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Past, present and two potential futures for managing New Zealand's mammalian pests

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Abstract: In 2003, a review of how introduced mammals were managed as pests in New Zealand was published. Since then trends for the control of these mammals include moves from pest-by-pest prioritisation towards site-based and multiple-pest management, extension of large-scale aerial control of predators to include beech forests, increasing intensive management of sites by private and non-government agencies, and increasing effort by regional councils and managers of vectors of bovine tuberculosis. The current deployment is the sum of largely independent decisions made by different agencies and individuals with different priorities. National agencies might optimise their own decisions, but overall deployment will always be nationally suboptimal when objectives are set at regional or local scales. This system includes both small areas where most of the mammals present are managed intensively and large areas where fewer species are managed. We discuss how this deployment might evolve as a network of smaller core areas aiming to achieve zero or low densities of all or most pests, with surrounding halos with lesser control effort against fewer species, enough to allow for at least 'safe passage' of native animals between the cores. This system might work best along the more-or-less contiguous native habitats along the axial ranges of the North and South Islands, especially if agencies with a national mandate are prepared to act in the extensive areas between core sites. Some have asked whether the successful eradication of mammals on small islands can be scaled up to the main islands of New Zealand. The current version of this predator-free model aims at the ubiquitous ship rat, brushtail possum and stoat. A key need for the predator-free model is a tool that kills 100% of each of the three main target species, ideally with one large-scale, socially-acceptable application. Without this tool the cost to find and kill survivors would raise the costs of national eradication to about $32 billion, assuming current costs of multiple-species eradications on islands. For sustained control options, research is needed to inform the frequency and intensity of control, and thus the best control tools. The ability to detect target pests at low densities and management of reinvasion are essential for achieving zero or low pest density goals. We suggest that the core/halo model of pest management, within a network of assets to be protected, will best protect New Zealand's biodiversity for the foreseeable future. The national scale pest- or predator-free aspiration is not currently (and may never be) feasible and risks diverting resources from more optimal solutions, as occurred with the 'last rabbit' and 'last deer' programmes promoted last century.

Keywords: biodiversity assets; eradication; invasive mammals; pest-free; predator-free New Zealand; sustained control

Introduction

In this paper we update and extend the last published summary of mammal pest management in New Zealand (Parkes & Murphy 2003). We summarise the components of New Zealand's exotic mammal management by describing the taxa to be managed, the strategic options for management, the control toolbox available or required to achieve both large-scale and local goals, and the social context, particularly where it constrains some options. We further describe trends in the way exotic mammals, particularly those affecting biodiversity, have been managed since the earlier review and discuss how the current deployment might evolve towards either a network of managed sites or to a pest-free or predator-free status for New Zealand.

Changes in the system to be managed

Five components must be understood to manage mammalian pests effectively: (i) the mammals, their ecology and how they interact when they are sympatric; (ii) the pests' effects on biodiversity and economic assets; (iii) whether they can be eradicated, constrained to smaller areas, or reduced in abundance; (iv) which of the variety of control tools is best in each circumstance; and (v) the social context under which people may either value the asset and so benefit from pest control or at least support control, value the pest species and so oppose some forms of management, support or oppose some of the control tools, and either pay for the control directly or via their taxes or rates. The earlier review (Parkes & Murphy 2003) described how these components were applied under different management approaches, i.e. large-scale management of herbivores, control of vectors of bovine tuberculosis, eradication on islands, mainland eco-sanctuaries and large-scale predator control. In this paper we review the changes in each component and how they have affected each of these deployment systems.

The mammals

No mammal species have established in New Zealand since chamois (*Rupicapra rupicapra*) in 1907 (King 2005) and none of the 29 species of exotic mammals that have established wild populations have been eradicated nationally. Mammals have been one of the main causes of modification to native ecosystems and are a threat to native species (Parliamentary Commissioner for the Environment 2011). Some are also pests to agriculture (e.g. rabbits (*Oryctolagus cuniculus*)) or other production systems, and others are maintenance wildlife hosts of diseases such as bovine tuberculosis (e.g. brushtail possums (*Trichosurus vulpecula*)) (King 2005). The discussion in this review will focus on a few species that are more or less ubiquitous across mainland New Zealand, i.e. mice (*Mus musculus*), ship rats (*Rattus rattus*), stoats (*Mustela erminea*) and possums. Other introduced mammalian species are either restricted to particular habitats or locations and/or are found only on one island (King 2005).

The biodiversity assets

New Zealand has 839 islands ranging from small islets up to the North (11.3 million ha) and South (15 million ha) Islands. About 12.6 million ha (49% of New Zealand) is dominated by native ecosystems, albeit from more-or-less intact vegetation in forest and alpine ecosystems to highly modified states in many grassland habitats. In 2012, some form of formal status to protect native biodiversity covered about 8.5 million ha (32% of New Zealand), with 8.2 million ha of this protected tenure being managed by the Department of Conservation (DOC), 154 000 ha of Māori-owned land by Ngā Whenua Rāhui, 86 000 ha of private land by the Queen Elizabeth II Trust, and 62 000 ha by regional councils (Cieraad et al. 2013). Biodiversity assets are not restricted to the land under formal protection, but these places represent the minimum where New Zealanders demand their protection. Most management of mammal pests for conservation is aimed at protecting individual native species. Currently there are 41 Threatened Species Plans covering 187 native taxa out of the 799 species listed as threatened or 2741 at risk (Hitchmough 2013) with almost a third of native vertebrates under threat.

Management strategies

There are three basic strategies to manage established pests: eradication, sustained control at various frequencies and intensities, or a conscious decision to do nothing (Parkes 1993). Eradication is the permanent removal of entire populations and some rules must be met for success: all individuals capable of breeding must be put at risk from the control tool(s) being used, removal rates must exceed rates of increase at all densities, and there must be no immigration (Parkes 1993). Feasibility also requires that sensible constraints should be overcome: no net adverse effects (Parkes & Panetta 2009), but with social acceptability and financial viability (Bomford & O'Brien 1995).

Sustained control implies a reduction in the pest population followed by ongoing interventions to maintain the lowered densities. It requires some understanding of the pest-asset relationship and how it may change in time and space so that target densities or conditions can be set for either the pests or assets, especially when the relationships are non-linear (Nugent et al. 2001; Norbury et al. 2015), vary between sites (Holland et al. 2016), or are affected by extrinsic events such as rainfall (Choquenot & Parkes 2001). Setting target densities for pests allows planned intervention to be applied depending on the initial population reduction and the rate at which the target population recovers (Choquenot & Parkes 2001). Other variants of sustained control include: (i) extirpation, where the target density is set, as with eradication, at zero or near-zero but the certainty of immigrants requires ongoing management (e.g. Edge et al. 2011); (ii) actions to stop invasion into new areas, e.g. for Himalayan thar (*Hemitragus jemlahicus*) (Hughey & Parkes 1996); (iii) management by commercial or recreational hunters whose primary motivation is not as pest controllers (Nugent & Choquenot 2004); and (iv) biocontrol, of which the only successful agent against mammals has been rabbit haemorrhagic disease virus and then only transiently (Parkes et al. 2008).

Control tools

We have no types of control methods to manage mammalian pests that were not available to our ancestors (Mascall 1590; Dagg 2011). However, we have the advantage of modern technology that makes traps, poisons, hunting systems and biocontrol agents much more effective and we better understand how and when to apply them. Some control tools, e.g. aerial poisoning, can be applied at large scales and work against several pest species. These can either: (i) reliably kill 100% of the target population(s) in a single control event or (ii) are effective but rarely kill 100% of the target population(s) in a single control (or release in the case of biocontrol) event. In contrast, other tools, e.g. trapping, usually are applied at smaller scales only, target single species, require continuous application, and rarely kill 100% in one control operation. Some control tools, e.g. aerial baiting, have a cost per unit area that is largely independent of pest density, while others have a cost per pest removed which increases as pest density decreases, e.g. aerial or ground shooting (Pople et al. 1998).

For our focus species, aerial baiting has become the primary basis for large-scale control operations. The first use of aircraft to sow toxic baits was aimed at rabbits and possums in the mid-1950s (MacLean 1966). Helicopters started to replace fixed-wing aircraft in the late 1980s and with the addition of GPS technology in 1991 these were soon being used to ensure uniform bait coverage of targeted areas (Morgan 1994). Two toxins, brodifacoum and sodium monofluoroacetate (1080), are commonly used in aerial baiting. Second generation anticoagulant toxins such as brodifacoum (Parkes et al. 2011) are the only large-scale tool we have that reliably kills 100% of rodents in a single application but usually leaves survivors of other target pests. The technique began with the eradication of kiore from the Mokohinau Islands in 1990 (McFadden & Greene 1994) and has remained the same with the addition of GPS technology to ensure optimal bait coverage. Although these anticoagulants have the advantage of potentially killing all rodents and a high proportion of other mammals, their repeated use for sustained control projects is not advisable because of the persistence of toxic residues in the food chain (Fisher et al. 2010).

The other (and most predominant) large-scale tool is aerial baiting against possums, rats and rabbits using 1080 in cereal baits. Ongoing improvements in bait quality and baiting practices have resulted in a decline in the rates at which baits are sown from >20 kg toxic bait ha^{-1} in the 1990s (Morgan 2004) to as low as 167 g ha^{-1} in some recent trials against possums (Nugent & Morriss 2013). Modern operations typically use cereal baits and pre-feed with non-toxic baits to increase subsequent acceptance of toxic bait (Coleman et al. 2007). Aerial 1080 baiting against possums also kills other mammal species, with ship rat populations commonly reduced by over 90%; additionally, a high proportion of stoats may be killed via secondary poisoning (Murphy et al. 1999). Conversely, a downside of this control is often an increase in mouse numbers (Nugent et al. 2011; Goldwater et al. 2012) as a consequence of reduced predation and competition from rats (Ruscoe et al. 2011). Ungulates may also be killed in aerial 1080 operations but generally this by-kill is too low and too infrequent to count as effective control (Veltman & Parkes 2002). However, it does often annoy recreational deer hunters, leading to one source of opposition to aerial baiting (Green & Rohan 2011). Despite ongoing opposition to the use of aerial 1080, baiting has increased with the species targeted broadening from rabbits in semi-arid grasslands and possums in predominantly broadleaf-podocarp forest (Parkes et al. 1996), to include ship rats and stoats (and possums) in masting beech forests (DOC 2014). Since 2006, TBfreeNZ, DOC, regional councils and private landowners have baited, on average, a total of 557 000 ha per year. Generally, TBfreeNZ applies its baiting on a 5–10 year cycle of repeat control to reduce tuberculosis (TB) levels in possums, and DOC on about a 4 year cycle to protect forest canopies from possums, or on an 'as required' frequency to minimise impacts on native animals when rodent and stoat populations irrupt in beech forests following periodic mast events. In total about three million ha are treated under these intervention strategies. Most of the aerial baiting by regional councils and private individuals is aimed at rabbits (EPA 2014).

There are also many tools such as traps, shooting and toxins in bait stations that can be applied to control mammal pests – albeit limited by topography, scale and high costs as pest densities are reduced. Since 2003, we have better traps (e.g. Barr et al. 2011), new toxins (Eason et al. 2014), baits (Johnston et al. 2013) and delivery devices (e.g. Blackie et al. 2013), and new ways of using dogs and hunters to control ungulates (Parkes et al. 2010). Inventors may promote their devices as solutions for large-scale pest management but none as yet appear likely to be as effective or efficient as aerial baiting against the ubiquitous species across large areas, and none yet (to our knowledge) are able to achieve 100% reductions in the target populations in the short time period and over sufficiently large areas essential in efforts to eradicate rapidly-reproducing species such as rodents. However, at smaller scales for long-term sustained use (Blackie et al. 2013) or to remove the survivors of aerial baiting or immigrants from recently-treated areas, new tools such as self-resetting traps and low-cost remote monitoring devices are likely to have a niche role for some pest species. Control methods for mammals that were not available to our ancestors, such as vectored immuno-contraception (Tyndale-Biscoe 1994), species-specific toxins (Rennison et al. 2013) or various genetic manipulations (Gemmell et al. 2013) have yet to deliver on their potential promises (Cohn & Kirkpatrick 2015).

People

Pest management is intrinsically a value-loaded activity (Craig et al. 2013). Overlapping subsets of New Zealanders value different aspects of native biodiversity, and consequently allocate differing degrees of 'pestiness' to introduced (and sometimes native) species that they perceive to be affecting these values (Farnworth et al. 2014). However, New Zealanders view conservation of native biodiversity as a 'public good' and have a high willingness to pay to minimise or mitigate the threats from pests to the surviving native ecosystems and species. This has resulted in growing enthusiasm from private citizens, philanthropists, NGOs and corporate businesses to be involved with, and fund, pest management (Russell et al. 2015). Conversely, attitudes to the tools used have become more divergent since 2003, especially with the growing use of aerial deployment of 1080, largely because of the risks it poses to non-target mammals. Most eradication projects have been on land with few, if any, inhabitants and therefore obtaining the social licence to operate has been relatively easy (Glen et al. 2013a). To step up to large areas that include many private tenures and a wider range of people (and therefore views) will entail large and complex public engagement. Even if new technologies, e.g. based on GMOs, are developed, the social licence to use them will be the most important constraint to overcome and early engagement with stakeholders and the wider communities will be critical (Boudjelas 2009).

Trends in management

The current system for managing introduced mammals is the sum of a large number of individual projects that have been independently added (or abandoned) according to local, regional and national priorities assigned by a largely uncoordinated mix of funders, agencies, and stakeholders with different goals and objectives. The five main types of mammal control described by Parkes and Murphy (2003) have all changed over the last decade.

Large-scale management of mainland herbivores

Large-scale control of some herbivorous mammals for conservation has declined in importance, at least relative to the control of predators. DOC's earlier (1990s) national planning process began with budgets allocated to key pest species at priority places and began with control of feral goats (Parkes 1993), Himalayan thar (Hughey & Parkes 1996) and possums (Parkes et al. 1996) but then evolved. Some local allocations of resources to specific herbivores have continued, e.g. management of deer in Northland or on the islands of Fiordland. However, DOC has been developing more generic asset prioritisation and threat assessment schemes (Stephens et al. 2002; Moilanen et al. 2009; Overton et al. 2015) to allocate funds to manage critical threats at key sites, rather than to individual pests per se. In addition, possums are controlled by the large-scale aerial poisoning operations of areas of masting beech forest, which primarily target ship rats and stoats. A significant change has been the increase in activity funded by regional councils, mostly against goats and pigs.

Control of possums as vectors of bovine tuberculosis

Control of vectors (largely possums but also ferrets in a few places) to eliminate bovine TB from wildlife remains the single largest mammalian pest management programme in New Zealand. It began in the 1970s, paused in the 1980s, and then increased again to an annual expenditure in 2014 of c. $54 million. Possum control to suppress bovine TB covers over eight million ha (Livingstone et al. 2015). Over the last decade about 75% of TB-possum management has been undertaken on farmland or in accessible areas adjacent to farmland where leg-hold traps or hand-laid toxins, such as cyanide or brodifacoum, are used on a 1 to 3 year cycle depending on whether the goal is simply to lower TB risks to livestock or to eradicate the disease locally (Warburton & Livingstone 2015). These ground control methods have minimal incidental impacts on rodents and stoats (Byrom et al. 2016). However, areas of the conservation estate (about 2 million ha) are also subject to TB-possum control, mostly using aerial 1080 baiting. The aerial baiting provides incidental conservation benefits, as apart from killing possums it also kills most rats and stoats and sometimes most mice (Nugent et al. 2011). However, these benefits can be short-lived as fast-breeding rodents and stoats can recover within 1–2 years, while reduced competition from possums allows rats to rapidly reach higher densities than before the control (Ruscoe et al. 2011).

The TB-possum control programme has been highly effective at reducing the incidence of TB in domestic cattle and deer herds, by more than 95% since 1994. From 2011 the objectives for TB control in possums have included eradication, by 2026, of TB from about nine million ha of New Zealand once considered to harbour infected possums (Livingstone et al. 2015), and there is now a formal proposal to attempt national freedom from TB in both livestock and wildlife by 2040 (Anon. 2015). An emerging issue for conservation is that if the new goal is achieved, TB-related control efforts against possums (and collaterally against rats and stoats) will eventually cease.

Table 1. Mammal species eradicated from islands in New Zealand and globally. Data from the Database on Island Invasive Species (www.islandconservation.org).

Mammals species	No. NZ island populations removed (up to 2003, current, and outcome pending)	Largest NZ island (ha) Largest world island (ha)	No. confirmed eradications internationally other than NZ[1] (outcome unknown or pending)
Mus musculus	12, 29, 3	Rangitoto/Motutapu (3830) Macquarie (12 785)	39 (12)
Rattus exulans	34, 58, 0	Rangitoto/Motutapu (3830) Vahanga, Tuamotus (382)	70 (13)
Rattus rattus	9, 66, 2	Rangitoto/Motutapu (3830) Macquarie (12 785)	232 (41)
Rattus norvegicus	30, 87, 1	Campbell (11 331) Campbell (11 331)	94 (23)[1]
Oryctolagus cuniculus	14, 25, 0	Rangitoto/Motutapu (3830) Macquarie (12 785)	72 (5)
Erinaceus europaeus	0, 3, 0	Rangitoto/Motutapu (3830)	0 (0)
Mustela erminea	5, 39, 2	Rangitoto/Motutapu (3830)	0 (0)
Mustela furo	0, 3, 0	Stephensons (65) Phillip (57)	3 (0)
Mustela nivalis	0, 5, 0	Quail (85)	0 (0)
Capra hircus	22, 28, 0	Great Barrier (part 27 760) Isabela (part 458 812)	128 (7)
Sus scrofa	16, 19, 0	Kapiti (1970) Santiago (58 465)	29 (0)
Felis catus	10, 18, 0	Rangitoto/Motutapu (3830) Marion (29 000)	92 (3)
Trichosurus vulpecula	10, 20, 0	Rangitoto/Motutapu (3830)	0
Petrogale penicillata	2, 2, 0	Rangitoto/Motutapu (3830)	0
Bos taurus	2, 3, 0	Campbell (11 331) Cedros (34 830)	10 (1)
Cervus elaphus	1, 4, 1	Secretary (8140) Santa Rosa (22 197)	1 (0)
Dama dama	0, 1, 0	Kaikoura (535) Sunday (1620)	1
Odocoileus virgineanus	0, 0, 0	- Monhegan (237)	1
Ovis aries	2, 4, 0	Campbell (11 300) Santa Cruz (28 500)	

[1] One pending outcome is from 103 000 ha treated on South Georgia Island, representing an order of magnitude increase in island size for rodent eradications.

Eradication of mammals on islands

Eradicating mammals from New Zealand's small islands began in the early 20th century and by 2003, 168 populations of 14 mammal species had been eradicated from New Zealand islands (Parkes & Murphy 2003). Since then the total has more than doubled with success against 18 mammal species (Table 1). The total area of New Zealand islands freed of introduced mammals has doubled since 2003 to 48 706 ha. If we add islands that have never had mammals or where they died out naturally, nearly 61 000 ha (about 0.2% of New Zealand) are now free of introduced mammals (Table 2).

Trends in eradication tactics have been: (i) better training and use of dogs fitted with GPS collars to assist with ungulate eradication (Parkes et al. 2010); (ii) development of analytical systems to validate success for species reduced to zero by a series of control events (Ramsey et al. 2009) and for rodents after one-hit aerial baiting (Samaniego-Herrera et al. 2013); (iii) deliberate targeting of sympatric species with aerial baiting for rodents, i.e. by-kill of some of the predators followed by ground control to remove survivors (Griffiths et al. 2015); and (iv) a growing intent to tackle islands inhabited by people (Glen et al. 2013a).

Mainland eco-sanctuaries

Before 2003, DOC established 13 'mainland island' areas, where intensive control of most or all introduced mammals was undertaken in unfenced areas of up to 6000 ha (Saunders & Norton 2001). Some of these mainland islands are isolated areas of natural habitat while others are intensively managed core areas nested within larger areas of native forests.

Since this central government initiative began, there has been growth in community involvement with over 600 private or community projects to restore areas by eradicating or controlling pests (Peters et al. 2015), often within pest-proof fences. At the most recent count there were 38 community-led eco-sanctuaries including 13 with predator-proof fences protecting (or partially protecting) nearly 10 000 ha (Innes et al. 2015).

Large-scale mainland predator control

Sustained control specifically targeting mammalian predators such as mustelids, cats and rodents on the main islands was very limited in extent until this century (Clout & Saunders 1995). Small-scale control was delivered largely as part of projects for threatened species (e.g. stoat control to protect kiwi; Holzapfel et al. 2008), or in experimental programmes (e.g. at Mapara to protect kokako; Sinclair et al. 2006), or by private initiatives (Ritchie 2011). Success in these projects (and the mainland island programme) encouraged larger-scale efforts by DOC using ground-based methods to maintain control of key predators (e.g. O'Donnell & Hoare 2012). Large-scale control of possums and predators across private and DOC estate by partnerships of DOC, regional councils, NGOs and private landowners has also developed since 2003, e.g. the Cape to City project in Hawkes Bay (www.capetocity.co.nz). However, the main change has been the growing recognition that aerial baiting at appropriate intervals can achieve large-scale predator control (Nugent & Morriss 2013). In the largest example to date, a beech mast event in 2014 resulted in a 1080 aerial baiting programme (named the 'Battle for our Birds') over 641 000 ha in the 2014/15 financial year largely to target ship rats and stoats, with mice and possums as secondary targets (DOC 2014). The assumption is that this programme will be repeated in future mast events in some or all affected areas. In fact DOC is reacting to a mast occurring as this paper goes to press.

The future: some possibilities

Continuous improvement: evolving the current management system

The strength of the current deployment of pest control in New Zealand is that it takes account of regional, local and special interest priorities. Conversely, a consequential weakness is that regional and local decisions may not take explicit account of national priorities, other than to avoid areas already being treated by national funding agencies (such as DOC). Interested parties could pool their money and agree on a national approach, but that is unlikely even among those aiming to protect just one type of asset such as indigenous biodiversity. People value assets differently and in particular tend to value their local biodiversity assets more than those elsewhere, and the various major pest programmes have fundamentally different goals, e.g.

Table 2. Current status of introduced mammals (wild, feral and domestic) on 846 New Zealand islands over 1 ha (excluding North and South Islands).

Status	No. islands	Total area (ha)	Mean island area (ha)	Largest island (ha) and species removed
Never had mammals	136	1559	12	Disappointment (375)
All mammals died out naturally	9	10 519	1169	Adams (9896). Sheep, goats died out.
All mammals eradicated/ removed	134	48 706	363	Campbell (11 331). Sheep, cattle, Norway rats eradicated. Mice, cats, rabbits, pigs, goats, dogs died out.
Total mammal-free	**277**	**58 921**		
Some eradicated, some remain	42	250 813	5972	Stewart (173 500). Rabbits, pigs from part.
Mammals present and either not managed or not eradicated	127	74 510	1390	Resolution (20 860). Mice, stoats, red deer.
Unknown status but probably with at least rodents	271	2244	12	Rangiwaea (356)

protection of livestock from TB versus protection of indigenous biodiversity. The current 'system' reflects these preferences.

A key question is how future additions (and deletions) to the areas and/or pest species to be managed might be used to enhance the national conservation interest. This is not a simple question to answer even within one agency. DOC's process to classify (Singers & Rogers 2014 and references therein) and integrate its different approaches for ecosystem, pest-driven and threatened species-driven priorities (Stephens et al. 2002) remains to be resolved. DOC had ranked 941 'ecosystem management units', and anticipate they will be able to manage threats in the top 400 units. The implications for those with a national perspective on the future of pest control lies in the potential to redirect funding from completed projects ('eradication' in the pest management context) or from currently-managed areas with lower priority. However, there is also some funding for pest control from outside DOC (such as funds from corporate donors or lump-sum payments provided as part of compensatory programmes (Norton & Warburton 2015) as a result of Environment Court decisions (e.g. Newhook 2013)). This non-DOC funding can be targeted at areas outside DOC's 'top 400' or can replace or subsidise DOC's efforts within their 'top 400', both resulting in more areas being under pest management. Beyond that, increasing the efficiency of pest control is seen, by us at least, as the best way to include more priority areas in the action list. Of course this 'improving by accretion' approach could also include consideration of the benefits of managing more intensively among a portfolio of sites to include habitat heterogeneity, isolation versus connectivity, and ecosystem successional processes; but since these are a critical element of the core/halo model, they are discussed in more detail in the next section.

There is also a risk of reduced funding of pest control for conservation: as already noted, a major reduction in action looms as TBfreeNZ moves closer to eradicating bovine TB from wildlife vectors and hence from livestock (Anon. 2015; Livingstone et al. 2015).

Greater spatial integration: towards networks of mainland islands and halos

There is a growing literature on prioritising and optimising the spatial layout of biodiversity assets, usually with a focus on reserve design (e.g. McGeoch et al. 2016). However, in New Zealand, the 'reserves' are essentially in place and the main management issue is to maintain or improve their quality by controlling threats such as introduced mammals. Glen et al. (2013b) have argued that the national outcomes of such management would be better if an integrated network of intensive and large-scale control of the pests could be designed. The current intensively managed mainland island sanctuaries provide *in situ* benefits in the small areas managed as refugia, and in a halo of adjacent habitats as native animals move out from the managed core (Miskelly et al. 2005). Of course expanding the size of intensively managed cores will often be desirable because theory suggests sets of small protected-areas will not by themselves protect the full complement of New Zealand's biodiversity, but this is expensive. Benefits in the halo and beyond can be enhanced by less intensive management if the sanctuary is sited within large-scale herbivore and predator control projects which may also have layers of lesser control intensity (or pest species targeted) with distance from the core – the onion model of Parkes and Nugent (1995). Pest management in the halo also benefits the core by reducing migration of pests back into the core.

Most of the information required for nationally coordinated pest management is readily available. The national conservation estate and its tenure status has been mapped, and the priority ecological management units delineated. Most of the forested and alpine areas of New Zealand are connected along the main axial ranges. The problem is not a lack of native habitat connectivity but lack of 'safe passage' for native animals between safe refugia. It is these contiguous areas that best suit the network model because supressing pests to make safe linkages along these large areas allows for natural metapopulation processes such as source/sink and sub-population persistence, as well as other ecological (and even evolutionary) processes (Urlich 2015) to operate. Outside the main axial ranges conservation units are in more-or-less isolated patches (e.g. the native forests in Northland, Egmont National Park, Banks Peninsula) and connecting management units will require pest management in agricultural or urban habitats or active restoration of linking habitats. The distributions of pest mammals are known with some key species being almost ubiquitous in most habitats (ship rats, mice, possums, stoats) while others are patchily distributed by habitat or simply because they have not had time to occupy all suitable range. The places where current management is undertaken are known but not, to our knowledge, mapped across all tenures. What is required is a continuously updated map of which mammals are managed by whom, and how intensively and frequently each is controlled in the cores and adjacent areas.

Assuming most of the current deployment of pest control will remain, we can ask how much more would it cost to fill the gaps (in space and in pests managed) to improve the network, or if no more funds were available which current projects should be dropped to fund the highest priority new linkages. Research activity needs to focus on knowing how the different pest species' rates of recovery from control are driven by *in situ* breeding or immigration (e.g. Abdelkrim et al. 2010) and the scale, frequency and intensity of maintenance control in core or buffer areas (e.g. Griffiths & Barron 2016). The problem of managing reinvasion of mammals into cleared areas is one of the aims of a trial being conducted on an unfenced peninsula in Marlborough by Zero Invasive Predators and their partners (www.nextfoundation.org.nz).

Quantum leap: predator-free New Zealand

The most aspirational goal, first proposed by Les Kelly and Paul Jansen and given impetus by Sir Paul Callaghan in his *Transit of Venus* lecture in 2012, is a '*pest-free*' future for New Zealand. The initial grand 'all species' vision has contracted to one of Predator-Free New Zealand, or at least the key mammalian predators (www.predatorfreenz.org), or to being implemented in just parts of the main islands (e.g. Nugent et al. 2013), or on some of the larger secondary islands such as Stewart (Bell & Bramley 2013) and Great Barrier (Ogden & Gilbert 2011). Questions that must be resolved before even these reduced visions could be seriously contemplated are as follows.

1. Which pest species should be targeted?

Proponents envisage eradicating at least three (or maybe four if mice are included) of the more-or-less ubiquitous mammal species (possums, ship rats, mice and stoats) that are the main threat to native animals. Cats are not included, perhaps because of their direct relationship with humans as pets, and the larger herbivores (all with patchy distributions) are absent from the proposals.

There are strong trophic interactions between these ubiquitous species (Ruscoe et al. 2011; Norbury et al. 2013). For example, in mixed podocarp-hardwood forests, reducing stoat numbers had no effect on the density of their prey (rats and mice), but control of possums allowed rats to increase while control of rats allowed mice to increase (Ruscoe et al. 2011). That study did not measure the effect of more rodents on stoat numbers but other studies show that higher prey densities (rodents) result in higher stoat densities (King & Murphy 2005). The consequence for the pest-free vision is that removing possums alone could exacerbate ship rat impacts, or removing possums and rats but not mice could increase mouse impacts. The implication is that, ideally, all four pests should be removed, simultaneously. That necessity inevitably makes the most difficult species to remove (mice or stoats?) the primary target for improving control techniques.

2. Can 100% of targeted populations be reliably removed?
Aerial baiting is the only tool currently available that is capable of delivering widespread, simultaneous control of possums, rodents, mustelids and cats at landscape scales for realistic costs (around $20 per ha). As noted above this tool can reliably kill 100% of rodent populations only (not possums, mustelids or cats), and then only if anticoagulants are used, particularly second-generation ones (Parkes et al. 2011). Sub-lethal exposure is avoided with anticoagulants because individuals do not exhibit symptoms for many days and so do not avoid multiple exposures to baits. Evidence from mainland control operations using 1080 suggests 100% kills are rare, as expected with an acute-acting toxin where some individuals eat a sub-lethal dose, react to the toxin, and become anorexic and/or learn to avoid further ingestion of baits (Hickling 1994). The major issue for the predator-free model is whether survivors can be removed by niche control tools: they can be removed but usually at considerable cost (e.g. Griffiths et al. 2015).

Given that currently no tool can reliably kill all individuals in the suite of targeted pests, the ability to detect survivors or re-invaders, and to be able to locate and remove them all, is clearly an essential prerequisite for the predator-free vision. Some estimates of detection probabilities, the probability that a surveillance device or array will detect an animal given its presence, are published for the key pest species, e.g. for ship rats (Parkes & Byrom 2009; Samaniego-Herrera et al. 2013), mice (Gsell et al. 2010), stoats (Smith et al. 2008) and possums (Ball et al. 2005). The general questions for managers are: (i) what is the probability that no target animals are present if we have conducted our surveillance over all or part of the area and found none? and (ii) how much more surveillance is required (without finding an animal) to be close to certainty that there are none left?

To be 100% sure that no individuals remain requires investigators to look everywhere in the target area using a detection-perfect device. Generally, it is not possible to search everywhere and most devices are not perfect so there is always a risk of falsely declaring success when there are cryptic survivors or undetected immigrants. The level of risk that will be acceptable will depend on the consequences and costs, i.e. wasting money on too much surveillance versus the costs of having to redeploy control if the assumption of eradication proves wrong (Ramsey et al. 2009).

3. Rolling out the campaign in space and time
Based on the costs of the successful multispecies eradication on Rangitoto/Motutapu Islands (Griffiths et al. 2015), the minimum cost to eradicate ship rats, mice, stoats and possums (and maybe cats and other predators) from the three main islands of New Zealand would be $1200 per ha. Across all of New Zealand this equates to about $32 billion or 15% of New Zealand's GDP. If a tool could be developed to kill 100% of all target species reliably in a single application, the costs might be reduced to $6.8 billion judging by costs to eradicate rodents alone on islands (e.g. McClelland 2001). Clearly this scenario is not something that can be funded in a short timeframe (the logistics of providing enough helicopters, pilots and bait alone is daunting) and would have to be rolled out across decades – with all the financial, biological and political risks that a drawn-out funding model entails.

4. Social licence to operate
The role of citizens in helping or hindering a predator-free vision remains unclear. There is growing awareness that people can play a part in removal of pests from urban and peri-urban areas and they welcome the increase in native biodiversity that results from such activity (Cote et al. 2013). The growth of pest control initiatives by community groups and NGOs (Innes et al. 2015) indicates that there is no shortage of enthusiasm for the type of pest-free vision represented by Predator-Free New Zealand (Russell et al. 2015). However, consent to eradicate is not decided by the majority of citizens, rather it is proscribed if any stakeholder has the power to say no, if only on their land. Inevitably, there will be such naysayers with objections to the use of toxins, some animal-rights groups, hunters worried about poisoning deer, or general antipathy toward intervention by government or environmentalists. It is possible some objections can be overcome, for example, by using niche control tools such as new traps or self-disseminating biological control agents (Cross et al. 2010), with the potential consequence of a substantial increase in the risk of failure as cleared areas are reinvaded. With the exception of self-disseminating control tools, all new tools are likely to be more expensive than current aerial baiting methods.

Conclusions

The current mix of mammalian pest control in New Zealand, which targets single species or multiple sympatric species, reflects the ever-changing priorities of national, regional, and local agencies, groups and individuals, and the changing enthusiasms of New Zealanders to protect particular assets or kill the *bête noire* pest species of the moment. There is no doubt that this strategy can be improved with more funding and by continuing the recent shift from the 1990s focus on single pest plans towards management at prioritised conservation sites where the particular suite of threats at that site is controlled. A key question is whether the principal decision-makers for public lands (usually DOC) can apply their general policy on pest management (DOC 2005), and the consequent lists of priority ecosystems, to influence others' actions to achieve a coordinated portfolio that not only covers priority sites, but also accounts for habitat fragmentation and heterogeneity, successional processes, and potential effects of climate change. Pest management also needs to be integrated with other conservation actions (such as other active restoration, rewilding and engineered disturbance projects) across a portfolio of actively managed sites. Even if priorities are agreed across national and regional scales and become more consistent leading to stable actions, management of threats will always be sub-optimal unless it also takes into account the population dynamics, distributions, range use, dispersal and reinvasion rates, and manageability of the different pest species. We consider some form of nested management across space and over time to suit these different parameters, at least in the major areas of indigenous habitats, will at present provide the best way to improve outcomes. All this pest management can be done based on the current wildlife management toolkit, such that improvements in efficiency will allow more areas at larger scales (and more pest species) to be added to the portfolio.

The predator-free vision has echoes of past eradication failures where government policy had visions of national rabbit and deer eradication. The reasons these grand schemes failed provide lessons for the predator-free visions reviewed here. These aspirational goals were criticised by Howard (1958) for rabbits and Riney (1956) for deer for two main reasons. First, eradication was not feasible (at least with the funding, tools and resources available in the mid-1950s). Second, the intrinsic assumption that all rabbits or deer were equally problematic (and hence killing any animal was worthwhile) was (and still is) a questionable assumption (except where eradication is practical, affordable and attempted seriously, i.e. where the obligate rules were met and major constraints overcome). These same flaws remain in the current predator-free proposals. Unless we develop new tools, gain the social licence to use them everywhere, develop much more cost-effective tools and systems to prevent most reinvasion and to detect and kill survivors and invaders, local elimination of pests from unfenced mainland areas will usually be undone by reinvasion.

Some individuals of some species usually survive our current best tool, but not all the reasons for that survival are yet known, hence we do not know how to overcome this fatal flaw for the grand predator-free vision. Even if this problem is resolved, gaining social licence to use the tools over all landscapes and tenures is highly unlikely in the foreseeable future, and whether alternative methods (either from among the niche tools or new ones) are capable of achieving eradication in a timely way is a moot point. This issue of community support does not apply only to the control methods, but also to the goals of pest management, especially as these increase in scale and vision. To gain complete support will require the lead agencies to work with communities in partnership, rather than through the currently used consultation process in which decisions are made essentially without wider inputs, and then delivered to communities more or less as *fait accompli* (Green & Rohan 2011). The risk with the vision is that, despite local and international enthusiasm, it may distract focus and resources from advancing the practical improvements we know we can achieve under the current or enhanced mainland island/network models, i.e. lead to slogans rather than the thoughtful solutions we can already achieve – and lead us down the failed 'last rabbit' and 'last deer' policies of the past.

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