SPECIAL ISSUE

CSIRO PUBLISHING

Pacific Conservation Biology
https://doi.org/10.1071/PC18013

Review

An overview of introduced predator management in inhabited landscapes

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Abstract. Predators play a critical role in ecosystems; however, when overly abundant, they can disrupt natural processes and cause extinctions of species. In particular, oceanic islands have endured many impacts of introduced mammalian predators. Whereas knowledge and management of introduced mammalian predators on islands is well advanced in natural landscapes, in inhabited landscapes, spanning rural and urban environments, comparatively less is known. We summarise key issues from the natural and social sciences in the management of introduced mammalian predators in inhabited landscapes of Aotearoa–New Zealand. We describe the shift in focus over the past few decades from management of introduced mammalian herbivores to predators in rural environments, and the growth in management of introduced mammalian predators in urban environments, both seeking to emulate conservation gains made in forested landscapes. We discuss the circumstances around companion animal management at the interface of the natural and social sciences. We summarise surveys of attitudes towards introduced mammalian predators, the role of biodiversity co-management between Māori and Pakeha, and the importance of also considering non-biodiversity benefits from introduced predator management. We describe the rise of community predator control and large landscape projects aspiring for a 'Predator Free New Zealand', and how such an aspiration must be concurrent with habitat restoration. We make recommendations for further research on the basic population biology of predators in inhabited landscapes, and more long-term studies. Such studies should be integrated with examination of the motivations for predator management, as well as the biodiversity and social outcomes of such management. We conclude by remarking that introduced predator management is only one component of a robust national strategy for conservation of native biodiversity in New Zealand.

Additional keywords: eradication, island, mammal, New Zealand, rural, urban

Received 30 January 2018, accepted 05 June 2018, published online 2 July 2018

Introduction

Predators play a critical role in ecosystems through their consumption of prey species (Estes 1996). Their predatory activities affect prey populations to such an extent that predators can be keystone species causing top-down forcing on ecosystems (Terborgh *et al.* 2001). For this reason, predators are often managed, both to maintain balance in natural systems (Hecht and Nickerson 1999) and to mitigate unwanted impacts on human populations (Treves and Karanth 2003). In particular, large native mammalian predators on continents strongly regulate the dynamics of lower trophic levels (Ritchie and Johnson 2009) and are often in conflict with humans, leading to their persecution (Reynolds and Tapper 1996).

In contrast, terrestrial mammal species are conspicuously absent from oceanic islands, not having been able to naturally colonise such locations (Paulay 1994). However, following discovery by humans, many islands have subsequently had terrestrial mammals introduced (Courchamp *et al.* 2003). These introductions have served as game animals (e.g. rabbits), companion animals (e.g. cats), biocontrol agents (e.g. stoats) or arrived accidently as stowaways (e.g. rodents). The introduction of mammalian predators to islands has introduced strong unnatural top–down ecosystem forcing on sites that historically would have been predominantly bottom–up controlled (Polis and Hurd 1995) except for the role of some native predators and herbivores (Lee *et al.* 2010). This mammalian predation has driven many species to extinction (Blackburn *et al.* 2004) and altered ecosystem dynamics (Fukami *et al.* 2006), leading introduced mammalian predators on islands to be classified as invasive species (Russell and Blackburn 2017). Introduced mammalian predators can be now routinely eradicated from small uninhabited islands and this usually brings about recoveries in native species, and the potential to reintroduce extirpated species (Jones *et al.* 2016). However, on larger islands, which also tend to be inhabited by people, managing introduced mammalian predators can be more challenging (Allen *et al.* 2018). In these

contexts, the management (i.e. control or eradication) of invasive mammalian predators can bring about benefits much wider than those for biodiversity alone, including for agriculture and public health (Russell *et al.* 2017*a*), although alongside potential perverse outcomes from increased native species, such as kaka damaging houses and trees (Charles and Linklater 2015; Linklater *et al.* 2018).

Historically, the focus of conservation biology has typically been uninhabited protected natural wilderness areas. However, there has been a growing realisation that native biodiversity persists, sometimes even flourishes, in human-modified landscapes, and that most biodiversity will remain outside of protected areas (Ives *et al.* 2016). Today, in an increasingly human-modified world (Turner *et al.* 2004), the arbitrary distinction between what constitutes a human-modified and natural environment is less clear, and so too is debated the role of human kind in nature (Redford and Sanderson 2000). This has also meant that predator management in inhabited landscapes has become increasingly common, and come under scrutiny (Doherty and Ritchie 2017). Management of predators strives for evidence-based decision-making, and such evidence typically occurs when a damage threshold is exceeded (Norbury *et al.* 2015). Whereas management of native predators must balance predator control (non-lethal or lethal) with preservation, management of introduced predators can choose to aspire to complete removal of the target species, given the appropriate social context.

In the present paper, we briefly summarise the history of research on invasive mammalian predators in inhabited landscapes in Aotearoa (the New Zealand archipelago), highlighting representative studies where appropriate, and finally suggesting further research to increase our knowledge. We operationally define inhabited landscapes broadly to include both rural (primary production) and urban (high density residential or commercial development) environments, acknowledging a large disparity between them in the level of human habitation. The knowledge that is required to advance predator management in such inhabited landscapes must necessarily come from both the natural and social sciences (Allen *et al.* 2018). Such a review is timely, because progress in eradicating invasive mammalian predators on islands has stalled in New Zealand because remaining invaded islands are larger, in mixed land ownership, and typically inhabited (Russell *et al.* 2018). Nonetheless, New Zealand has ambitiously embarked on a campaign to increase the scale of invasive mammalian predator eradication, ultimately aspiring to remove three taxa (invasive rats, mustelids and brushtail possums (*Trichosurus vulpecula*)) from the entirety of the archipelago, and achieve a 'Predator Free New Zealand' (Russell *et al.* 2015).

Natural sciences

The natural sciences enable research on the population biology, behaviour and community ecology of predators, as well as technical developments in predator management, such as trap manufacture, toxin development, barrier technology and biological control (disease or genetic).

The predator with the longest history of research in New Zealand is the omnivorous Australian brushtail possum. In pastoral landscapes, it is a vector of bovine tuberculosis and has, thus, for some time been managed as a pest to agriculture (Livingstone *et al.* 2015; Nugent *et al.* 2015). Research has focussed on improved understanding of its biology (Montague 2000) and improved control (Byrom *et al.* 2016), and, as such, it is a good model organism for a cross-sector invasive species research agenda. Much of the modern knowledge for landscape-level predator control on the main islands of New Zealand has come from the multi-decadal possum management research agenda (Montague 2000), and possums could likely be eradicated from the entirety of New Zealand using existing tools and technologies.

There has been a long history in New Zealand of separating vulnerable native species from predators (e.g. Bell *et al.* 2016). However, it is only since the start of the 21st century that there has been a major shift in the focus of mammalian pest management in New Zealand from herbivores (rabbits, deer and the herbivorous impacts of possums) to small predators (rats and mustelids; Russell 2014). Invasive rats have been targeted for eradication on New Zealand offshore islands for over 50 years (Towns *et al.* 2013). On the main North and South Islands of New Zealand (the 'mainland'), research has investigated the biology and management of rats and stoats, with an emphasis on native forest and other natural ecosystems (Glen *et al.* 2012; Brown *et al.* 2015; O'Donnell *et al.* 2017). Control of these predators in 'mainland islands' (Saunders and Norton 2001) and eradication from predator-proof fenced sanctuaries (Innes *et al.* 2012) has led to localised biodiversity gains mirroring those of offshore islands. These gains for biodiversity conservation from predator management in uninhabited landscapes have been underpinned by decades of scientific research (Russell and Broome 2016).

Rodents have long been controlled in urban environments of New Zealand as a human nuisance pest. However, only recently has research in to the biology of the suite of introduced mammalian predators (i.e. rodents and mustelids) been undertaken in urban ecosystems of New Zealand (e.g. Morgan *et al.* 2009; Lincoln 2016). Research in rural ecosystems has investigated the role of native forest fragmentation on pest dynamics within agricultural landscapes (Innes *et al.* 2010*b*), and biology of pests in pastoral landscapes (Nichols 2018). Hedgehogs (*Erinaceus europaeus*) remain an understudied mammalian predator in New Zealand, and are abundant in inhabited landscapes. There is currently a paucity of effective control tools for hedgehogs (Griffiths *et al.* 2015), and they are generally overlooked as mammalian pests. Generally, compared to uninhabited landscapes little remains known about the biology and management of mammalian pests in urban landscapes for biodiversity, and a research agenda similar to what has occurred in uninhabited forested landscapes is required.

Companion animals (cats and dogs) can reach extremely high densities in urban environments because of the prevalence of human ownership and subsidy. Cat ownership is estimated at almost half of New Zealanders (NZCAC 2016). At the same time as being valued companion animals, these introduced mammals are also competent predators (Farnworth *et al.* 2013). A single cat can kill hundreds of animals in its lifetime outside its human subsidised diet (Flux 2007), and dogs are a major predator of adult kiwi in Northland (McLennan *et al.* 1996). However, until recently, compared to other introduced predators little research has been undertaken in to the biology of companion animals as predators. Several studies have recently

investigated the behaviour of cats in urban environments (Gillies and Clout 2003; van Heezik *et al.* 2010). Many proposed management measures are unpopular with cat owners, and cat owners have been found to be less likely than non-owners to support restrictions (Hall *et al.* 2016). Distinguishing owned from abandoned and stray animals is also difficult (Dias *et al.* 2017). The ownership and management of companion animals, thus, lies definitively at the interface between the natural and social sciences.

Social sciences

The social sciences enable research into human attitudes and the underpinning beliefs and values of humans towards predators, as well as the economics and politics of predator control, among other aspects of the human dimensions of predator management.

Surveys have been used to understand the attitudes of people towards introduced mammalian pests. These surveys have been most powerful when they are underpinned by a theory of social change, and draw on replicate questions used elsewhere, both of which facilitate inference beyond the population of the study. In 1994, Fraser (2001) undertook one of the first comprehensive studies of attitudes to pests and their management in New Zealand, and this survey was longitudinally repeated in 2012 by Russell (2014). A large number of instructive surveys were also undertaken by Gerard Fitzgerald into attitudes towards feral predators and their management (summarised in Fitzgerald 2009). Attitudes to stray and feral cat management have also been undertaken (Farnworth *et al.* 2011). More recently, surveys have investigated the collaborative aspects of landscape pest control by private land owners (Niemiec *et al.* 2017).

Islands have typically experienced several waves of human colonisation. New Zealand was first colonised by the Māori ~1300 (Wilmshurst *et al.* 2008) and, subsequently, by Europeans from the late 1700s. The history of dual colonisation has brought to bear different, sometimes conflicting, perspectives on biodiversity management in New Zealand (Taiepa *et al.* 1997), although for introduced predator management this has been less of an issue. Only recently has true co-management begun to be developed and achieved (Harms 2015). More recently, other cultures have immigrated to New Zealand, including continental Europeans, North Americans and Asians. This has brought new cultural perspectives to bear on predator management, including an increasing Anglo-Saxon value on animal rights and welfare (Dubois *et al.* 2017), and valuing of wildlife independent of biogeographic origin (Davis *et al.* 2011).

Although the focus on introduced mammalian predator management and biosecurity in New Zealand originated from agricultural and biodiversity protection, there is a growing emphasis on the non-biodiversity benefits. Although biodiversity protection may be a sufficient reason to support introduced mammalian predator management for some people (Russell *et al.* 2017*b*), for others, the motivations to support management may be different. Management of introduced mammalian predators can bring several social, economic and public health benefits, among others (Russell *et al.* 2017*b*; Wilson *et al.* 2017). For this reason, introduced mammalian predator management should be seen within a wider remit of strategic environmental assessment (Russell and Taylor in press).

Policy and action

Although research such as that described earlier is critical to improve management of introduced mammalian predators, and avoid unnecessary conservation conflict (Linklater *et al.* 2018), it must be utilised appropriately through policy and action. Indeed, in managing conservation conflict, ecological and social science make up only a small part of the resolution landscape (Redpath *et al.* 2013). Without careful consideration, disagreements over management of invasive species can escalate rapidly (Crowley *et al.* 2017).

Policy for introduced predator management is set out at the national and regional levels. Nationally, laws such as the *Wildlife Act* 1953 and *Biosecurity Act* (1993; and *Biosecurity Amendment Act* 2012) set out expectations and powers for predator management within the context of other laws (e.g. the *Animal Welfare Act* 1999 and the *Resource Management Act* 1991). Territorial authorities develop regional pest-management plans (under the rules of the *Biosecurity Act*) that set out the strategic and statutory framework for pest management within their regions.

There has also been a rapid rise in collective action towards introduced mammalian predators in New Zealand, because it has become clear that predator management must also occur outside of government conservation lands (33% of New Zealand) and that the Department of Conservation is not sufficiently resourced to attend to all conservation needs. There are over 1000 community groups undertaking introduced mammalian-predator control in New Zealand, alongside countless other private landowners (PFNZ Trust, unpubl. data). Although the motivations to engage in such collective action are varied (Campbell-Hunt *et al.* 2010; Shanahan *et al.* 2018), across the main North and South islands of New Zealand, nearly half of the country receives some form of monitoring or management of introduced mammalian predators (Russell *et al.* 2015). However, the effectiveness of predator management in terms of outcomes for biodiversity is mostly unknown, particularly for community-led programs.

Eradication of introduced mammalian predators from offshore islands of New Zealand is now largely complete for wholly Department of Conservation-managed uninhabited islands (Towns *et al.* 2013). Further eradications of introduced mammalian predators from islands must now occur on islands with private or mixed land tenure, and typically some level of inhabitation (Russell *et al.* 2018). Such eradications from islands are at the critical juncture of the natural and social sciences (Allen *et al.* 2018). Two case studies in point are proposals to eradicate introduced cats and rodents from Aotea (Great Barrier Island) and Rakiura (Stewart Island). Although there are still technical limitations to the feasibility of eradication of introduced mammals on both islands, social conflict has also arisen, around diverse topics from poison-use (Ogden and Gilbert 2009) to biosecurity (Russell *et al.* 2017*b*). Further conflict arises when the philosophical justification for pest control is called into question in its entirety (Wallach *et al.* 2015).

Introduced mammalian predator-proof fences have also emerged as a powerful tool for wildlife protection within larger islands ('mainlands') where entire introduced mammalian predator eradication is currently not feasible (Duron *et al.* 2017).

Such sanctuaries in the order of hundreds of hectares allow eradication of introduced mammalian pests where reinvasion can be managed (Burns *et al.* 2012), as occurs on islands, although the costs of such sanctuaries can be high (Scofield *et al.* 2011). These sanctuaries typically occur in fragmented rural landscapes, although currently do not enclose any settlements beyond staff quarters, camp grounds and military bases. Although the public generally has unrestricted visitor access to these sanctuaries, proposals to include inhabited areas within predator-proof fences have generated social conflict from those who would be affected (Russell *et al.* 2017*b*). Larger still are landscape restoration projects in New Zealand, such as Cape to City (Hawkes Bay) and Project Mounga (Taranaki), among others. These projects combine the natural and social sciences (Glen *et al.* 2017; Niemiec *et al.* 2017) to enable community-led restoration over tens of thousands of hectares of uninhabited and inhabited environments.

Managers of introduced mammalian predators in New Zealand today are considering how to respond to the aspirational goal of a 'Predator Free New Zealand' (Russell *et al.* 2015; Parkes *et al.* 2017*b*). Predator Free New Zealand is the national social movement that sees New Zealanders collectively seeking to remove invasive rats, mustelids and possums from the entirety of the New Zealand archipelago. This movement constitutes both a bottom–up groundswell towards predator control for conservation of iconic New Zealand species (van Heezik and Seddon 2018), enabled by organisations such as the Predator Free New Zealand Trust and the Department of Conservation's predator-free rangers, coupled with top–down governance nationally through the government's Predator Free 2050 Ltd, the National Science Challenge for Biological Heritage, and Territorial Local Authorities' commitments to predator-free regions. This movement captures not just the end point desire of removing all three taxa from New Zealand at some point in the distant future, but also a scaling up of existing efforts to manage introduced mammalian predators at the landscape level, such as through the 'remove and protect' or 'core' and 'halo' models (Bell *et al.* in press), and additional eradications from offshore islands (Parkes *et al.* 2017*a*).

Predator management alone will not always restore populations of native species, and habitat quality is important (Ruffell and Didham 2017). This is particularly so in lowland coastal areas of New Zealand, which have undergone the largest reduction in native habitat alongside rural and urban intensification. Exotic vegetation, such as pine plantations, provides appropriate habitat for some species (Pawson *et al.* 2010), but must provide adequate food resources (Innes *et al.* 2010*a*), while connectivity among native forest fragments can be a pathway for both native and exotic species (Green 1994). In inhabited environments, restoration of degraded forest sites must include all of the following: control of invasive weeds, control of pest animals, exclusion of stock, new or supplementary native planting, and removal of introduced canopy trees.

Future research

There is clearly a growing need for more research in both the natural and social sciences, and, critically, at their intersection, for introduced mammalian predators in inhabited landscapes of New Zealand (e.g. Glen *et al.* 2017). Inhabited landscapes can be as divergent from uninhabited landscapes, as biomes are from one another (e.g. the three-dimensional nature of urban infrastructure). Basic population biological data are still unknown for many introduced mammalian predators in urban landscapes, and are likely to differ in biologically meaningful ways (e.g. characteristics such as density and home-range size, knowledge of which is critical for efficient management). Subtle differences among species within guilds (e.g. rats and mustelids) are also likely to be more important that currently appreciated. Of the types of predator management tools and techniques currently available, only a subset are feasible in inhabited landscapes (e.g. aerial distribution of broad-spectrum toxin is unlikely to receive widespread public support).

Long-term studies in natural landscapes have produced some of the most important results for ecological management in New Zealand (e.g. Brockie 1992), and such similar long-term studies in peopled landscapes would produce results of similar importance. The occurrence and interactions of the suite of introduced mammalian pests in New Zealand appears to differ among forested, rural and urban landscapes, and, so, evidence from one landscape may not apply to the others. The presence of many conservation-engaged citizens in inhabited landscapes, even if their primary motivation is not biodiversity conservation, creates unique opportunities to leverage citizen science in the pursuit of native biodiversity outcomes (Peters *et al.* 2015).

Reduction in predator numbers is measured most easily by numbers of animals removed, and movements such as Predator Free New Zealand are motivated by the action of removing such predators. However, the ultimate goal of such actions is their consequences for biodiversity, namely, increases in abundance and diversity of native species. Pest control achieves such biodiversity outcomes only when its spatial and temporal scale reduces pest numbers below their damage threshold (Norbury *et al.* 2015), which, at the same time, ethically justifies the animal welfare costs (Dubois *et al.* 2017). Currently, much community predator control in New Zealand is motivated by factors such as civic participation. Although this raises awareness of the impact of introduced predators, more work is required understanding and setting standards for the biodiversity outcomes of such community projects (Peters *et al.* 2016; Sullivan and Molles 2016).

Knowledge of the non-biodiversity impacts of introduced mammalian predators, particularly on public health, is also rudimentary; however, impacts are likely to be high, particularly for invasive rodents (e.g. leptospirosis) and cats (e.g. toxoplasmosis). The interface between introduced mammalian predator control tools, and public acceptability (so called 'social licence'), particularly concerning animal welfare, will always require ongoing investigation. Such research will be particularly important where social acceptability is unknown as new tools are developed (Warburton *et al.* 2017). However, it may never be possible to fully resolve the disparity between animal and environmental ethics (Parkes and Russell 2018).

Surveys of attitudes linked to respondent demographics (e.g. age, gender, ethnicity) are informative, but they are more effective when they can be linked to other psychological traits of respondents, such as their trust in science, ideologies, and wider value orientations. Broader psychological studies in this form

can identify the values underlying attitudes, and identification of archetypes of people independent of demography. Such studies acknowledge that there is no single 'public', and help develop conservation messaging targeted to particular archetypes, known as 'conservation marketing' (Wright *et al.* 2015). It may turn out that appealing to values rather than evidence is more powerful in enacting conservation action (Schultz *et al.* 2005).

As the number of predator control projects led by community groups continues to grow, greater attention must be given to monitoring both conservation and social outcomes from them (Peters *et al.* 2016), and greater alignment in their strategy and the role they play nationally. Further research is also required on the psychology of group dynamics and conservation voluntarism, as participation in such community events creates a social dynamic with wider consequences. Management of predatory companion animals continues to be a complex issue, although not necessarily intractable once initial emotional reactions are put aside. To that end, the New Zealand National Cat Management Strategy is a great example of a multi-stakeholder document (NCMSG 2017). However, much more work is required to socialise the kinds of behavioural change that are recommended for responsible companion animal ownership.

Conclusions

We have touched on several key issues in the history of research on introduced mammalian predator management in New Zealand, with a focus on inhabited landscape, in contrast to the much more exhaustive literature on their management in natural landscapes (see reviews in King 2005). Research on introduced mammalian predators in inhabited New Zealand landscapes is increasing, but remains patchy in its geographic and taxonomic coverage (Clarkson and Kirby 2016). Similarly, research from the natural sciences dominates, although this is also changing with more social science studies being undertaken on predator management.

Although introduced mammalian predators are one of the gravest threats to the animal subset of New Zealand's native biodiversity, there are many other invasive species, and conservation threats (e.g. freshwater quality, land clearance and climate change), which must also be attended for New Zealand to achieve the sustainable biodiversity goals it aspires to. So, although advocating for greater research on introduced mammalian predator management in inhabited landscapes of New Zealand, we caution that this must be balanced against the priorities of other research investments.

Conflicts of interest

James Russell is an advisor to the Predator Free New Zealand Trust and Predator Free 2050 Ltd, and project leader in the Biological Heritage National Science Challenge.

Acknowledgements

Thanks go to Heiko Wittmer for inviting this special issue contribution and his patience with its preparation, and three anonymous reviewers for their comments.

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