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REVIEW

Management of cats in Aotearoa New Zealand: a review of current knowledge and research needs

Alistair S. Glen[1,2*], Sarah Edwards[3], Susanna Finlay-Smits[3], Chris Jones[3], Chris N. Niebuhr[3], Grant L. Norbury[4] and Araceli Samaniego[1]

[1]Manaaki Whenua – Landcare Research, Private Bag 92170, Auckland 1142, New Zealand
[2]Joint Graduate School in Biodiversity and Biosecurity, School of Biological Sciences, Waipapa Taumata Rau – University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
[3]Manaaki Whenua – Landcare Research, PO Box 69040, Lincoln 7640, New Zealand
[4]Manaaki Whenua – Landcare Research, PO Box 282, Alexandra 9340, New Zealand
*Author for correspondence (Email: glena@landcareresearch.co.nz)

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Abstract: Cats (*Felis catus*) are among the most damaging invasive predators in the world, and their impacts in Aotearoa New Zealand (NZ) are particularly severe. However, unlike the invasive predators that are targeted for eradication under the Predator Free NZ initiative, cats are also highly valued by people and therefore will likely remain widespread in NZ for the foreseeable future. This raises the question of how to manage the impacts of cats, which include predation, competition, and disease affecting native species, livestock, and humans. Appropriate management actions will depend on land use (e.g. urban areas vs wilderness), the values to be protected (e.g. wildlife, human health), as well as safety, humaneness, social acceptability, and cost-effectiveness. We review current knowledge on the impacts and management of cats in NZ and overseas, identify knowledge gaps preventing effective management, and suggest approaches for research to address these gaps. Our suggested research priorities include: (1) improved methods for monitoring cats and their impacts on natural, social and economic values, (2) development of humane, effective, and socially acceptable methods to manage the impacts of cats, (3) engagement with cat owners to improve outcomes for cats, people, and the environment, and (4) investigating potential indirect ecological effects of cat control, such as ecological release of prey or competitors.

Keywords: competition, disease, *Felis catus*, impacts, invasive predators, predation, predator management

Introduction

Globally, cats (*Felis catus*) have been implicated in the declines or extinctions of more species than any other invasive predator (Doherty et al. 2016). Eradication of cats from islands and fenced sanctuaries has led to substantial conservation gains in many countries (Nogales et al. 2004; Campbell et al. 2011; Fitzgerald et al. 2019). Cats are also vectors of diseases that can affect humans, livestock, and wildlife with costly implications for both the health and environment sectors (Lepczyk et al. 2015). However, in Aotearoa New Zealand (hereafter NZ), cats are not being comprehensively managed nor targeted for nation-wide eradication under the Predator Free NZ initiative, which focuses on rats (*Rattus* spp.), possums (*Trichosurus vulpecula*), and mustelids (*Mustela* spp.) (Russell et al. 2015). This leaves wildlife managers with the question of how to deal with cats (Rouco et al. 2017), which are widespread across most of mainland NZ (Gillies & van Heezik 2021).

Different terms have been used in the scientific literature for different categories of cats (Farnworth et al. 2010). The term 'domestic cat' refers to all members of the species *Felis catus*. Among this species, individuals or populations are often classified into three general categories: companion, stray, and feral cats (NAWAC 2018; NPCA 2018):

(1) *Companion cat*: A cat that lives with humans as a companion and is dependent on humans for its welfare. Sometimes referred to as 'pet cat' or 'owned cat'.

(2) *Stray cat*: A cat that relies only partly on humans for provision of its ecological requirements (e.g. food, shelter), either directly or indirectly. Stray cats often live around centres of human habitation and are likely to interbreed with unneutered companion cats.

(3) *Feral cat*: A cat that has minimal or no reliance on humans, and which survives and reproduces in self-perpetuating populations independent of the companion cat population. Stray and feral cats are sometimes referred to collectively in the literature as 'unowned cats' (Horn et al. 2011).

Whereas companion cats are the responsibility of their owners, it is less clear who is responsible for managing unowned cats. This suggests that classifying cats as feral, stray or companion is inappropriate for guiding management and that the simpler classification as owned or unowned may be

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more useful in certain contexts (e.g. legislation) (Kikillus et al. 2017). Since their social, economic, and environmental impacts typically vary, it is important to consider these categories when making research, management, or policy decisions. For example, Horn et al. (2011) reported seasonal shifts in habitat use of unowned cats, likely reflecting prey availability. This was not observed in owned cats.

NZ has the highest rate of cat ownership in the world; in 2011, 48% of households owned at least one cat, and 20% owned two or more (Mackay 2011). However, the rate of cat ownership appears to have declined slightly in the last decade, partly due to concern for native species (McClure 2023). The NZ Companion Animal Council (NZCAC) has established a set of strategic goals for management of all cats in NZ: (1) all cats should be responsibly owned, (2) humane, effective cat management, (3) protection of native species, and (4) adverse impacts of cats on community and environment are minimised (NZCAC 2017). Achieving these goals will require detailed ecological knowledge, an understanding of current guidelines for cat ownership and management (e.g. through legislation), an understanding of cat-human relations in a range of settings, and maintaining social licence for any cat management interventions. The aim of this review is to identify research needs relating to cat management in NZ for the benefit of native biodiversity, human and animal health, and social wellbeing.

Threats posed by cats

Predation

The prey species consumed by cats have been well documented across a range of island and mainland habitat types around the world (Doherty et al. 2015; Palmas et al. 2017; Gillies & van Heezik 2021; Mella-Méndez et al. 2022). Cats are opportunistic, generalist predators that feed on a range of vertebrate and invertebrate species. Staggering estimates of numbers of prey individuals consumed by cats have been derived by combining cat population densities with the frequency of prey items in their diet (Loss et al. 2013; Woinarski et al. 2017, 2018, 2020; Woolley et al. 2020).

Globally, most studies of cat predation report significant negative impacts on native species (Dowding & Murphy 2001; Frank et al. 2014; Doherty et al. 2017; Loss & Marra 2017), including species extinctions (Medina et al. 2011; Doherty et al. 2016). There are, of course, caveats. Cat impacts vary in time and space (Badenes-Pérez 2023), and the level of impact on some prey species is not always clear, in part because there are often several invasive species at play (Calver et al. 2011; Rowland et al. 2020). Most impact studies have focused on feral cats, although similar impacts have been attributed to companion cats (van Heezik et al. 2010; Bamford & Calver 2012; Legge et al. 2020a; but see also Choeur et al. 2022).

In NZ, our ability to gauge the impacts of cats is hindered by a lack of knowledge of cat population densities and how these vary with habitat and season (Jones 2019). A key priority for research is therefore to establish reliable estimates of cat numbers in NZ, including owned and unowned cats (Kikillus et al. 2017). A related question is the contribution of abandoned companion animals to feral cat populations (Cross 2016). Estimating cat population densities will require improved monitoring tools, likely including optimised use of cameras, automated recognition of species in photographs, and improved methods of managing and analysing the resultant data (Jones 2019). Such improvements will help with understanding the magnitude of the problem, planning for management action, and evaluating results of management.

There is also an urgent need for experimental studies on the impacts of cats in NZ. A related research gap is understanding how impacts are affected by cat density, for example, in the form of "density-impact functions" or DIFs (sensu Norbury et al. 2015). Understanding the shapes of these relationships is important for cost-effective cat management. Density impact functions can take various linear or non-linear forms and can indicate threshold densities of invasive predators at which impacts change rapidly, suggesting a tangible management target. For some prey species, any degree of predator reduction may be beneficial (i.e. linear relationships), while some highly vulnerable prey species may not respond unless invasive predators are totally absent. While there are published estimates of DIFs for some invasive predators in NZ (Norbury et al. 2015), we are not aware of any estimates of DIFs for cats, either in NZ or elsewhere. We also have little understanding of how these may change if some other, but not all, invasive mammals were to be nationally supressed or eradicated.

Cat removal experiments (Garvey et al. 2022) are required, and should preferably use a replicated before-after, control-impact (BACI) design (Underwood 1994). Such experiments should aim not only to measure the impacts of cats, but to determine how these are influenced by cat population density. However, such experiments are expensive and must be conducted over several years. In the interim, ecological information could be used to rank native species in NZ in terms of their susceptibility to predation by cats, as has been done for Australian species (Radford et al. 2018).

Overseas studies in the past decade have revealed the pivotal role of habitat complexity in reducing exposure of native fauna to cat predation. For example, McGregor et al. (2016a) suggested that loss of habitat cover and complexity leads to elevated cat predation, driving native mammal decline across northern Australia. Fire and grazing create open habitat where cats prefer to hunt (McGregor et al. 2014, 2016a; Davies et al. 2020; Stobo-Wilson et al. 2020) and catch more prey (McGregor et al. 2015; Hodgens et al. 2022). Most of these studies have been conducted in Australia. The influence of habitat type on the home ranges and diets of feral cats has been investigated in agroecosystems in NZ (Nottingham 2022; Nottingham et al. 2022); however, similar studies are required in other systems.

The impacts of cats may also vary between individual animals due to physical and/or behavioural traits (Dickman & Newsome 2015; Kikillus et al. 2017; Garvey et al. 2020). For example, in Australia, Moseby et al. (2015) reported individual cats that had previously caught a certain species were more likely to do so again. Variation in the impacts of individual cats in NZ requires investigation. Identifying and targeting problematic individuals could greatly increase the biodiversity benefits of cat control (Garvey et al. 2020). Similarly, behavioural differences among individuals could make some cats resistant to existing control methods (Litchfield et al. 2017; Swan et al. 2017; Garvey et al. 2020). Behavioural differences among animals of the same species can be innate (Merrick & Koprowski 2017) or learned (Hollender et al. 2023). Research should address behavioural differences among cats and develop tools to target those individuals that are not readily removed by current methods. Care should also be taken so that cats do not learn to avoid control devices. For example, poorly maintained traps may allow animals to escape, and these individuals may subsequently avoid traps.

The common management approach currently used to protect native prey species from feral cats in NZ is lethal cat control. Conservation outcomes might be significantly improved by including more holistic, ecosystem approaches that consider introduced primary prey and habitat structure. Further trials across a range of ecosystem types would be valuable.

Competition

In addition to their predatory impacts, cats can compete with other species for resources such as prey and habitat (Medina et al. 2014; Doherty et al. 2017). Although NZ has no native mammalian carnivores, the potential for cats to compete with native avian predators warrants investigation (Glen et al. 2017).

Disease

Globally, cats are a source of various infectious agents, many of which can cause diseases in humans, companion animals, livestock, and wildlife (Gerhold & Jessup 2013; Lepczyk et al. 2015). In NZ, a variety of cat-associated diseases have been identified (Thompson 2009). Of particular concern is toxoplasmosis, caused by the protozoa *Toxoplasma gondii*; cats are necessary hosts for the life cycle of this parasite. While *T. gondii* infection in humans is often subclinical, risk of severe symptoms and neurological damage increases with pregnancy and in those who are immunocompromised (Montoya & Remington 2008). One study in NZ reported 33% of pregnant women were seropositive for *T. gondii* (Morris & Croxson 2004). Currently no vaccine exists to protect humans from toxoplasmosis, which can lead to miscarriages and vision loss, and has been linked to schizophrenia and Alzheimer's disease (de Wit et al. 2019). Contamination of commercial green-lipped mussels (*Perna canaliculus*) by *T. gondii* has led to additional public health concerns in NZ (Coupe et al. 2018). Clinical toxoplasmosis has also been reported in a number of NZ wildlife species, such as kiwi (*Apteryx* spp.), kākā (*Nestor meridionalis*), kererū (*Hemiphaga novaeseelandiae*), red-crowned kākāriki (*Cyanoramphus novaezelandiae*), and Hector's (*Cephalorhynchus hectori hectori*) and Māui dolphins (*C. hectori maui*). In many cases the infection has been fatal (Roe et al. 2013; Roberts et al. 2021).

Toxoplasmosis infections in livestock are also a concern and can lead to abortions in sheep and deer (Dubey 2009; Patel et al. 2019). As a result, the first commercial vaccine for toxoplasmosis was developed in NZ to reduce losses to the sheep industry. However, this vaccine has shortcomings including cost, short shelf life, and safety concerns due to it being a live vaccine (Dubey 2009). Currently, no vaccine exists for any other species, including cats. Research on toxoplasmosis in cats should focus on reducing oocyst shedding by the cat host, as opposed to preventing abortions.

Costs

Feral cats are reported to be one of the costliest invasive species worldwide, with estimated costs (in 2017 value) of US$43 billion (Cuthbert et al. 2022). One Australian study estimated the annual costs to livestock production caused by cat-dependent diseases at nearly AU$12 million, and to the public health sector at over AU$6 billion (Legge et al. 2020b). In the Hawke's Bay region of NZ, toxoplasmosis was estimated to cost the sheep industry NZ$18 million in 2014 (Walker 2014). These estimates do not include other potential economic impacts such as costs to nature-based tourism or outdoor recreation due to the impact of cats on wildlife. Furthermore, there is often an intrinsic value associated with biodiversity, which can be difficult to quantify, but substantial. For example, in the USA, the damage to wild bird populations by feral cats is estimated at US$17 billion per year (Pimentel et al. 2005).

Management tools and methods

Managing feral cats

There are two main management options for feral cat populations: eradication (permanent removal of the entire population) and control (ongoing removal of a proportion of the population) (Bomford & O'Brien 1995). Doing nothing would have disastrous consequences for native biodiversity. Cat eradication has been achieved on at least 84 islands worldwide (DIISE 2018), including 15 islands in NZ (ranging in size from 0.2 to 31 km^2) (Gillies & van Heezik 2021). More ambitious projects are being planned, such as the eradication of cats (as well as pigs (*Sus scrofa*), and house mice (*Mus musculus*)) on 460 km^2 Auckland Island, NZ (Horn et al. 2022). Achievements, operational details, and challenges of cat eradications on islands around the world have been reviewed by Nogales et al. (2004), Campbell et al. (2011), and Parkes et al. (2014). Algar et al. (2020) provide a detailed account of the planning and implementation of the largest cat eradication up to 2023 (Dirk Hartog Island, Australia; 630 km^2). On mainland NZ, cat eradication has also been achieved in fenced sanctuaries ranging in size up to 3842 ha (Innes et al. 2019).

An ongoing challenge preventing the eradication of feral cats in unfenced mainland areas (e.g. reserves) is reinvasion. This can be managed to some extent by controlling cats in a buffer zone outside the area targeted for eradication (Short et al. 1994). However, little is known about the dispersal behaviour of feral cats, which makes it difficult to judge the optimal size of an effective buffer. Ideally, a buffer strategy would be informed by the timing and distance of dispersal movements, and the behaviour and demographics of dispersing individuals (Glen et al. 2013). Population genetics suggest male-biased dispersal in feral cats in Hawaii (Hansen et al. 2007) and north-western Australia (Cowen et al. 2019). Long-distance movements usually involve dispersing juveniles, males searching for mates, or individuals facing severe food shortage (Norbury et al. 1998; McGregor et al. 2016c). In a 7 km^2 pastoral area in Hawke's Bay, Nichols et al. (2023) reported minimal reinvasion six months after intensive cat removal. However, reinvasion after this time was not measured. Improved estimates of the rates of dispersal, and the distances dispersed by cats, would help to inform management (Jansen et al. 2021).

Where eradication is not feasible, which is the case of most mainland situations, cat control is recommended. The range of methods for cat control and eradication overlap (Table 1), noting that no single method can reliably target every individual of a cat population at large scale; therefore, a multi-method approach is standard practice, particularly when eradication is the goal (Parkes et al. 2014; Horn et al. 2022). Useful guidelines for NZ operators can be found in the Ministry for Primary Industries' Bionet online portal (www.bionet.nz/library/npca-publications/) and the Australian PestSmart online portal (https://pestsmart.org.au/framework-overview). A model for assessing the relative humaneness of each method is provided

Table 1. Methods of feral cat management in NZ and frequency of their use for control and eradication.

Method	Use for control?	Use for eradication?	Notes
Lethal baiting	Not typically	Main method for knockdown	Primary poisoning via toxic bait Secondary poisoning via poisoned prey
Trapping	Main method	Common as a mop-up method	Live trapping requires daily checking Kill-trapping requires approved traps
Shooting	Remote areas only	Mop-up method	Can be used in conjunction with trained dogs
Fencing	No	Common for mainland sanctuaries	Fences require constant checking and maintenance

by Sharp and Saunders (2011). The cost-effectiveness of each method has been evaluated for Australian conditions (Sharp 2012), but not for NZ conditions. A key difference between NZ and most other parts of the world is that NZ has no native land mammals other than bats. This means that there are fewer constraints on the use of lethal traps and toxins targeting mammals in NZ. However, it also means that knowledge from elsewhere cannot necessarily be applied directly to NZ. Our limited knowledge of the humaneness, cost-effectiveness, and practicalities of some methods is hindering progress on cat management for biodiversity conservation in NZ.

Lethal baiting

Two toxins, 1080 (sodium fluoroacetate) and PAPP (para-aminopropiophenone), are registered for feral cat management in NZ (NPCA 2018). Developed in the 1940s, 1080 has been used and researched extensively in Australia and NZ for the control of invasive mammals (Eason et al. 2011). PAPP is a newer, more targeted option for eutherian mammals such as cats (Murphy et al. 2011). Its toxicology (Eason et al. 2014) and effects on welfare (Johnston et al. 2020) have been reviewed; case studies (de Burgh et al. 2021) and local guidelines (Shapiro 2018) are available for NZ. Yet there are knowledge gaps. Although 1080 and PAPP kill cats (LD_{50} 0.4 mg kg^{-1} and 5.6 mg kg^{-1}, respectively) (McIlroy 1981; Eason et al. 2014), low palatability of toxic baits is an ongoing problem (Gillies 2001). Using fresh (as opposed to dried) baits appears to increase the likelihood of bait uptake by cats, particularly if delivered when natural prey are scarce (Short et al. 1997; Wickstrom et al. 1999; Fisher et al. 2015). However, more research on bait formulations would increase baiting efficiency and inform best practice.

In NZ, cat baits with either 1080 or PAPP have been delivered in bait stations, traps, or directly on the ground. There are currently no toxic cat baits registered for aerial application in NZ. Development and registration of PAPP baits for aerial use in NZ is being pursued by the Department of Conservation and is a potential method for the proposed Auckland Island multi-pest eradication (Cox et al. 2022; Horn et al. 2022). Large-scale projects elsewhere rely on lethal baiting (Campbell et al. 2011), and in Australia aerial baiting is becoming a common control method (Algar et al. 2013). However, the effectiveness of baiting is variable and successful campaigns often involve a combination of baiting and trapping (Algar et al. 2013). Secondary poisoning of cats can occur during baiting operations targeting rats and other pests, although the success rate is not well understood (Alterio 1996, 2000; Gillies & Pierce 1999; Heyward & Norbury 1999; Elliott & Kemp 2016). Given that multi-species pest management programmes are more cost-effective and deliver better outcomes (Springer 2018), further research should investigate ways to improve secondary poisoning of cats (among other pests). This should examine the influence of factors such as choice of toxin, delivery method, and population density of vectors such as rabbits and rodents.

New methods of delivering toxins to feral cats are being investigated, including new baits for ground and/or aerial deployment (Cox et al. 2022), and ejectors that dispense toxin either onto the cat's fur or into the animal's mouth (Jones 2019; Murphy et al. 2019; Moseby et al. 2020). Further research will be needed to determine efficacy and target-specificity in a variety of landscapes (Moseby et al. 2020). In Australia, toxic implants are also being developed, which can be inserted under the skin of a prey animal and will deliver a lethal dose of toxin to a predator that eats the animal (Brewer et al. 2022). The effectiveness of such implants for protecting NZ fauna from cat predation should be tested.

Trapping

The variety of trap designs permitted for cat management in NZ (NPCA 2018) can be split into two main categories: restraining and kill-traps. Restraining traps, such as cages and leghold traps, capture and hold the cat alive to be released or dispatched quickly and humanely following the principles of the *Animal Welfare Act* (1999). In urban areas, cage traps are preferred over leghold traps as fewer injuries are sustained, and non-target animals (e.g. owned pets) can be released unharmed. Kill-traps aim to dispatch feral animals immediately, which minimises stress to the animals. Kill-traps are only recommended for remote areas where there are no companion animals. Nonetheless, trapping in general is labour intensive and therefore inefficient for large-scale feral cat management (Sharp 2016), although innovations such as wireless trap monitoring devices can increase efficiency in some cases (Croft et al. 2016). However, trapping is currently the standard method of cat control on mainland NZ. Trapping is likely to be most effective when food is scarce (NPCA 2018). Meat-based lures are commonly used in traps. We recommend research to determine whether combinations of lures (e.g. sound, scent, and visual cues) can increase trap success (Warburton et al. 2017; Garvey et al. 2020).

In NZ, a need has been identified for a kill-trap that can achieve a capture rate of feral cats at least as high as that of a leghold trap, and preferably requiring little or no interaction from the cat in order for the trap to be triggered (Jones 2019). The trap would also need to be humane, safe for non-target species, and capable of working in a range of environments in NZ with minimal operator input. The ability for the trap to identify owned cats (e.g. using a microchip reader) and disarm itself would also be an advantage (Jones 2019).

Shooting

Shooting is considered a humane method of dispatching cats when it is carried out by experienced, skilled, and responsible shooters; the animal can be clearly seen, is within range, and the correct firearm, ammunition, and shot placement are used (Sharp 2018). As it is labour-intensive, shooting is recommended for small-scale operations only. Shooting is also a method available to dispatch cats caught in restraining traps.

Fencing

In NZ and Australia, exclusion fencing is increasingly being used as a tool to protect and restore areas of high conservation value by allowing eradication of invasive species within the enclosure, while providing defence against reinvasion. The setup and maintenance costs tend to be high (Norbury et al. 2014), hence fencing is usually done as part of muti-pest eradication initiatives to restore and maintain a pest-free area (Innes et al. 2019, 2023). A variety of fence designs are available (Long & Robley 2004; Day & MacGibbon 2007). Pest reinvasion, although uncommon, is more frequent at peninsula-fenced sanctuaries (where animals can walk or swim around fence ends); a key issue requiring research is whether the pests are detected and removed before significantly harming resident biodiversity (Innes et al. 2012). Emerging technologies, such as cameras that use machine learning to identify target animals and send an alert when a predator is detected (Meek et al. 2020), could help to ensure a rapid response.

Deterrents

Ultrasonic deterrents can be effective in reducing nuisance behaviours of cats in urban areas (Crawford et al. 2018), and further research should investigate whether similar deterrents could help protect environmentally sensitive areas, such as bird nesting sites. Other non-lethal means of reducing the impacts of cats on wildlife also warrant investigation. For example, the emerging field of "coexistence conservation" (Manning et al. 2021; Evans et al. 2022) may offer ways in which the behaviour of cats and/or their prey can be altered to reduce predation. Additionally, prey odour can be used as misinformation to disrupt the search strategies of predators, reducing their hunting success (Norbury et al. 2021).

Managing cats in urban environments

Cat management in and around towns and cities is inherently more complex than in conservation or production landscapes. Cats can exist at very high densities (200–300 per km^2) in urban environments (van Heezik et al. 2010), likely sustained by human-supplied resources (Sims et al. 2008; Aguilar & Farnworth 2012). As land use changes, human perceptions of the relative values of cats change from pest to companion, and management goals and methods must change accordingly (Debrot et al. 2022). While lethal control may be cost-effective and acceptable in rural and wilderness areas, more nuanced management tools will be required where both owned and unowned cats occur. The most appropriate methods will also depend on management goals. For example, minimising nuisance to urban residents may require a different approach to protecting native wildlife in urban bush fragments.

Lethal control of cats will rarely be appropriate in urban environments due to safety concerns, the difficulty of discerning owned from unowned animals, and public sensitivities about lethal control (Farnworth et al. 2014). Where lethal control is necessary in urban areas, it is most likely to consist of live trapping, which allows owned cats (e.g. those with collars or microchips) to be identified and released, whereas unowned individuals can be euthanised or re-homed.

In recent years, the technique of trap-neuter-release (TNR), and variations thereof, have been cited by cat advocates and animal welfare agencies around the world as effective methods for reducing the abundance of unowned cats. Using this approach, cats are live-trapped, surgically sterilised, and released. The assumption is that, if reproductive rates are reduced below mortality rates, the population declines from natural attrition. Research on TNR has led to contrasting conclusions, depending on the methods used, the underlying assumptions and, particularly, the definition of success. Programmes based solely on TNR may reduce cat numbers only if: (1) very high rates of sterilisation ($\geq 75\%$) are sustained for long periods, and (2) there is no recruitment of new individuals (e.g. abandonment of companion animals). In reality, these criteria are unlikely to be met (Crawford et al. 2019; Hostetler et al. 2020). Indeed, the very existence of a TNR programme may encourage "guilt-free abandonment" (Lepczyk et al. 2022). In the few examples where a TNR programme has been considered successful, it is invariably part of a wider strategy that includes significant levels of removal through targeted adoption (Andersen et al. 2004; Spehar & Wolf 2017; Swarbrick & Rand 2018).

If an alternative method of inhibiting reproduction could be developed that was less labour-intensive than TNR, this could improve the cost-effectiveness. There has been considerable research into immunocontraception in mammals (Johnston & Rhodes 2015; Jewgenow 2017). Such an approach could be useful in areas where rapid reductions in cat numbers are not required and where there is little social licence for trapping and/or euthanising unowned cats. However, despite success in suppressing reproduction in some species (Massei & Cowan 2014), trials on cats have yet to achieve the level and duration of reproductive inhibition necessary for an effect at population level (Fischer et al. 2018).

Management of companion cats is even more challenging than that of unowned cats. Companion cats have impacts on native biodiversity (van Heezik et al. 2010; Bamford & Calver 2012; Legge et al. 2020a), they can breed with unowned cats, their breeding and territorial behaviours can contribute to public nuisance, and they also contribute to the prevalence of toxoplasmosis in urban areas (Dabritz et al. 2007). Reducing these impacts is primarily the responsibility of owners, who can minimise the impacts of their cats in three main ways: (1) by partial or complete confinement of cats, (2) ensuring cats are neutered, and (3) by using devices worn by the cat to reduce the success of predation attempts. Nevertheless, many owners are unlikely to engage in these interventions without supporting policies and legislation; furthermore, it is important to understand the cultural norms and social practices that maintain the status quo.

Confinement of companion cats, while effectively removing the risks to and from individual animals, requires the active support of owners, and can involve infrastructural changes to the home environment. Physical containment options range from simply keeping pet cats indoors to the use of outdoor enclosures ("catios") or fences to constrain them

Table 2. Summary of research needs for effective monitoring of cats and/or their effects on natural, social and economic values in Aotearoa New Zealand.

Research need	Rationale	Potential methods
Improve monitoring protocols	• Current monitoring methods for cats are not cost-effective • Compare cost-effectiveness of each method	• Estimate detection probabilities for commonly used monitoring methods (e.g. camera traps, spotlighting)
Investigate the influence of habitat complexity on the impacts of cats	• Clarify the effects of habitat restoration/degradation on hunting success of cats	• Sample scat/gut contents of cats from various habitat types • Collar-mounted cameras to estimate hunting success of cats in different habitats
Develop more reliable methods to enumerate cat populations from camera trap data	• There is currently no widely accepted method to estimate population density of cats from camera trap data	• Compare estimates derived from a range of modelling methods (e.g. spatially explicit capture-recapture, mark-resight, occupancy) in terms of cost-effectiveness, accuracy and precision
Estimate population densities of owned and unowned cats in different environments in NZ	• Inform estimates of cat impact • Prioritise areas for population management	• Camera trapping • Cat detection dogs • Replicated spotlight counts
Measure the dispersal behaviour of cats	• Guide decisions on the size of cat removal areas and/or adjacent buffer zones	• Landscape genetics investigating how relatedness of cats changes with increasing distance • GPS and/or radio telemetry to monitor dispersal events
Characterise individual variation in behaviour among cats	• Some individuals may have disproportionate impacts on particular prey species • Management methods may be less effective for some individuals	• Test behavioural traits of individual cats; compare diets of individuals through scat analysis, matching scats to individuals through faecal DNA
Measure the impacts of cat-associated diseases	• Cats carry diseases (e.g. toxoplasmosis) that affect humans, livestock and wildlife	• Compile data on prevalence and effects of toxoplasmosis in humans, livestock, and wildlife • Compare prevalence of toxoplasmosis in livestock and wildlife before and after intensive cat • Control

to property boundaries. Construction of outdoor containment spaces imposes a cost on the owner that not all will be able, or willing, to cover. Costs may not be the only barrier to confinement; surveys of NZ cat owner attitudes consistently show a reluctance to constrain cats' movements (Hall et al. 2016; Linklater et al. 2019; Woolley & Hartley 2019). Despite this, advocacy for the approach that emphasised the welfare benefits to cats has been effective in changing attitudes in Australia (Linklater et al. 2019). This, along with collaborative development of cat legislation with owners and advocacy groups, has allowed some Australian local authorities to better manage owned cats (Midena 2021). In comparison, legislation relevant to managing owned cats in NZ deals primarily with identification, desexing, and, occasionally, limits on the number of cats owned by a household (Kikillus et al. 2017; Somerfield 2019; Sumner et al. 2022). There has been pressure from management agencies and advocacy groups in NZ to establish a national cat management act to allow consistency in legislative approaches and mandate humane management approaches (NZNCMSG 2020). However, there is little evidence of this being a priority for central government. Further research is required to determine what drives acceptance of, or opposition to, containment of owned cats (Kikillus et al. 2017). Practical means to distinguish feral cats from stray or domestic individuals are also needed (Nottingham et al. 2022).

Developing cat management legislation and/or changing ownership practices will take time. Meanwhile, owned cats in NZ are able to roam with impacts on native wildlife (van Heezik et al. 2010). These impacts may increase as native species spill over from intensively managed urban sanctuaries into other suburbs (McArthur et al. 2022). Predation of small fauna by individual cats can be reduced by the use of collar-mounted devices. Bibs (Calver et al. 2007) and bells (Gordon et al. 2010) can reduce predation on birds and small mammals. Bright collar covers that provide a visual warning to prey may be even more useful in NZ as studies overseas show they can reduce cat predation on birds and herpetofauna, but not on small mammals (Hall et al. 2015; Cecchetti et al. 2021; Geiger et al. 2022). Given that NZ native species evolved in the absence of mammalian predators, it would be useful to test the effectiveness of such devices in NZ urban settings (Kikillus et al. 2017).

Multi-species pest management

Some land managers in NZ express concern that cat control leads to increases in herbivores (e.g. introduced rabbits *Oryctolagus cuniculus*) and mesopredators (e.g. introduced rodents) that are the primary prey of cats in most parts of NZ (Norbury & Jones 2015). However, the evidence does not support these concerns (Norbury & Jones 2015; Parsons et al. 2018; Legge et al. 2020a). Cats only limit rabbit populations under some circumstances; for example, when cat predation is combined with other limiting factors such as unfavourable climate, limited food, poor habitat, or disease (Norbury & Jones 2015). Cats also have little effect on rat numbers, although rat behaviour can change such that they are seen less often when cats are present (Parsons et al. 2018). The effect of cat removal on stoats (*Mustela erminea*) is not well understood, although Garvey et al. (2022) found evidence for an increase in stoats following removal of cats and ferrets (*M. furo*).

Rather than cats suppressing rabbit and rodent populations (top-down effects), the evidence is far stronger that cat populations in NZ and elsewhere are driven by rabbits and rodents (bottom-up effects) (Norbury & McGlinchy 1996; Norbury 2001; Cooke 2012; Cruz et al. 2013). When these primary prey are abundant, cats are abundant and predation rates on native fauna are elevated (Medina et al. 2011; Herrera et al. 2022). An Australian study found that, when the abundance of primary prey is reduced, cat abundance declines (Pedler et al. 2016). Rabbit and rodent control are therefore commonly proposed as viable indirect methods to control the impacts of feral cats (Norbury 2001; McGregor et al. 2020; Stobo-Wilson et al. 2020; Rendall et al. 2022). Experiments should compare the effectiveness of simultaneously suppressing cats and invasive prey with that of controlling only cats (Norbury & McGlinchy 1996; Norbury 2001). Controlling invasive prey should also increase the effectiveness of baiting or trapping for cats, as reduced prey availability makes cats more likely to consume baits or interact with food-based lures (Algar et al. 2013).

Monitoring

Any form of cat management will require monitoring to indicate if management goals are being met and to inform managers where and when resources should be applied (Clayton & Cowan 2010). However, cats can be difficult to detect, especially when they occur at low density. The available methods include live-trapping, camera trapping, footprint counts, spotlighting, and wildlife detection dogs. Each method has advantages and disadvantages.

Feral cats are difficult to capture in traps and tend to exhibit learned avoidance once they have been trapped, making them even more difficult to recapture. For example, Gillies and Brady (2018) captured and marked 44 individual cats, only 9 of which were ever recaptured. Cage trapping also suffered from trap saturation by ferrets (Gillies & Brady 2018). Due to such difficulties, live trapping is rarely used for enumerating cat populations, but generally for procedures such as fitting telemetry devices (Recio et al. 2010; McGregor et al. 2016b).

Motion-triggered cameras (camera traps) have several advantages over live-trapping for monitoring cat abundance. As camera trapping does not require animals to enter or interact with a trap, it can achieve higher detection probabilities. Camera traps can also be left in place for extended periods without the need for daily checking and a single camera can record many detections. Thus, camera trapping generally detects more cats than live-trapping (Gillies & Brady 2018; Hansen et al. 2018).

Camera traps can allow identification of individual cats using natural features such as coat pattern and/or artificial marks such as collars (Hohnen et al. 2020; Glen et al. 2022; Juhasz et al. 2022). This allows population estimation using capture-mark-recapture methods; however, some cats may lack distinctive features and some images may be unclear. Spatial mark-resight models may be more suitable when some cats cannot be individually identified (Rees et al. 2019; Jiménez et al. 2022). Camera trap data may also be used to estimate occupancy, or indices of relative abundance (Bengsen et al. 2011). Gillies and Brady (2018) found modest but significant positive correlations between camera trap indices of feral cat abundance and catch per unit effort indices derived from live capture. Further research should compare statistical models for enumerating cat populations in terms of accuracy, precision, cost, and ease of use.

Strategic placement of camera traps (e.g. along trails or forest margins) can increase detection probability of cats (Read et al. 2015; Nichols et al. 2019; Geyle et al. 2020; Wysong

Table 3. Summary of research needs for effective management of cat impacts in Aotearoa New Zealand.

Research need	Rationale	Potential methods
Develop and test an effective kill trap for feral cats	• Provide a humane, cost-effective means of reducing feral cat density in areas where toxic baiting is not suitable	• New and/or modified trap designs; captive trials to estimate effectiveness and humaneness; field testing
Develop more effective lures for cats	• Attract cats to traps, bait stations or monitoring devices	• Compare capture rates of cats using camera traps with various lures • Test combinations of lures (e.g. scent, sound, visual)
Test the effectiveness of bottom-up control for feral cats	• Effective long-term suppression of cat populations; additional benefits of reduced density of invasive prey	• Replicated experiments comparing effectiveness of controlling cats and invasive prey (e.g. rabbits) simultaneously vs controlling cats only. Response variables would include cat density, invasive prey density, and biodiversity outcomes
Test the efficacy and target-specificity of toxin ejectors	• More effective and target-specific methods of delivering toxins to cats are required	• Pen and field trials to estimate population reductions of cats, and identify any non-target effects
Test the effectiveness of toxic implants in prey animals	• In eradications, a small percentage of cats are likely to evade standard removal techniques	• Pen and field trials to establish whether cats consume subcutaneous implants in prey animals (e.g. rodents), and are killed humanely
Measure the effectiveness of incursion response in cat-free areas	• Cats must be removed sufficiently soon after incursions to protect valued species	• Collate data from pest-free islands and fenced sanctuaries to estimate the relationship between time elapsed after a cat incursion and impacts on native species
Develop procedures to distinguish owned cats from unowned ones	• Cat management close to human habitation needs to target unowned cats without harming owned cats	• Explore mechanisms for co-developing legislation (in collaboration with owners and advocacy groups) requiring owned cats to be registered and microchipped • Quantify the reliability of microchipping for identifying owned cats (e.g. can microchips be lost or lose functionality? Are databases accurate?) • Qualitative case study research (using interviews and document analysis) to clarify the roles of various groups (e.g. cat owners, local government, cat rescue organisations/charities, landowners, DOC) in cat management; explore how these groups distinguish between owned unowned cats; and investigate their acceptance (or not) of microchipping legislation
Identify the factors influencing effectiveness of secondary poisoning	• Increased benefit from multi-species control • Cat populations likely to recover more slowly if invasive prey are reduced • Avoid potential for prey switching	• Controlled, replicated experiments to estimate how the success of secondary poisoning is affected by choice of toxin, delivery method, and population density of vectors
Estimate density-impact functions for cats and native wildlife	• Guide decisions on target population densities	• Controlled, replicated cat removal experiments • Monitor abundance, survival, breeding success of vulnerable prey species
Identify species or populations most likely to be under threat from cats	• Guide decisions on where and when to manage the impacts of cats	• Rank native species based on ecological criteria relating to their susceptibility to predation, competition or disease caused by cats

Table 4. Summary of research needs for effective engagement with cat owners in Aotearoa New Zealand.

Research need	Rationale	Potential methods
Explore the diversity of social and cultural attitudes and norms regarding cats, cat ownership, the control of owned and unowned cats, and the harm cats can cause to native species	Public acceptance of, and/or opposition to, cat management strategies such as containment, neutering, and registering of owned cats, and the detection, trapping, and potential euthanasia of unowned cats are shaped by social and cultural norms and attitudes. Any attempts to increase acceptance of these strategies will need to be informed by an understanding of these norms and attitudes	• Historical analysis of New Zealand's relationship with cats • Surveys of the public and of those with a special interest in the control, or absence of control, of cats • Interviews with a broad range of individuals (including cat owners, cat rescue organisations, environmental NGOs, local government etc.) to provide insights into the diversity of social and cultural attitudes and norms of behaviour around cats
Gain an in-depth understanding of the complex system of cat ownership/ management	Cat movements are influenced by a range of interacting factors that range from the household level through to regulatory level. Rather than frame cat management 'issues' in terms of the attitudes and behaviours of individual cat owners, it is important to take a systems-level approach. This could be used to identify leverage points that enable systemic change	• Place-based qualitative case studies that collect data through a range of methods (including document analysis, in-depth interviews, focus groups). This should include various groups associated with cat ownership/management in addition to cat owners, e.g. local authorities, cat rescue organisations/advocates, vets. Analysis should be through the lens of a theoretical approach from the social sciences that is suited to exploring complex systems

Table 5. Summary of research needs to evaluate the potential indirect ecological effects of cat management in Aotearoa New Zealand.

Research need	Rationale	Potential methods
Measure the effects of cat control on invasive prey and/or mesopredators	• Any potential for perverse outcomes from cat control should be identified and managed	• Controlled, replicated cat removal experiments measuring numerical or behavioural responses of other invasive species
Estimate the effects of cat control on avian predators	• Interactions between terrestrial and avian predators are largely unexplored, but could have important ecological consequences	• Estimate resource use overlap between cats and avian predators • Controlled, replicated cat removal experiments to measure the effects on avian predators

et al. 2020). The height and orientation of cameras can also affect detection probability (Nichols et al. 2017; Moore et al. 2020), as can the use of a lure (Garvey et al. 2017), and the model of camera used (Robley et al. 2010). The NZ Department of Conservation has developed an interim camera trapping protocol to monitor cats, rats, and mustelids (Gillies 2023). Ongoing research should investigate how the detection probability of cats is influenced by factors such as camera specifications, camera placement, the type of lure used, and the frequency of lure replacement.

Footprint counts are commonly used as an index of relative abundance for feral cats. These can be obtained using tracking tunnels (Pickerell et al. 2014; Glen et al. 2019), plots of smoothed sand or soil (Catling & Burt 1994; Mahon et al. 1998; Claridge et al. 2010), or by searching for footprints in the natural substrate (Edwards et al. 2000; Pickerell et al. 2014). Lohr and Algar (2020) found that camera traps provided more reliable data than footprint counts. However, camera trapping was more expensive and time-consuming (Lohr et al. 2021). Footprint counts can be useful in areas where the natural substrate shows tracks (Lohr et al. 2021). Where the natural substrate is not suitable, artificial soil plots can be created. However, this is labour-intensive, requires daily checks, and is easily disrupted by weather or other animals (Glen & Dickman 2003; Pickerell et al. 2014).

Wildlife detection dogs can detect cat scats or follow scent trails left by cats and can assist with locating cats for capture or removal (Johnston & Algar 2020). On Auckland Island, for example, dogs found more cat scats than human searchers. Analysis of scat DNA provided information on the minimum number of individuals present and the movements of individuals (Glen et al. 2022). Detection dogs were highly effective at locating cat scats in a woodland reserve in Western Australia. On average, dog teams took less than 13 minutes to search an area of 1.5 ha and found 55% of scats in a single pass (Baker et al. 2021). McGregor et al. (2016b) used dogs to locate and bail up feral cats, which were then captured by hand net or tranquiliser dart. This method was six times more time-efficient and resulted in fewer animal injuries than leghold trapping.

Glen et al. (2016) compared the cost-effectiveness of wildlife detection dogs and camera traps for detecting feral cats. The two methods were comparable in cost and had similar probabilities of detecting a cat, if present. Dogs were able to detect cats more rapidly than cameras and were less susceptible to interference by people or livestock. However, cameras were more robust to weather conditions such as rain and wind. They concluded that dogs may be particularly useful when rapid detection and/or intervention is required, e.g. when responding to an incursion into a cat-free area. Similar comparisons should be conducted in a range of habitat types and weather conditions.

Spotlight counts have also been used to provide an index of relative abundance for feral cats (Mahon et al. 1998; Read & Eldridge 2010). Cruz et al. (2013) used repeated spotlight surveys within seasons to estimate detection probability, which enabled estimation of feral cat abundance from spotlight data. One limitation of spotlight counts is that cats are not strictly nocturnal; thus, individuals that are active during daylight may be overlooked.

Research needs

Our review has identified numerous knowledge gaps that currently hinder effective cat management in NZ. Tables 2–5 list these research needs, briefly explain the reasons for each, and suggest how research should address each question. These research priorities can be loosely grouped into those relating to monitoring (Table 2), impacts (Table 3), engagement with cat owners (Table 4), and potential indirect effects of cat management (Table 5). The relative importance of these research needs will depend on the aims, perspectives and priorities of the organisation or management programme, the environment in which they are working (e.g. urban, rural or wilderness), and the resources and expertise available to them. While our recommendations focus on NZ, similar research is required elsewhere.

Furthermore, we recognise that cat management is as much a social issue as an ecological one and there is therefore a need for social science-led research in this area. Although a review of social science literature on cats and cat management is beyond the scope of this paper, we nevertheless include some key research needs that, from an ecological perspective, will require a social science approach.

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