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ECOLOGICAL CONSEQUENCES OF TOXIN USE FOR MAMMALIAN PEST CONTROL IN NEW ZEALAND — AN OVERVIEW

Summary: Toxins, especially sodium monofluoroacetate (1080) and brodifacoum, are widely used throughout New Zealand for control of introduced mammals that are considered pests. This level of toxin use (not necessarily with these toxins) is unlikely to decline for at least 5–10 years. Ecological consequences derive both from mammal population reduction or eradication, and from using toxins as the control method. Scientists have not examined the net ecological outcomes of these consequences at the community level due to their daunting complexity, although managers usually manipulate whole communities and key conservation legislation demands that they do so. A food web could be a useful conceptual framework to generate hypotheses about toxin movement through communities, and to explore net outcomes of pest control at the community level. It could also sharpen objectives for ecosystem restoration on the New Zealand mainland, and help to find common ground between different participants in ecosystem management. We interpret present evidence to suggest that the ecological costs of using toxins are much less than the damage costs if they are not used, due to the magnitude of known impacts of introduced pest mammals. This suggestion deserves exploration; it may not be true when persistent toxins such as brodifacoum are used repeatedly. Research on toxin use should continue on its present broad front, but we suggest that priorities are to measure net ecological outcomes at the community level, to reduce toxin use, and to improve pest control strategies and techniques in the maintenance phase of control operations. Finally, we suggest that an annual ecosystem management conference in New Zealand, which explicitly brings together managers, policy-makers, landowners, and scientists from the many disciplines now relevant to the complex field of pest mammal control, would enhance progress and co-operation.

Keywords: 1080; brodifacoum; toxins; mammal pest control; food webs; New Zealand; review.

Introduction

Of the 31 exotic mammal species extant in New Zealand and its offshore islands, 14 are widespread (King, 1990). None of these 31 mammal species has any legal protection in New Zealand. The ungulates and marsupials are defined, generally as pests, under the Wild Animal Control Act 1977, and the rodents, mustelids, feral cats (*Felis catus*[1]) and hedgehogs (*Erinaceus europaeus*), as unprotected animals, under Schedule 6 of the Wildlife Act 1953. Rabbits (*Oryctolagus cuniculus*) and hares (*Lepus europaeus*) are not specifically defined under any act, but may (along with any other nominated species) be managed as pests under regional pest management strategies under the Biosecurity Act 1993. Because none have any legal protection, any may be controlled by private landowners providing they do so by legal methods.

Central and regional government may control mammals where they are convinced that it is worth doing so. The goals that direct such action are largely described in the Conservation Act 1987 for central government, and in the Resource Management Act 1991 and in regional pest management strategies for regional government. Restrictions on how anyone may control mammals are set in the Animals Protection Act 1960 and by agency policies. The Pesticides Act 1979 defines who may use certain methods (particularly toxins).

Most mammal species have some populations that are controlled as pests (Parkes, 1996), even if only indirectly by recreational or commercial hunting (Parkes, Nugent and Warburton, 1996). The ubiquitous possum (*Trichosurus vulpecula*) is controlled under both a national plan under the Wild Animal Control Act for conservation purposes, and under a National Pest Management Strategy as a vector for bovine tuberculosis. The only other

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[1] Zoological nomenclature follows King (1990) for mammals and Turbott (1990) for birds. Botanical nomenclature follows Allan (1961).

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species with formal national control plans are feral goats (*Capra hircus*) and Himalayan thar (*Hemitragus jemlahicus*). The Department of Conservation (DOC) also controls a variety of other pest species at much smaller scales under its island management schemes (where eradication of the pests is the usual aim), under its threatened species recovery plans (where control of the critical predators is the main task) and under its Mainland Island initiative (where all or most species are controlled). It is not known how much the DOC spends on mammal pest control, but a large part of its "Ecological Management" budget of $72.5 million per year is spent killing mammals. Regional Councils also control many pest species, particularly possums, as agents for the Animal Health Board, and possums and rabbits under Regional Pest Management Strategies (Table 1).

Toxins, such as sodium monofluoroacetate (1080), brodifacoum, pindone, cholecalciferal, and cyanide are routinely used against possums, rodents, mustelids and rabbits, but only rarely (and usually experimentally) against the larger species. Sodium monofluoroacetate (1080) is the toxin used most on the New Zealand mainland (Livingstone, 1994). The anticoagulant brodifacoum was used in 28 of 33 mammal eradication programmes undertaken by the DOC on offshore islands in the last decade (I. McFadden, *pers. comm.*; DOC), and until recently was increasingly used on the mainland. Nationally, use of 1080 has been declining and use of brodifacoum has been increasing (Fig. 1).

The magnitude of the mammal pest control task is unlikely to decline in the foreseeable future.

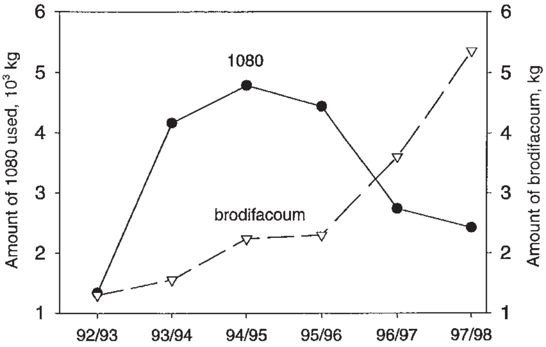

Figure 1: *The amounts of active ingredient of the mammal toxins sodium monofluoroacetate (1080) and brodifacoum sold in New Zealand in 1992–93 to 1997–98 (B. Simmons, Animal Control Products Ltd,* in litt.*). 1080 is used at greater concentrations (200–1500 mg kg $^{-1}$) than brodifacoum (20–50 mg kg $^{-1}$)*

Animal Health Board expenditure on tuberculosis vector control is likely to continue at present levels because although the number of infected domestic herds of cattle and deer has declined since 1995 (Livingstone, 1998; N. Hancox, *pers. comm.*; Animal Health Board, Wellington), the area with infected wild and domestic animals continues to expand. Increasingly, 'cause-of-decline' research for threatened indigenous species on the mainland has identified introduced mammals as key regulatory agents (e.g., Brown, 1997; Sherley *et al.*, 1998; Wilson *et al.,* 1998; Innes *et al.,* 1999) so that future

Table 1: *Scale and frequency of pest mammal control operations in New Zealand.*

	Scale	**Frequency**
Animal Health Board		
Objective: Tuberculosis eradication	large (to 50 000 ha)	infrequent (repeat 4–8 yrs)
Department of Conservation		
Objective: Restoration of off-shore islands	small-medium (average 180ha)	once only (eradication)
Objective: Maintenance of mainland ecosystems	large (to 60 000 ha)	variable (repeat 1–8 yrs)
Objective: Restoration of mainland ecosystems	medium-large	frequent (annual)
Regional Councils		
Objective: Environmental protection	medium-large	variable
Objective: Protecting production	small-large	variable
Private landowners		
Objective: Maintenance of profitability in farming; small-scale conservation	small-large	frequent
Objective: Forestry protection	large	infrequent

conservation management will inevitably focus on the control of these mammals. Non-toxin techniques, such as immunocontraception, may be available for some species such as possum within 5–10 years (Cowan and Bayliss, 1998), but toxins will remain the key control method for many other species, public attitudes permitting (Williams, 1994). The land area subjected to possum control has increased for both the Animal Health Board and the DOC in recent years (Fig. 2). An increasing proportion of operations for both agencies is 'maintenance' rather than initial control. For example, in 1993–94, all control operations performed by the Animal Health Board were initial control, but this decreased to about 10% by 1996–97 (N. Hancox, *pers. comm.*), and the proportion of maintenance control operations conducted by the DOC increased from 21% to 32% between 1993 and 1995 (Parkes, Baker and Ericksen, 1997).

Ecological consequences of toxin use

Two contexts for 'ecological consequences'

Using toxins in preference to traps, fences, shooting, or immunocontraception as the method of pest control has particular ecological consequences, such as secondary and non-target poisoning. These are often mentioned as 'impacts' or 'costs' (e.g., Spurr, 1994a, b; Eason and Spurr, 1995). Other consequences may occur due to the reduction or eradication of pest mammals. These are likely regardless of the pest control method used, and are frequently perceived as 'benefits'. In this setting, 'cost' and 'benefit' are terms of value, not science. In fact all pest control methods have both direct (first-order) and indirect (second-order, and further) ecological consequences which may be seen as costs or benefits, depending on the objectives of the particular pest control operation.

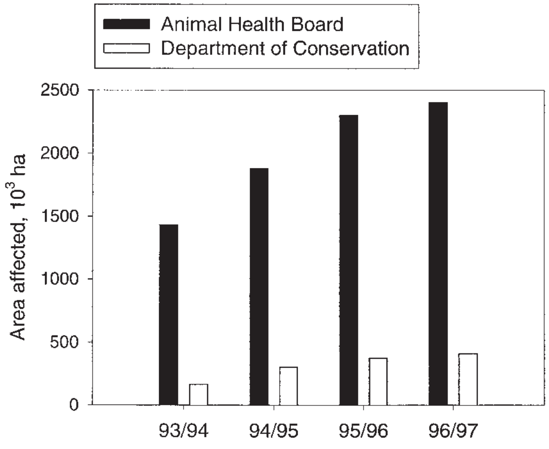

Figure 2: *Area of possum control operations by the Animal Health Board and the Department of Conservation, 1993–94 to 1996–97 (N. Hancox, Animal Health Board,* in litt.*; DOC Annual Reports to its Minister).*

Consequences at different ecological levels

As a consequence of toxin consumption, *individuals* may die, or can suffer sub-lethal effects. Sub-lethal doses can have physiological effects that manifest themselves as altered behaviour (e.g., increased susceptibility to predation), or decreased breeding success. These effects are combined to a response at the *population* level, where definite effects on individuals (e.g., death, decreased number of progeny) appear as population characteristics (such as density, sex ratio, age structure, mortality rates). In one sense, a population could be said to be 'impacted' if any individuals die, but individuals make differing contributions to key population processes. Population impacts are especially determined by the proportion of individuals in the effective breeding population killed or sublethally affected by the toxin, and the rate of population recruitment. For example, impact may be greater on populations of K- than r-selected species, since the former will take longer to make up the losses (Spurr, 1979).

A biological *community* is an assemblage of populations which occur together in space and time (Begon *et al.*, 1990). Communities have specific attributes such as species diversity, stability, complexity, and succession. Nutrients cycle through a community and its physical environment, together usually referred to as an ecosystem. New Zealand researchers and managers are increasingly aware of community level interactions because pest control can have unforeseen repercussions such as prey-switching (Murphy and Bradfield, 1992; Norbury and Heyward, 1996; Murphy *et al.*, 1998).

Pests, and control methods such as toxin use, can have *ecosystem-level effects* by influence on properties emergent from the interaction of the biota and the physical environment. These ecosystem-level properties include litter decomposition rates, relative size of different nutrient pools, and net primary productivity.

There are two powerful reasons why better understanding of communities in New Zealand is required. First, managers *have to* manage whole communities, although most scientists choose not to study them, mainly because of their daunting complexity. Second, information on processes at the community level is needed before an understanding of ecosystem-level changes can be achieved. Key conservation legislation such as the Reserves Act 1977, the National Parks Act 1980, and the Conservation Act 1987 demands that ecological *systems* of various kinds be managed and preserved. Pest mammals and toxins have ecological consequences at both the community and ecosystem level, which can be explored by food webs.

Food web theory as a conceptual framework?

A food web can be defined as “a network of consumer resource interactions among a group of organisms, populations, or aggregate trophic units” (Winemiller and Polis, 1996), as a diagram “depicting which species in a community interact” (Pimm, 1982), or as a diagram depicting interactions between community members and their linkages with ecosystem-level processes (Bengtsson and Martinez, 1996). The latter two definitions allow the explicit inclusion of a variety of non-trophic population interactions, such as pollination, seed dispersal or competition for nesting sites, but most community interactions are trophic.

While food webs are the arena for many theoretical debates, such as the association of complexity with stability, they have also been useful in resource management, including fisheries management, responses of communities to exotic introductions, pest control, and environmental contamination (Polis and Winemiller, 1996). In all these cases, understanding the regulation of populations and regional biodiversity requires basic knowledge of community structure and population interactions. Despite their use overseas, food webs have been little used in the study of terrestrial ecology, pure or applied, in New Zealand, although for major ecosystems preliminary webs could probably be constructed readily from existing data. Currently, the food web probably comes as close as anything to a holistic descriptive model of community interactions.

We suggest that food webs are useful conceptual tools because they:

(1) Can be used to trace toxin movement ‘ecologically downstream’ or to trace its ‘upstream’ origins. Following Cohen (1978), a *sink subweb* consists of all the prey taken by a predator plus all food consumed by the prey of this designated top predator, and so on. Alternatively, *source subwebs* include a set of one or more basal species (usually, but not necessarily, plants), their consumers, and predators of their consumers.

(2) Can be used to identify species and functional links that characterise historic and contemporary communities, thus sharpening objectives for system restoration at any site, and providing a rationalisation for the choice of biodiversity ‘indicators’.

(3) Can be used to integrate disparate information on many unrelated species.

(4) Can serve as conceptual foci for research. Studies of individual processes often proceed from general to more specific problems. As researchers focus on a given process, parallel processes of equal importance can be neglected.

(5) Offer an excellent start-point for all organisations interested in pest control and ecosystem management in New Zealand to find common ground and discuss desired outcomes. Such groups include policy-makers, pest managers, the local iwi (Maori tribes), scientists, public interest groups, and local residents such as farmers.

Figure 3 shows our attempt at a topological or descriptive web (Paine, 1980) for a mainland podocarp-hardwood forest. Such forests occur at Pureora, Te Urewera or Waipoua. Similar webs could be drawn for the community dominated by rabbits in the Mackenzie Basin, for that dominated by mice in South Island *Nothofagus* forest, or for any offshore island with its own particular combination of species. All arrows imply trophic or other nutrient flow connections between the linked boxes.

An aggregated account of toxin fate or ‘impact’ after aerial 1080 operations derived from all available literature is shown in Fig. 4. This explores the first context of ‘ecological consequences’, as described above. The figure does not imply that 1080 routinely is moved through the community in the way depicted, but is intended to provide a community perspective to existing disparate data, and to generate hypotheses about the routes of toxin movement which can be tested with more refined datasets or in future aerial 1080 operations. Detailed accounts of the varied operations and species monitoring which form the basis of Fig. 4 are given in the numbered references listed in the Appendix. The absence of arrows to some boxes (e.g., parasites; reptiles and amphibians) is because no published accounts of monitoring these fauna are available, whereas 1080 impacts on other fauna (e.g., some herbivorous birds; Spurr, 1994b) have been sought but not found.

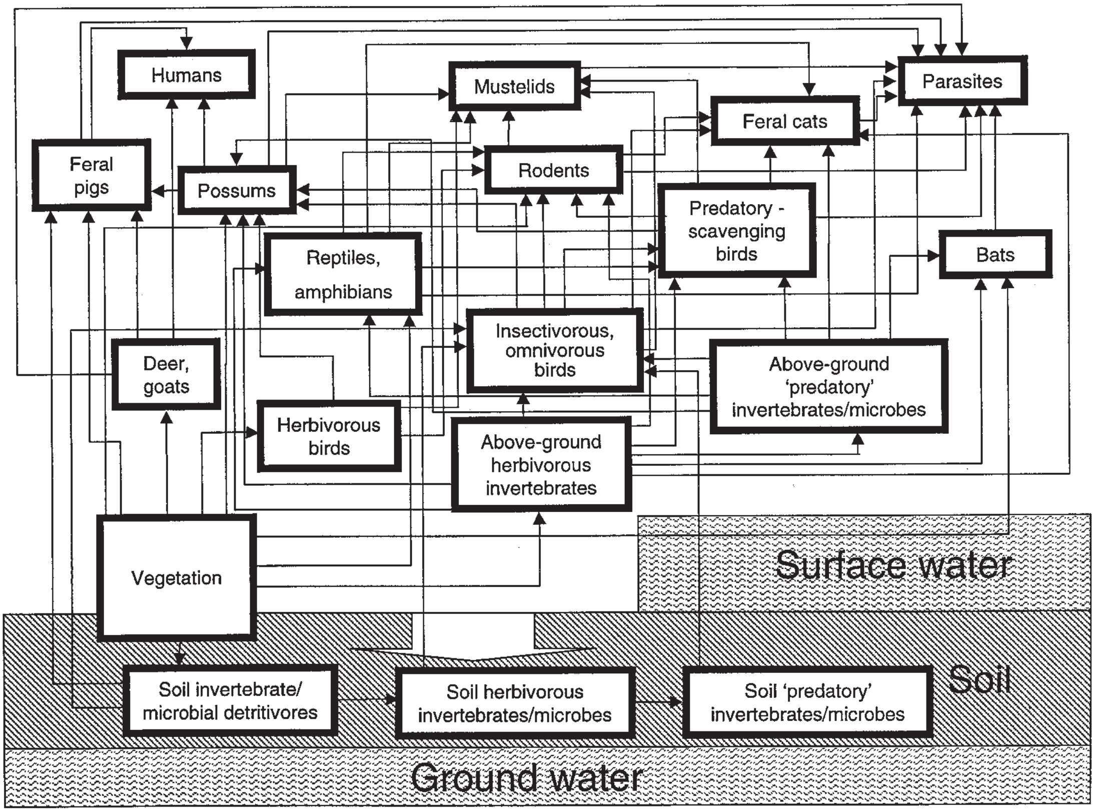

Figure 3: *Descriptive food web for a model New Zealand podocarp-broadleaved forest. The web has been constructed to provide an example community setting for analysis of ecological consequences of toxins (see Figs. 4–6). Note some boxes are species aggregates. Arrows point to the consumer group.*

Most research has been on direct (primary) impacts of 1080; recently some studies have examined secondary impacts, mostly to introduced mammal predators, but none has looked for impacts at tertiary level or beyond. This may be because 1080 is generally not a persistent toxin, and is usually rapidly eliminated from live animals, and rapidly broken down by microbial activity in baits, water and soil (Eason *et al.*, 1993b; Eason, Gooneratne and Rammell, 1994; Parfitt *et al.,* 1994, and references therein). Nonetheless, the links depicted in the foodweb (Fig. 3) clearly suggest that such third order impacts are possible if the rate of species interactions exceed the rate of toxin decay.

Very few accounts describe population-level impacts of aerial application of 1080, for example (for vertebrates) with more than half of monitored individuals dying. In recent years, only Powlesland *et al.* (1999) describe such a level of loss for any taxon. The North Island robin (*Petroica australis*) population which he observed at Pureora in September 1996 recovered to pre-application levels within a year, due to improved nesting success after robin predators (mainly ship rat; *Rattus rattus*) were killed by the 1080. Further, the robin kill was caused by excess chaff in the carrot bait, which can be remedied by quality operational management, so that this outcome is unlikely to characterise more routine aerial applications.

However, most attempts to quantify impacts on non-target species level are very simplistic and short-term. Commonly, changes in the abundance in one or more life stages, relative to untreated reference sites, are interpreted and extrapolated to suggest that the management practice is adverse. Little consideration is given to the distribution of mortality through the life cycle and little appreciation that marked changes in mortality in a particular part of the life cycle may have no real impact on the population trend of the animal if variation in that stage is not critical to population regulation (i.e., an upper limit imposed on their

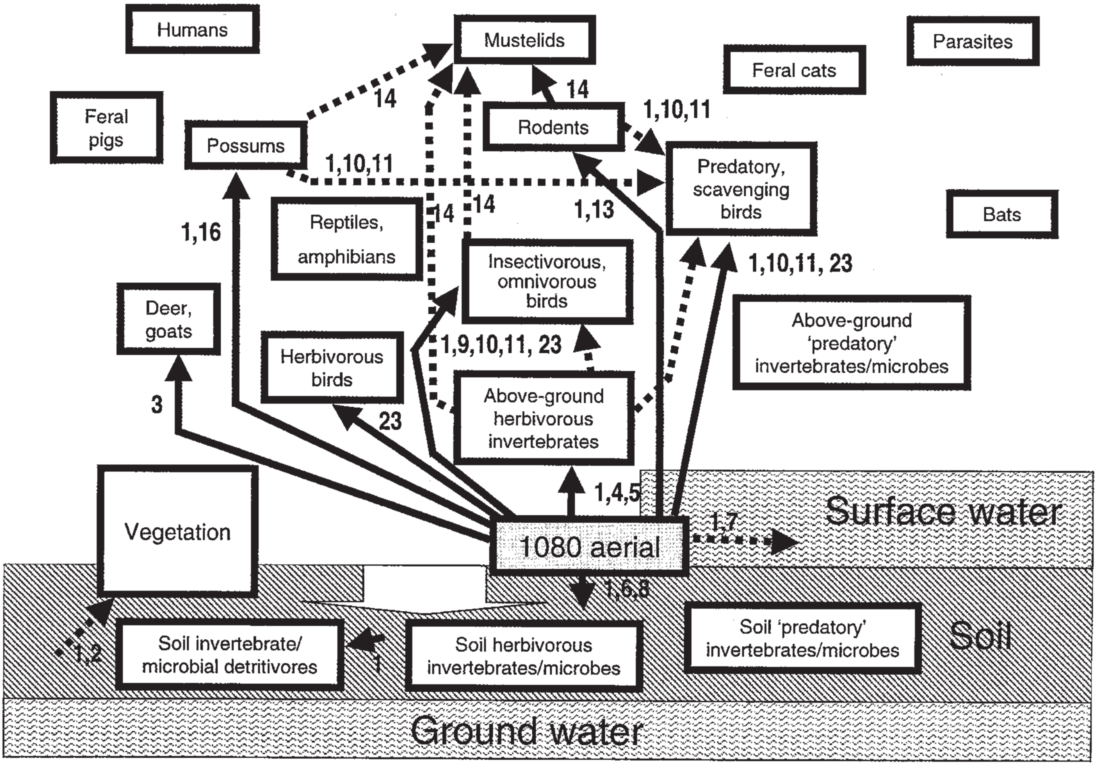

Figure 4: *Documented routes of toxin after aerial 1080 drops, shown in the food web format of Fig. 3, derived from literature. Numbers in the figure are references (Appendix) to the trophic linkage indicated by the adjacent arrow(s). Solid arrows indicate that the toxin has been verified in the boxed species or group to which the arrow is pointing (the* sink box*), and that the source of the toxin has been identified with at least a high probability (our assessment). Dashed arrows indicate either that toxin arrival in the sink box has been suggested in laboratory studies but not verified in the wild; or that toxin is known to reach the sink box but the route by which it got there is uncertain, or that toxin is known to reach the sink box but that this occurs very rarely. Neither solid nor dashed arrows imply that the toxin causes lethal or sublethal effects on fauna in sink boxes. They show simply that toxin was, or was likely to be, detected there.*

population growth via density-dependent feedback). Disturbance effects of toxins on population dynamics and thus intergeneration trend in abundance is dependent on the level of irreplaceable mortality (Thompson, 1955; Morris, 1965) imposed by that toxin. Toxins that alter the abundance of natural enemies may, for example, have profound effects on density fluctuations in an invertebrate herbivore regulated by these natural enemies. Conversely, such changes in natural enemy abundance will have little impact on a herbivore whose populations are primarily regulated by food.

The presentation of 1080 baits in stations greatly reduces the exposure of toxin to many primary non-target species such as deer, but not to secondary predators such as mustelids and feral cat (Fig. 5).

Brodifacoum dispensed in bait stations also reaches mammalian predators by secondary poisoning, and feral pig perhaps by tertiary poisoning (Fig. 6; Eason *et al.*, 1999 b; Murphy *et al.*, 1998 b). The greater persistence of brodifacoum relative to that of 1080 (Eason and Spurr, 1995; Eason *et al.*, 1999 b) makes it slower and more difficult to link brodifacoum application to ecological consequences in perturbation experiments.

Consequences of reductions in pest mammals

The second context for 'ecological consequences' of toxin use is that due to reduction of pest mammals

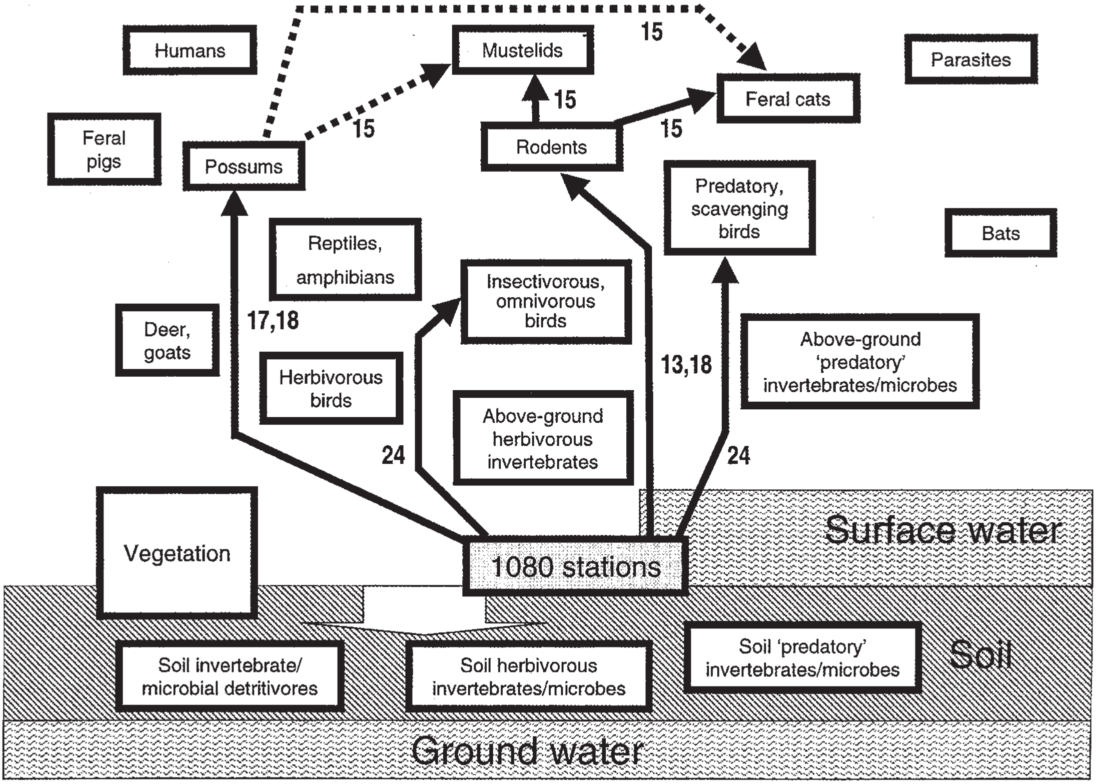

Figure 5: *Documented routes of toxin occurrence after application of 1080 in bait stations on the two large islands (North and South) of New Zealand, shown in the food web format of Fig. 3, derived from data in the literature. See caption to Fig. 4 for explanations and limitations of data.*

after toxin poisoning. An example of how food webs can be used to generate hypotheses for testing is shown in Fig. 7, demonstrating food web responses to the near-eradication of possum and rodents in the mainland podocarp-hardwood community depicted in Fig. 3. The number of trophic interactions (linkage arrows) declines by one third with the removal of these two boxes, because both possum and rodents are omnivores which feed on vegetation, invertebrates and vertebrates. More food may be available for most (70%) other sink boxes from the former prey (source boxes) of possum and rodents, and predators which formerly ate rodents and possum may now need to eat more of other prey. Only first order responses to possum and rodent removal in both source and sink directions are shown. Clearly the actual community response will be more complex, depending on the relative importance of 'top-down' and 'bottom-up' controls on individual species, and may be site- and time-specific. Figure 7 does, however, present many hypotheses which could be tested in the field. One of these - prey-switching by mustelids - has already been verified (Murphy and Bradfield, 1992; Murphy *et al.*, 1999a).

When all introduced mammals are removed from the web, the number of trophic group links declines by two thirds, and predatory and scavenging birds (and their parasites) are identified as top predators in the community, as they were historically in New Zealand.

Ecological relationships other than trophic

Not all interactions between species are trophic, or even biotic. Examples of non-trophic relationships are pollination and seed dispersal, or competition for nest or roost sites. Parasitic New Zealand mistletoes (*Peraxilla* spp.) are declining, perhaps due to collecting, habitat clearance, and browsing by possum (Ladley *et al.*, 1997). However, Ladley *et al.* (1997) suggest also that they suffer a shortage of tui and/or bellbird that pollinate flowers and disperse seeds. Each *Peraxilla* flower is dependent on a tui (*Prosthemadera novaeseelandiae*) or bellbird

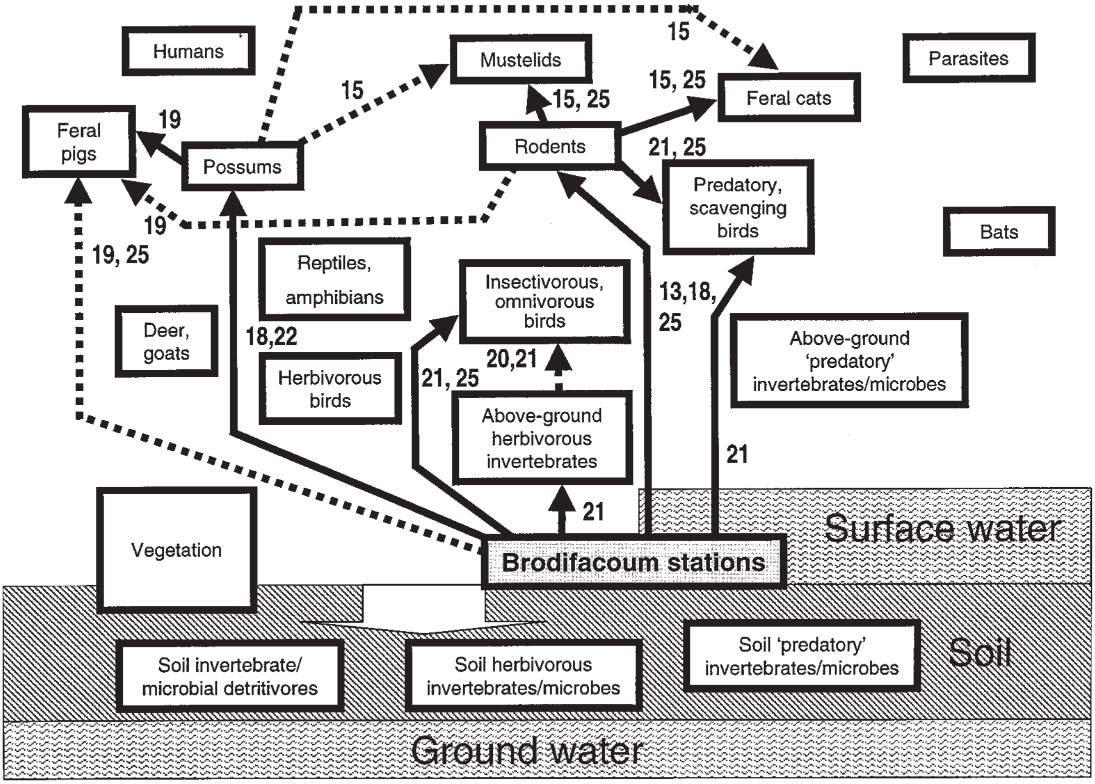

Figure 6: *Documented routes of toxin occurrence after application of brodifacoum in bait stations on the two large islands (North and South) of New Zealand, shown in the food web format of Fig. 3, derived from data in the literature. See caption to Fig. 4 for explanations and limitations of data.*

(*Anthornis melanura*) to open it with a twist of the bill, to pollinate the flower, and later to disperse the seed to another host tree (beech; *Nothofagus* spp.). They plan to test the hypothesis that predator control is required to increase numbers of tui and bellbirds to ensure adequate pollination and seed dispersal. Identity of the most important predator species is unknown, but candidates are possum, stoat, ship rat and feral cat (Fig. 8). If secondary poisoning is used in the operation to control stoat and feral cat, then the planned manipulation will be fourth order — poisoning rodents, to decrease stoat and cat abundance, to increase bellbird and tui, to increase *Peraxilla* pollination and seed dispersal. Ecological consequences of this complexity after pest control operations are probably very common, but few have been verified. Within-trophic group, interspecific competition may be an important force in structuring communities and regulating abundance in individual species (e.g., Denno *et al.*, 1995). These interspecific interactions are sensitive to perturbation by toxins, with potential cascade effects in food webs.

Abiotic factors such as density independent mortality due to severe weather events, and nutrient availability, can limit populations in some circumstances, and may need to be factored into a food web (Winemiller and Polis, 1996).

Influence of pest control timing and frequency

The timing of pest control operations is an important influence on its ecological consequences, and also on its perceived costs and benefits. For example, large-scale poisoning of possum and ship rat to protect North Island kokako (*Callaeas cinerea wilsoni*) is known to be effective if undertaken in late spring just before kokako breed (Innes *et al.*, 1995; 1999). However, it may not be if undertaken in autumn (Fig. 9) because ship rat populations recover within 3–5 months (Innes *et al.*, 1995). Also, gains (recruitment) to the kokako population will be small if the poisoning is undertaken in one year only. The most effective long-term maintenance of kokako will be from poisoning effort which is compressed into 'pulses' of

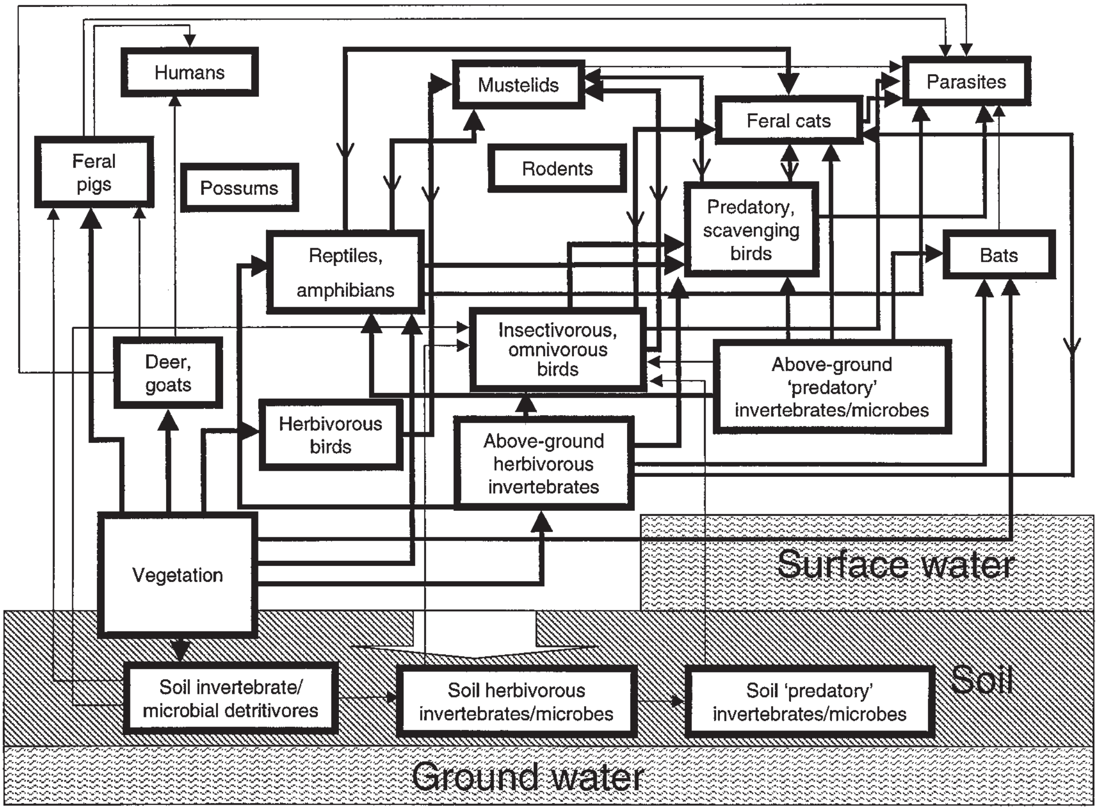

Figure 7: *Food web responses to the near-eradication of possums and rodents in the mainland podocarp-hardwood forest depicted in Fig. 3. All source boxes previously giving food to possums and rodents may now be more available for other sink boxes; first order increases of this nature are indicated by thickened linkage arrows. All sink boxes which previously ate either possum or rodents may now need to eat more of other prey; possible first order responses of this nature are indicated by hollow 'upstream-pointing' arrowheads.*

effort, each lasting perhaps 3–5 years (Innes *et al*., 1999). This regime allows fledged young to mature in 1–2 years and then breed. Kokako adults are long-lived, and most survive inter-pulse periods without pest control. However, this regime may be ineffective for increasing populations of species such as weta (Insecta, Orthoptera) whose adults would be vulnerable to predation in the inter-pulse periods.

'Net outcome' at community level?

The ecological consequences of toxin use for pest mammal control are complex. Toxins kill many targets directly but non-target individuals may also be lethally or sublethally poisoned. Secondary or even tertiary poisoning of individuals of other species may occur (Eason *et al*., 1999 b; Gillies and Pierce, 1999; Murphy *et al*.,1999; Murphy *et al*., 1998 a, b; other papers, this proceedings). Large reductions in pest mammal populations also have many consequences (Fig. 7). The cascading community outcomes of pest control will vary with operation details (toxin type, toxicity, bait formulation, application rate, timing, weather, quality control), control history (e.g., toxin or bait aversion, diet, population structure), and the particular ecological community where the operation occurs. Finally, whether the ecological outcome will be successful or not depends on what the objective of the particular operation was, which attributes of what species were measured, and how long after poisoning these measurements were taken.

We suggest that large-scale use of toxins continues in New Zealand despite these large knowledge gaps, because research consistently suggests that the harmful effects of pest mammals are overwhelmingly greater than those of the toxins used. One way to examine this is to picture pests as toxins. Table 2 compares attributes of 1080, the most widely

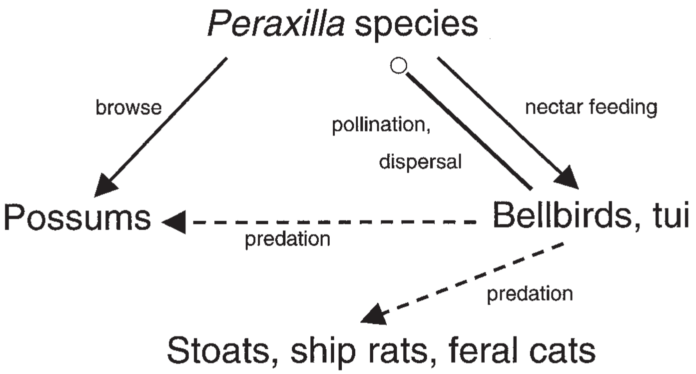

Figure 8: *Trophic and other ecological interactions centred on mistletoes (*Peraxilla *spp.), based on data by Ladley* et al. *(1997).* Peraxilla *is browsed by possum, but long term conservation of mistletoes may require control of possum, stoat, ship rat and feral cat which prey on bellbird and tui, which in turn are needed to open and pollinate* Peraxilla *flowers, and to disperse their seeds. Bellbird and tui obtain nectar from* Peraxilla *flowers.*

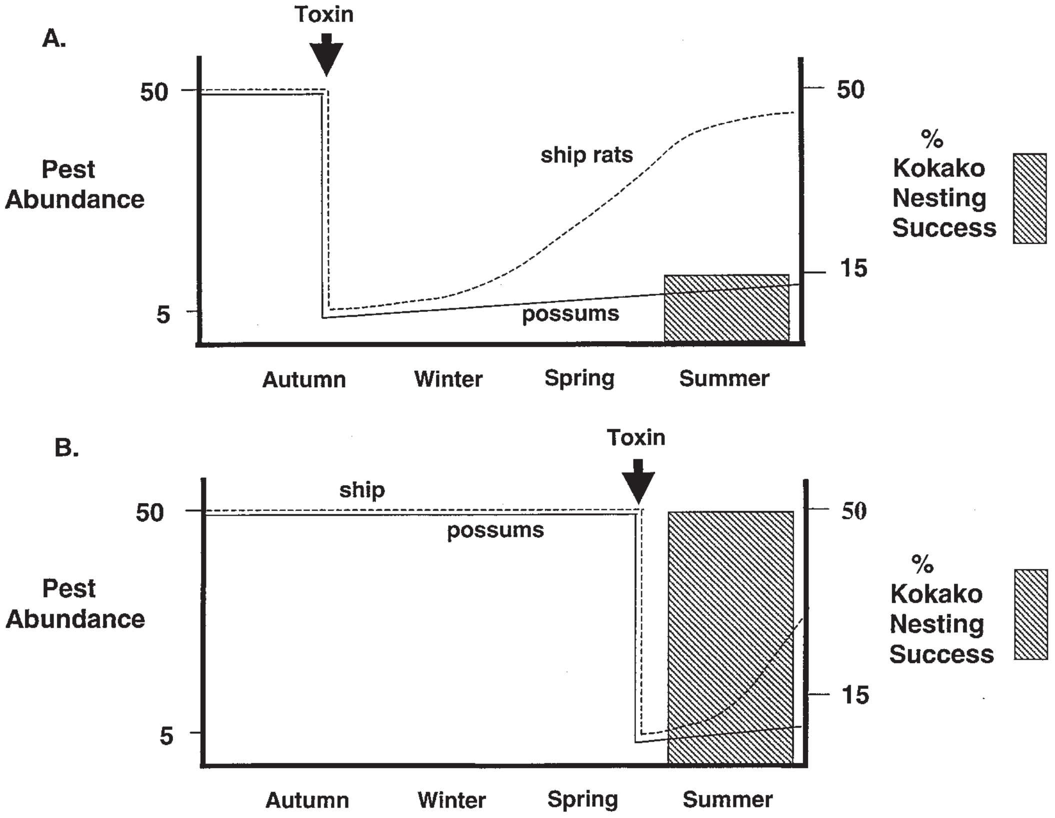

Figure 9: *The impact of pest mammal control timing on kokako nesting success.* ***A:*** *Effective poisoning of key pests (ship rat and possum) in autumn may not alter kokako nesting success if ship rat populations recover before kokako begin nesting in November. Ship rat and possum recovery rates are hypothetical; kokako nesting success data are from Innes et al., 1999.* ***B:*** *The same operation conducted in spring does help kokako, because ship rat and possum numbers remain low in the crucial nesting season. (Data from Innes* et al.*, 1995, 1999. Possum abundance was measured as captures per 100 trap-nights, and ship rat abundance as percent of tracking tunnels with rat footprints, using particular indexing techniques).*

used toxin, with those of possum, the most widely targeted pest. Possum occur throughout 92% of New Zealand; they browse hundreds of species of plant and prey on native fauna, threatening some with extinction. They alter ecological systems at the community level as well as individuals and populations. Uncertainties of other toxins could be added to the left hand column of Table 2, so long as uncertainties of other pests are added to the right.

The precautionary principle can be applied to toxin use. This says that managers should not apply toxins unless they know what most of the resultant ecological consequences are. The essence of the managers' burden, however, is that they know equally little about the ecological consequences of pest mammals. Possums were only discovered to be predators of wild birds and their eggs in 1991, and this species is probably the best known pest. Until new pest control tools (such as immunocontraception) are available to managers, we suggest that the ecological consequences of using toxins may be much less than the consequences of not using them. This suggestion badly needs exploration by researchers. Known risks associated with repeated use of some cumulative toxins such as brodifacoum may already falsify the starting hypothesis for this particular toxin.

Ecosystem management objectives — integrity and health?

Why is pest mammal control undertaken at all? Objectives of control are clear for the Animal Health Board (reduce Tuberculosis occurrence in cattle and deer herds) and for the DOC regarding island eradications (remove all individuals of a pest species) and threatened species population recovery (increase the abundance of threatened species). The goals are less clear for mainland ecosystem maintenance and restoration.

Objectives for ecosystem management by the DOC originate in key legislation which outlines a philosophy and general goals for management. Most important of these are the Wildlife Act 1953, the Reserves Act 1977, the National Parks Act 1980, and the Conservation Act 1987. These Acts primarily mandate that species, ecological systems and landscapes be managed to remain, as far as possible, in their natural state. Perhaps the most lucid expression of the mandate is in Part I, Section 3 of the Reserves Act 1977: "Ensuring, as far as possible, the survival of all indigenous species of flora and fauna, both rare and commonplace, in their natural communities and habitats, and the preservation of representative samples of all classes of natural ecosystems and landscape which in the aggregate originally gave New Zealand its own recognizable character."

International agreements such as the Convention on Biological Diversity 1992, and national conservation strategy documents such as the Environment 2010 Strategy (Ministry for the Environment, 1995), and the 'State of New Zealand's Environment' report (Ministry for the Environment, 1997) support but do not substantially clarify management objectives. Actions for implementing the relevant Acts are outlined further in the DOC's Strategic Business Plan (DOC, 1998) and in DOC conservancy Conservation Management Strategies (CMS; e.g., DOC, 1996).

Many planning documents refer to ecosystem 'health' and 'integrity'. The general management objective for protection of natural and historic

Table 2: *Regarding possum as a chemical toxin, POS$_2$UM. Comparison of attributes of 1080 and possum to clarify the relative ecological consequences of toxins and pests. The 1080 application rate of 7.5 g ha^{-1} is the standard usage of active ingredient (Livingstone, 1994). The 1080 coverage of 9% was calculated on the basis that 1080 was the toxin used on 90% of the 1996–97 area poisoned for possum by the Department of Conservation and the Animal Health Board. Possum application rate of 10 kg ha^{-1} was derived from a mean national density of 4 possums per ha, and mean possum weight of 2.5 kg (Cowan, 1990).*

	1080	POS$_2$UM
Application		
- First use	1954	1858
- Frequency	Repeated	Once only
- Notification	Yes	No
- Rate	7.5 g ha^{-1}	10 kg ha^{-1}
Coverage — area of NZ	9%	92%
Persistence	Days to months	Years Biocumulative, to carrying capacity
Selectivity	Fauna	Fauna and flora
Level of Impact	Individual - population	Community - ecosystem
Humane	Yes?	No

resources in the Waikato CMS (DOC 1996, Volume I, Section 8.1.1) is : "To preserve the health and diversity of existing terrestrial, freshwater and marine ecosystems, and maintain or increase the variety and abundance of indigenous species". In the Waikato CMS and the Resource Management Act 1991, an ecosystem's intrinsic values are defined as "those that determine its integrity, form, and functioning and resilience".

While some scientists (e.g., Rapport, 1989; Beasley, 1993; Cairns *et al.*, 1993) support the concept of ecosystem health, others (e.g., Calow, 1992; Suter, 1993; Wicklum and Davies, 1995) question whether ecosystems can have either health or integrity. Wicklum and Davies (1995, p. 997) argue that: "The phrase ecosystem health is based on an invalid analogy with human health requiring acceptance of an optimum condition and homeostatic processes maintaining the ecosystem at a definable optimum state. Similarly, ecosystem integrity is not an objective, quantifiable property of an ecosystem. Health and integrity are not inherent properties of an ecosystem and are not supported by either empirical evidence or ecological theory".

Ecosystem restoration scientists need to work more closely with pest managers to refine ecosystem maintenance and restoration objectives in New Zealand, because pest mammal management is the major tool by which key conservation legislation is enacted. 'Mainland Islands' (Saunders, 1998), which are mainland sites prioritised for experimental ecological restoration, are an important opportunity for such collaboration.

Clarification of mainland management objectives will resolve managers' uncertainties about the required frequency and intensity of pest control. We suggest that construction of the existing food web at each managed site, plus construction of the historic web at that site, will sharpen ecosystem restoration objectives of management. Further, this approach would assist different participants such as local residents, policy makers, politicians, land managers and scientists, who could use food webs to illustrate and discuss "alternative restoration trajectories" (Fig. 10; Cairns *et al.*, 1993).

Priorities for future research

In this overview we did not encounter major research lines in the field of ecological consequences of toxin use which we thought were fruitless or misdirected. Research should continue on its present broad front including physiology, ecotoxicology, ecology and animal behaviour, but we believe the following are priorities:

Research at community and ecosystem levels

Multi-species responses to management aimed at populations of single species often nudge researchers into working at the community level. However, more methodical community and ecosystem-process research is required so that resource managers using toxins for pest control can have better tools for understanding and measuring *net ecological outcomes for ecosystems*, as key legislation demands.

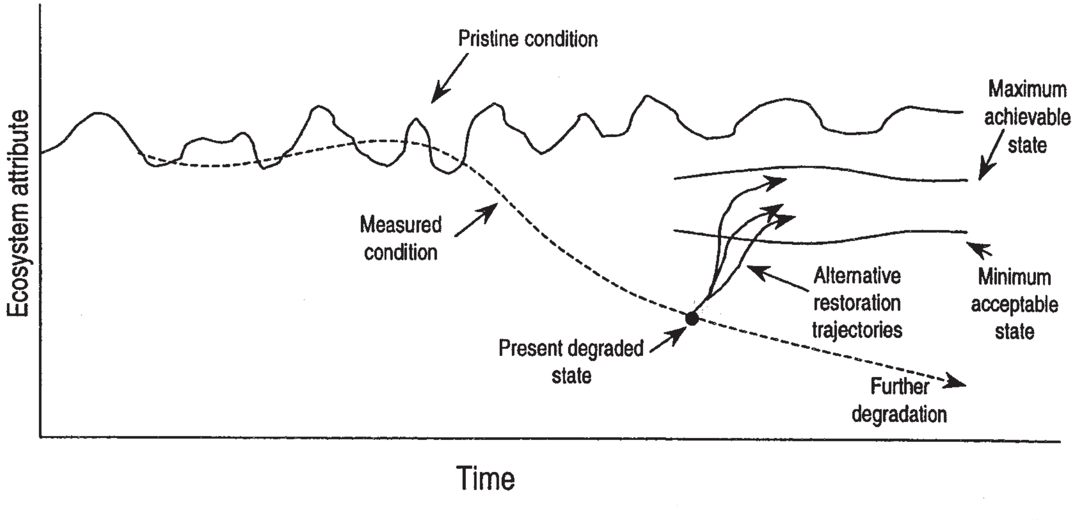

Figure 10: *Model of ecosystem condition over time, showing scope for alternative restoration scenarios which could be explored with food webs. Redrawn from Cairns* et al. *(1993), with kind permission from John Cairns Jr and Kluwer Academic Publishers.*

The three key tools, namely an experimental approach, systems models, and good field observation, need to be applied by teams of researchers who work with resource managers in major ecological systems in which toxins are used. In the first instance, emphasis could be on a North Island podocarp-broadleaved forest as at Pureora, a South Island *Nothofagus* forest as at Eglinton or Craigieburn, and a high altitude pastoral system as in the Mackenzie Basin.

Working at each site, the teams should describe food webs for both the currently and previously existing communities. The webs should be regarded as provisional models for ongoing development. This development would be assisted by the use of a nationally co-ordinated food web database applied at each site, in which annotated references relevant to each web box and trophic link could be displayed upon request. Persistent toxins such as brodifacoum can be viewed as chemical tracers which assist food web model development.

Compiling similar food webs for offshore islands, especially those subjected to mammal eradications, could also greatly sharpen management objectives on the mainland by providing examples of particular restoration outcomes.

Priority or focus species in constructing these webs should be those which are threatened, culturally important, economically important, or indicators of ecosystem processes.

Reduce toxin use

Reducing the amount of toxin used is a sensible way to minimise expense and unwanted ecological consequences of toxins, regardless of the outcome of research examining those consequences. Necessary first steps are to identify accurately when and where particular pest mammals limit prey populations, spread Tuberculosis, or cause unacceptable damage, and to determine damage threshold densities at which control is necessary. This research ensures that poisoning operations are accurately targeted, and that the minimum control effort to achieve the desired outcome is applied.

Much valuable research has been undertaken in the last three decades to reduce application rates of both carrot and pollard baits in aerial poisoning operations against possum. Pollard bait application rates have been reduced from *c*. 20 to *c*. 7 kg ha^{-1}, and further reductions to 2 kg ha^{-1} may be possible at some sites (Morgan *et al*., 1997).

More research should be directed towards alternative toxin-free methods of pest control.. These include fences, fertility control, traps, and manipulation of behaviour (for example, conditioned taste aversion, Cowan *et al*., in press).

Maintenance operations

After successful initial pest control, maintenance control is needed to sustain the threatened resource. The required frequency, intensity and scale of maintenance pest control determine the tactics and methods which managers should use, given the constraints (e.g., risk, non-target effects, bait shyness, cost, topography) associated with each control technique. Pest densities may or may not need to be maintained at low levels to sustain the resource (Choquenot, Parkes and Norbury, 1998). Generally, maintenance operations can be more difficult than ‘knock-down’ ones. Resistance or aversion to baits, toxins or traps may occur, and more expensive control methods (e.g., station-based instead of aerial poisoning) may be required. Due to lower pest density, some beneficial secondary poisoning effects are less significant, and public support can be more difficult to maintain once the major pest damage has disappeared. Finally, managers and field workers may tire of working repeatedly at one location. Pulsed pest control effort may overcome some of these problems.

Good communication

If ecosystem restoration is the task that pest managers are undertaking in New Zealand, then most biological researchers here are engaged on this common task, and their work is increasingly relevant to that of previously distant colleagues such as botanists, anthropologists, landscape ecologists, and geologists who are also interested in restoring ecosystems. Land managers routinely undertake large-scale manipulations of mainland and island ecosystems, and these are most valuable when they are regarded as experiments and treated as such, in co-operation with scientists. Policy-makers can also regard ecosystem management policy in this way, so that pest control programmes can equally be framed as testing different *policy* stances in different locations, to guide a rational choice between difficult alternatives. Finally, pest mammal management is increasingly undertaken in the public eye, and the public in its many sectors wants to be involved in decision-making on pest management issues. Good communication between these parties is needed now more than ever before. This would be helped by an annual dedicated ecosystem management conference, which explicitly welcomed managers, policy-makers, and landowners, as well as scientists from the many relevant disciplines.

Ecological researchers should focus on net outcomes of toxin use for mammalian pest control rather than just on one aspect such as non-target effects. Between them, managers and scientists need to communicate more accounts of successful outcomes of toxin use. This will demonstrate to the public that the inevitable ecological risks associated with disciplined use of toxins are much smaller than the equally inevitable risks to natural ecosystems due to the introduced pest mammals which toxins target.

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