedes & centipedes)	8 (11%)	5 (18%)
Malacostraca (Slaters & amphipods)	5 (7%)	17 (61%)
Total	70	28

Table 3. The 1080 concentrations of the 8 samples of arthropods found feeding on baits. Details of the composition of the three collections of smaller arthropods (Collections No.s 1-3) are in Appendix 1.

Night after broadcast	Arthropods	n	Sample mass (g)	1080 conc. ($\mu g\ g^{-1}$)
1	*Hemideina thoracica*	1	4.7	66
1	*Gymnoplectron tuarti*	1	4.2	32
1	Collection No. 1	15	2.6	22
2 & 3	Collection No. 2	24	2.4	46
2 & 3	*G. tuarti*	3	3.4	53
4	*G. tuarti*	2	4.4	130
6	*G. tuarti*	3	7.3	60
6 & 8	Collection No. 3	19	3.6	14
	All Samples Combined	68	32.6	56.8

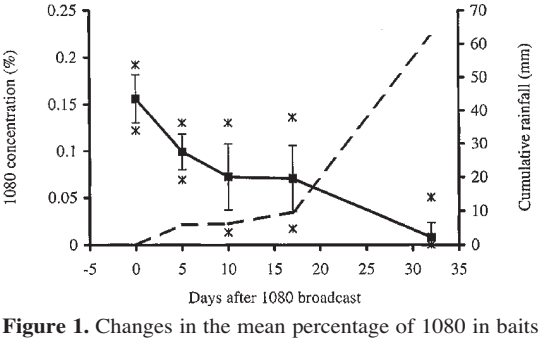

Figure 1. Changes in the mean percentage of 1080 in baits (n=10) (solid line) and cumulative rainfall (dashed line) with time. Also shown for each mean 1080 concentration value are ± standard deviation (vertical line) and sample maximum and minimum values (crosses).

Table 4. Estimated amounts of 1080-contaminated arthropods required to provide a LD_{50} of 1080 for seven forest-dwelling insectivorous species at three different concentrations of 1080 contamination (12 μg g^{-1}, 57 μg g^{-1} and 130 μg g^{-1}).

	Body mass (g)	Daily food intake (g/day)	LD_{50} of 1080[1] (μg g^{-1})	LD_{50} dose of arthropods (g (%)) 12 μg g^{-1}		57 μg g^{-1}		130 μg g^{-1}	
Tomtit	11	9.01	6.85	6.28	(69.7)	1.32	(14.7)	0.58	(6.4)
Hedge sparrow	21	14.62	6.85	11.99	(82.0)	2.52	(17.3)	1.11	(7.6)
Robin	35	21.44	6.85	19.98	(93.2)	4.21	(19.6)	1.84	(8.6)
Kingfisher	65	34.08	6.85	37.10	(108.9)	7.81	(22.9)	3.43	(10.0)
Blackbird	90	43.49	9.5	71.25	(163.8)	15.00	(34.5)	6.58	(15.1)
Morepork	175	71.56	6.85	99.90	(139.6)	21.03	(29.4)	9.22	(12.9)
Short-tailed bat a[2]	14	5.60	0.15	0.18	(3.1)	0.04	(0.7)	0.02	(0.3)
Short-tailed bat b[3]	14	5.60	0.37	0.43	(7.7)	0.09	(1.6)	0.04	(0.7)

[1] LD_{50} estimates are given as both fresh weight (g), and % of the estimated daily food intake, in parentheses.
[2] Estimates for short-tailed bat a are based on a LD_{50} of 0.15 μg g^{-1}, the LD_{50} for the American big brown bat from Timm (1983).
[3] Estimates for short-tailed bat b are based on a LD_{50} of 0.37 μg g^{-1}, the mean LD_{50} for 50 mammal species from McIlroy (1986).

concentration 130 μg g^{-1}, and the minimum sample concentration 14 μg g^{-1} (Table 3). Concentrations of 1080 in arthropod collections from the toxic baits did not consistently increase or decrease during the 8-day monitoring period (Table 3). The peak value of 130 μg g^{-1}, for two cave weta (*Gymnoplectron tuarti* Richards) collected on the fourth night, is likely to be the result of the small sample size rather than a real peak in concentrations of 1080 in arthropods feeding on baits at that time.

LD_{50} estimates of 1080 contaminated arthropods for the six avian species range from 6.4% to 163.8 % of their daily food requirements (Table 4). The short-tailed bat could receive an LD_{50} from as little as 0.3% of its daily food intake.

A sample of four spiders (two collected from toxic baits, and two from pitfalls traps) had a 1080 concentration of 14 μg g^{-1}. The sample of 26 arthropods (mass 1.5 g) collected from pitfall traps (Table 1) in the operational area during the ten days after the 1080 operation had a 1080 concentration of 0.8 μg g^{-1}.

1080 concentrations in baits

Mean concentrations of 1080 in the bait samples (n = 10) declined slowly during the first seventeen days after the baits were broadcast (Figure 1). An increase in the cumulative rainfall during the period 17-32 days after broadcast, accelerated the decline in mean 1080 concentration.

Discussion

Although the results of this study do not prove secondary poisoning of forest insectivores occurs after aerial 1080 operations, they provide persuasive supportive evidence. Short-tailed bats are more vulnerable than birds to secondary poisoning because mammals are extremely sensitive to 1080. A short-tailed bat can consume an LD_{50} from a single *Nuncia* harvestman (mass 0.05 g) containing 130 μg g^{-1} of 1080, two *Nuncia* containing 57 μg g^{-1}, or a single *Dimerogonus* millipede (mass 0.59 g) containing 12 μg g^{-1}. The results for avian insectivores also indicate some cause for concern. The tomtit, which is the smallest of the avian species considered, is at most risk because it has the highest ratio for daily food intake to body mass. A tomtit could receive a lethal dose from a single *Dimerogonus* millipede (mass 0.59 g) containing 130 mg g^{-1} of 1080, a single average sized *Gymnoplectron tuarti* (White) weta (mass 1.96 g) containing 57 μg g^{-1} or two *Hemideina thoracica* (Richards) weta (mass 4.7 g) containing 12 μg g^{-1}. Thus, the high levels of mortality reported for tomtits after aerial 1080 operations (R.G. Powlesland, *pers. comm.*) could be caused by secondary poisoning.

During this study the risk of secondary poisoning probably remained high for a considerable period. The 1080 concentrations in arthropods collected from baits were high for the entire eight-day monitoring period and concentrations of 1080 in baits remained high for at least 17 days after application. As high concentrations of 1080 persist within arthropods for up to 4 days after ingestion of sub-lethal doses (Eason *et al.*, 1993; Booth and Wickstrom, 1999), it is probable that arthropods with moderate to high 1080 concentrations were present in the forest for at least 21 days after bait application.

With 1080-contaminated arthropods present for a 21-day period, insectivores may consume repeated sub-lethal doses of 1080. Consumption of repeated doses would be especially prevalent when a high proportion of arthropods is contaminated with low concentrations of 1080. In this situation median lethal

concentrations (LC_{50}) may be more appropriate statistic for assessing the impact of secondary poisoning than LD_{50}, which describe the impact of a single dose of toxin. Unfortunately there are relatively few LC_{50} estimates for 1080 in the literature. Repeated consumption of sub-lethal doses can have variable and sometimes adverse effects (Atzert, 1971; Eisler, 1995). They may increase an individuals tolerance to 1080, or alternatively they may accumulate to a lethal level (McIlroy, 1981). Repeated sub-lethal doses can also adversely affect reproduction, growth and behaviour (Eisler, 1995). Despite the sometimes adverse affects from repeated sub-lethal doses, 1080 is not generally considered a cumulative toxin, as it has a plasma half-life of between 1 and 14 hours in a range of mammal species (Eason, 1993; Gooneratne *et al.*, 1995). The risk of secondary poisoning following repeated sub-lethal doses would be far greater for persistent and cumulative toxins such as the second-generation anticoagulants (e.g., brodifacoum) which have tissue half-lives of months.

The mean 1080 concentration of the arthropods (56.8 $\mu g\ g^{-1}$) is higher than the mean concentrations (0-12 $\mu g\ g^{-1}$) reported in previous studies (Eason *et al.*, 1991; Pierce and Montgomery, 1992; Eason *et al.*, 1993). Although mean sample concentrations were low, individual sample concentrations as high as 46 $\mu g\ g^{-1}$, which approaches the sample mean in this study, were reported by Eason *et al.* (1993).

The difference between the concentrations of 1080 in arthropods collected from toxic baits in this study and the values reported in previous studies has probably arisen because in previous studies the arthropods were collected randomly (C.T. Eason, *pers. comm.*), not from toxic baits. Only one of the mean concentrations reported in previous studies was higher than 2.1 $\mu g\ g^{-1}$, thus most sample mean concentrations are of a similar order to the mean 1080 concentration of arthropods collected from pitfall traps (0.8 $\mu g\ g^{-1}$) during this study. There was a significant difference between the species composition of samples of arthropods feeding on baits and collected in pitfall traps in this study. Thus, many of the taxa collected from pitfall traps may never feed on baits. This is probably also the case for random collections. Among taxa that feed on baits many of the individuals collected may not have fed on baits, and the 1080 concentrations of those that have fed on baits may have declined between feeding and collection. The probability of random capture of individuals that have consumed high doses of 1080 may also be reduced, because these individuals are likely to die from 1080 poisoning before capture.

The risk of insectivores being affected by secondary poisoning will be strongly influenced by the behaviour of arthropods after they ingest 1080. There are three LD_{50} estimates available for arthropods, 91 $\mu g\ g^{-1}$ for tree weta (*Hemideina crassidens* Blanchard) (M. Wickstrom, *pers. comm.*), 42 $\mu g\ g^{-1}$ for striated ants (*Huberia striata* Smith) (Booth and Wickstrom, 1999) and 9 $\mu g\ g^{-1}$ for honey-bees (*Apis melifera* L.). [The LD_{50} estimate for honey-bees was calculated from the LD_{50} of 0.8 μg per honey-bee, reported by Palmer-Jones (1958), using a mean mass of 90 μg for honey-bees (n =10) weighed by the author.] The three LD_{50} estimates for arthropods encompass the mean 1080 concentrations in arthropods collected from baits during this study. Thus, some of these arthropods may have ingested only sub-lethal doses of 1080, while others may have ingested lethal doses. Those arthropods that have consumed lethal doses may take between 1.5 hr (Goodwin and Ten Houten, 1991) and fourteen days (Hutcheson, 1989) to die, during this time they are available for predation by insectivores. The large variation in estimates of the time between ingestion and death for arthropods may be a consequence of faulty estimates, but it is consistent with the pattern in vertebrates. For most vertebrates the time between ingestion and death is between 1 hr and 1 day (Eisler, 1995), but delays as long a 7 days occur in some species (McIlroy, 1981). Significant concentrations of 1080 persist in arthropods that have consumed sub-lethal doses for up to 4 days after ingestion (Eason *et al.*, 1993; Booth and Wickstrom, 1999). Arthropods that have consumed 1080 may be prone to predation by insectivores as their normal behaviour patterns can be disrupted as a consequence of 1080 intoxication (McIntyre, 1987; Hutcheson, 1989; Goodwin and Ten Houten, 1991).

Errors in estimating lethal consumption levels may arise from a number of sources, including errors in the estimates of 1080 concentrations in the arthropods, errors in the original LD_{50} estimates, and errors in estimates of the daily food intake. The mean 1080 concentration in arthropods collected from the baits is likely to underestimate the actual concentrations for two reasons. Firstly, there will have been a decline in the 1080 during the delay between collection and freezing. Secondly, the arthropods were collected from the baits at random times during their feeding bouts, thus, on average they will have been collected half way through their feeding bouts.

Although the LD_{50} of a species for 1080 cannot be accurately predicted from data obtained on other closely related species (McIlroy, 1986; Calver *et al.*, 1989), the best available estimates of LD_{50} for species which have not been tested is the mean LD_{50} for related taxa (McIlroy, 1986). This may be true for most species but can be misleading for individual species, as some species have very different LD_{50} values to related taxa.

For instance, the red-browed firetail *Neochmia temporalis* (Latham) has an LD_{50} of 0.63 μg g^{-1}, less than one tenth of the mean LD_{50} for other bird species (McIlroy, 1984). The estimates of lethal consumption levels in Table 4 are based on LD_{50} values typical of the species' wider taxonomic group, atypically low values for a species could increase its vulnerability considerably.

Published LD_{50} estimates are obtained using orally administered solutions of 1080 (McIlroy, 1981). Although oral toxicity of 1080 is independent of all the carriers tested (Atzert, 1971), 1080 in contaminated arthropods may not all be available for absorption. If this is the case LD_{50} of 1080-contaminated arthropods calculated from published LD_{50} estimates may underestimate the true values.

Nagy and Obst (1991) and Nagy (1994) concluded that the 95% confidence interval for estimates of daily food requirements obtained using the allometric equations is ± 40% of the predicted value. Within-species variation, resulting from seasonal and geographic variation in activity, is large enough to encompass most between-species variation. Estimates of daily food requirements are likely to underestimate the actual daily food requirements, as they do not include growth needs or periods of hyperphagy, such as pre-ovulation in birds or pre- and post-hibernation in bats. Direct observations confirm the estimated daily food intake for short-tailed bats. Captive short-tailed bats regularly consume 5-7 g of insects in a night (i.e., 36-50% of pre-feeding body mass) as well as honey water (Daniel, 1979; B. Blanchard, *pers. comm.*; B.D. Lloyd and S.M. McQueen, *unpubl.*). This is close to the estimated daily food intake of 5.6 g (i.e., 40% of body mass). Further support for the estimated figures comes from Gould (1955) and Ransom (1990), who report that free-flying insectivorous microbats consumed 18-41% of their own pre-feeding weight within 30-70 min of emergence from their day roosts.

None of the seven species considered are exclusively insectivorous. Thus, the daily consumption of arthropods may be over-estimated when non-arthropod food-types are also taken. Morepork and kingfisher feed on small vertebrates (Heather and Robertson, 1996). Tomtit, robin, hedge sparrow and blackbird all supplement their arthropod diet with small fruits when available (Moeed and Fitzgerald, 1982; Heather and Robertson, 1996) and the short-tailed bat eats fruit, pollen and nectar when available (Daniel, 1979; Arkins, 1996). Generally there are few, or no, fruit or flowers available in late winter when possum control operations are commonly undertaken, therefore over-estimation of daily consumption of arthropod at this time of the year may be minor.

Continuous video surveillance of baits, undertaken in a concurrent study by the authors, showed that almost all bait consumption by arthropods was at night. Thus nocturnal insectivores (i.e., short-tailed bats and morepork) are at greater risk of secondary poisoning than diurnal insectivores. Nevertheless, diurnal insectivores may consume nocturnal arthropods that have fed on baits. They take nocturnal arthropods during the day by gleaning them from crevices and under bark and leaf litter. Some diurnal insectivores (e.g., robin, tomtit and blackbird) engage in crepuscular foraging (B.D. Lloyd, *pers. obs.*) when nocturnal arthropods are active. In addition, nocturnal arthropods that have ingested 1080 may become active in daytime as a result of 1080 intoxication (Hutcheson, 1989).

Proving that small free-living forest insectivores have succumbed to secondary poisoning following a 1080 operation will be difficult because insectivore gut retention times are generally less than the time between ingestion of 1080 and death. Gut-retention times for two avian insectivores [starlings (*Sturnus vulgaris* L.) and house wren (*Troglodytes aedon* L.)] are between 10 min and 2 hr, with mean retention times of *c*.50 min (Levey and Karasov, 1989, 1992 , 1994; Dykstra and Karasov, 1992), whereas the time from ingestion of 1080 to death is 1.4-262 hr (335 individuals, 33 species) (McIlroy, 1984). Thus, when individuals that have died of secondary poisoning are autopsied the 1080-contaminated arthropods will no longer be in the gut.

It should not be assumed that populations of insectivorous species are safe from poisoning during aerial 1080 operations, nor should it be assumed that any mortality of insectivores observed after 1080 operations is a result of primary poisoning caused by consumption of bait fragments. Where vulnerable populations of insectivores are present other methods of possum control such as trapping or the use of cyanide in bait stations should be considered.

Acknowledgements

We would like to acknowledge a number of people who made this work possible: Rex Williams for his assistance with field work; Mike Meads for identifying arthropod specimens; the Ngati Rangi (tangata whenua and kaitiaki for the Karioi Rahui/Sanctuary) for allowing the work to proceed; staff from the Department of Conservation's Taupo-Tongariro Conservancy whose co-operation, assistance and encouragement were essential to this study, in particular Harry Keys, Cam Speedy and John Luff. Sodium monofluoroacetate assays were undertaken by the National Chemical Residue Laboratory, Wallaceville Animal Research Centre, Upper Hutt, New Zealand.

References

Arkins, A.M. 1996. *The diet and activity patterns of short-tailed bats (Mystacina tuberculata auporica) on Little Barrier Island*. M.Sc. thesis, University of Auckland, Auckland, N.Z.

Atkinson, I.A.E. 1981. *Vegetation map of Tongariro National Park*. New Zealand Department of Scientific and Industrial Research, Wellington, N.Z.

Atzert, S.P. 1971. *A review of sodium monofluoroacetate (compound 1080): its properties, toxicology and use in predator and rodent control*. US Bureau of Sports, Fisheries and Wildlife, Washington D.C., U.S.A.

Barker, D.; Fitzpatrick, M.P.; Dierenfeld, E.S. 1998. Nutrient composition of selected whole invertebrates. *Zoo Biology 17:* 123-134.

Booth, L.H.; Wickstrom, M.L. 1999. The toxicity of sodium monofluoroacetate (1080) to *Huberia striata* a New Zealand native ant. *New Zealand Journal of Ecology 23:* 161-165.

Calver, M.C.; McIlroy, J.C.; King, D.R.; Bradley, J.S.; Gardner, J.L. 1989. Assessment of an approximate lethal dose technique for determining the relative susceptibility of non-target species to 1080 toxin. *Australian Wildlife Research 16:* 33-40.

Daniel, M.J. 1976. Feeding by the short-tailed bat (*Mystacina tuberculata*) on fruit and possibly nectar. *New Zealand Journal of Zoology 3:* 391-398.

Daniel, M.J. 1979. The New Zealand short-tailed bat, *Mystacina tuberculata*; a review of present knowledge. *New Zealand Journal of Zoology 6:* 357-370.

Department of Conservation, 1994. *National possum control plan: A strategy for the sustained protection of native plant and animal communities 1993-2002*. Department of Conservation, Wellington, N.Z.

Dykstra, C.R.; Karasov, W.H. 1992. Changes in house wren gut structure and function in response to increased energy demands. *Physiological Zoology 65:* 422-442.

Eason, C.T.; Batchelor, D.; Wright, G.R. 1991. *Environmental impact assessments on 1080 associated with possum control in the Waipoua Forest Sanctuary, Northland*. Contract Report FWE 91/8, Forest Research Institute, Rotorua, N.Z.

Eason, C.T.; Gooneratne, R.; Wright, G.R.; Pierce, R.; Frampton, C.M. 1993. The fate of sodium monofluoroacetate (1080) in water, mammals and invertebrates. *Proceedings of the 46th New Zealand Plant Protection Conference:* 297-301.

Eisler, R. 1995. *Sodium monofluoroacetate (1080) hazards to fish, wildlife and invertebrates: a synoptic review*. National Biological Service Biological Report 27 (Contaminant Hazard Reviews Report 30). U.S. Department of the Interior, Washington D.C., U.S.A.

Gillies, C.A.; Pierce, R.J. 1999. Secondary poisoning of mammalian predators during possum and rodent control operations at Trounson Kauri Park, Northland, N.Z. *New Zealand Journal of Ecology 23:* 183-192.

Goodwin, R.M.; Ten Houten, A. 1991. Poisoning of honey bees (*Apis mellifera*) by sodium fluoroacetate (1080) in baits. *New Zealand Journal of Zoology 18:* 45-51.

Gooneratne, S. R.; Eason, C. T., Dickson, C.J.; Fitzgerald, H.; Right, G. 1995. Persistence of sodium monofuoroacetate in rabbits and risks to non-target species. *Human and Experimental Toxicology 14:* 212-216.

Gould, E. 1955. The feeding efficiency of insectivorous bats. *Journal of Mammalogy 36:* 399-407.

Harrison, M. 1978. 1080. *Wildlife - a Review 9:* 48-53.

Heather, B.; Robertson, H. 1996. *Field guide to the birds of New Zealand*. Viking, Auckland, N.Z.

Hegdal, P.L.; Fagerstoone, K.A.; Gatz, T.A.; Glahn, J.F; Matschke, G.H. 1986. Hazards to wildlife associated with 1080 baiting for California ground squirrels. *Wildlife Society Bulletin 14:* 11-21.

Hoogenboom, J.J.L.; Rammell, C.G. 1987. Determination of sodium monofluoroacetate (compound 1080) in tissues and baits as its benzyl ester by reaction-capillary gas chromatography. *Journal of Analytical Toxicology 11:* 140-143.

Hutcheson, J. 1989. *Impact of 1080 on weta populations*. Report for Department of Conservation, Inv. No. S5020/560. Forest Research Institute, Rotorua, N.Z.

Levey, D.J.; Karasov, W.H. 1989. Digestive responses of temperate birds switched to fruit or insect diets. *Auk 10:* 675-85.

Levey, D.J.; Karasov, W.H. 1992. Digestive modulation in a seasonal frugivore, the American Robin (*Turdus migratorius*). *American Journal of Physiology 262:* G711-G718.

Levey, D.J.; Karasov, W.H. 1994. Gut passage of insects by European starlings and a comparison with other species. *Auk 111:* 478-481.

Livingston, P.G. 1994. The use of 1080 in New Zealand. *The Royal Society of New Zealand Miscellaneous Series 28:* 1-9.

Lloyd, B.D. 1994. *Evaluating the potential hazards of 1080 aerial operations to short-tailed bat populations*. Conservancy Advisory Science Notes, No. 108. Department of Conservation, Wellington, N.Z.

Marsh, R.E. 1968. An aerial method of dispensing ground squirrel baits. *Journal of Range Management 21:* 380-384.

McIlroy, J.C. 1981. The sensitivity of Australian animals to 1080 poison. I. Intraspecific variation and factors affecting acute toxicity. *Australian Wildlife Research 8:* 369-383.

McIlroy, J.C. 1984. The sensitivity of Australian animals to 1080 poison. VII. Native and introduced birds. *Australian Wildlife Research 11:* 373-385.

McIlroy, J.C. 1986. The sensitivity of Australian animals to 1080 poison. IX. Comparisons between the major groups of animals and the potential danger non-target species face from 1080-poisoning campaigns. *Australian Wildlife Research 13:* 39-48.

McIlroy, J.C. 1992. The effect on Australian animals of 1080 poisoning campaigns. *In:* Borreco, J.E.; Marsh, R.E. (Editors) *Fifteenth Vertebrate Pest Conference*, pp. 356-359. University of California, Davis, U.S.A.

McIlroy, J.C.; Gifford, E.J. 1992. Secondary poisoning hazards associated with 1080 treated carrot-baiting campaigns against rabbits, *Oryctolagus cuniculus*. *Australian Wildlife Research 19:* 629-641.

McIntyre, M.E. 1987. *Ecological and behavioural relationships of some native cockroaches (Dictyoptera and Blattidae)*. Ph.D. thesis, Victoria University, Wellington, N.Z.

Moeed, A.; Fitzgerald, B.M. 1982. Food of insectivorous birds from forest of the Orongorongo Valley, Wellington, NZ. *New Zealand Journal of Zoology 9:* 391-402.

Murphy, E.C.; Robbins, L.; Young, J.B.; Dowding, J.E. 1999. Secondary poisoning of stoats after an aerial 1080 operation in Pureora Forest, New Zealand. *New Zealand Journal of Ecology 23:* 175-182.

Nagy, K.A. 1987. Field metabolic rate and food requirements scaling in mammals and birds. *Ecological Monographs 57:* 111-128.

Nagy, K.A. 1994. Field bioenergetics of mammals: what determines field metabolic rates? *Australian Journal of Zoology 42:* 43-53.

Nagy, K.A.; Obst, B.S. 1991. Body size effects on field energy requirements of birds: what determines their field metabolic rates? *Acta XX Congressus Internationalis Ornithologica IV:* 793-799.

Notman, P. 1989. A review of invertebrate poisoning by compound 1080. *New Zealand Entomologist 12:* 67-71.

Palmer-Jones, T. 1958. Laboratory methods for measuring the toxicity of pesticides to honey bees. *New Zealand Journal of Agricultural Research 1:* 290-300.

Pierce, R.J.; Montgomery, P.J. 1992. *The fate of birds and selected invertebrates during a 1080 operation*. Science and Research Internal Report No.121: Department of Conservation, Wellington, N.Z.

Powlesland, R.G.; Knegtmans, J.W.; Marshall, I.S.J. 1999. Costs and benefits of aerial 1080 possum control operations using carrot baits to North Island robins (*Petroica australis longipes*), Pureora Forest Park. *New Zealand Journal of Ecology 23:* 149-159.

Ransom, R. 1990. *The natural history of hibernating bats*. Christopher Helm, London, U.K.

Redford, K.H.; Dorea, J.G. 1984. The nutritional value of invertebrates with emphasis on ants and termites as foods for mammals. *Journal of Zoology, London 203:* 385-395.

Sherley, G.; Wakelin, M.; McCartney, J. 2000. Forest invertebrates found on baits used in pest mammal control and the impact of sodium monofluoroacetate ("1080") on their numbers at Ohakune, North Island, New Zealand. *New Zealand Journal of Zoology 26* (in press).

Spurr, E. B. 1979. A theoretical assessment of the ability of bird species to recover from an imposed reduction in numbers, with particular reference to 1080 poisoning. *New Zealand Journal of Ecology 2:* 46-63.

Spurr, E.B. 1991. Effects of brushtail possum control operations on non-target bird populations. *Proceedings of the International Ornithological Congress 20:* 2524-2545.

Spurr, E.B. 1994. Review of the impacts on non-target species of sodium monofluoroacetate (1080) in baits for brushtail possum control in New Zealand. *The Royal Society of New Zealand Miscellaneous Series 28:* 116-123.

Spurr, E.B.; Drew, K.W. 1999. Invertebrates feeding on baits used for vertebrate pest control in New Zealand. *New Zealand Journal of Ecology 23:* 167-173.

Spurr, E.B.; Powlesland, R.G. 1997. *Impacts of aerial application of 1080 on non-target native fauna: Review and priorities for research*. Science for Conservation No. 62. Department of Conservation, Wellington, N.Z.

Timm, R. 1983. *Prevention and control of wildlife damage*. Great Plains Agricultural Council Wildlife Resources Committee and Nebraska Cooperative Extension Service, USA: University of Nebraska-Lincoln, Nebraska, U.S.A.

Twigg, L.E.; King, D.R.; Davis, H.M.; Saunders D.E.; Mead, R.J. 1988. Tolerance to and metabolism of fluoroacetate in the emu. *Australian Wildlife Research 15:* 239-247.

Appendix 1. The composition of pooled collections sent for 1080 assay.

Taxonomic group	Lowest taxonomic unit	Collection No. 1	2	3
Cockroach (Blattaria)	Blattaria	1	1	0
Weta (Orthoptera)	Rhaphidophoridae	3	0	4
	Neonotus sp.	1	0	0
	Zealosandrus gracilis	1	0	1
	Weta sp.	1	4	1
Beetles & weevils (Coleoptera)	*Ctenognathus adamsi*	0	2	0
	Saphobius squamulosa	1	5	5
	"weevil"	1	0	0
Harvestmen (Phalangidae)	*Nuncia* sp.	4	1	1
	Pristobunus sp.	1	1	3
	Soerensenella rotara	0	1	0
	Pantopsalis sp.	0	1	0
Millipedes (Diplopoda)	*Dimerogonus* sp.	0	1	2
	Icosidesmus sp.	0	1	0
Centipedes (Chilopoda)	"orange centipedes"	1	2	1
Amphipod (Amphipoda)	Amphipods	0	4	1