Diagnosing the cause of failure to eradicate introduced rodents on islands: brodifacoum versus diphacinone and method of bait delivery

John Parkes*, Penny Fisher & Guy Forrester
Landcare Research, PO Box 40, Lincoln 7640, New Zealand

*Corresponding author e-mail: parkesj@landcareresearch.co.nz

SUMMARY

Two types of anticoagulant rodenticides have proven successful at eradicating invasive rats and mice from islands. Brodifacoum is the most commonly used and has a low failure rate both when delivered from the air and from ground-based systems. It does, however, present a risk to non-target animals such as birds. When such risk is not acceptable or cannot be mitigated, diphacinone has been favoured by some managers because it is less toxic to birds and less persistent in rodents. However, unlike brodifacoum, diphacinone requires a rodent to eat several baits over several days to ingest a lethal dose. This increases the risk that not all rodents will be killed. When data on attempts to eradicate rats and mice for both aerial and ground-based methods are combined, brodifacoum has a significantly lower failure rate at 17% (54 of 322 attempts) than diphacinone at 33% (13 of 39 attempts). The difference is more significant when just rats are considered. Ground-based methods show similar failure rates for both rodenticides, but to date the very few attempts using aerially sown diphacinone baits have had a high failure rate compared with that for brodifacoum.

BACKGROUND

The rodents associated with human colonization, house mouse *Mus musculus*, Pacific rat *Rattus exulans*, brown rat *R. norvegicus* and ship rat *R. rattus*, have variously invaded many islands (Atkinson 1985) and have been a significant cause of extinction and decline of island biodiversity. They have impacts on ecosystem-level processes (Fukami *et al.* 2006), flora (Meyer & Butaud 2009) and fauna, including invertebrates (Hadfield & Saufler 2009) and vertebrates (Robinet *et al.* 1998, Harris 2009). In the 1970s and 1980s, removing rodents was thought impossible on all but the smallest islets (Dingwall *et al.* 1978, Atkinson 1986), but since the 1980s availability of anticoagulant toxins in new bait formulations and new ways of delivering them (Thomas & Taylor 2002, Towns & Broome 2003) have facilitated attempts at eradicating one or more of these rodent species from nearly 600 islands around the world (see ACTION). Successful eradication has major benefits to the native plants and animals on these islands (Courchamp *et al.* 2003, St Clair 2011). Nevertheless, a large number of islands still have exotic rodents and invasion of rodent-free islands remains an ongoing problem (Russell *et al.* 2008). There is still, therefore, plenty of work to do and benefits to be gained (Saunders *et al. in press*).

Bait applications developed for eradication are generally 'over-engineered' (Cromarty *et al.* 2002) to maximize the chances that every individual will encounter and eat enough baits to be poisoned. However, there are still occasional failures, which are costly and may discourage further attempts. A total of 12 rodenticides have been used in attempts to eradicate rodents (Table 1). The two of particular current interest in eradication projects are the anticoagulants brodifacoum and diphacinone - in part because these are the only two toxins registered for aerial use against insular rodents in the USA. Brodifacoum has high oral toxicity to rodents such that a lethal amount is often ingested in a single feed of bait (Kaukeinen & Rampaud 1986). It is also highly toxic to other mammals and birds, posing an unwanted hazard to non-target wildlife that ingest bait (primary exposure) and

those that eat live animals or carcasses that contain brodifacoum (secondary exposure). A recent example of such mortality came from the successful eradication of *R. norvegicus* from Rat Island in Alaska during which unexpectedly high numbers of bald eagles *Haliaeetus leucocephalus* and glaucous gulls *Larus hyperboreus* were also killed (Salmon & Paul 2010). Mitigation of non-target risk can add significantly to the costs of an eradication attempt (Howald *et al*. 2010). Diphacinone is most effective against rodents when ingested as multiple consecutive doses over several days (Ashton *et al*. 1987), and is considerably less toxic to birds than brodifacoum (Eisemann & Swift 2006, Rattner *et al*. 2010) reducing avian primary risk. Diphacinone also has a much lower persistence in rodent liver tissue than brodifacoum (Fisher *et al.* 2003) so the risk of secondary poisoning of non-target predators and scavengers is reduced (Fisher *et al*. 2004).

The difference between the toxicity profiles of these two anticoagulants may (or may not) have implications for failure to eradicate the target rodents. Those planning an eradication attempt might choose brodifacoum with arguably higher chances of success but accept or mitigate its non-target risks, or diphacinone with arguably a higher chance of failure but with lower non-target risks. This paper addresses these arguments by looking at past success rates using the two toxins. Wider diagnoses of causes of failure (reinvasion, inadequate bait delivery, rodent behaviour, etc.) are not addressed.

Table 1. Summary of the toxins used in 546 rodent eradication attempts 1971-2011 where the toxin used was reported. Note: the sum of the brodifacoum and diphacinone attempts includes those where outcomes are pending or not reported and where the bait delivery method was not stated.

Class	Toxin	Number of attempts
Acute toxins	Strychnine	1
	Cholecalciferol	1
	Sodium fluoroacetate	2
Anticoagulant: 1st generation coumarins	Warfarin	5
	Coumatetrylyl	2
Anticoagulant: 1st generation indandiones	Pindone	8
	Diphacinone	50
	Chlorophacinone	1
Anticoagulant: 2nd generation coumarins	Brodifacoum	396
	Bromadiolone	32
	Flocoumafen	9
	Difenacoum	2
Mix of toxins		37

ACTION

The database of eradication attempts was collated from several previously published (Howald *et al*. 2007, MacKay *et al.* 2007) and unpublished (www.issg.org) sources and updated by JP from recent reports and contact with local managers. To determine whether we needed to take account of possible effects of island size, distance from source populations or the species of rodent, we looked at all attempts (n = 546) against all rodent species using any rodenticide. This was modelled as a binary regression (success or failure) using GLM in sR (R Development Core Team 2011). Then, since there were no effects of island size or distance from source on success or failure, we collated all the outcomes (eradicated or not) in attempts to eradicate 361 populations of rodents where either brodifacoum or diphacinone was used and where the method of bait delivery and the outcome (success or failure to eradicate) was recorded in the literature or project report. However, while failure rates were similar (15-17%) for all *Rattus* spp., mice were more difficult to eradicate, with a failure rate of 38% (see also MacKay *et al.* 2007). We therefore also considered eradication attempts for rats and mice separately.

We used some rules to define an 'attempt', and 'success' or 'failure' to eradicate. An attempt was defined as a project to eradicate a species of rodent in a single population. Therefore an island with several species of rodent may have that number of attempts, but a group of islands with clearly a single population of the target species were accounted as a single attempt. For example, the complex campaign on the180 islands of the Montebello group in Western Australia where *R. rattus* were eradicated (Burbidge 2004), the group of 20 small islands in the Bay of Islands off Adak Island in Alaska where *R. norvegicus* were removed from some but not others and where reinvasion is probable (Dunlevy & Scharf 2007), or the 17 islets of the Black Rocks off Moturoa Island in the Bay of Islands in New Zealand where both species of rats were removed but are likely to swim back (Shaw 1997). For aerial baiting, success has been defined as the absence of the target rodent species after two years (Howald *et al*. 2007), although it was not always clear from project reports in our database how success was determined or declared. Bait stations deployed across an island for use in eradications can later function as detection grids where the absence of bait-take, for example, is used to judge success more quickly (Thomas & Taylor 2002). Failure is any recorded presence over a few years and makes no judgement about the origin of the rodents as survivors (true failure) or new immigrants (extirpation but subsequent reinvasion) unless the latter was confirmed by genetic studies (Abdelkrim *et al.* 2007) and the original claim of eradication confirmed. Obviously, assessing success can be uncertain as absence of evidence does not equal evidence of absence. We note recent work on search and detection theory that is attempting to increase managers' ability to assess absence of sign in terms of the probability of eradication success (e.g. Ramsey *et al.* 2011).

CONSEQUENCES

Ignoring the method by which baits were delivered and pooling all four rodent species, there was a significant difference between failure rates for the two rodenticides at 17% (54 of 322 attempts) for brodifacoum and 33% (13 of 39 attempts) for diphacinone; $\chi^2 = 6.31$, P = 0.01, df = 1) (Fig. 1). When the bait delivery method was considered, both rodenticides had similar failure rates in various ground-based applications at 24% (42 of 173) for brodifacoum and 24% (8 of 33) for diphacinone; $\chi^2 = 0.001$, P = 0.997, df = 1). However, diphacinone had a significantly higher failure rate in aerial applications at 83% (5 of 6 attempts) than brodifacoum at 8% (12 of 149 attempts); Fisher's Exact Test, P < 0.001).

Diphacinone has been used against mice only once (on Buck Island in the Caribbean where it failed; Witmer *et al*. 2007). However, brodifacoum has been used in 26 aerial and 21 ground attempts against mice with 35% and 52% failures rates, respectively. Subtracting these results from our comparisons, the differences between outcomes for the two rodenticides for all rats remain the same as when mice are included; $\chi^2 = 9.83$, P = 0.002, df = 1 for all methods, $\chi^2 = 0.035$, P = 0.85, df = 1 for ground-based methods and P < 0.001 in the Fisher's Exact Test for aerial delivery. Our initial belief that the risk of failure to eradicate rodents is lower using brodifacoum than diphacinone (Parkes & Fisher 2011) is only partly supported by the evidence analysed here. The hypothesis was based on the different exposure requirements for the two toxins in the usual bait formulation - a single feed is potentially fatal with brodifacoum while diphacinone requires a rodent feed every day for several days.

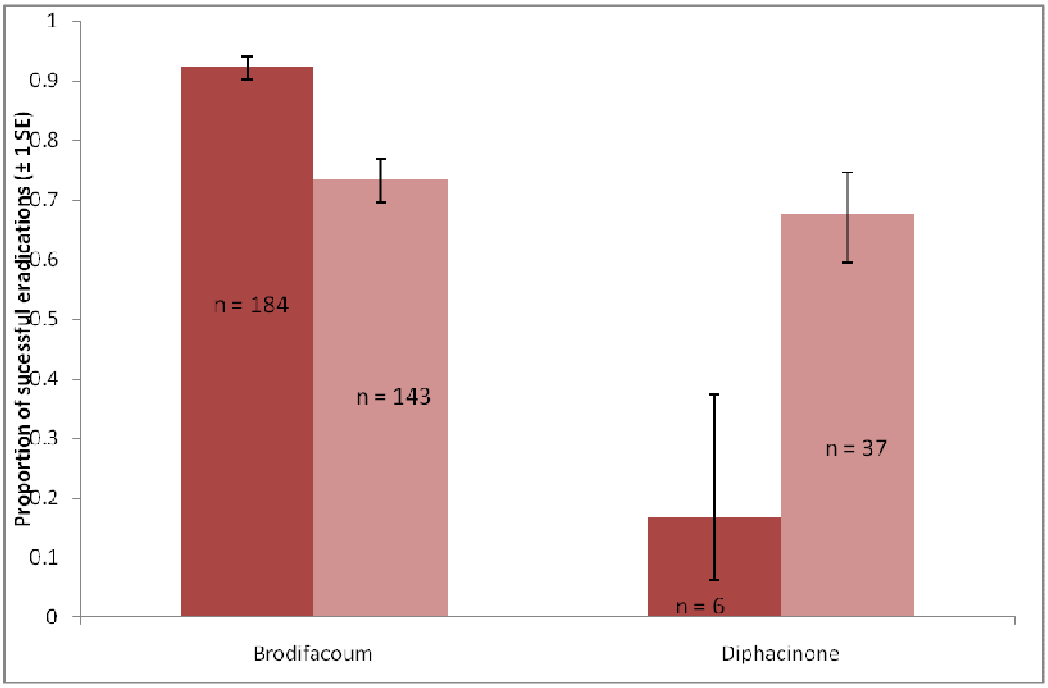

Figure 1. Proportion of successful eradication attempts against four rodent species (*Mus musculus*, *Rattus exulans*, *R. norvegicus* and *R. rattus*) that succeeded using two rodenticides delivered by aerial (first bar) and ground-based systems (second bar).

There was no evidence from the analysis of previous attempts that indicated a preference for one rodenticide or the other when baits were deployed by ground-based methods. However, the failure rate of aerial baiting with diphacinone is significantly higher, but the small sample size (n = 6) is weighted by the cluster of four recent failures against *R. rattus* in the Ogasawara Islands (Hashimoto 2010). However, these projects apparently did not use the usual baits or aerial sowing method, so failure might not be due to the rodenticide used. The four islands (along with several others) were re-baited in 2010 (Harrison 2010) with outcomes pending. Putting these failures to one side, aerial baiting with diphacinone has succeeded once (on 4 ha Mokapu Island) and failed once (on 126 ha Lehua Island), both in Hawaii, both against *R. exulans* (Parkes & Fisher 2011). There have also been attempts on eight islands in 2009-2010 against *R. norvegicus* in the Falkland Islands, using ground-based methods with diphacinone baits, whose outcomes are also pending (Poncet 2011, Sally Poncet *pers. comm*.). The results of these attempts will be of obvious interest to questions about toxin choice.

We can speculate on potential causes in bait delivery that might account for the difference in failure rates between the two rodenticides. First, there must be sufficient diphacinone baits remaining in all locations for the last rodent to encounter bait and get a lethal dose. The 'excess baits at the end' argument may be why ground methods developed for brodifacoum, such as replenished bait stations (Thomas & Taylor 2002), can also succeed with diphacinone. Thus there is some rationale for the 'over-engineering' that has developed as best practice for both aerial and ground-based baiting when diphacinone is used (Cromarty *et al*. 2002). This involves distributing many more baits than can possibly be eaten by the rodents in two or more sowings, overlapping swaths in aerial baiting or bait lines or stations set close enough to ensure at least some bait is in every rodent's home range. Applying the inverse of this logic to brodifacoum baiting suggests that currently too much bait is being used with consequent increased risks to non-target species, presumably because of the perception that it increases the chance of successful eradication (Cromarty *et al*. 2002). While the problem with bait competition from land crabs (Wegmann 2008) is a special case, we note recent reductions of at least an order of magnitude in bait densities with no loss of efficacy in sustained control using compound 1080 baits against possums *Trichosurus*

vulpecula and rodents in mainland forests in New Zealand (Nugent *et al.* 2011).

The timing of baiting to avoid periods when there is abundant natural food available to rodents may be more critical for diphacinone when each rodent has to eat bait every day for perhaps a week to obtain a lethal dose. This may indicate that diphacinone should not be the toxin of choice on tropical islands with year-round rainfall.

Conclusions: In conclusion, precedence and logic indicate brodifacoum as the rodenticide of choice if non-target impacts are acceptable or can be mitigated cost-effectively. Acceptability and the extent of mitigation has both an absolute component of risk (some people might consider any non-target mortalities as unacceptable) and a relative component (where the benefits of removing the rodents allow a net gain in values). As part of this mitigation, research on whether bait densities using brodifacoum can be reduced with no loss of efficacy would be worthwhile. However, if non-target risks are not acceptable or cannot be mitigated, or if the predicted benefits of removing the rats are not clear, diphacinone does offer an alternative for ground-based methods and may eventually do so for aerial methods. For the latter, managers must be willing to take risks in setting and learning from more precedents - essentially as has been done to refine methods for the use of brodifacoum. Alternatively or concomitantly, researchers need to better characterize bait encounter and consumption behaviours of rodents under the different bait delivery options to understand the exposures needed to kill 100% of the population using diphacinone. This would be important to test in the presence of alternative natural foods and when eradication, rather than sustained control, is the aim (e.g. Swift 1998, Pitt *et al.* 2010). Direct extrapolation of application methods developed for eradication using brodifacoum to baits containing diphacinone does not take adequate account of the differences in the toxicity profiles of the two anticoagulants.

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