REVIEW

The impact of brodifacoum on non-target wildlife: gaps in knowledge

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Abstract: Anticoagulant poisons, especially the second-generation anticoagulant brodifacoum, are used worldwide to eradicate pest mammals from high priority nature sites. However, the potency and persistence of brodifacoum may present threats to non-target species. In New Zealand, most ecosystems lack native terrestrial mammals; instead, birds, reptiles and invertebrates fulfil key ecosystem roles. Introduced mammals represent the biggest threat to persistence of native species. Therefore, in addition to use in eradications, brodifacoum is often continuously supplied in ecosystems for pest mammal control and detection of mammalian reinvasions, creating a potential long-term risk of poisoning to non-target species. We reviewed literature concerning brodifacoum effects on non-target native fauna in New Zealand as a framework for discussing current research requirements. Birds and their invertebrate prey have, to date, been the focal taxa of such empirical studies (26 species and 11 orders studied, respectively). Brodifacoum is linked to both mortality and sub-lethal contamination in native birds, and the toxicant is consumed by a range of native invertebrates. Reptiles, amphibians, bats and aquatic invertebrates are considered at low risk of anticoagulant poisoning and are not routinely included in risk assessments. However, recent field evidence demonstrates that native geckos consume brodifacoum bait. Reptiles are often abundant on mammal-free offshore islands where brodifacoum is used persistently as a simultaneous rodent detection and killing strategy. Ectothermic vertebrates, though at low risk of toxicosis themselves, may act as vectors of brodifacoum and create a risk of secondary poisoning to native birds. The effectiveness of using poison bait to protect mammal-free ecosystems is uncertain, due to the abundance of alternative food supplies available to an invading rodent. However, where sustained brodifacoum use is deemed appropriate, the role of reptiles as consumers and vectors of anticoagulant poison should be a research priority.

Keywords: anticoagulant; poison; non-target; brodifacoum; toxicology; reptile; food web; ecosystem

Introduction

Introduced mammalian predators have caused catastrophic declines or extinctions of many species world-wide (Case and Bolger, 1991). Thus, eradication and control of mammalian pests have been necessary in order to protect native biodiversity (e.g. Innes and Barker, 1999; Atkinson, 2001; Towns and Broome, 2003). Anticoagulant toxins (particularly the second-generation poison brodifacoum) are powerful conservation tools for poisoning rodents and other vertebrate pests (e.g. Donlan *et al.*, 2003). Use of anticoagulants has increased world-wide (e.g. Godfrey, 1985), and is currently the most commonly used method of pest-mammal eradication (Stone, Okoniewski and Stedelin, 1999; O'Connor and Eason, 2000; Towns and Broome, 2003). While using brodifacoum to eradicate mammals poses a risk to non-target native species through primary and secondary poisoning, the benefits of eradication usually outweigh costs (Innes and Barker, 1999). However, concerns about brodifacoum persistence and potency have resulted in restrictions on its use in many parts of the world (e.g. field use is banned in the United States of America; Stone *et al.*, 1999).

Brodifacoum is a potent rodenticide that binds strongly to vitamin K epoxide reductase and persists for at least six months in organs and tissue containing this enzyme, such as the liver, kidney and pancreas (Stone *et al.*, 1999; Eason *et al.*, 2002). The persistence of brodifacoum in tissue exacerbates the risk of secondary poisoning of non-target species (Eason, Wright and Batcheler, 1996; Eason and Wickstrom, 2001; Eason *et al.*, 2002), and poses a clear risk to avian predators and scavengers (e.g. Mendenhall and Pank, 1980; Howald *et al.*, 1999). A lethal dose (LD_{50})

in birds is usually 3–20 mg/kg (compared with <1 mg/kg in target mammals), though some bird species are highly susceptible (e.g. pukeko, *Porphyrio porphyrio melanotus*, has a LD_{50} of ≤1 mg/kg; Eason and Spurr, 1995b).

New Zealand as a case study for investigating the non-target effects of brodifacoum

Native mammals are extremely widespread on a global scale. Therefore, eradicating pest mammals for conservation frequently encounters the problem of simultaneously protecting non-target native mammals. As such, global research effort into the effects of brodifacoum on non-target species has focused on the risks of primary consumption to native mammals, and of secondary poisoning to large predatory birds (e.g. Howald *et al.*, 1999; Shore, Birks and Freestone, 1999; Burn, Carter and Shore, 2002; Brakes and Smith, 2005). However, targeting these species for research may obscure patterns of anticoagulant poison transport through a native ecosystem as other potential pathways, especially via native vectors, are not considered.

New Zealand's fauna evolved in isolation from terrestrial mammals (apart from bats; King, 1990). Recent mammalian introductions have resulted in many extinctions and declines of native populations not adapted to mammalian predation (e.g. Cassels, 1984; Towns and Daugherty, 1994). However, the lack of native mammalian fauna also means that use of anticoagulant poisons as a conservation tool has been a viable, successful and widely used option (e.g. Dilks and Towns, 2002). Monitoring of non-target species following brodifacoum-mediated mammal eradications in New Zealand provides much of the current knowledge on the effects of second-generation anticoagulant poison on non-target wildlife.

Mammal eradication and control programmes in New Zealand provide an opportunity for long-term research into non-target effects of anticoagulant poisons and inform vertebrate pest control operations worldwide. However, we suggest that research on non-target effects of anticoagulant poison use in the wild is taxonomically unrepresentative, which is of concern to native (i.e. mammal-free) ecosystems particularly where poison is continually available (see Hoare and Hare, in press). In the present paper we synthesise existing information on the effects of brodifacoum on non-target species in the wild, using a literature review of New Zealand-based research as a case study. We aim to determine the status of knowledge about toxic effects of brodifacoum in native ecosystems and to recommend future research directions.

Patterns of brodifacoum use in New Zealand

Anticoagulant poisons have been used as a conservation tool in New Zealand to achieve mammal eradication, control and detection of reinvasion (Dilks and Towns, 2002; Towns and Broome, 2003). Aerial distribution of brodifacoum has been a key tool in eradication of mammals from key offshore islands targeted for conservation and ecological restoration (Towns and Broome, 2003). Brodifacoum is one of five pesticides currently registered for rodent control (O'Connor and Eason, 2000). In mammal-control operations, and as a means of simultaneously detecting and killing invading rodents (termed 'island protection'), brodifacoum bait is replenished on a regular and continuous basis to bird-excluding bait boxes (Dilks and Towns, 2002).

We conducted a survey of major pest control companies, the New Zealand Department of Conservation (DOC) pest control staff from all 13 Conservancies, and all Regional Councils to investigate patterns of brodifacoum use in New Zealand. We accessed a database managed by DOC that contains records of brodifacoum use in pest control in all Conservancies. This database (Pestlink; K. Vincent, Department of Conservation, Research Development & Improvement, Wellington, pers. comm.) is currently not publicly available, but can be accessed by negotiation on a case-by-case basis. We searched the database for records of brodifacoum use since 2000 (database accessed 29 November 2005. Pestlink reference numbers are available from the authors on request). An estimated 6 kg of pure brodifacoum active ingredient are contained within all of the brodifacoum products sold in New Zealand each year (B. Simmons, Animal Control Products Ltd, Wanganui, N.Z., pers. comm.). Of the brodifacoum sold, ca. 50% is used by private contractors. Other users are Regional Councils (ca. 30%), DOC (ca. 15%; mostly in eradication operations) and private landowners (ca. 5%; B. Simmons, pers. comm.).

Private contractors use brodifacoum as one of a variety of tools, mostly in bovine tuberculosis (Tb) vector (possum and ferret) control in New Zealand. The company Epro Ltd alone is responsible for pest control over 780 000 ha of the North Island, and estimates that brodifacoum is used across 20% of this area (C. Speedy, Epro Ltd, Taupo, N.Z., pers. comm.).

Regional Councils use brodifacoum principally in protection of sites identified as 'Key Native Ecosystems' and as a mechanism to control possums, as vectors of Tb. Sustained brodifacoum use continues in some areas to protect threatened native fauna. For example, in the Auckland Region, brodifacoum has been used in ongoing mammal control operations in an 850 ha area in the Hunua kokako (*Callaeas cinerea wilsoni*) management area (12 years to date) and in the 80 ha Wenderholm Regional Park (to protect North Island robins, *Petroica australis longipes*; 11 years to date; Lovegrove *et al.*, 2002). Brodifacoum has been

an effective tool in possum control to minimise spread of Tb in many regions. For example, of the 1 000 000 ha of Animal Health Board funded possum control in the Manawatu/Wanganui Region, 300 000 is under a brodifacoum-bait station programme (C. Mitchell, Animal Pest Unit, Horizons Regional Council, Palmerston North, N.Z., pers. comm.). A further 70 000 ha of private possum control using brodifacoum is supported by the Regional Council, and an estimated 150 tonnes of brodifacoum is used in the region annually (C. Mitchell, pers. comm.).

A policy on use of second generation anticoagulant poisons on public conservation land (DOC, 2000), formulated in response to concerns over bioaccumulation of anticoagulant poisons and associated risk to non-target fauna, has resulted in reduction of their use by DOC at mainland sites. Anticoagulant poisons, particularly brodifacoum, are used to control mammals at a few key mainland sites in most conservancies to protect threatened fauna. For example, in the Hawdon, Hurunui and Poulter catchments, Canterbury, brodifacoum is used in an attempt to protect orange-fronted parakeets, *Cyanoramphus malherbi* (S. Hooson, DOC, Christchurch, N.Z., pers. comm.). The policy does not affect anticoagulant poison use on offshore islands, and brodifacoum is used frequently in a sustained manner for protection of islands considered to be key ecological sites and visited regularly. For example, the Sugar Loaf Islands in the Wanganui Conservancy and Kapiti, Mana and Matiu Islands in the Wellington Conservancy are protected by sustained brodifacoum baiting (Williams, 2003).

Overall, brodifacoum is the key poison that has enabled eradication of mammals from many offshore islands of conservation importance (Towns and Broome, 2003). Brodifacoum baiting is one of a number of strategies used in a sustained manner for widespread pest control in New Zealand. Although use in the conservation estate has decreased since 2000 due to concerns over the persistence of brodifacoum (DOC, 2000), it continues to be used in island protection strategies (Dilks and Towns, 2002). As sustained use of brodifacoum forms part of key strategies to protect native wildlife and reduce the spread of Tb, its use is likely to continue in the foreseeable future.

Sources of information about non-target impacts of brodifacoum

Our literature review of journal publications, theses and technical reports (Table 1) demonstrates that information about non-target effects of brodifacoum poison comes primarily from eradication operations, where poison is distributed in a single event. It has also been collected opportunistically, following the environmental contamination caused by a recent spill of 20 tonnes of brodifacoum bait into the ocean (Pestoff®; Primus, Wright and Fisher, 2005). Relatively little research has been based on monitoring of sustained anticoagulant use, despite it being common in long-term pest control and in detection of rodent invasions (O'Connor and Eason, 2000; Dilks and Towns, 2002; Roberts, 2003). Even among studies that use pest control operations as a means of investigating non-target effects of brodifacoum, long-term monitoring of the impacts of poison in native systems is rare. Of the seven studies that have investigated non-target effects of brodifacoum in New Zealand (categories 'C' and 'IP' in Table 1), only one has involved following potential non-target consumers of the toxin for more than three months (Robertson *et al.*, 1999). Robertson *et al.* (1999) monitored the effects of sustained exposure to brodifacoum poison in brown kiwi, *Apteryx mantelli*, for up to 32 months. Knowledge from long-term studies would greatly enhance risk management assessments concerning sustained brodifacoum use.

Empirical research into the non-target effects of anticoagulant poisons to native ecosystems has often occurred on a species-by-species basis, despite recent theoretical discussion about ecosystem-level impacts (Innes and Barker, 1999) and demonstration of secondary poisoning of non-target consumers in a mammalian food chain (Alterio, 1996). Current methods of evaluating non-target impacts rely on information about toxic brodifacoum residues in the livers of dead animals collected from within the vicinity of the poison drop (e.g. Rammell *et al.*, 1984; Ogilvie *et al.*, 1997; Robertson *et al.*, 1999). This approach enables the identification of species at risk of mortality and sub-lethal contamination in poisoning operations, and the establishment of likely pathways of poison through an ecosystem. However, it does not allow quantification of either the relative importance of different vectors of brodifacoum, or the risk posed to non-target wildlife by a brodifacoum poisoning operation relative to its dosage and longevity.

Current knowledge of non-target effects of brodifacoum use in New Zealand

Birds and terrestrial invertebrates have been focal taxa in evaluations of non-target impacts of brodifacoum (Table 1). The effects of brodifacoum use have been studied in relation to 26 bird species, four fish species, seven aquatic invertebrate species and 11 terrestrial invertebrate orders and brodifacoum bait consumption has been noted in two reptile species. However, there are no post-baiting monitoring data on amphibians, reptiles, bats or parasites of these taxa (though Eason and Spurr, 1995a assess the theoretical risk to bats).

Of New Zealand's 53 extant native terrestrial bird species (Atkinson and Millener, 1991), 22 have been studied in relation to non-target effects of brodifacoum

Table 1. Non-target native animal taxa studied in the wild in relation to potential brodifacoum poisoning in New Zealand. We define mortality as confirmed death of at least one individual from brodifacoum poisoning. E = eradication; C = control; IP = island protection; S = accidental spill; 1° = primary poisoning; 2° = secondary poisoning; Y = yes; N = no; ? = unknown; • indicates presence in a category; ○indicates inferred by primary authors to be in category; * indicates that the study includes observational data only. Note that brodifacoum content is 50 ppm in Talon® 50 WB, and 20 ppm in all other bait types.

Non-target native species monitored	Location (eradication, control or island protection operation)	Brodifacoum-based bait type	Brodifacoum residue or observed bait consumption			Level of consumer			Mortality?			References
			Y	N	?	1°	2°	?	Y	N	?	
BIRDS												
Anas platyrhyncos (mallard duck)	Motuihe Island (E)	Talon® 7-20	•					•	•			Dowding, Murphy and Veitch, 1999
A. superciliosa (grey duck)	Motuihe Island (E)	Talon® 7-20	•					•	•			Dowding *et al.*, 1999
Anthornis melanura (bellbird)	King Country (C)	Talon® 50 WB		•						•		Murphy *et al.*, 1998
	Nelson Lakes (C)	Talon® 20WP		•						•		Spurr *et al.*, 2005
Apteryx australis (brown kiwi)	Northland (C)	Talon® 20P; Pestoff®	•					•	•			Robertson *et al.*, 1999
A. owenii (little spotted kiwi)	Red Mercury Island (E)	Talon® 20P		•						•		Robertson, Colbourne and Nieuwland, 1993
	Kapiti Island (E)	Wanganui No. 7	•			•					•	Empson and Miskelly, 1999
Callaeas cinerea (kokako)	Kapiti Island (E)	Wanganui No. 7			•						•	Empson and Miskelly, 1999
Charadrius obscurus (New Zealand dotterel)	Motuihe Island (E)	Talon® 7-20		•						•		Dowding *et al.*, 1999
Circus approximans (Australasian harrier)	Canterbury (C)	Mapua	•				○		•			Rammell *et al.*, 1984; Williams *et al.*, 1986
	King Country (C)	Talon® 50 WB		•						•		Murphy *et al.*, 1998
	Motuihe Island (E)	Talon® 7-20	•					•	•			Dowding *et al.*, 1999
Cyanoramphus novaezelandiae (red-crowned kakariki)	Lady Alice Island (E)	Talon® 20P	•					•	•			Ogilvie *et al.*, 1997
Cyanoramphus spp (kakariki)	Nelson Lakes (C)	Talon® 20WP		•						•		Spurr *et al.*, 2005
Gallirallus australis (weka)	Tawhitinui Island (E)	Talon® 50WB	•			•			•			Taylor, 1984
	Kapiti Island (E)	Wanganui No. 7	•			•			•			Empson and Miskelly, 1999
	Nelson Lakes (C)	Talon® 20WP	•					•		•		Spurr *et al.* 2005
Haematopus unicolor (variable oystercatcher)	Motuihe Island (E)	Talon® 7-20		•						•		Dowding *et al.*, 1999
Larus bulleri (black-billed gull)	Nelson Lakes (C)	Talon® 20WP	•					•			•	Spurr *et al.*, 2005
L. dominicanus (southern black-backed gull)	Canterbury (C)	Mapua	•				○		•			Rammell *et al.*, 1984; Williams *et al.*, 1986
	Motuihe Island (E)	Talon® 7-20	•					•	•			Dowding *et al.*, 1999
Mohoua albicilla (whitehead)	King Country (C)	Talon® 50WB		•						•		Murphy *et al.*, 1998
Nestor meridionalis (kaka)	Whatupuke Island (E)	Wanganui No. 7; Talon® 20P			•					•		Pierce and Moorhouse, 1994
	Nukuwaiata Island (E)	Talon® 7-20		○		○				•		Brown, 1997a
	Kapiti Island (E)	Wanganui No. 7	•					•	•			Empson and Miskelly, 1999
	Nelson Lakes (C)	Talon®	•					•	•			Moorhouse *et al.*, 2003
	Nelson Lakes (C)	Talon® 20WP	•					•	○			Spurr *et al.*, 2005
N. notabilis	Nelson Lakes (C)	Talon 20WP	•					•		•		Spurr *et al.*, 2005
Ninox novaeseelandiae (morepork)	Lady Alice Island (E)	Talon® 20P	•				•				•	Ogilvie *et al.*, 1997
	Nukuwaiata Island (E)	Wanganui No. 7	•				•		•			Walker and Elliott, 1997
	King Country (C)	Talon® 50WB	•				•				•	Murphy *et al.*, 1998
	Kapiti Island (E)	Wanganui No. 7	•				•		•			Empson and Miskelly, 1999
	Mokoia Island (E)	Talon® 7-20	•				•		•			Stephenson, Minot and Armstrong, 1999
	Nelson Lakes (C)	Talon® 20WP	•					•			•	Spurr *et al.*, 2005
Petroica australis (robin)	King Country (C)	Talon® 50WB		•						•		Murphy *et al.*, 1998
	Kapiti Island (E)	Wanganui No. 7	•			•			○			Empson and Miskelly, 1999
P. australis australis (South Island robin)	Breaksea Island (E)	Talon® 50WB			•	○				•		Taylor and Thomas, 1993
	Maruia (C)	Talon® 20P	○			○			○			Brown, 1997b
	Nelson Lakes (C)	Talon® 20WP	•					•			•	Spurr *et al.*, 2005
P. macrocephala (tomtit)	King Country (C)	Talon® 50WB		•						•		Murphy *et al.*, 1998
	Nelson Lakes (C)	Talon® 20WP		•						•		Spurr *et al.*, 2005
Philesturnus carunculatus (saddleback)	Red Mercury Island (E)	Talon® 20P	•					•	•			Towns *et al.*, 1994
	Kapiti Island (E)	Wanganui No. 7	•			•					•	Empson and Miskelly, 1999
Porphyrio p. melanotus (pukeko)	Motuihe Island (E)	Talon® 7-20	•					•	•			Dowding *et al.*, 1999
Prosthemadera novaeseelandiae (tui)	Nelson Lakes (C)	Talon® 20WP		•						•		Spurr *et al.* 2005
Rhipidura fuliginosa (fantail)	King Country (C)	Talon® 50WB		•						•		Murphy *et al.*, 1998
	Nelson Lakes (C)	Talon® 20WP		•						•		Spurr *et al.*, 2005
Tadorna variegata (paradise shelduck)	Canterbury (C)	Mapua	•			○			•			Rammell *et al.*, 1984; Williams *et al.*, 1986
	Motuihe Island (E)	Talon® 7-20	•					•	•			Dowding *et al.*, 1999
Zosterops lateralis	Nelson Lakes (C)	Talon® 20WP	•					•			•	Spurr *et al.*, 2005
FISH												
Notolabrus celidotus (spotty)	Kapiti Island (E)	Wanganui No. 7			•			•			•	Empson and Miskelly, 1999
Odax pullus (butterfish)	Kaikoura (S)	Pestoff®	•			○				•		Primus *et al.*, 2005
Scorpaena papillosus (scorpion fish)	Kaikoura (S)	Pestoff®	•			○				•		Primus *et al.*, 2005
Sprattus sp. (herring)	Kaikoura (S)	Pestoff®	•			○				•		Primus *et al.*, 2005

Table 1. contd.

Non-target native species monitored	Location (eradication, control or island protection operation)	Brodifacoum-based bait type	Brodifacoum residue or observed bait consumption			Level of consumer			Mortality?			References
			Y	N	?	1°	2°	?	Y	N	?	
INVERTEBRATES												
aquatic												
Cellana ornata (limpets)	Kaikoura (S)	Pestoff®	●					●		●		Primus *et al.*, 2005
Coscinaterias muricata (starfish)	Kaikoura (S)	Pestoff®	●					●		●		Primus *et al.*, 2005
Evechinus chloroticus (sea urchin)	Kaikoura (S)	Pestoff®	●					●		●		Primus *et al.*, 2005
Haliotis iris (abalone)	Kaikoura (S)	Pestoff®	●					●		●		Primus *et al.*, 2005
Jasus sp. (rock lobster)	Kaikoura (S)	Pestoff®	●					●		●		Primus *et al.*, 2005
Mytilis edulis (blue mussels)	Kaikoura (S)	Pestoff®	●			○				●		Primus *et al.*, 2005
Perna canaliculus (green lip mussels)	Kaikoura (S)	Pestoff®	●			○				●		Primus *et al.*, 2005
INVERTEBRATES												
Terrestrial												
Araneae (spider)	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Blattodea (cockroaches)	Lady Alice Island (E)	Talon® 20P	○			●					●	Ogilvie *et al.*, 1997
	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Coleoptera (black beetles)	Lady Alice Island (E)	Talon® 20P	○			●					●	Ogilvie *et al.*, 1997
	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Chilopoda (centipede)	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Diplopoda (millipede)	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Gastropoda (slugs)	Red Mercury Island (E)	Talon® 50WB	●					●			●	Morgan *et al.*, 1997
Gastropoda (snails)	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Hymenoptera (ants and wasps)	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Huberia brouni (ant)	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
Prolasius advena (ant)	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
Isopoda (slater)	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Opisthopora (worm)	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Orthoptera (weta)	Red Mercury & Coppermine Islands (E)	Talon® 50WB		●				●		●		Morgan *et al.*, 1997
Gymnoplectron sp.	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
	Lady Alice Island (E)	Talon® 20P	●			●					●	Ogilvie *et al.*, 1997
Hemideina crassidens	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
H. thoracica	Lady Alice Island (E)	Talon® 20P			●						●	Ogilvie *et al.*, 1997
Isosplectron sp.	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
Pleioplectron sp.	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
Talitropsis sp.	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
Weta sp.	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
Zealandosandrus sp.	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
Zealandosandrus aff. *gracilis*	West Coast (C)	No. 7, AgTech	○			●					●	Spurr and Drew, 1999
REPTILES AND AMPHIBIANS												
Hoplodactylus duvaucelii (Duvaucel's gecko)	Lady Alice Island (E)	Talon® 20P	●			●				●		Christmas, 1995 *
H. maculatus (common gecko)	Mana Island (IP)	Pestoff®	●			●					●	Hoare and Hare, in press *

(Table 1). Seabirds are not so well represented in the literature: four of 75 extant species (Turbott, 1990) have been studied (Table 1). The lethal effects of brodifacoum to native shorebirds have been confirmed in northern New Zealand dotterels, *Charadrius obscurus acquilonius*, and observed in a further two species, pied stilts, *Himantopus himantopus*, and spur-winged plovers, *Vanellus miles novaehollandiae*, following a mainland island mammal eradication attempt at Tāwharanui Regional Park, Auckland (J. Dowding, DM Consultants, Christchurch, unpubl. data). However, non-avian taxa have received very little attention. For example, although New Zealand has 82 native reptile species (Hitchmough, Patterson and Daugherty, 2005) reports of brodifacoum consumption are only known for two species (Christmas, 1995; Hoare and Hare, in press).

Brodifacoum has been implicated in lethal primary and secondary poisoning and sub-lethal contamination of non-target native species in New Zealand (Table 1). The only known non-target deaths caused by brodifacoum poisoning are in birds. In an extreme case, a flightless bird population (the western weka, *Gallirallus australis australis*) was extirpated from Tawhitinui Island, Marlborough Sounds, by primary and secondary consumption of Talon® 50WB targeted at ship rats, *Rattus rattus* (Taylor, 1984). However, most eradications facilitated by the use of brodifacoum

poisoning result in much smaller bird population die-backs (Table 1). Brodifacoum is known to have lethal consequences for 16 non-target native New Zealand bird species, and another 12 species are considered at risk of dying following pest control operations (Eason *et al.*, 2002).

Concerns that invertebrate populations are susceptible to poisoning from vertebrate pest control and eradication operations have led to a number of studies in recent years (Spurr and Drew, 1999; Booth, Eason and Spurr, 2001; Table 1). Although we have found no records of lethal impacts of brodifacoum poisoning for insects, a wide variety of aquatic and terrestrial invertebrates are known to consume toxic brodifacoum pellets (Table 1; Pain *et al.*, 2000).

The only information about interactions between brodifacoum poison and native reptiles is observational, confirming brodifacoum consumption by two New Zealand gecko species (Christmas, 1995; Hoare and Hare, in press). Common geckos, *Hoplodactylus maculatus*, on Mana Island, eastern Cook Strait, show evidence of bait consumption where brodifacoum (Pestoff®) is continuously supplied in bait stations as a strategy to simultaneously detect and kill invading rodents (Hoare and Hare, in press). Similarly, bait consumption (Talon® 20P) by a single Duvaucel's gecko, *Hoplodactylus duvaucelii*, was discovered on Lady Alice Island, Hen and Chickens Group, Northland, following rodent eradication (Christmas, 1995).

Potential vectors of brodifacoum through a native ecosystem

On a global scale, discussions concerning the risk of secondary poisoning to non-target native species have focussed on target (i.e. mammalian) prey species as vectors for anticoagulant transportation (e.g. Eason and Wickstrom, 2001). However, over the past decade, non-target (mostly invertebrate) consumers of toxins have also been the focus of research assessing the non-target impacts of anticoagulant poisons (e.g. Morgan *et al.*, 1997; Ogilvie *et al.*, 1997; Spurr and Drew, 1999; Pain *et al.*, 2000).

Invertebrates consume anticoagulant bait (Ogilvie *et al.*, 1997; Spurr and Drew, 1999) but do not have the same blood clotting systems as vertebrates (Shirer, 1992; Morgan *et al.*, 1997) and are therefore thought to be at low risk of toxicosis from ingesting brodifacoum (e.g. Morgan and Wright, 1996). However, recent evidence demonstrates lethal consequences even at low doses in some molluscs (Gerlach and Florens, 2000). Two snail species, *Pachnodus silhouettanus* and *Achatina fulica*, from Frégate Island, Seychelles suffered mortality as a result of exposure to doses of 0.01 to 0.2 mg and 0.04 mg of brodifacoum, respectively, over a 72–h period and brodifacoum is likely to be lethal to another snail, *Pachystyla bicolor*, from Mauritius (Gerlach and Florens, 2000; Booth *et al.*, 2001). Although brodifacoum-related primary poisoning of native *Powelliphanta* species in New Zealand is considered unlikely, native snails may be at risk of secondary poisoning through consumption of other invertebrates (Booth *et al.*, 2003). Brodifacoum residues of up to 7.47 μg/g have been recorded in native terrestrial invertebrates (Craddock, 2003). Residue levels take in excess of four weeks to return to background levels, and trace levels are detectable up to ten weeks following brodifacoum baiting operations, which poses a risk to native insectivorous bird species and possibly molluscs (Booth *et al.*, 2003; Craddock, 2003).

The potential risk of brodifacoum poisoning to ectothermic vertebrates (reptiles and amphibians) is also considered to be low, as they have a distinct blood coagulation chemistry to that of mammals (Merton, 1987). However, few studies world-wide have investigated whether reptiles consume anticoagulant bait (exceptions are Merton, 1987; Freeman, Hickling and Bannock, 1996; Thorsen *et al.*, 2000) or have sufficient data on reptiles to indicate consumption (Empson and Miskelly, 1999).

Reptiles are an important component of some New Zealand food webs, especially on mammal-free offshore islands where they are abundant (Daugherty *et al.*, 1990; Heather and Robertson, 1996; Keall *et al.*, 2001; Towns, 2002) and at some mainland locations (Towns, 1996). However, despite observational (Christmas, 1995; Hoare and Hare, in press) and laboratory (Freeman, Hickling and Bannock, 1995; Freeman *et al.*, 1996) evidence indicating that New Zealand lizards consume anticoagulant baits, the potential role of reptiles as vectors for transport of toxin through a natural food web is rarely considered (but see Innes and Barker (1999) for a theoretical discussion). Even on a global scale information about interactions between reptiles and brodifacoum world-wide is sparse. We found only two reports of the impacts of brodifacoum on reptiles: toxic bait consumption has been reported in Telfair's skink, *Leiolopisma telfairi*, from Round Island, Mauritius (Talon® 20P; which proved lethal in some individuals; Merton, 1987, 1988; Merton *et al.*, 2002) and Wright's skink, *Mabuya wrightii*, from Frégate Island, Seychelles (Talon® 50 WB; Thorsen *et al.*, 2000).

Lethal doses of anticoagulant poison for reptiles are not known. Hypothesised sub-lethal effects of brodifacoum include interference with reptiles' abilities to thermoregulate, which may prove fatal under conditions of environmental stress (Merton, 1987). However, the main risk associated with reptiles consuming anticoagulant baits is likely to be secondary poisoning of their native avian predators.

To date, focal taxa for investigations into non-

target effects of brodifacoum on wildlife have been birds and terrestrial invertebrates. In mammal-free systems where brodifacoum is used continuously to detect rodent invasions, native ecosystems contain a more representative suite of native fauna. In such systems, native taxa, such as reptiles, occur at densities that enable them to play a functional role in ecosystems (Towns, 1991, 2002).

Current research does not enable assessment of the roles that various trophic groups play in food (and hence poison) pathways through these ecosystems. Bioaccumulation of persistent toxins such as brodifacoum puts top consumers most at risk of secondary poisoning (Eason *et al.*, 1996; Eason and Wickstrom, 2001; Eason *et al.*, 2002). Native invertebrate consumers of brodifacoum bait (Ogilvie *et al.*, 1997; Spurr and Drew, 1999), though not known to suffer mortality from the toxin, may pose a risk of secondary poisoning to their avian predators (Craddock, 2003), both directly and via reptiles as an intermediate vector. Additionally, reptiles may be significant direct vectors of brodifacoum to birds in a native ecosystem.

Research and conservation priorities

Current management practice in New Zealand views ecological costs of using toxins, where pest mammals are present, as much lower than damage costs if they are not used (Innes and Barker, 1999). However, information about sustained toxin use and its flow through a native food web is lacking. As a precautionary approach, DOC has adopted a policy to reduce the use of brodifacoum and other anticoagulant poisons in the conservation estate. However, it is used in a sustained manner by DOC in island protection, by Regional Councils to control mammalian pests at key ecological sites and by the Animal Health Board and Regional Councils over vast tracts of the country in Tb vector control.

In native systems where anticoagulant poison is used to detect rodent invasions, toxins may be distributed via native vectors. The consequences of sustained poison use for non-target wildlife in these systems are unknown. Recent field evidence suggests that reptiles and other primary consumers may take toxic baits where it is used repeatedly (Hoare and Hare, in press). One approach to investigate poison distribution in these systems is to test for brodifacoum residues in carcasses of a variety of native fauna collected opportunistically from an island. Toxicological and stomach contents analyses from a variety of fauna could be used to infer toxin pathways and information on the accumulation of toxin in higher-trophic level species. However, we question whether toxic baits are the best tool to use in island protection.

Present island protection measures involve rodenticide bait stations, which have not been trialled for effectiveness and were not designed for their current use (O'Connor and Eason, 2000; Dilks and Towns, 2002; Roberts, 2003). Lack of detection of experimentally released (Russell *et al.*, 2005) and accidentally introduced (Thorsen *et al.*, 2000) rodents onto offshore islands confirm fears that traditional methods may fail to detect invading rodents on mammal-free islands where there is a natural abundance of food (Dilks and Towns, 2002). Successful use of brodifacoum as a rodenticide where rodents are present in an ecosystem does not necessarily translate to effectiveness at attracting rats which arrive on an island with an abundance of seeds, fruit and invertebrates (Dilks and Towns, 2002).

We recommend that managers consider alternatives to anticoagulant poison use in rodent detection on mammal-free islands. Bait stations are designed to provide an early warning of introduced mammals, as well as having the potential to kill an invading rodent in a single dose. Early warning could equally be performed by a non-toxic method of identifying the presence of mammals, such as tracking tunnels, wax tags or electronic detection (see Dilks and Towns (2002) for a description of these methods). Such use of non-toxic methods should be backed up by a contingency plan, i.e. a pre-established standard procedure of trapping and monitoring to be implemented following rodent detection (see Roberts, 2003).

Conclusion

Most knowledge of non-target effects of brodifacoum use is derived from post-baiting monitoring of one-off island eradication operations. The risk of secondary exposure to native non-targets is likely to be greater when brodifacoum is applied to the environment in a sustained manner. In New Zealand, brodifacoum is widely used in continuous mammal-control operations and in island protection. Protecting the mammal-free status of offshore islands with brodifacoum involves continuous supply of anticoagulant poison to systems in which a more representative suite of native fauna interact than that found in sympatry with introduced mammals on the mainland. In these systems, taxa which have not been the focus of research into effects of brodifacoum poisoning to date are often abundant and fulfil important ecosystem roles. Native invertebrates and reptiles consuming brodifacoum may pose a significant risk of secondary poisoning to birds, exacerbated by its sustained use and the process of bioaccumulation. As a precautionary approach, we recommend reducing the sustained use of brodifacoum baits in mammal-free locations by implementing non-toxic methods of rodent detection. However, where

sustained brodifacoum use is required, research priority must be given to investigating the roles of all potentially significant native consumers as vectors of the toxin.

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