Identification of weta foraging on brodifacoum bait and the risk of secondary poisoning for birds on Quail Island, Canterbury, New Zealand

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Abstract: Brodifacoum is a second-generation anticoagulant used for rodent control in New Zealand. Concerns about the poisoning of non-target species have resulted in restrictions being imposed on the mainland. It is, however, still commonly employed on offshore islands. Previous research investigating the poisoning risks of brodifacoum has generally focused on birds eating brodifacoum bait (primary poisoning) or through depredation of live rodents or carrion containing brodifacoum residues (secondary poisoning). Other research has highlighted the potential for secondary poisoning of birds via the consumption of contaminated invertebrates. An inspection of rodent bait stations undertaken on Quail Island revealed that both cave and ground weta were feeding on brodifacoum bait. A sample of ground weta (*Hemiandrus* n. sp.) and cave weta (*Pleioplectron simplex*) was removed from Quail Island and exposed to toxic bait for 60 days. These weta were then assayed for brodifacoum residues and the values used to quantify the secondary poisoning risk for bird species found around Quail Island. We also calculated the risk to birds of secondary poisoning from the tree weta (*Hemideina ricta*) and the risk of primary poisoning via direct consumption of brodifacoum bait. The LD_{50} estimates indicated a low risk of secondary poisoning from contaminated ground weta and cave weta. By contrast, the estimates indicated a higher risk from larger-bodied tree weta; however, our calculations were based on a single residue concentration value and should be treated with caution. Of most concern was the primary poisoning risk from the brodifacoum bait. The results indicated that all the 17 bird species assessed are more susceptible to primary poisoning than secondary poisoning and access to brodifacoum bait by non-target bird species needs to be minimised.

Keywords: weta; secondary poisoning; brodifacoum; residues; Raphidophoridae; Anostostomatidae; Quail Island; birds

Introduction

During the 1990s, the use of cereal bait containing the second-generation anticoagulant brodifacoum for mammalian pest control in New Zealand increased (Innes and Barker, 1999). Certainly, such compounds are very potent and can be highly effective in reducing the abundance of possums and rodents (Eason *et al*., 1999; Empson and Miskelly, 1999; Stephenson *et al.,* 1999). However, concerns about primary and secondary poisoning of non-target species (Eason and Spurr, 1997; Dowding *et al*., 1999; Eason *et al*., 1999; Stephenson *et al*., 1999) has increasingly necessitated the use of bait stations in an attempt to reduce the amount of toxic bait used and to restrict access by non-target species (Thomas and Taylor, 2001). More recently, organisations such as the Department of Conservation (DOC) have restricted the use of this compound on the mainland (Eason *et al*., 2002) and research is currently investigating alternative compounds for rodent control (Eason *et al*., 2002; Fisher *et al*., 2003; Fisher, 2005).

All pest control activities require careful risk-benefit assessment in view of their potential to cause adverse environmental impacts (Eason *et al*., 2002). The purpose of brodifacoum cereal bait on Quail Island is to prevent reinvasion of rats (M. Bowie, pers. obs.). Removal of rodents is viewed as a major advancement for conservation on Quail Island and there are numerous studies detailing the benefits (Newman, 1994; Eason and Wickstrom, 2001; Towns and Broome, 2003). Unfortunately Quail Island is close to the mainland and affords the opportunity for reinvasion at low tide and mice are certainly still present (M. Bowie, unpubl. data). Whilst the use of brodifacoum may have been restricted on the mainland, this compound is still commonly used for 'one-off' rodent eradication campaigns on offshore islands, compared with sustained mainland applications (Thomas and Taylor, 2001). Baits containing

brodifacoum are also permanently left out to prevent rodent re-establishment on islands located close to the mainland, with bait wrapped in tinfoil or in plastic ziplock bags to improve field longevity (Airey and O'Connor, 2003). Whilst the sustained use of brodifacoum can be highly effective for suppressing rodent abundance, there are concerns being raised regarding the risk to indigenous invertebrate communities on these offshore islands (Eason *et al*., 2002). For example, on Quail Island/Otamahua (Lyttelton Harbour, Banks Peninsula, Canterbury, 43° 38' S, 172° 41' E) brodifacoum cereal baits wrapped in aluminium foil were found to have forage holes that differed subtly in nature from mouse (*Mus musculus* L.) damage. A night inspection revealed that weta (Orthoptera) and other invertebrate species were visiting bait stations and consuming toxic bait (M. Bowie, pers. obs.). Invertebrate bait interference has also previously been misidentified in the field. For example, on Matiu/Somes Island brodifacoum bait consumption was initially thought to be caused by reinvading mice. After substantial investigation it actually turned out to be caused by a tenebrionid beetle (*Mimopeus opaculus* Bates; Rob Stone, Department of Conservation, Wellington, pers. comm.). Consumption of rodent bait by weta is of concern as considerable effort has gone into weta conservation on Quail Island (Bowie *et al*., 2003) and the rare Banks Peninsula tree weta (*Hemideina ricta* (Hutton)) has recently been reintroduced to the island (Bowie *et al*. in press). Weta are also an icon species for invertebrate conservation in New Zealand because many species are threatened or endangered, and recovery plans have been published by DOC (Sherley, 1998).

While many invertebrate species are known to feed on the cereal bait used for mammalian pest control (Spurr and Drew, 1999; Wakelin, 2000), studies have primarily focused on baits containing 1080 (sodium mono-fluoroacetate) and the risks of poisoning for non-target bird species (Eason and Spurr, 1995; Sherley *et al*., 1999; Eason *et al*., 2002; Spurr and Berben, 2004). Acute toxicity studies with brodifacoum in captive weta indicate that orally-dosed individuals were unaffected in the short term (Morgan *et al*., 1996; Booth *et al*., 2001); however, survival was only monitored for 14–21 days. Of weta collected after baiting operations in the field, 11 out of 24 had detectable brodifacoum residues in their whole bodies, in the range of 0.06–7.47 mg/kg (Booth *et al*., 2001). Unfortunately, most of this field research has focused on 'one-off' applications of brodifacoum in island eradication programmes. Accordingly, it is difficult to determine the effects of sustained exposure to brodifacoum cereal bait on weta survival and likely residue concentrations in weta.

In consideration of the previous research, the aim of this paper was to report on the typical interference with rodent baits by weta, so that it can be distinguished in the field from that caused by mammals (i.e. mice). Second, we attempted to quantify the risk of secondary poisoning as the result of consuming brodifacoum-contaminated weta for non-target bird species (both native and exotic) residing on Quail Island, as well as primary poisoning of these bird species.

Material and Methods

Field observations

Two types of bait stations are used for rodent control on Quail Island: a plastic yellow PESTOFF® brand and Novacoil drain pipe. A single cereal-based Talon® 50WB 'egg' (0.005% w/w) wrapped in aluminium foil was placed in each station. All bait stations (n = 550) were then monitored for activity after a rodent poisoning operation, and on the 21–24 January 2003, 33 stations were found with nibbled bait. Seven of these active bait stations (selected at random) were marked with a cane and reflective tape to enable them to be found in the tall exotic grass at night. Between 10.00 pm and 11.00 pm on 7 February 2003 these bait stations were rechecked for invertebrate activity. All invertebrates located either on the baits or within the bait stations were collected and identified.

Laboratory experiments

Three adult cave weta (*Pleioplectron simplex* Hutton; Raphidophoridae) (one female, two male) and five male ground weta (*Hemiandrus* n. sp.; Anostostomatidae) collected from Quail Island were weighed and individually placed into polypropylene containers with moistened tissue paper and a single Talon® 50WB bait wrapped in aluminium foil. Seven more *P. simplex* (two female, one male) and four more *Hemiandrus* n. sp. (four male) were collected and fed non-toxic cereal bait as a control. A mixture of these two species was used as they are of similar weight (mean (±1 SEM) mass = 0.375 ±0.03 g) and both were observed feeding in the bait stations (see Results). Based on Barrett (1991), all weta were maintained in an incubator at 15 ±1°C, 90 ±10% relative humidity and a photoperiod of 16 h light: 8 h dark, but with a black cotton sheet over the containers to reduce light levels. The moist tissue and baits were replaced if mould spots started to appear.

Survival was assessed daily for a 60-day period. Bait consumption was assessed by measuring the dry weight of bait after 21 days with fresh bait put out at this time. Bait was dried out in an oven for 24 h at 55 °C before the start of the feeding trial and then again before final weighing. This was done to ensure the weight of the baits was not influenced by moisture, as

cereal baits are hydroscopic and will generally absorb moisture over time. All weta were weighed at the start of the experiment, then at 26 and 47 days. The length, width and depth of the forage holes in the baits were measured to gain a size profile of the weta foraging.

As well as in weta, brodifacoum residues have also been detected in beetles (Coleoptera) and there is research suggesting that molluscs may be susceptible to brodifacoum (Booth *et al*. 2003). Accordingly, 12 introduced carabids *Laemostenus companatus* (Dejean) and eight introduced slugs *Deroceras panormitanum* (Lessona and Pollonera) and *Deroceras reticulatum* Müller (the same species as on Quail Island; Bowie *et al*., 2003) were collected from compost at Lincoln (Canterbury, New Zealand) and fed Talon® 50WB for 40 days. Non-toxic cereal bait was fed to seven carabids and seven slugs as a control. A selection of Talon® 50WB baits were also exposed to mice known to be residing near the compost in order to describe typical feeding damage caused to bait by mice.

LD_{50} estimates of brodifacoum-contaminated weta for bird species

The risk of secondary poisoning was estimated using similar methods to those employed by Lloyd and McQueen (2000) (see formulas below). After 60 days, surviving weta that had fed on control and brodifacoum baits were killed by cooling in ice slurry and then freezing (Reilly, 2001). They were then stored at -70°C until they could be analysed for residues. Only six individuals (three of each species) from each group were assayed. These included three weta that had died plus a random selection of survivors. High Pressure Liquid Chromatography was used by the Landcare Research Toxicology laboratory (Lincoln, New Zealand) for the determination of brodifacoum in the weta as 'whole body' samples. The method is based on Primus *et al*. (2001) with a detection limit of 0.01 mg/kg and uncertainty (95% C.I.) of ±22%. The weighted-mean brodifacoum residue concentration was calculated as

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

where: n is the number of samples, m_i is the mass of the sample, and c_i is the brodifacoum concentration.

The standard error of the weighted mean was calculated as $\sqrt{s^2/n}$, where s^2 is calculated as

$$\sum m_i (c_i - \overline{c}_w)^2 \Big/ (n-1)$$

Seventeen bird species were considered as potentially subject to secondary poisoning because they forage on, or close to, the ground and consume a wide variety of invertebrate species, including some species that have been directly observed feeding on cereal baits (Eason and Spurr, 1995; Hartley *et al*., 1999; Haw *et al*., 2001; Torr, 2001; Veitch, 2001; Greene and Dilks, 2004). These species were: little owl (*Athene noctua*), morepork (*Ninox novaeseelandiae*), southern black-backed gull (*Larus dominicanus*), white-backed magpie (*Gymnorhina tibicen*), pheasant (*Phasianus colchicus*), harrier (*Circus approximans*), blackbird (*Turdus merula*), hedge sparrow (*Prunella modularis*), Canada goose (*Branta canadensis*), house sparrow (*Passer domesticus*), California quail (*Callipepla californica*), pukeko (*Porphyrio melanotus*), mallard (*Anas platyrhynchos*), black-billed gull (*Larus bulleri*), silvereye (*Zosterops lateralis*), paradise shelduck (*Tadorna variegata*) and New Zealand kingfisher (*Halcyon sancta*). Fortunately, acute oral toxicity data (LD_{50} values) for brodifacoum is available for most of these species (see Godfrey, 1985); however, there were no published values for the little owl, kingfisher, morepork and magpie. Accordingly, we used a mean value of 5.6 mg/kg, calculated using the other 13 values. It is recognised that this approach may not be particularly precise given the wide variability of the LD_{50} dose estimates; however, there is no other formal way to more accurately estimate a LD_{50} value for these four species and the mean-value approach has been used by previous researchers for similar estimates (Lloyd and McQueen, 2000).

Quantities of brodifacoum-contaminated weta that represented LD_{50} intakes for birds were calculated using two weta-residue concentration values. The first residue value (ground weta and cave weta) was the weighted mean of 1.19 mg/kg derived from weta assayed in this study (see Results). The second residue concentration value of 7.47 mg/kg was used for the larger-bodied Banks Peninsula tree weta, as tree weta have previously been observed feeding on cereal bait (Spurr and Berben, 2004). Whilst we did not assay any tree weta, we obtained this value from a 4.3 g individual recorded in the National Wildlife Residue database (Booth *et al*., 2001). Another relevant consideration, because of the higher brodifacoum concentrations in bait, was the direct consumption (i.e. primary poisoning) of brodifacoum cereal bait by the bird species. Many of the bird species detailed above have been directly observed eating cereal based bait and are considered likely to consume rodent bait if encountered (Eason and Spurr, 1995). Accordingly, we also calculated the amount of brodifacoum bait required for a LD_{50} dose for each bird species using a bait concentration of 0.005% w/w. Daily food consumption was calculated for each of the bird species as FMR/ME (grams per day): FMR is the field metabolic rate (Kilojoules per day); and ME is the metabolisable energy in food (kilojoules of dry matter). FMR estimates were calculated using the allometric equation

FMR = am^b,

where m is body mass, and a and b are parameter estimates. Values for the parameter values were a = 8.88 and b = 0.749 for passerine birds; a = 8.01 and b = 0.704 for sea birds; and a = 10.9 and b = 0.64 for all other species (see Nagy, 1987 for explanation of formula).

Body mass estimates for the bird species are from Heather and Roberston (1996). ME estimates for arthropods are 18.0 kJ g^{-1} when consumed by birds (Nagy and Obst, 1991). The water content estimate for adult arthropods (67%) is the average of published values for ten species (see Lloyd and McQueen, 2000). ME estimates for cereal bait are 14.0 kJ g^{-1} when consumed by birds (Nagy, 1987). The water content estimate for cereal baits was estimated at approximately 14% (M. Thomas, Pest Control Solutions Ltd., Christchurch, *pers. comm.*). The LD_{50} dose of weta and cereal bait containing brodifacoum was then expressed as the proportion of the estimated daily food consumption (fresh weight) for each bird species.

Results

Field observations

All monitored bait stations had between one and three weta feeding on the poison bait, inside the bait station, or 'queuing up' to enter. Both cave weta and ground weta were directly observed consuming bait at night. Slugs (*Deroceras panormitanum* and *Deroceras reticulatum*) were regularly found during the day in bait stations and sometimes found feeding on the baits, while others were found dead. Other invertebrate species found directly foraging on the baits included: *Ptinus tectus* Boieldieu (Anobiidae); *Pilacolaspis* sp. (Chrysomelidae); *Otiorhynchus ovatus* (L.) (Curculionidae); *Makawe hurleyi* (Duncan) (Talitridae). Invertebrate species found inside bait stations in large numbers included *Scotophaeus pretiosus* (L. Koch) (Gnaphosidae); nr *Tomocoris* sp. (Rhyparochromidae); *Celatoblatta* sp. (Blattidae); and *Forficula auricularia* L. (Labiduridae).

Laboratory experiments

Both control and brodifacoum cereal baits were consumed by all weta with green dye often observed in the frass. It was also observed that weta avoided any bait that became mouldy because of the high humidity in the plastic containers (cf. baits in the field); these baits were replaced throughout the trial. Total individual bait consumption was variable over the 21-day period (range 5.36–336.93 mg dry weight) with a mean consumption of 106.61 mg dry weight (± 49.56 mg SEM).

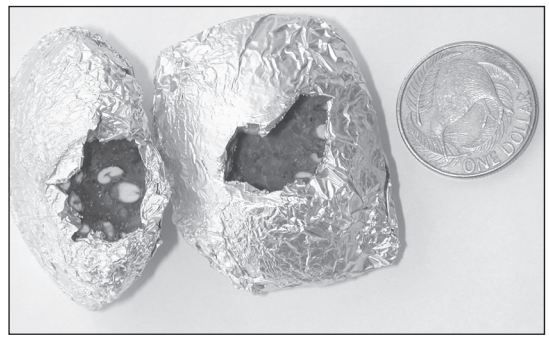

Figure 1. Two Talon® 50WB baits (wrapped in aluminium foil) showing typical weta feeding damage.

Figure 2. Talon® 50WB bait (wrapped in aluminium foil) showing typical mouse feeding damage.

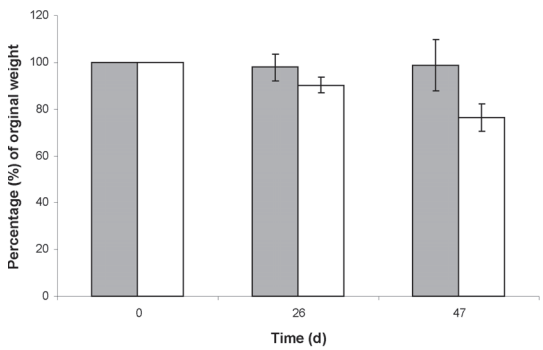

Figure 3. Mean percentage weight loss of ground (*Hemiandrus* n. sp.) and cave weta (*Pleioplectron simplex* Hutton) fed Talon® 50WB bait (treatment; open bars) and non-toxic control (filled bars) cereal bait (n = 7) over 47 days. Error bars are ± SEM.

Baits eaten by weta had up to four holes in them with the aluminium foil neatly trimmed around the edge of each hole (Fig. 1). In some cases, baits were almost hollowed out inside the foil wrapping. In contrast, mouse damage was characterised by roughly ripped aluminium foil with foraging over a wide area of the bait (Fig. 2). The mean and SEM for weta browse hole length, width and depth were: 9.56 ± 2.04 mm; 4.44 ± 0.41 mm; and 2.78 ± 0.52 mm respectively. Given the destructive and haphazard nature of the mouse browsing (see Fig. 2), it was impossible to accurately measure forage holes.

After 60 days, only 50% (4/8) of the weta feeding on brodifacoum cereal bait survived, compared to 71.4% (5/7) of the weta feeding on control baits. Differences in mortality were not significant over the duration of the feeding trial (log-rank test; $P = 0.419$). No slug or carabid mortality was recorded for the period of the experiment even though foraging was directly observed and green dye was present in the frass. The mean weight of surviving weta in both groups decreased during the experiment (Fig. 3). A repeated-measures ANOVA indicated that these weight reductions were significant over time ($F_{2,20} = 9.70$; $P = 0.001$); however there was no significant difference between the groups ($F_{2,20} = 2.995$; $P = 0.073$).

LD_{50} estimates of brodifacoum-contaminated weta for bird species

The 'whole body' weighted-mean residue concentration of ground weta or cave weta that consumed bait was 1.19 mg/kg (± 0.15 SEM; range 0.48–2.3 mg/kg). None of the weta in the control group had detectable brodifacoum residues. The LD_{50} estimates of brodifacoum-contaminated weta (ground and cave) varied immensely from a low of 157 weta (hedge sparrow) up to 69833 weta for the paradise shelduck (Table 1). In terms of a proportion of daily food intake,

Table 1. Estimated numbers of brodifacoum-contaminated weta and brodifacoum rodent bait (g wet weight) required to provide a LD_{50} dose for 'at-risk' bird species located on or near Quail Island. The amount of food intake required to give the LD_{50}, as a percentage of average daily food intake, is given in brackets.

Species[1]	Body mass (g)[2]	Food intake g/day		LD_{50} mg/kg[3]	Weta tissue (g) for LD_{50}[4] Residue conc. (mg/kg)		Consumption for LD_{50} Ground/ cave weta[5]	Tree weta[6]	Cereal bait[7]
		inverts.	cereal		1.19	7.47	*n*	*n*	g
Little owl	180	50.9	25.1	5.6†	849.5	134.9	2514 (1668)	31 (265)	20.2 (80)
Morepork	175	50.0	24.7	5.6†	825.9	131.2	2444 (1651)	31 (262)	19.6 (79)
Southern black-backed gull	1050	157.5	89.1	0.75§	663.7	105.4	1964 (421)	25 (67)	15.8 (18)
White-backed magpie	350	120.3	38.5	5.6†	1651.8	262.5	4888 (1374)	61 (218)	39.2 (102)
Pheasant	1200	171.5	84.6	10.0	10 113.3	1606.4	29 928(5896)	374 (937)	240.0 (284)
Harrier	650	115.9	57.2	10.0	5478.0	870.2	16 211(4729)	202 (751)	130.0 (227)
Blackbird	90	43.5	21.5	3.0‡	227.6	36.1	673 (523)	8 (83)	5.4 (25)
Hedge sparrow	21	14.6	7.2	3.0‡	53.1	8.4	157 (363)	2 (58)	1.3 (17)
Canada goose	4500	399.7	197.2	0.75§	2844.4	451.8	8417 (712)	105 (113)	67.5 (34)
House sparrow	30	19.1	9.4	6.0*	151.7	24.1	449 (794)	6 (126)	3.6 (38)
California quail	180	50.9	25.1	3.3	500.6	79.5	1481 (983)	18 (156)	11.9 (47)
Pukeko	850	137.6	67.9	0.95	680.5	108.1	2014 (495)	25 (79)	16.2 (24)
Mallard	1100	162.2	80.0	4.6	4264.4	677.4	12 620 (2629)	158 (418)	101.2 (126)
Black-billed gull	250	62.9	32.5	5.0§	1053.5	167.3	3118 (1676)	39 (266)	25.00 (77)
Silvereye	13	10.2	5.0	6.0‡	65.7	10.4	195 (644)	2 (102)	1.56 (31)
Paradise shelduck	1400	189.3	93.4	20.0‡	23 597.6	3748.3	69 833 (12 466)	872 (1980)	560 (600)
New Zealand kingfisher	65	26.5	13.1	5.6†	306.8	48.7	908 (1156)	11 (184)	7.28 (56)

[1]Names follow Turbott (1990).
[2] Lighter of male or female mass (in Turbott, 1990)
[3]LD_{50} of brodifacoum values follow Godfrey (1985). § Lowest dose tested, ‡ Highest dose tested, † Mean value calculated from the other LD_{50} values used in this table (n=13)
[4]LD_{50} in grams (fresh weight) of contaminated weta.
[5]Assumes mean weta bodyweight = 0.34 g, and
[6] Assumes mean weta bodyweight of 4.3 and brodifacoum residue value of 7.47 mg/kg. This data was obtained from the National Wildlife Residue database (Booth *et al*., 2001).
[7]Assumes toxicant concentration of 50 mg/kg.

none of the bird species could physically consume a LD_{50} dose of contaminated weta in the equivalent of a single day of feeding. In a worse case scenario, a hedge sparrow would need to feed continuously on ground or cave weta for nearly four days to ingest a LD_{50} dose. The results for the larger-bodied tree weta were more concerning, with LD_{50} dose estimates ranging from a low of two weta up to 872 weta. In terms of a proportion of daily food intake, four of the bird species (southern black-backed gull, blackbird, hedge sparrow and pukeko) could consume a LD_{50} dose in the equivalent of a single day of feeding on tree weta (Table 1). Of most note were the results for direct consumption of the brodifacoum cereal bait. Even though birds needed to consume a lesser weight of cereal bait to satisfy their daily food requirements (primarily due to the lower water content in cereal bait), 12 of the bird species could consume a LD_{50} dose in the equivalent of a single day of feeding.

Discussion

Field observations

Numerous invertebrates were observed in or around the bait stations on Quail Island. This is similar to previous research which identified a broad range of invertebrate species visiting 1080 baits broadcast for possum control (Sherley *et al*., 1999; Spurr, 1994; Spurr and Powlesland, 1997; Spurr and Berben, 2004). Complementary research suggest that the numbers of invertebrates on bait may be correlated with leaf-litter depth and temperature (Wakelin, 2000), with the dominant proportion of visitors being leaf-litter inhabitants that feed on decaying plant or fungal material. Most of the invertebrate species visiting the baits are likely to be using bait as a food source and some predatory species could be attracted in to prey that is feeding on the baits.

Laboratory experiments

Both toxic and non-toxic baits were readily consumed by all captive weta. Examination of the bait indicated that weta foraging was discreet and different from mouse foraging. By using the description and images of the foraging highlighted above it is hoped that mice and weta foraging can now be easily differentiated in the field; however, this would most likely only work in areas of low rodent abundance as the mouse foraging was quite destructive and may mask signs of weta forage. Weta themselves would be prone to predation by mice as they are both nocturnal and both attracted to the bait. As mentioned above, on Matiu/Somes Island foraging damage to bait thought to be caused by reinvading mice actually turned out to be a tenebrionid beetle. In such cases where mice are the culprits, a quick response is essential for successful eradication; however, if resident invertebrates are responsible, then a speedy and correct identification of foraging would avoid an unnecessary waste of labour and time trying to eradicate non-existent mice.

Of interest was the fate of weta continuously exposed to brodifacoum bait. After 60 days there was higher weight loss and mortality in the toxic group but, neither result was statistically significant. This could be the result of the lack of alternative food sources affecting survival of both groups, a lack of statistical power with relatively small sample sizes, or there may not be any differences. A follow up study with larger sample sizes may provide a more robust result. Interestingly, there was no mortality observed for the slugs or carabids that were exposed to brodifacoum bait for 40 days. These results support previous research that observed little or low mortality of invertebrates feeding on brodifacoum bait (summarised in Booth *et al*., 2003).

LD_{50} estimates of brodifacoum-contaminated weta for bird species

The risk of accidental poisoning has previously been expressed by Eason & Wickstrom (2001) as:

$$Risk = Hazard \times Exposure$$

We estimated the hazard using LD_{50} values obtained from the research literature. Accordingly, the hazard for a non-target bird species is determined by the sensitivity of that species to brodifacoum. We estimated exposure by feeding rodent bait to captive weta for 60 days and measuring brodifacoum residues.

Hazard

The data in Table 1 indicate that the LD_{50} values for bird species are extremely variable (range <1–20 mg/kg). For example, the southern black-backed gull and pukeko both have high sensitivity to brodifacoum and could theoretically consume a LD_{50} dose in the equivalent of a single day of feeding on contaminated tree weta. The other bird species most at risk of poisoning are those with moderate sensitivity and smaller body mass such as the blackbird and hedge sparrow. Both of these smaller species consume proportionally higher amounts of food per day in relation to their body size and could also theoretically consume a LD_{50} dose in the equivalent of a single day of feeding on contaminated tree weta. Field studies have reported a wide range of both large and small-sized bird species found dead following the use of brodifacoum, although it is difficult to determine whether death was the result of primary or secondary poisoning (Eason and Spurr, 1995; Eason and Spurr, 1997; Dowding *et al*., 1999; Empson and Miskelly, 1999; Eason *et al*., 2002).

Obviously, a problem using this approach to assess the hazard for a bird species is the robustness of the LD_{50} dose estimates. In Table 1, we collate LD_{50} dose values from many different research studies. These research teams may have utilised different experimental methodologies and/or sample sizes (Eason *et al*., 2002). We do not have a measure of precision for the LD_{50} values (i.e. ± 95% CI), which may vary considerably. Also, some of the values are the lowest and highest doses used in the experiment. This means that the LD_{50} dose estimates for some species may be understated. Another confounding factor is that we used a mean LD_{50} value of 5.6 mg/kg for four of the bird species. As detailed above, brodifacoum toxicity is variable and we could be widely inaccurate in our dose estimates for these four species.

Exposure

Certainly all of the bird species could theoretically be poisoned by brodifacoum-contaminated weta; however, we are talking about hundreds of ground or cave weta required for a LD_{50} dose. Perhaps of most concern are the tree weta calculations, where four of the 17 bird species could consume a LD_{50} dose in the equivalent of a single day of feeding on contaminated tree weta; however, there are three issues that need to be considered. First, the residue value used for tree weta is the highest recorded in the National Wildlife Residue database (G. Wright, Landcare Research, Lincoln, pers. comm.) and the only value we have for tree weta. The residue concentration values for ground and cave weta were much lower than this and we may be presenting an extreme-case scenario for tree weta. Also, tree weta have only recently been reintroduced and it is unlikely there are great numbers currently residing on Quail Island.

Second, our daily food-intake calculations are based on a bird feeding entirely on contaminated weta. Whilst the daily food intake calculations enable us to compare risk between species, it is unlikely that any free-ranging bird would feed solely on weta with alternative food available. Whilst this may cast some doubt on our LD_{50} calculations, the risk of encountering contaminated weta is likely to be higher in areas of intensive pest management. For example, intensive rodent control has decreased the numbers of mammalian predators on Quail Island and invertebrate numbers are on the increase (M. Bowie, unpubl. data). Also, the chance of a bird consuming a lethal dose of contaminated prey is likely to be higher when prey such as cave weta have a clumped distribution. Many individual cave weta were found near bait stations on Quail Island at night apparently queuing to enter (M. Bowie, unpubl. data). In addition to this, there is evidence of birds focusing on weta in high-density areas with research indicating that morepork diet can contain a lot of tree weta (Lindsay and Ordish, 1964).

Third, previous research indicates that weta fed brodifacoum cereal bait had non-detectable residues in less than 12 days (Lloyd, 1997 cited in McClelland, 2001), and possibly as low as four days after consumption (Booth *et al*., 2001). This suggests that brodifacoum is quickly excreted from weta thus reducing the opportunity for biological accumulation. Another factor is that not all weta will locate and feed on rodent bait on Quail Island. For example, no detectable residues were found in any of the invertebrate samples collected on Coppermine Island 2, 3, 9, 30 and 240 days after the sustained application of Talon® 50WB in bait stations similar to those used on Quail Island (Morgan and Wright, 1996). Accordingly, the only poisoning risk would come from invertebrates that have located and recently fed on brodifacoum cereal bait; however, the opportunity for weta accessing rodent bait on Quail Island is reasonably high with 6.47 bait stations/ha (a total of 550 stations over 85 ha).

Whilst the retention of brodifacoum in invertebrates is currently not well known (Primus *et al*., 2005), research suggests a heightened risk from invertebrates with the ability to accumulate fat-soluble compounds (e.g. snails, slugs and earthworms; Booth *et al*., 2001; Eason and Wickstrom, 2001). This issue has recently been examined. Common garden snails (*Cantareus aspersus*) exposed to brodifacoum bait suffered no mortality, but had measurable residues in body and foot tissue (Booth *et al*., 2003). In another study, two snail species, *Pachnodus silhouettanus* and *Achatina fulica*, from Frégate Island, Seychelles suffered mortality following exposure to quite low doses of brodifacoum (0.01–0.04 mg/kg) over a 72-h period (Gerlach and Florens, 2000). Certainly the slugs in this study consumed brodifacoum bait; however, none were assayed and we have no data on the potential residues accumulating in molluscs located on Quail Island. No slugs died after 40 days of exposure to brodifacoum; however, many have been found dead in bait stations on Quail Island. Given the mortality observed with snails in the Seychelles it is possible that the slugs on Quail Island died as a result of ingesting brodifacoum and this issue warrants further investigation. Accordingly, whilst this research currently suggests a low risk of secondary poisoning from ground and cave weta, there certainly exists the potential for birds to eat other contaminated invertebrates (e.g. molluscs) or reptiles (Hoare and Hare, 2006) in combination with the brodifacoum cereal bait. Brodifacoum is also a cumulative toxicant in both mammals and birds with research demonstrating that this compound can be retained in the liver for 6–12 months (Eason *et al*., 1996; Murphy *et al*., 1998; Eason *et al*., 2001; Eason *et al*., 2002; Fisher *et al*., 2003). Even infrequent exposure to contaminated

invertebrates could mean that residue levels in bird species accumulate over time to lethal levels; however, it is likely that the risk of this happening remains low on Quail Island.

Whilst the calculations of LD_{50} for tree weta may be of concern, all of the bird species are at relatively much higher risk of primary poisoning via direct consumption of brodifacoum bait. This is due to the fact that the concentration of brodifacoum is much higher in bait (50 mg/kg) than in contaminated weta (range 0.48–7.47 mg/kg). Obviously not all bird species would eat cereal bait; however, most of the species (listed in Table 1) have been observed or are considered likely to consume cereal bait if encountered (Eason and Spurr, 1995; Eason *et al*., 2002). Whilst the bait station design discourages direct feeding by birds, any discarded bait around the station is likely to pose a risk. Another factor is the potential secondary poisoning of predatory/scavenger species (e.g. weka, harrier, morepork and southern black-blacked gull; Eason and Wickstrom, 2001) via the consumption of poisoned rodents (i.e. the target species). Analysis of rats poisoned with brodifacoum on Langara Island suggests that these residues can be substantial with whole-carcass fresh tissue residues of 1.57–3.50 mg/kg (Howald *et al*., 1999) and substantially higher residues concentrated in the liver and gastrointestinal tract. Whilst complementary research suggests that many poisoned rodents die below ground (Taylor, 1993), there is certainly the potential for secondary poisoning from rodents found dead above ground (Hooker and Innes, 1995).

Although the current control strategy on Quail Island does generate risk for non-target species, it appears that weta survival is not seriously affected by brodifacoum; however, our knowledge of the fate of this compound in invertebrates is limited. Brodifacoum is toxic (at high concentrations in soil) to earth worms (*Aporrectodea calignosa*; Booth *et al*., 2003) and we do not know what sub-lethal effects brodifacoum may be having on other invertebrate species on Quail Island. It also appears that the risk of secondary poisoning for birds from contaminated weta is relatively low; however, we have not directly measured brodifacoum residues in birds on Quail Island or investigated whether they are increasing with continued exposure to contaminated invertebrate prey.

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