



# Predator guild responses to control: a review of current knowledge, data opportunities, and gaps

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# Summary

## Project and client

There has been increasing interest from Predator Free 2050 (PF2050) project managers in the benefits or negative consequences of removing or significantly reducing the densities of any of the seven target mammalian predator species (ship rats *Rattus rattus*, Norway rats *R. norvegicus*, kiore *R. exulans*, brushtail possums *Trichosurus vulpecula*, stoats *Mustela erminea*, ferrets *M. furo*, and weasels *M. nivalis*). As part of its collective delivery of the PF2050 strategy, DOC contracted Manaaki Whenua – Landcare Research (MWLR) to review and synthesise existing literature, and conduct a stocktake of available data, in order to summarise current knowledge on how pest guilds respond to selective predator removal and identify critical knowledge gaps to inform further research.

## Objectives

- Synthesise published and grey literature to review the evidence on the responses of predators (cats *Felis catus*, European hedgehogs *Erinaceus europaeus occidentalis*, house mice *Mus musculus* and the seven target PF2050 species) to selective removal of any of the seven PF2050 target species in New Zealand.
- Where possible, clarify the ecological mechanisms that underlie these predator guild responses (e.g., predation or competitive interactions), and assess how and why predator guild responses vary geographically or for different ecosystem types.
- Conduct a stocktake of the relevant data held by eradication and control projects nationally that could be analysed to further investigate predator guild responses.
- Identify critical knowledge gaps that hinder current understanding of predator responses, the ecological mechanisms that drive them, and how they vary across New Zealand's environments.

## Methods

### Literature synthesis

- We primarily reviewed studies conducted on New Zealand's North and South Islands, and offshore islands, supplemented by key findings from international studies, particularly for species that are data poor. We included published evidence (journal articles, books), grey literature (theses, technical reports, conference proceedings), and findings from recent unpublished analyses, where available. Publications were mainly identified using keyword searches in Google Scholar and MWLR's, Manaaki Whenua Landcare Research's (MWLR) digital library for contract reports, and by following citation trails.

### Data stocktake

- We collated meta-data from three national data sources – PF2050 landscape projects, ecosanctuaries (ring-fenced, peninsula-fenced and unfenced), and DOC's tracking tunnel database – which span a range of predator management approaches aimed at eradicating or suppressing one or more PF2050 predator target species.

- We assessed the suitability of data sets for analysing predator responses to control, and assigned priority ranks based on which species were monitored, the robustness of the study design, and the monitoring duration.

## Review findings

- We identified 27 studies reporting predator responses to PF2050 target species removal. The vast majority were related to rodent responses to combined rat and possum removal (13 studies).
- Most research has focused on forest systems for rodents and possums, beech forest for selective stoat removals, and open habitats (dry grass/shrublands, farmland) for mustelid interactions.
- Most studies monitored predators using indices of relative abundance, making it challenging to ascertain whether responses were largely due to enhanced detectability (e.g. increased activity), increased population density, or both.
- *Effects of rat and combined rat & possum removal:* Increasing mouse activity or density was frequently observed following the combined removal of rats and possums (e.g. aerial 1080 operations) in forest ecosystems, although there is some evidence that the mouse response is not universal and is likely to be mediated by food supply. Competitive release of rat populations (mainly ship rats, although rat species are not always specified) following possum removal is also comparatively well reported for forest ecosystems.
- *Effects of mustelid and feral cat removal:* Among New Zealand's three invasive mustelid species, ferrets are expected to dominate over stoats and weasels, and stoats are expected to dominate over weasels, where they co-occur.
  - There is some evidence that, although cats compete with ferrets for resources, removal of cats is unlikely to have a major impact on ferret populations.
  - Stoats can exhibit a behavioural release (e.g. an immediate increase in activity) following feral cat and ferret control.
  - Weasels are probably vulnerable to interference competition from stoats, so control of stoats could lead to the release of weasels. However, there is not strong evidence that aerial 1080 operations regularly lead to substantial increases in weasel populations in forest ecosystems.
  - Mesopredator release of rodents following stoat trapping is sometimes observed, although the effects vary substantially across major environmental gradients and over time.
- *Effects of possum-only removal:* Possum control operations often also remove other invasive predators, either deliberately or incidentally. In three studies on the outcomes of removing only possums, rat responses were variable (increases in two studies, no response in another) and there were no clear mouse responses. Little is known about the potential effects of possum removal on predators that eat possums (e.g. cats).
- Datasets identified through our data stocktake have the potential to address some of these key gaps, particularly mouse responses to control of one or more PF2050 target species in urban and open country habitats. Most data sets are from trail-camera or tracking-tunnel monitoring that concurrently measures multiple species. Some projects are selectively removing a single predator species, which may clarify the effects of individual species within the predator guild.

## Knowledge gaps

- Specific species interactions that we identified as current knowledge gaps include:
  - possum responses to rat-only removal
  - responses of a particular rat species to removal of a different rat species
  - weasel responses to stoat-only removal
  - bottom-up impacts of removing predator species that are prey for top predators (e.g. feral cats, ferrets)
  - hedgehog responses to removal of any PF2050 target species.
- Other key gaps are:
  - whether responses to control were due mainly to demographic or behavioural changes in predator populations
  - responses in urban, coastal, alpine or wetland habitats, and the influence of habitat on predator dynamics more generally.

## Conclusions

- Rodent responses to the removal of PF2050 target predators (primarily rat and possum control) in forest ecosystems have received the most attention. Releases of mouse and rat populations frequently arise following control, although the responses vary across environmental gradients.
- Pest monitoring by DOC, PF2050 landscape projects, and ecosanctuaries has generated data sets that could contribute to addressing some knowledge gaps, particularly regarding mouse responses to PF2050 control in under-studied urban, coastal, and open-country habitats (as well as in more frequently studied forest habitats).
- Priorities among these key knowledge gaps will likely change with time during the PF2050 programme. In the short term (i.e. 5–10 years), current tools and technologies available to PF2050 project managers will mean that one or a subset of species from the full PF2050 target list are more likely to be selected as initial targets (e.g. possums, ship rats, stoats), and therefore it may be more important to understand the possible consequences of reducing populations of those selected species. In the longer term (i.e. post-2050), if PF2050 is successful in its goal it will become increasingly important to understand how the remaining non-target predator species (cats, hedgehogs, and mice) respond to eradication of all 7 target species.
- Priorities for addressing knowledge gaps in predator guild response could also be aligned with the biodiversity and habitat priorities of the wider Te Mana o Te Taiao – Aotearoa New Zealand Biodiversity Strategy, focusing on those relationships that pose the highest potential risk for vulnerable native species or ecosystems, in line with biodiversity objectives.
- Addressing these knowledge gaps could improve current PF2050 management. For example, it may suggest a more effective sequence of species removals to mitigate unintended management outcomes, or how to leverage trophic relationships, for instance, by manipulating the target species' food supply ('bottom-up control'), thereby reducing their numbers or driving increased interactions with traps or baits.

## 1 Introduction

Protecting and restoring populations of indigenous species is a major goal of invasive pest mammal control. However, some pest control projects can have unintended consequences that reduce the benefit to wildlife and may even cause harm. Unintended effects include the ecological release of non-target pest populations (e.g. rodents) through the removal or behavioural suppression of their predators (e.g. stoats) or competitors (e.g. possums). There is also potential for the development of bait or trap shyness in predators through non-lethal exposure to tools aimed at other species, for example induced bait-shyness in possums following sub-lethal dosing of toxin applied for rabbit control (Hickling et al. 1999).

In 2016 the New Zealand government announced an ambitious 'Predator Free 2050' (PF2050) goal to eradicate seven introduced mammalian species (brushtail possums, ship rats, Norway rats, kiore, stoats, ferrets, weasels) from the mainland by 2050. Although PF2050 has funded 18 (four island, 14 mainland) landscape projects, which manage one or more of these target species, decision-makers and managers lack a full understanding of the potential downstream ecosystem consequences of these selective removals. This is further hindered by conflicting results in previous studies of ecosystem consequences of pest removals (Binny et al. 2021, Towns et al. 2006, Wardle & Peltzer 2017).

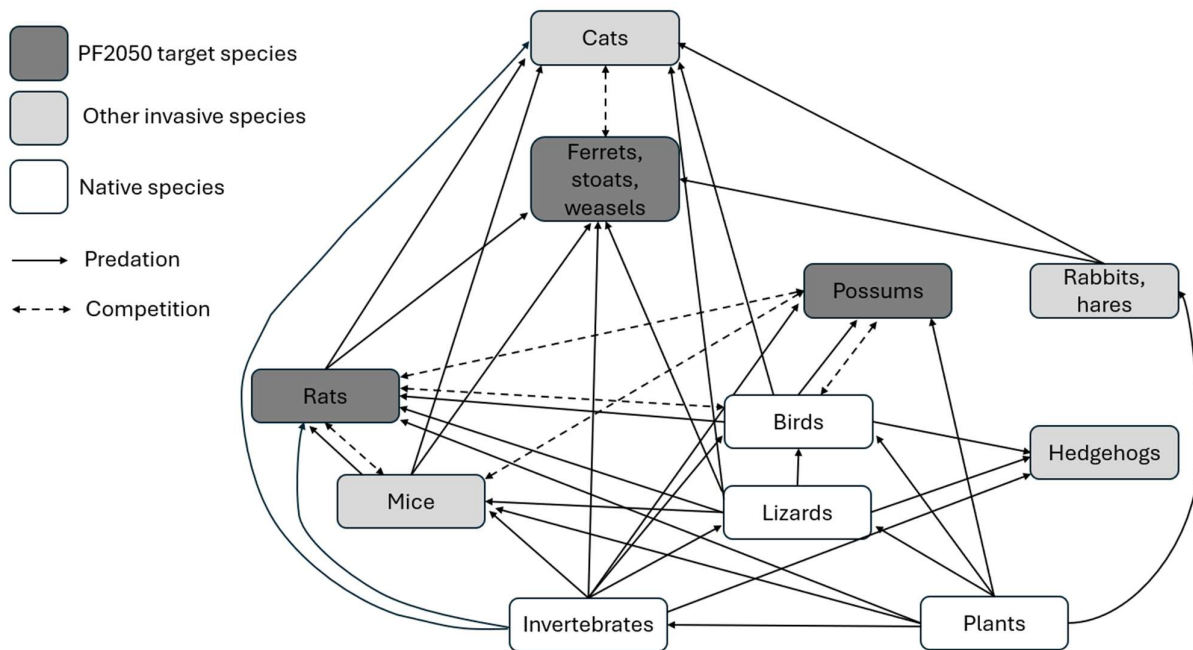
This report is a review and synthesis of existing literature, and a stocktake of available data, on pest guild responses to management in New Zealand. The aims of the synthesis and stocktake is to clarify what is currently known about pest guild responses to management and the consequences for native species, and to identify critical knowledge gaps to inform further research prioritisation by DOC as part of its collective delivery of the PF2050 strategy. Filling the identified knowledge gaps is expected to better inform the projects undertaken by agencies, communities and individuals, enabling them to improve conservation outcomes and the cost-effectiveness of pest management.

## 2 Background

There are several mechanisms that can lead to unintended changes in the distribution, abundance or behaviour of non-target pest mammals in response to pest management, which may undermine the desired benefits. Consideration of the trophic interactions (feeding relationships) that connect species within an ecosystem (either directly or indirectly) can help to identify which species are most likely to respond to removal of one or a subset of predators.

Invasive predator species within New Zealand ecosystems can interact in complex ways through predation or competition (Figure 1). Within ecosystems, populations can be regulated by 'bottom-up' effects, whereby species at higher trophic levels are influenced by lower trophic levels (e.g. mouse populations responding to seed availability). Conversely, 'top-down' effects of predators at higher trophic levels may control lower trophic level predators, or native species, through predation. In some cases, the removal or addition of a top predator can trigger powerful top-down effects that cascade down the food web ('trophic cascades') and indirectly influence populations at multiple trophic levels beyond the primary predator-prey relationship. Predator guild responses to

control are expected to vary geographically and across different ecosystem types (e.g. due to variation in food supply or the availability of complex habitats that provide refuges for prey).



**Figure 1. Generalised food web for New Zealand ecosystems representing current understanding of interactions between PF2050 target predator species (dark shading), other invasive mammals (light shading), and native taxa (white).**

Notes: Predation (solid arrows, with arrow direction indicating the predator species) and competition (dashed arrows) are two major mechanisms that can limit population growth or change the behaviour of species. These interactions therefore indicate where potential unintended changes in predator distribution, abundance or behaviour might arise in response to predator control.

The mechanism relating to unintended management impacts that has perhaps received most attention is *mesopredator release*, which is a change in the abundance, distribution or behaviour of a middle-ranking predator (e.g. rats and mice) in response to a decrease in density or distribution of an apex predator (e.g. feral cats and mustelids). Early reviews suggested that mesopredator release was common in continental systems, but a review of 38 North American studies by Jachowski et al. (2020) found a large amount of conflicting evidence for and against mesopredator release. They suggested there is a need to re-evaluate the pervasiveness of mesopredator release and to define more clearly when and how the term 'mesopredator release' should be applied.

A second potential mechanism is *competitive release*, in which control of one species leads to an increase in one or more of its competitors. Interference competition, whereby an individual directly interacts to restrict another individual's access to a common resource, is frequently the primary form of competition among predators, particularly when food resources are plentiful (Creel 2001; Schoener 1982). Conversely, exploitation competition occurs when resources are depleted by individuals of one species and are therefore no longer available to those of another.

Interspecific competitive interactions among invasive predators and unintended consequences of management are often difficult to observe in the wild. However, they can be inferred by examining

niche partitioning, where competing species use different resources or access the same resources in different ways (e.g. at different times), thereby reducing direct competition and allowing more species to coexist in an ecosystem. Interactions among invasive predators are often asymmetrical, with the weaker competitor being the smaller of the two species (Schoener 1974). Examples of competitive release from overseas include an increase in house mice on Buck Island, US Virgin Islands, from which rats were eradicated in 1999 (Caut et al. 2007). The study of Ruscoe et al. (2011) in mixed podocarp-broadleaved forest in the North Island of New Zealand concluded that responses to pest control in the community are dominated by competitive release rather than mesopredator release.

The responses of untargeted pest mammals to selective removal of other mammal species can be behavioural, or demographic, or both. Behavioural changes could encompass altered activity patterns, habitat selection, or diet. For example, lower-ranking predators may perceive a 'landscape of fear' of being attacked or preyed on by higher-ranking predators, leading to behaviours or space use patterns that reduce this perceived risk (e.g. reduced foraging). Removal of the higher-ranking predator may produce changes in these behaviours, with possible flow-on effects for prey or management efficacy.

Demographic changes could encompass increased reproduction, enhanced juvenile survival, or increased immigration into a site, and generally lead to a change in density. Behavioural changes can also result in demographic changes; for example, mice may restrict their foraging in the presence of predators, resulting in lower reproductive rates (Arthur et al. 2004). Disentangling whether responses to selective pest removal are behavioural or demographic is often difficult, particularly if responses are measured solely using indices of relative abundance rather than population density. Increases in indices of relative abundance (e.g. increased mouse tracking-tunnel rates in response to rat removal) could be driven by either enhanced detectability due to behavioural changes, or a true increase in density because of enhanced vital rates.

In situations where multiple invasive species are being targeted for eradication, managers must decide whether to remove all species simultaneously or to target species sequentially. When simultaneous eradications are unfeasible, for instance due to high costs, the sequencing of species removals should proceed in an order that minimises undesired consequences. For example, on the California Channel Islands, introduced pigs provided an abundant food resource for golden eagles, enabling their colonisation of the islands; eagles then preyed heavily on endemic foxes, driving fox populations to near-extinction. Modelling by Bode et al. (2015) proposed to first remove the predator (eagles) before shifting to removal of invasive prey (pigs), in order to minimise the risk to native prey (foxes). The sequencing of removals can also leverage trophic relationships to increase the efficacy of management for subsequent target species. For instance, removing an invasive prey species early in the eradication schedule could reduce the food supply for a top predator ('bottom-up control') targeted later in the sequence, thereby reducing their abundance or increasing their interactions with traps or baits (Norbury 2017). However, there is a risk of these prey manipulations resulting in short-term adverse outcomes if the top predator switches to consuming more native prey (Courchamp et al. 2003).

### **3 Objectives**

- Synthesise published and grey literature to review evidence for the responses of predators (cats, European hedgehogs, house mice, and the seven target PF2050 species) to selective removal of any of the seven PF2050 target species (ship rats, Norway rats, kiore, brushtail possums, stoats, ferrets and weasels) in New Zealand.
- Where possible, clarify the ecological mechanisms that underlie these predator guild responses (e.g. predation or competitive interactions), and assess how and why predator guild responses vary geographically or for different ecosystem types.
- Conduct a stocktake of the relevant data held by eradication and control projects nationally that could be analysed to further investigate predator guild responses.
- Identify critical knowledge gaps that hinder current understanding of predator responses, the ecological mechanisms that drive them, and how they vary across New Zealand's environments.

### **4 Methods**

#### **4.1 Literature review**

For our synthesis of studies on the responses of predator guilds to control, we mainly reviewed studies conducted on New Zealand's North and South Islands, and offshore islands. We also supplemented the review with key findings from international studies, particularly for species that are data poor. We included published evidence (journal articles, books), grey literature (theses, technical reports, conference proceedings), and findings from recent unpublished analyses, where available. Publications were primarily identified using keyword searches in Google Scholar and by following citation trails through reference lists within identified articles or other articles that cited them. We also searched the MWLR digital library for contract reports.

To organise our findings and clarify trends, this review is structured into sections focused on removals of PF2050 target species, as follows:

- section 5.1 Effects of rat (and combined rat and possum) removal
- section 5.2 Effects of mustelid and feral cat removal
- section 5.3 Effects of possum removal.

Within each section we discuss the effects of these removals on other predator species.

#### **4.2 Data stocktake**

For the data stocktake we collated meta-data from multiple national data sources and identified which predator guild interaction(s) each data set could inform, and whether the data described control effort (e.g. kill-trap captures / bait take) or residual abundance of a target species using an independent monitoring method (e.g. mustelid tracking-tunnels in mustelid removals). We then assessed their suitability for analysing predator responses to control using the following criteria.

- Species monitored: is there concurrent monitoring of multiple predator species using suitable methods?
- Robust study design: is there an experimental control (e.g. monitoring prior to predator control or at a non-treatment comparison site)? Is there replication? Were survey methods consistent over time?
- Monitoring duration: is the monitoring period sufficient to measure a response to predator control?

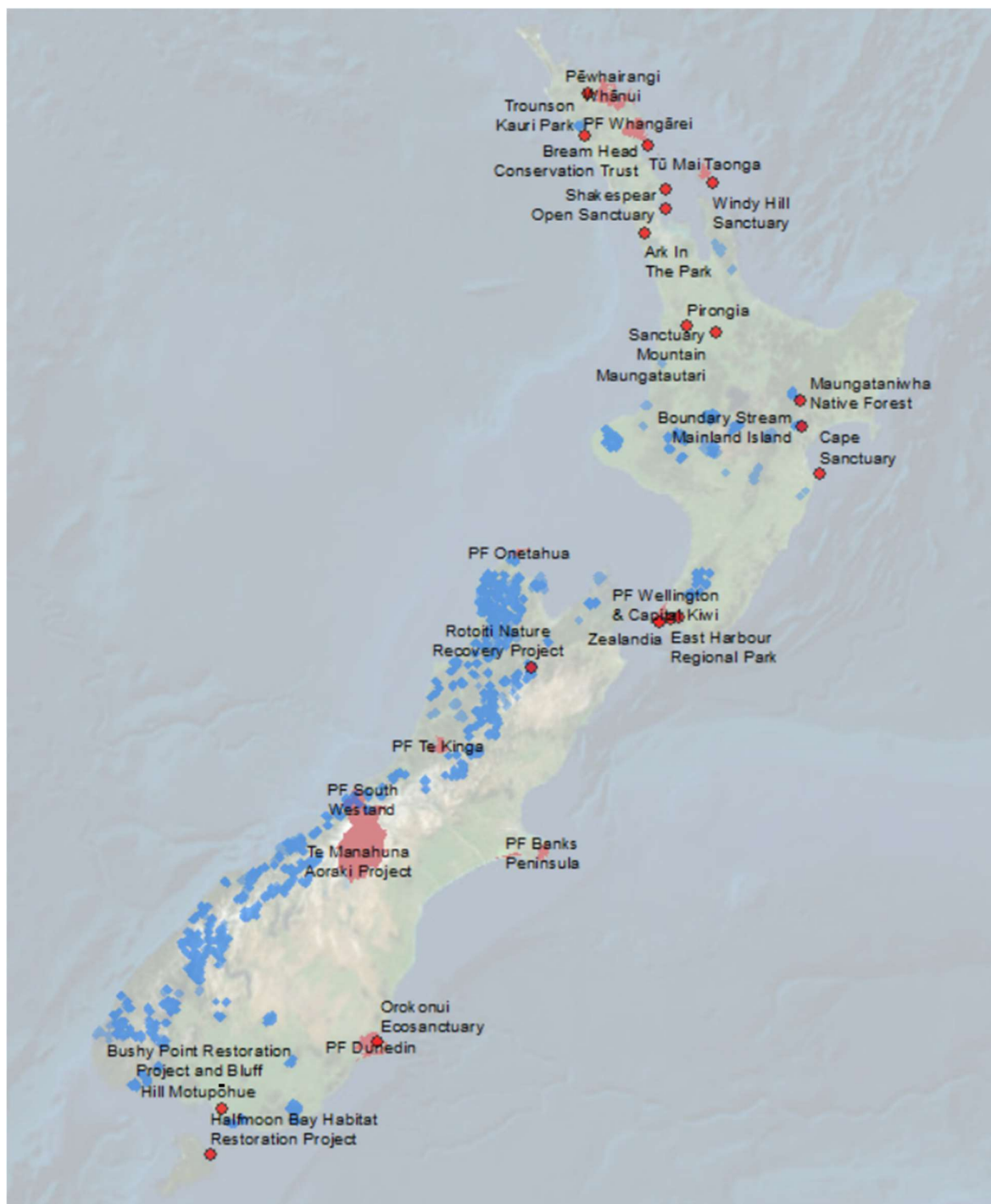
Based on these criteria we allocated a priority level (high, moderate, low or unsuitable) to each data set to identify the best candidates for statistical analyses that could inform predator guild responses to control as follows:

- unsuitable: incidental observations, no survey effort recorded, or pre-control monitoring only
- low: provides estimates of the control effort or residual abundance of at least one PF2050 target species
- moderate: monitors the response of at least one non-target predator species to removal of a PF2050 target species, with pre-treatment/non-treatment monitoring *or*  $\geq 1$  year of post-treatment monitoring
- high: monitors the response of at least one non-target predator species to removal of a PF2050 target species, with pre-treatment/non-treatment monitoring *and*  $\geq 1$  year of post-treatment monitoring.

We included data sets from three sources (see Figure 2 for site locations) that span a range of predator management approaches aimed at eradicating or suppressing one or more PF2050 predator target species.

- 1 PF2050 landscape projects: these target at least one of the seven PF2050 target species but may also manage feral cats and/or hedgehogs.
- 2 Ring-fenced, peninsula-fenced and unfenced ecosanctuaries (which include DOC mainland island projects): for this stocktake we use the Innes et al. (2019) definition of an 'ecosanctuary' to mean 'a project larger than 25 ha implementing multi-species, pest mammal control for ecosystem recovery objectives, and with substantial community involvement'. Ring-fenced ecosanctuaries exclude all mammals except mice, although must occasionally remove reinvasers. Peninsula-fenced ecosanctuaries generally maintain predators at near-zero abundance but have higher risks of reinvasion around the fence ends. Unfenced ecosanctuaries suppress multiple predators (typically at least ship rats, possums and mustelids, although often also feral cats) to varying degrees, largely through trapping and ground-based toxins, with occasional aerial 1080 operations also conducted at some sites.
- 3 DOC's tracking-tunnel database: this records standardised data from rodent (1-night and 14-night) and mustelid (3-, 7 and 21-night surveys) tracking-tunnel surveys at National Predator Control Programme (NPCP) sites. The NPCP aims to protect threatened native species (including rock wrens, kiwi, whio, kea, kākā, kākāriki karaka, mohua, North Island kōkako, bats, *Poweilliphanta* snails, and Archey's and Hochstetter's frogs) at 67 forest sites across New Zealand's North and South Islands, totalling c. 1.8 million ha of public conservation land and including remote, inaccessible areas. These sites span a gradient of climatic and environmental conditions, which are associated with varying temporal dynamics of rodent populations

(Walker, Kemp, et al. 2019). Aerial 1080 toxin is the primary control tool used to suppress ship rats, stoats and possums, with operations at beech forest sites timed to reduce the adverse impacts of irrupting rodent and stoat populations following mast-seeding events. Aerial operations are supplemented with large-scale trapping and ground-based baiting at some sites.



**Figure 2. Locations of PF2050 landscape projects (pink polygons), ecosanctuaries (red circles) and DOC National Predator Control Programme tracking tunnels (blue diamonds) that contributed meta-data to the data stocktake.**

We contacted project managers and GIS/operational leads of the 18 PF2050 landscape projects to request meta-data on their predator monitoring, including data on kill-trap captures and bait take, which can provide estimates of predator management effort (e.g. captures per unit effort). MWLR had previously collated historical monitoring data sets from New Zealand ecosanctuaries, primarily during 2016–2018. We extracted meta-data directly from these data sets but did not attempt to contact ecosanctuary owners to request new information on more recent monitoring.

This is therefore a collation of available pest monitoring in ecosanctuaries up to c. 2018. For ongoing monitoring programmes in ecosanctuaries there are likely to be more recent data available to extend the monitoring duration of these studies, and new monitoring methods may have been introduced that could also strengthen future analyses. Similarly, for the DOC tracking-tunnel database we used an instance of the database extracted in 2020, although more recent data should also be available.

For the stocktake of data from ecosanctuaries and PF2050 landscape projects we recorded the following information:

- project name
- pest species targeted by control
- pest species present at the site
- area of control (ha) (in the case of ecosanctuaries, where management areas differed by target species we recorded the area of ship rat control)
- habitat description
- location
- date control started
- control type (aerial, ground-based, or aerial + ground-based)
- control method summary
- experimental design (monitoring before and after control, BA, in a managed and unmanaged 'non-treatment' area, CI ('control-impact'), or both, BACI)
- replicated sites (yes/no)
- predator monitoring (or trap catch / bait take) method
- predator monitoring follows standard operating procedure (yes/no)
- predator monitoring timing (e.g. annual, quarterly, one-off)
- predator monitoring duration
- years in which monitoring was undertaken
- availability of GIS data for device locations.

We also asked PF2050 landscape project managers whether:

- their data could be shared for potential future analyses of predator guild responses to control
- data were already available on a public repository (e.g. trap.nz, which records trap, bait, monitoring, and biodiversity outcome data)
- there have been past formal analyses or publication of the data.

Managers could also (optionally) provide further details on monitoring survey layout (e.g. numbers of devices and device spacings), and, if applicable, whether past analyses had shown a change in monitored predator populations in responses to predator control. Our data stocktake is presented in section 5.4.

Finally, in section 5.5, we summarise the general findings from sections 5.1–5.4 and highlight critical knowledge gaps.

## **5 Review findings**

### **5.1 Effects of rat (and combined rat and possum) removal**

#### **5.1.1 Effects on other rodents**

Rat removal often occurs in tandem with possum removal, so there are few studies examining residual pest responses to rat removal only. Most studies have examined the response of mice to the removal of ship rats, or to the removal of both ship rats and possums.

Mice have generally responded positively to the removal of ship rats only, or ship rats and possums, with responses covering both short-term behavioural responses, indicating increased detectability (e.g. Brown et al. 1996 – rat removal only) and demographic responses of increased density due to enhanced vital rates (Ruscoe et al. 2011 – rat and possum removal; Bridgman et al. 2018 – rat and possum removal). However, most studies used indices of relative abundance to measure mouse response and therefore could not disentangle whether responses were behavioural or demographic.

There are several mechanisms by which ship rats may have an impact on mice. Ship rats prey on mice directly, which could reduce mouse populations numerically (Bridgman et al. 2013), although this effect is probably quite weak. Predation could also impose a ‘landscape of fear’ effect on mice, which may reduce mouse foraging opportunities and thereby curb their full reproductive potential (e.g. Arthur et al. 2004). Finally, rats may outcompete mice for food resources, through either interference or exploitation competition, and thereby reduce their populations numerically.

Studies of mouse density and population dynamics in the complete absence of other mammalian predators or competitors have shown mice reaching high densities (Wilson et al. 2018), although maximum observed densities differ by habitat. This suggests that either top-down predation effects (through direct predation or through landscape of fear effects), competition, or both, can act to limit mouse populations, but which of these mechanisms is the main limiting factor is currently unknown, and densities following predator removal will probably vary depending on the bottom-up effect of food supply.

Two studies failed to find a positive response of mice to rat control. Knight (2025) did not detect increased mouse tracking when ship rats were controlled in urban Dunedin, although rats were already at low densities (generally less than 10% rodent tracking index, RTI) prior to control, and so a large response by mice might not have been expected. Also, Carpenter et al. (unpublished) did not detect an increase in mouse tracking in response to rat control, or to combined rat and possum control, in podocarp-broadleaf forest in Te Urewera in the eastern North Island.

Aerial 1080 operations reliably reduce the tracking rates of ship rats as well as reducing possum numbers to low levels where they are present (Nugent et al. 2019), but mice are known to be killed less consistently than ship rats in aerial 1080 operations (Fisher et al. 2009; Nugent et al. 2011). Analysis of DOC's long-term tracking-tunnel data set (Walker, Kemp & Elliott, unpublished) shows that aerial 1080 operations between 2013 and 2022 suppressed mouse-tracking rates less consistently than the tracking rates of ship rats, especially in intermediate and colder zones of beech-forested regions. Median mouse-tracking rates became higher than in unmanaged sites within 6 months of operations. In most regions the mouse 'rebounds' peaked within a year of the operation, and ended within about 18 months of an aerial 1080 operation (although rebounds could last for up to 3 years after an operation in some regions). Mouse rebounds were briefer in warmer, more productive environments where ship rats recovered more strongly from aerial 1080, suggesting the effects of ship rat recovery on mice quickly outweighed any bottom-up effect of greater food resources.

The effects of selective removal of one rat species on the other rat species are understudied, although studies on niche partitioning and behaviour have generally shown that in New Zealand forest habitats ship rats often have a competitive advantage over both Norway rats and kiore (King et al. 2011; Harper et al. 2005). Harper (2006) attempted to test whether ship rats were excluding kiore from forested habitat on Pearl Island (off Rakiura / Stewart Island) by selectively removing ship rats from this habitat type. However, that experiment failed because kiore were also found to be present (i.e. they were already sympatric with ship rats in forest), which demonstrates that kiore can be present but hard to detect in the presence of ship rats.

An experimental removal of kiore on Raoul Island from 1994 to 1996 showed that kiore were trappable only after Norway rat numbers were reduced by half, suggesting intense interference competition or intra-guild predation (Harper & Veitch 2006). However, kiore were abundant and easily trapped within certain habitats on Kapiti Island in the presence of Norway rats, although Norway rats may have excluded kiore from other habitat types (Bramley 2014). The research to date suggests that interactions and strength of dominance between the three species are nuanced and habitat-specific, and that there is potential for changes in behaviour and density by Norway rats and kiore if ship rats were selectively removed without also removing the other two species.

### **5.1.2 Effects on other pest mammals**

We could find only one study that had explicitly examined how mammals other than mice responded to control of rats alone. Carpenter et al. (unpublished) observed increased detections of possums (through a chew-card index) on blocks where rats were controlled in Te Urewera, indicating some form of competitive release.

We did not find any studies that examined how mustelids respond to the removal of rats alone, although Murphy et al. (1998) examined how mustelid numbers (measured through a trap catch index) responded to combined rat and possum poison operations in two North Island podocarp-broadleaf forests. However, the response of stoats to rat and possum removal was difficult to assess because stoats were also killed by secondary poisoning in the operation (i.e. stoats died after consuming other animals that had eaten the bait).

Knight (2025) examined the response of hedgehogs (using a tracking-tunnel index) to the control of ship rats and possums in urban Dunedin and found no effect. The limited effect of controlling rats was not surprising because rat tracking was low in both treated and non-treated areas.

## **5.2 Effects of mustelid and feral cat removal**

In New Zealand, three invasive mustelid species (ferrets, stoats and weasels, all members of the genus *Mustela*) coexist with just one larger carnivore (feral cat) and with smaller mesopredators (Norway rats, ship rats, and mice). Although cats are not currently a PF2050 target species, we include them here because predator control often targets cats and mustelids simultaneously, making it difficult to disentangle their effects.

In general, the removal of cats would be expected to benefit populations of mustelids and rodents, and the removal of mustelids would be expected to benefit rodent populations. However, a dominance hierarchy is likely to exist among New Zealand's three invasive mustelids: based on their size differences, taxonomic relatedness, and propensity for interspecific killing, ferrets are expected to dominate over stoats and weasels, and stoats are expected to dominate over weasels where they co-occur (Clapperton & Byrom 2005; King & Murphy 2005). Therefore, the removal of a larger mustelid species (e.g. ferret) would be expected to benefit a smaller mustelid species (e.g. stoat). Furthermore, the release of smaller mustelid species following the removal of feral cats or larger mustelid species might in turn dampen any release of a rodent population. Predator guild responses and cascades such as these are also likely to vary geographically and with ecosystem type; for example, mice might show a weaker effect of release from mustelid predation in a more complex habitat that provides more refuges for mice.

### **5.2.1 Effects of cat removal on ferrets**

Ferrets are the second-largest invasive predator in New Zealand. Ferrets and cats are frequently sympatric in ecosystems with high rabbit abundance, where coexistence may be achieved by the use of different habitat strata and contrasting hunting strategies (Alterio et al. 1998; Norbury et al. 1998). Interference competition between ferrets and cats has been recorded. For example, a large cat was observed trying to steal a rabbit from a ferret, but the ferret retained the kill without harm to either predator (Peach 2005). A study by Ragg et al. (2000) recorded interactions between cats and ferrets at carcasses, and in seven out of eight instances, ferrets maintained possession or displaced the cats from the carcass.

In Hawke's Bay farmland, ferrets and cats were observed to have similar spatial distribution and temporal activity, as both dominant predators and their prey were crepuscular and nocturnal (Garvey et al. 2022). There was no evidence of competitive exclusion, and in fact ferrets were more than twice as likely to be detected if a cat was recorded at that site. Cats and ferrets co-occurred at over a third of monitoring sites, with sequential sightings less than 5 hours apart, suggesting that, although cats compete with ferrets for resources, removal of cats is unlikely to have a major impact on ferret populations or their niche breadth.

### **5.2.2 Effects of cat and ferret removal on stoats**

As one of the smallest members of the order Carnivora, stoats elsewhere in the world suffer high mortality and intense persecution from larger predators, particularly canids (e.g. foxes, coyotes), felids (e.g. feral cats), and raptors (e.g. hawks, owls) (Jedrzejewska & Jedrzejewski 1998; King & Powell 2007). In New Zealand, stoats coexist with just two larger predators, cats and ferrets, and removal of these predators can result in competitive release of stoats. Ferrets and stoats have comparable ecological niches, and ferrets have occasionally been known to kill stoats (Wodzicki 1950; Erlinge 1983). Cats limit stoat populations through predation as well as competition: the killing of stoats by both domestic and feral cats has frequently been reported (e.g. Fitzgerald & Karl 1979; Gillies & Clout 2003; Flux 2007).

In a control operation in Hawke's Bay farmland, ferrets and cats were removed from a 7 km<sup>2</sup> area to test whether removal of larger predators benefited stoats (Garvey et al. 2022). Stoats exhibited behavioural release in accordance with the mesopredator release hypothesis, as they increased in detections immediately after the control operation and were the most common predator 6 months after the operation. These observations align with other studies where stoats increased following the control of cats and ferrets (Gibb et al. 1978; Pierce 1987).

Alterio and colleagues studied the diets, movements, and temporal activity patterns of stoats, cats, and ferrets in coastal grassland in Otago. There was considerable dietary overlap among the three species (Alterio & Moller 1997), and radio-tracking revealed evidence of temporal and spatial partitioning (Alterio et al. 1998). Alterio et al (1998) hypothesised that stoats altered their spatial activity patterns to avoid competition and/or predation from the larger predators. Similarly, where stoats coexist with ferrets and cats in mixed pastoral and scrub farmland, the larger predators exhibited 'resource matching', whereby their spatiotemporal activity matched their primary prey. In contrast, stoats exhibited 'safety matching', with activity patterns opposing those of the larger predators, despite reduced overlap with prey (Garvey et al. 2022).

Captive trials can also help illuminate trophic hierarchies and the potential outcomes of predator control. Garvey et al. (2015) observed the foraging behaviour of stoats in outdoor arenas with a cat or ferret caged separately at one end of the arena. Stoats deferred to both larger predators, reducing foraging behaviour and food intake while increasing defensive behaviours (e.g. concealment, freezing, fleeing). Stoat behavioural responses to ferrets and cats in captivity align with observed distribution patterns in the wild and support the conclusion that stoats will benefit from the removal of these dominant adversaries.

### **5.2.3 Effects of stoat removal on weasels**

Where weasels and stoats coexist, stoats are usually dominant due to their larger physical size and their social behaviours (Sheffield & King 1994), but weasels can better exploit small rodent populations (King & Moors 1979; Erlinge & Sandell 1988; King & Murphy 2021). Coexistence can also be facilitated by employing different hunting strategies and by reproductive adaptations, as weasels can reproduce in response to increases in prey availability (Bonesi et al. 2004; King & Moors 1979). Stoats dominate weasels when they meet and may restrict their distribution and inhibit their hunting (King 1989).

Weasels exhibit a reciprocal distribution with stoats in parts of their native range, being rare or absent in optimal prey habitats, but occurring more frequently in less productive areas (Erlinge & Sandell 1988). Overall, the literature is consistent in showing that weasels are vulnerable to interference competition from stoats, so that the control of stoats might lead to the release of weasels.

Secondary poisoning of stoats in aerial 1080 operations (Murphy et al. 1998; Gillies & Pierce 1999) could potentially lead to a competitive release of smaller weasels, which can reproduce more quickly than stoats and might benefit from the temporary increases in mice that predictably follow aerial 1080 operations (King & Moors 1979). While there are some anecdotal accounts of weasels having been caught at higher rates after aerial 1080 operations in forests than before (see Haworth 2018), recent analyses show that mustelid tracking rates recover at rates that are biologically plausible for annually breeding stoats (Walker, Kemp & Elliott, unpublished), remaining lower than in unmanaged forests for 4 years in cooler southern and eastern South Island regions, for 3 years in warmer South Island regions, and for 18 months across most of the North Island. Mustelid recoveries therefore followed those of ship-rat-tracking rates after 1080 operations rather than following the more rapid and short-lived responses of mice. Therefore, the data provide no evidence that 1080 operations regularly lead to substantial increases in weasel populations.

#### **5.2.4 Effects of stoat removal on rodents**

Different place-based studies on the downstream consequences of stoat trapping on rodents have produced inconsistent results. Until recently it was largely accepted that trapping stoats had little effect on ship rats and mice in the predator community. In a field study in the eastern North Island, Blackwell et al. (2003) measured ship-rat-tracking rates, with and without stoats, through a seed masting event in beech forest. They found that removing stoats made no difference to ship rat captures, either early or at the peak of the rat irruption, while the role of stoats in the decline and low phases of rat cycles was still unclear. Then Jones et al. (2011) analysed data from stoat stomachs in three *Nothofagus* forest areas in the southwest of New Zealand for mice, and from podocarp forest at Ōkārito in south Westland for ship rats. They estimated that daily kill rates of rodents were relatively low, suggesting that the top-down effect of stoats on rodents must be weak. Finally, Ruscoe et al. (2011) found no clear evidence that rodents were released in an experimental selective removal of stoats from podocarp-broadleaved forest in the central North Island.

Contrary to these results, Whaitau et al. (2023) showed that a non-treatment site (Rotorua) in Nelson Lakes National Park had significantly lower ship-rat-tracking rates than in four sites with stoat trapping in the Park (Rotoiti, Lakehead, Big Bush, and Black Valley) and two stoat-trapped sites in Kahurangi National Park (Flora and Cobb). The analysis controlled for other management treatments (snap-trapping of rats, ground-laid diphacinone and brodifacoum, and aerially applied 1080). Whaitau et al. (2023) concluded that stoat control by mustelid trapping had led to the mesopredator release of ship rats.

Norbury et al. (2013) also found some evidence for mesopredator release of rodents in a study of non-forest (grassland) systems in Otago. Experimental removals of cats, stoats, ferrets and hedgehogs from grasslands led to an increase in mouse numbers at one site with regular high food supply (pasture seed), but not at a second site with episodic and usually lower food supply

(masting tussock). This result suggested that the mesopredator release of mice following predator control is mediated by food supply (Norbury et al. 2013).

Analyses of data from DOC's tracking-tunnel network (Walker, Kemp, Pickerell et al., unpublished) also suggest that stoat trapping can lead to mesopredator release of rodents, although the effects vary substantially across major environmental gradients and over time. The team collated comprehensive data on stoat-trapping effort from 2012 to 2021 in two large areas of the South Island (in Fiordland National Park and Kahurangi National Park) and analysed the effects of stoat-trapping effort on ship-rat- and mouse-tracking rates while also accounting for the timing and effects of background predator control operations. The two sites had quite different background rodent-tracking patterns: ship-rat-tracking rates were considerably lower in Fiordland than in Kahurangi, even in zones of similar mean annual temperature and in most years, while mouse-tracking rates were higher in Fiordland than in Kahurangi in most years.

These unpublished data show that the tracking rates of ship rats were higher in areas subject to higher stoat-trapping effort in all Fiordland environments in the summers of 2017 and 2020. This result suggests that stoat trapping led to the mesopredator release of ship rats during the two rat irruptions that followed beech mast seedfall (but not in other years, when rat-tracking rates were very low regardless of stoat trapping). In cool environments in Kahurangi, ship-rat-tracking rates were higher in areas with higher stoat trapping effort in 2015, 2017 and 2020. Again, this result is consistent with stoat trapping leading to mesopredator release of ship rats in the summers of mast seedfall-driven irruptions, but not in other years. However, unexpectedly, in warmer forests in Kahurangi, ship-rat-tracking rates were actually lower in areas with higher stoat-trapping effort than in areas with less (or without) stoat trapping.

These unpublished tracking rate data indicate that mesopredator release of ship rats by stoat trapping is more important in cooler environments, which may explain why two major field studies in North Island forests (Blackwell et al. 2003; Ruscoe et al. 2011) found little evidence for it. Although the estimated effects of stoat trapping on ship rats in Fiordland were small at most realistic levels of trapping effort (making less than a 5% difference to tracking rates at fewer than one trap set per kilometre, per season), those effects are proportionally large in the cool environments where ship rats are usually rare or absent. They could therefore represent a meaningful shift in predator guild for fauna dependent on thermal refuges in cooler environments (Walker, Monks et al. 2019).

Walker, Kemp, Pickerell et al. (unpublished) showed that mouse-tracking rates increased with stoat-trapping effort in Fiordland in most years in all but the warmest (lowest-elevation) environments, indicating that stoat trapping usually led to a mesopredator release of mice regardless of whether or not there was a food pulse. Mouse-tracking rates were also higher under stoat trapping in the cooler, higher environments of Kahurangi in the 2013, 2015, and 2020 summers when mice irrupted. There was little evidence that stoat trapping affected mouse-tracking rates in lower, warmer Kahurangi forests, even in summers of mouse irruptions. If (as suggested by Jones et al. 2011) stoats consume too few rats and mice to have an important effect on their numbers in irruptions, then clear increases in rodent-tracking rates under stoat trapping must be largely a result of behavioural changes. However, studies involving density estimates would be needed to test this.

## 5.3 Effects of possum removal

### 5.3.1 Effects of possum removal on rodents

Because possum control operations often also remove other invasive predators, either deliberately or incidentally (e.g. aerial 1080 removes possums, rats and stoats), there are relatively few studies that have published information on the outcomes of removing only possums for the predator guild.

Carpenter et al. (unpublished) carried out experimental possum-only control in podocarp-broadleaf forest in Te Urewera and found that rat-tracking rates increased relative to non-treated blocks. The abundance of seed increased with possum-only control, suggesting that there was more food available for ship rats when possums were removed. Similarly, a study by Sweetapple et al. (2006) in podocarp-hardwood forest in southeastern Bay of Plenty reported increases in rat-tracking rates following a 3-month pulse of possum-only ground control (using leg-hold trapping and sodium cyanide paste), peaking at levels 1.7–1.9 times higher than tracking rates of non-treatment blocks at 18 months after control, before declining to similar rates as the non-treatment blocks. Following control, a peak in mouse-tracking rates occurred later in the treatment block than in the non-treatment block, but the size of the peak was not significantly different from the non-treatment. Conversely, Wilson (2017) found no increase in rat tracking in mixed habitats across the Otago Peninsula in response to possum control using toxins and traps.

Populations of rodents can recover more quickly than possums from control operations that suppress both. If rodents experience less competition for food while possum populations remain small, their abundance may 'rebound' (i.e. recover to higher levels than were seen before possum control). Rebounds are commonly seen in mice. For example, on Rangitoto Island, Miller and Miller (1995) monitored rodent abundance by snap-trapping before and after an aerial 1080 operation that targeted possums and wallabies. Capture rates of mice and ship rats declined immediately after the aerial 1080 operation, but mouse captures increased around six-fold over the following 5 months (Miller & Miller 1995). DOC's tracking-tunnel data also show that rapid increases in mouse-tracking rates usually follow aerial 1080 operations (see section 5.1).

Several place-based studies that have monitored pests following 1080 operations (Innes et al. 2004; Sweetapple et al. 2006; Sweetapple & Nugent 2007; Griffiths & Barron 2016; Kemp et al. 2018; Bell et al. 2021) have found that, after an initial period of suppression, ship rat activity recovered to higher levels than in equivalent unmanaged forests for a period of time. And although most studies relied on indices of activity, Ruscoe et al. (2011) used mark-recapture analysis and confirmed that ship rats also increased in density during the rebound.

In their study of North Island forests, Sweetapple and Nugent (2007) showed that seeds and fruit dominated the diet of both ship rats and possums after possum control. The relative importance of seeds and fruit in ship rat diet exceeded that in other NZ ship rat diet studies, which were generally dominated by invertebrates and green plant parts. They therefore inferred that ship rat abundance recovered to higher levels than in equivalent unmanaged forests as a consequence of greater availability of, or reduced competition for, seeds and fruit. In other words, the main mechanism driving the rat 'rebound' was release from interspecific competition with possums. However, as no diet analyses were conducted prior to possum control, it is unclear to what extent this level of seed/fruit consumption by ship rats differed from pre-control levels at that specific site.

Analyses of ship-rat-tracking rates in DOC's tracking-tunnel data set (Walker, Kemp & Elliott, unpublished) showed that rat rebounds (i.e. recovery of ship-rat-tracking rates to higher levels than in equivalent unmanaged forests) following aerial 1080 varied widely among regions and temperature zones across public land. Ship rat rebounds were generally largest in floristically diverse, lower-elevation zones of northern and western regions, and smallest in southern and eastern regions of the South Island, especially those lacking large, lower-elevation tracts of red beech, hard beech, and/or rimu forest, where both possums (Forsyth et al. 2018) and ship rats (Walker, Kemp, et al. 2019) are normally more abundant. Higher-elevation forests in the west and north of the South Island, which adjoin extensive forests of red beech, hard beech and/or rimu at lower elevations (e.g. the Nelson Lakes and Kahurangi regions), experienced much larger ship rat rebounds than the southern and eastern forests which lack extensive, more-productive low-elevation forest zones (e.g. Fiordland, Canterbury). Ship rat rebounds also lasted longer in warmer, northern regions, although nowhere did they last as long as the 'up to 6 years' suggested by Sweetapple & Nugent (2007) in the North Island forests they studied.

Overall, these environmental patterns of ship rat rebounds are consistent with competitive release, because the size of the rebound reflects the expected quantity of residual food after mammal populations are reduced by an aerial operation. However, because both ship rats and possums are killed in 1080 operations, and both are more common in warmer environments, the rebound pattern does not reveal whether the release is from intraspecific competition or interspecific competition, or both.

Stoats are also killed by aerial 1080 operations, and lower rates of predation by stoats might also contribute to ship rat rebounds (i.e. through mesopredator release). However, DOC's tracking-tunnel data set (Walker, Kemp & Elliott, unpublished) shows that the timing of recoveries of mustelid tracking rates after aerial 1080 follows different regional and environmental patterns to ship rat rebounds. For example, ship rat rebounds are largest and last longest in the warmer North Island, where mustelid tracking rates initially lowest and recovered most rapidly. Conversely, ship rat rebounds after 1080 operations are smaller and briefer in cool southern regions, where stoat-tracking rates were typically higher and took many years to recover after 1080. If mesopredator release played an important role in promoting ship rat rebounds, we would have expected the opposite environmental pattern (i.e. larger, rather than smaller rat rebounds in cooler environments).

### **5.3.2 Effects of possum removal on other pest mammals**

Stoat abundance is driven largely by prey abundance (although suppression of stoats by larger predators may also be important – see section 5.2). Thus, if rodent numbers increase following possum removal, this could theoretically lead in turn to an increased abundance of stoats. However, a study by Sweetapple et al. (2006) in North Island podocarp-hardwood forest did not find evidence of significant mid-term (1- to 3-year) increases in either mouse or stoat abundance compared to unmanaged areas (although the peak in mouse abundance occurred later in the treatment block) (Sweetapple et al. 2006).

Poison baiting that targets possums can also kill other invasive predators through secondary poisoning (i.e. predators do not eat the bait themselves but die after consuming other animals that have been poisoned). For example, Murphy et al. (1999) monitored the outcomes of a 1080 operation targeting possums and rats in North Island podocarp-broadleaved forest. Tracking rates

of stoats declined to zero after 1080 baiting, and all of 13 radio-collared stoats died. Residue of 1080 was found in 12 of the 13 dead stoats, indicating secondary poisoning as the likely cause of death (Murphy et al. 1999). Tracking rates of rats declined after 1080 baiting, but tracking rates of mice increased (Murphy et al. 1999).

Gillies & Pierce (1999) monitored the fates of feral cats and mustelids after a 1080 operation targeting possums and rodents in mixed kauri-podocarp hardwood forest. Six feral cats, one stoat, and one ferret were radio-collared before baiting, and all were killed by secondary poisoning. The remains of rodents and/or possums were found in the guts (Gillies & Pierce 1999).

Little is known about the potential effects of possum removal on predators that eat possums. For example, possums were an important food for feral cats in the Orongorongo Valley, being found in up to 38% of cat scats in winter and spring (Fitzgerald & Karl 1979). While some of the possum flesh consumed may have been scavenged, the authors considered that cats could easily kill young possums (Fitzgerald & Karl 1979). However, the functional and numerical responses of feral cats to possum removal are unknown.

## **5.4 Data stocktake**

A table of all collated predator monitoring meta-data from PF2050 landscape projects, ecosanctuaries, and DOC's tracking tunnel database is provided in Appendix 1 (and see Figure 2 for project locations).

Twelve PF2050 landscape projects responded to our request, providing predator monitoring meta-data for 51 data sets from 20 management sites. Of these management sites, three target possums only (ranging from over 1,400 ha to 23,000 ha), one stoats only (24,000 ha), one ship rats and kiore only (100 ha), one feral cats only (4,560 ha), while the remaining seven target multiple predators (1,000 ha to 104,000 ha). Nine sites were predominantly open-country habitats (one was a sand dune and mānuka/kānuka scrub ecosystem, six included areas of podocarp-broadleaved forest, and one included drylands), four were in urban areas, three were in podocarp-broadleaved forest, one was in a braided river, and one was in an alpine environment.

Trail cameras were the most common monitoring method (21 data sets; one from a one-off survey), although survey layout varied between sites from one device per hectare to one per 35 hectares. Other methods comprised chew-cards (six data sets), tracking tunnels (three rodent data sets; one mustelid), wax tags (four data sets), dog surveys or incidental observations (seven data sets), and possum residual trap catch indices (RTCIs; one data set). Twelve sites also record kill-trap captures and/or bait take, which could inform estimates of management effort. Projects were all established within the past 7 years, with one starting predator control as recently as May 2025, and the duration of the monitoring studies ranged from one-off surveys to 6 years. Eight sites had conducted monitoring prior to control ('pre-treatment') and/or at an unmanaged comparison site ('non-treatment').

We extracted meta-data from 36 predator monitoring studies conducted in 20 ecosanctuaries: three ring-fenced projects (225–3,400 ha), three peninsula-fenced projects (500–2500 ha), and 14 unfenced mainland islands (90–2,270 ha for ship rat control, including three DOC mainland islands). These projects are largely in forest ecosystems (nine projects in podocarp-broadleaved, one in

beech, three in mixed beech-podocarp-broadleaved, and four in mixed kauri-podocarp-broadleaved forest) or in open country / regenerating coastal forest (three projects).

Rodent-tracking tunnels were by far the most common method (19 data sets; eight recording rats only, eleven recording all rodents), collected by all but one project, while mustelid-tracking tunnels were used by four projects (two peninsula-fenced ecosanctuaries, two unfenced mainland islands). Possums were monitored in nine unfenced mainland islands using RTCIs (five data sets), wax tags (three data sets), and chew sticks (one data set). In particular, the three DOC mainland island projects had concurrent monitoring of rodents, possums and mustelids (two projects), or of rodents and possums (one project). Most ecosanctuaries were established in the late 1990s or early 2000s, so study durations were generally longer than for PF2050 landscape projects, ranging from one-off surveys up to 22 years (average of 11.5 years). Twenty-four studies had conducted pre-treatment monitoring and/or non-treatment monitoring.

The DOC tracking-tunnel database comprised data from 53 NPCP sites, organised into 119 'line set groups' of tunnel lines. These sites span elevations ranging from 0 to 1,830 m a.s.l, mean annual temperatures from 3 to 14 °C, and mean annual rainfall from 750 mm to 7,960 mm, and include all EcoSat-categorised native forest and subalpine scrub classes. The frequency and duration of past aerial 1080 operations at monitored sites varied from a single operation to eight operations, conducted over periods of up to 26 years. Of the 53 sites, 42 contained non-treatment line sets (in 103 set groups) that had not had aerial 1080 control during the monitoring study period. Monitoring records started as early as 1996, and study durations ranged from one-off surveys to 21 years, with an average of 3.4 years.

In addition to these long-term tracking-tunnel monitoring data, DOC has recently established a new framework for monitoring predator and biodiversity outcomes at NPCP sites. Alongside three-per-year tracking tunnel surveys for rodents and mustelids, the new framework deploys unbaited trail cameras annually from November to March (and acoustic recorders for diurnal birds and bats in November, and nocturnal birds in February) to monitor all introduced mammals and ground birds at these forested sites. This concurrent monitoring of multiple target and non-target species could inform estimates of guild responses to aerial 1080 control operations in forest ecosystems. There has been a staged rollout of this framework, with data recorded at 500 sites over 3 years to date.

Except for the DOC tracking-tunnel database, the survey methods used to monitor predator species varied widely between different projects, and were sometimes inconsistent within projects over time. For example, tracking-tunnel monitoring for rodents did not always follow conventional 1-night survey standard operating procedure methods, particularly within fenced ecosanctuaries, where longer (3-, 7-, 21- or 28-night) surveys are often used to increase detectability in tunnels at low population densities. Similarly, the length of mustelid tracking-tunnel surveys was variable across sites. A wide variety of methods (RTCI and 1-, 3- or 7-night wax tags and chew-cards) are used to monitor possums. While trail cameras have the advantage of being able to concurrently monitor multiple species, the layout (e.g. device spacing) and set-up (e.g. bait type, camera position) affects the detectability of different species. This variability in monitoring methods limits the potential for data to be aggregated across multiple sites. However, several data sets identified through this stocktake have good potential for future within-site analyses of guild responses.

In total, we identified 22 data sets from PF2050 landscape projects and ecosanctuaries ranked as medium (12 data sets) or high (10 data sets) priority that hold potential for future analyses of

predator guild responses. Also, the DOC tracking-tunnel database and new NPCP monitoring are high priorities for analysis according to our assessment criteria. All these data sets are summarised in Table 1.

**Table 1. Summary of data sets from PF2050 landscape projects, ecosanctuaries and DOC NPCP sites, ranked as medium or high priority that could potentially inform analyses of predator guild interactions**

| <b>Predator guild interaction(s) data could inform</b>                                                 | <b>No. of data sets (no. of sites)</b> | <b>Monitoring methods (no. of data sets)</b>        | <b>Habitats</b>                                                                              | <b>Range of post-treatment monitoring duration</b>                               |
|--------------------------------------------------------------------------------------------------------|----------------------------------------|-----------------------------------------------------|----------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| <b><i>Eradication of all introduced mammals except mice</i></b>                                        |                                        |                                                     |                                                                                              |                                                                                  |
| Mouse responses                                                                                        | 3 (3)                                  | Rodent tracking tunnels (2); snap-trap captures (1) | Podocarp-broadleaved forest; podocarp-broadleaved / exotic forest                            | 5–14 years                                                                       |
| <b><i>Sustained suppression to near-zero abundance of all introduced mammals except mice</i></b>       |                                        |                                                     |                                                                                              |                                                                                  |
| Mouse responses                                                                                        | 3 (3)                                  | Rodent tracking tunnels                             | Open country; open country / farmland / exotic / kānuka forest                               | 6–14 years                                                                       |
| <b><i>Selective possum removal</i></b>                                                                 |                                        |                                                     |                                                                                              |                                                                                  |
| Rat and mouse responses                                                                                | 2 (1)                                  | Rodent-tracking tunnels; wax tags                   | Open country with mānuka and/or kānuka, and sand dunes                                       | 6 months                                                                         |
| Mustelid, feral cat, and rat (and possibly hedgehog) responses                                         | 2 (2)*                                 | Trail cameras                                       | Open country / mānuka and/or kānuka / sand dunes; open country / podocarp-broadleaved forest | 6 months – 3 years                                                               |
| <b><i>Selective ship rat and kiore removal (mustelids, Norway rats, possums, hedgehogs absent)</i></b> |                                        |                                                     |                                                                                              |                                                                                  |
| Mouse responses                                                                                        | 1 (1)                                  | Rodent-tracking tunnels                             | Podocarp-broadleaved forest                                                                  | 1 year                                                                           |
| <b><i>Selective feral cat removal (mustelids, Norway rats, possums, hedgehogs absent)</i></b>          |                                        |                                                     |                                                                                              |                                                                                  |
| Ship rat and kiore responses                                                                           | 1 (1)                                  | Trail cameras                                       | Podocarp-broadleaved forest                                                                  | 1 year                                                                           |
| <b><i>Possum and stoat removal</i></b>                                                                 |                                        |                                                     |                                                                                              |                                                                                  |
| Weasel and feral cat responses                                                                         | 1 (1)                                  | Trail cameras                                       | Alpine                                                                                       | 3 years                                                                          |
| <b><i>Possum, rat, and mustelid removal (sustained suppression)</i></b>                                |                                        |                                                     |                                                                                              |                                                                                  |
| Mouse responses                                                                                        | 2 (2)                                  | Rodent-tracking tunnels                             | Podocarp-broadleaved forest; urban                                                           | 5–7 years                                                                        |
| Feral cat responses                                                                                    | 1 (1)                                  | Trail cameras                                       | Open country / farmland / gorse/broom / podocarp-broadleaved forest                          | 4 years                                                                          |
| <b><i>Possum, rat, and mustelid removal (pulsed aerial 1080 control)</i></b>                           |                                        |                                                     |                                                                                              |                                                                                  |
| Mouse, rat and mustelid responses                                                                      | 2 (53)                                 | Rodent-tracking tunnels; mustelid tracking tunnels  | Various native forest types                                                                  | 1 week – 7.5 years since last 1080 operation (total study durations: 0–21 years) |
| Rodent, stoat, possum, hedgehog and cat responses                                                      | -                                      | New NPCP trail camera monitoring framework          | Various native forest types                                                                  | -                                                                                |

| Predator guild interaction(s) data could inform                                                             | No. of data sets (no. of sites) | Monitoring methods (no. of data sets) | Habitats                                                                                      | Range of post-treatment monitoring duration |
|-------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------------|-----------------------------------------------------------------------------------------------|---------------------------------------------|
| <b><i>Possum, Norway rat, hedgehog removal</i></b>                                                          |                                 |                                       |                                                                                               |                                             |
| Ferret responses                                                                                            | 1 (1)                           | Trail cameras                         | Open country / farmland / dryland                                                             | 2 years                                     |
| <b><i>Possum, rat, mustelid and feral cat (and incidental hedgehog) removal (sustained suppression)</i></b> |                                 |                                       |                                                                                               |                                             |
| Mouse responses                                                                                             | 5 (5)                           | Rodent-tracking tunnels               | Beech / podocarp-broadleaved / podocarp-broadleaved-kauri / beech-podocarp-broadleaved forest | 18–22 years                                 |

\*One data set includes kiore.

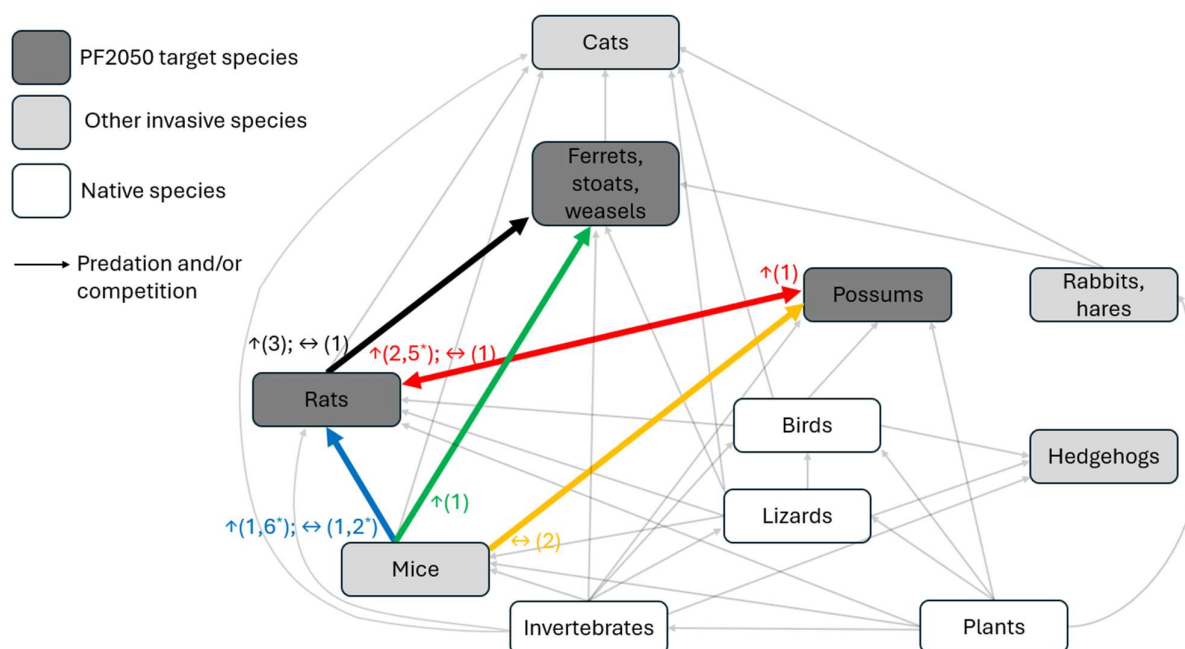
## 5.5 Summary of studied responses and knowledge gaps

A summary of all the reviewed studies measuring predator responses to removal of one or more PF2050 target species is provided in Appendix 2, Table A1, with more detailed study attributes and context for predator responses provided on MWLR's DataStore repository (link provided in Appendix 1).

In total, we identified 27 studies reporting predator responses to PF2050 target species removal (overviews in Table 2 and Figure 3), with the vast majority measuring rodent responses to combined rat and possum removal (13 studies). Increasing mouse and rat (mainly ship rat, although species was not always specified) activity or densities were frequently observed following the removal of both rats and possums (e.g. aerial 1080 operations), although there is some evidence that the mouse response is not universal and is likely to be mediated by food supply. Specific species interactions that emerged as key gaps include:

- 1 Possum responses to rat-only removal: although rat responses to possum (or combined rat and possum) removal are the most highly studied interaction, only one study (Carpenter et al. unpublished) investigated the converse and found that possums increased while mice had no obvious response to rat-only removal.
- 2 Responses of a particular rat species to removal of a different rat species: many studies employed monitoring tools that make it challenging to distinguish between different rat species (e.g. footprints in tracking tunnels).
- 3 Weasel response to stoat-only removal: in general, weasels are under-studied in New Zealand and little is known about their occupancy in different habitats and predator guilds.
- 4 Bottom-up impacts of predator removals on top predators (e.g. feral cats, ferrets): most studies reported changes in lower-ranking predators following removal of higher-ranking predators, while few studies examined how rodent or possum control affected the predators that prey on them (e.g. cats). Removing the prey of top predators is unlikely to cause adverse consequences unless it drives predators to prey switch to native species. In fact, removing prey could facilitate bottom-up-driven control of top predators (Norbury 2017).
- 5 Hedgehog response to removal of any PF2050 target species: we found only one study on hedgehog responses, and reported no response in hedgehogs or mice (monitored using tracking tunnels) to rat and possum removal in an urban environment. However, rat

abundances were very low (frequently <10% RTI) and control had only a very weak effect, which may have been insufficient to drive predator guild changes. Hedgehogs have the greatest dietary overlap with rats (see generalised food web in Figure 1), suggesting that the most relevant interaction to investigate would be whether hedgehogs benefit from rat removal via competitive release.



**Figure 3. Summary of studied interactions in the generalised food web for New Zealand ecosystems between PF2050 target predator species (dark shading), other invasive mammals (light shading), and native taxa\*\* (white).**

Notes: This summary includes predator responses to single species removals and combined rat + possum removals, and excludes all other studies in which multiple species were removed and so it was unclear which species' removal led to the observed response. Studies were found on rat responses to mustelid removal (black line); rat responses to possum (or rat + possum) removal and possum responses to rat removal (red line); and mouse responses to rat (or rat + possum) removal (blue line; note that these mouse responses to rat + possum removal could also be attributed, at least in part, to competitive release from possums), mustelid removal (green line) and possum removal (orange line). Numbers in parentheses indicate the number of studies. Labels are coloured to match the corresponding arrow in the food web, and positioned next to the responding species; small arrows in labels indicate whether a reported response was an increase (↑) or decrease (↓), or there was no response (↔) to control.

\* indicates studies that removed both rats and possums.

\*\* bird, lizard, invertebrate and plant communities also include exotic species. Within each taxonomic group, the ratio of native to exotic species varies widely across different locations and can also be affected by predator removals.

**Table 2. Population responses of other invasive species to the removal of PF2050 target species (plus feral cats) reported in 27 studies (including studies in which multiple species were removed, which are omitted in Figure 3)**

| Species removed (no. of studies)         | Response (no. of studies) |                           |                           |        |                    |
|------------------------------------------|---------------------------|---------------------------|---------------------------|--------|--------------------|
|                                          | Possums                   | Rats                      | Mice                      | Stoats | Hedgehogs          |
| Possums only (3)                         | -                         | ↑ (2); ↔ (1)              | ↔ (2) <sup>a</sup>        | ↔ (1)  | (0)                |
| Rats only (2)                            | ↑ (1)                     | -                         | ↑ (1); ↔ (1)              | (0)    | (0)                |
| Stoats only (4)                          | (0)                       | ↑ (3); ↓ (1) <sup>b</sup> | ↑ (1)                     | -      | (0)                |
| Rats + possums (13)                      | (0)                       | ↑ (5)                     | ↑ (6); ↔ (2) <sup>c</sup> | ↔ (1)  | ↔ (1) <sup>c</sup> |
| Rats + possums + stoats <sup>d</sup> (3) | -                         | ↑ (2)                     | ↑ (2)                     | -      | (0)                |
| Ferrets + cats (1)                       | (0)                       | (0)                       | (0)                       | ↑ (1)  | (0)                |
| Mustelids + cats + hedgehogs (1)         | (0)                       | (0)                       | ↑ (1); ↔ (1) <sup>e</sup> | -      | -                  |

Notes: Predator species that do not appear as a 'Response' column had not been reported in any studies. Studies on removal or responses of 'rats' refers mainly to ship rats, but rat species is not always known or reported in studies (e.g. for studies employing monitoring methods that do not readily distinguish between rat species), so we do not specify species here. ↑ = increase; ↓ = decrease; ↔ = no response to control. Numbers in parentheses indicate the number of studies that reported a given response.

<sup>a</sup> After possum control, mouse abundance peaked 6 months later in the treatment block than in the non-treatment block, but the size of the peak was not significantly different.

<sup>b</sup> In one study, stoat removal hastened the rat irruption but did not increase the peak size, nor did it significantly prolong the irruption. In another study, ship rats increased with stoat removal in cooler Kahurangi, but decreased with stoat removal in warmer Kahurangi.

<sup>c</sup> In one study that reported no change in mice and hedgehogs following rat and possum control, rat abundances were intrinsically very low (frequently <10% RTI) and control had only a very weak effect. In another study, mouse abundance peaked later in the treatment block compared to the non-treatment block, but the size of the peak was not significantly different.

<sup>d</sup> One study also removed cats.

<sup>e</sup> Mouse response may have been mediated by food supply: following predator control, mice increased at one site with regular high food supply but not at the site with low episodic food supply.

We also identified several more general key knowledge gaps. Most studies we reviewed involved predator control operations that removed multiple species (particularly combined rat and possum, or combined rat, possum, and stoat control), making it difficult to attribute effects to the removal of one species (e.g. Murphy et al. 1999). Studies in which individual species were selectively removed (e.g. Carpenter et al. unpublished) can shed more light on the ecological effects of single species.

Where possible, we attempted to infer the most likely mechanism driving an observed response. However, most studies measured responses using indices of relative abundance, making it challenging to ascertain whether responses were primarily due to enhanced detectability (e.g. increased activity) or increased population density, or both. Only two of the 27 reviewed studies had measured population densities through capture-mark-recapture. In general, there is considerable uncertainty about which processes underpin predator guild responses (except perhaps for rat responses to possum removal), which limits our ability to make more generalisable predictions. The occurrence and size of non-target predator responses following selective predator removals depends on the strength of species interactions and the extent to which the target

population density is reduced by control. In cases where no response was observed, this could either indicate that these species do not interact or that control did not reduce target populations to sufficiently low densities to trigger a substantial response. 'Density-impact functions', that describe the relationship between target predator density and the associated impact for other non-target predator (or native) species, can reveal the threshold densities that control must achieve in order to observe a significant change in an interacting species (Norbury et al. 2015). Quantifying these density-impact relationships could help explain why different responses are observed at different sites. Although outside the scope of this review, there is also little known about if or how changes in predator behaviour (as opposed to demographic changes) following selective species removals might affect biodiversity outcomes.

There is also considerable habitat bias in predator guild response studies. Most research has focused on forest systems for rodents and possums, beech forest for selective stoat removals, and open habitats (dry grass/shrublands, farmland) for mustelid interactions. Predator guild responses are less studied in urban (only one rat and possum removal study to date), coastal, alpine or wetland environments. The effects of habitat type on predator dynamics in general is also poorly understood.

Data sets identified in our data stocktake have potential for addressing some of these key gaps, particularly mouse responses to control of one or more PF2050 target species in urban and open country habitats (as well as forest habitats, which have received most attention in the literature). We identified five data sets from six sites where a single predator species (possums, rats or feral cats) is being selectively removed, which may clarify the effects of these individual species within the predator guild.

Although feral cats, mice and hedgehogs are not currently on the PF2050 target species list (and therefore not a focus for our literature searches), some landscape projects undertake control of these species alongside PF2050 targets, and at least one is selectively removing feral cats in their early management phase. Responses of other predators (e.g. rodents or ferrets) to feral cat removal are poorly understood.

Most of the medium- and high-priority candidate data sets in the stocktake use trail cameras and/or tracking tunnels, which have the advantage of concurrently measuring multiple species. DOC's new NPCP monitoring framework also presents an opportunity to monitor responses of multiple predator species to aerial 1080 operations. However, our data stocktake and priority rankings are based on meta-data only. Confirming their suitability for robust statistical analyses will require further interrogation of the original data sets, along with consideration of the variability in monitoring methods and study designs. For example, studies should have sufficient levels of experimental replication, sampling locations that are representative of the wider management area, sufficient detail on management activities to clearly define the 'treatment' (e.g. which species were removed and when) and control for the impacts of observer or analyst bias. If experimental design and data collection do not meet the required standards this will limit the power and interpretation of any statistical analyses (Allen et al. 2023).

## 6 Conclusions

- Responses of mice to the removal of PF2050 target predators have received the most attention. Increasing mouse activity or densities were frequently observed following the combined removal of rats and possums (e.g. aerial 1080 operations) in forest ecosystems, although there is some evidence that the mouse response is not universal and is likely to be mediated by food supply. Competitive release of rat populations following possum removal is also well studied in forest ecosystems.
- Key knowledge gaps that emerged from the literature synthesis included:
  - several hypothesised interspecific interactions within predator guilds (possum responses to rat-only removal, interactions between the three rat species, weasel responses to stoat-only removal, bottom-up impacts of predator removals on top predators, and hedgehog responses to removal of any of the PF2050 target species)
  - whether responses were due mainly to demographic or behavioural changes in predator populations
  - responses in urban, coastal, alpine or wetland habitats.
- Pest monitoring conducted by DOC, PF2050 landscape projects and ecosanctuaries has generated several data sets that could contribute to addressing some knowledge gaps, particularly regarding mouse responses to PF2050 control in under-studied urban, coastal and open country habitats (as well as more frequently studied forest habitats). Most candidate data sets concurrently measure multiple predator species using primarily camera traps and/or tracking tunnels. Some PF2050 landscape projects are selectively removing a single species, which is useful for understanding predator guild interactions.
- Priorities among these key knowledge gaps will likely change with time during the PF2050 programme. In the short term (i.e. 5–10 years), current tools and technologies available to PF2050 project managers will mean that one or a subset of species from the full PF2050 target list are more likely to be selected as initial targets (e.g. possums, ship rats, stoats), and therefore it may be more important to understand the possible consequences of reducing populations of those selected species. These target species choices and management approaches are based on several factors, including costs and biodiversity objectives, but do not currently consider the unintended or perverse outcomes that may occur. For example, several landscape-scale projects are focusing on possums as an initial target, and mustelid removal projects currently focus on removing larger mustelids (stoats and ferrets). Research gaps relating to responses (e.g. mice, rats) to possum-only removal, or the potential effects of stoat/ferret removal on weasels, may therefore be particularly salient. However, in the longer term (i.e. post-2050), if PF2050 is successful in its goal it will become increasingly important to understand how the remaining non-target predator species (cats, hedgehogs, and mice) respond to eradication of all seven target species.
- Priorities for addressing predator guild response knowledge gaps could also be aligned to the biodiversity and habitat priorities of the wider Te Mana o Te Taiao – Aotearoa New Zealand Biodiversity Strategy. Increases in abundance or changes in the behaviour of predators following selective predator removals can have adverse outcomes for biodiversity; for example, through increased predation or competition with native species. Knowledge gaps could be prioritised to focus on those relationships that pose the highest potential risk for vulnerable native species or ecosystems, in line with biodiversity objectives.

- Addressing these knowledge gaps could improve current PF2050 management. For example, they may suggest a more effective sequence of species removals to mitigate unintended management outcomes, or to leverage trophic relationships, for instance, by manipulating the target species' food supply (bottom-up control), thereby reducing their numbers or driving increased interactions with traps or baits.

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## **Appendix 1 – Data stocktake**

The full data stocktake table is available on the MWLR DataStore repository:

<https://datastore.landcareresearch.co.nz/dataset/predator-guild-responses-to-control-a-review>

## Appendix 2 – Literature synthesis summary

Table A1 is a summary of study attributes in the literature synthesis. More detailed study attributes are provided on MWLR's DataStore repository: <https://datastore.landcareresearch.co.nz/dataset/predator-guild-responses-to-control-a-review>

**Table A1. Summary of study attributes in literature synthesis: author (year); pest species removed by control; pest species present at site; area of control (ha); habitat type; control type (aerial, A, ground-based, G, or aerial and ground-based, A+G); predator monitoring method; predator response summary (increase/decrease/no effect); type of response (demographic, behavioural, functional, secondary poisoning or unknown); and predator response details.**

| Publication                    | Pest species targeted | Pest species present                        | Area of control (ha) | Habitat type                | Control type | Monitoring method                        | Predator response (increase / decrease / no effect) | Type of response              | Response details                                                                                                                                                                                                            |
|--------------------------------|-----------------------|---------------------------------------------|----------------------|-----------------------------|--------------|------------------------------------------|-----------------------------------------------------|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Selective rat removal</i>   |                       |                                             |                      |                             |              |                                          |                                                     |                               |                                                                                                                                                                                                                             |
| Brown et al. 1996              | Rats                  | Mice, rats, possums, mustelids              | 12.4                 | Podocarp-broadleaved forest | G            | Tracking tunnels, snap-traps             | Increase                                            | Behavioural                   | Mouse tracking and trapping index increased across the 5 nights as rats were removed.                                                                                                                                       |
| Carpenter et al. (unpublished) | Rats                  | Mice, rats, possums, mustelids, hedgehogs   | 25                   | Podocarp-broadleaved forest | G            | Chew-cards                               | Increase (rats); no effect (mice)                   | Unknown; probably behavioural | Increase in possums within 6 months following rat control relative to non-treated blocks. No obvious response of mice.                                                                                                      |
| <i>Rat and possum removal</i>  |                       |                                             |                      |                             |              |                                          |                                                     |                               |                                                                                                                                                                                                                             |
| Bell et al. 2021               | Ship rats, possums    | Mice, rats, possums, stoats, cats           | 4,300                | Mixed beech-podocarp forest | A            | Tracking tunnels, possum bite mark index | Increase                                            | Unknown                       | Ship rats exceeded pre-operation levels by 1 year after an operation. Somewhat unusual, because a beech mast followed in the year after 1st operation, and rats rebounded rapidly, leading to a 2nd operation 1 year later. |
| Bridgman et al. 2018           | Rats, possums         | Mice, rats, low numbers of mustelids & cats | 1,500                | Podocarp-broadleaved forest | A + G        | Tracking tunnels, live trapping          | Increase                                            | Mainly demographic            | Significantly higher minimum-number-known-alive and tracking of mice when rats were controlled, driven by increase in mouse density.                                                                                        |

| Publication             | Pest species targeted                                 | Pest species present                            | Area of control (ha) | Habitat type                                                                              | Control type | Monitoring method                        | Predator response (increase / decrease / no effect) | Type of response    | Response details                                                                                                                                                                                           |
|-------------------------|-------------------------------------------------------|-------------------------------------------------|----------------------|-------------------------------------------------------------------------------------------|--------------|------------------------------------------|-----------------------------------------------------|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Clout et al. 1995       | Ship rats, possums                                    | Mice, rats, possums, mustelids, cats            | 55                   | Podocarp-broadleaved forest                                                               | G            | Trap index                               | Increase                                            | Unknown             | No mice captured prior to rat control, but mice were captured following rat control.                                                                                                                       |
| Gillies & Pierce 1999   | Rats, possums (and later mice, feral cats, mustelids) | Mice, rats, possums, mustelids, cats, hedgehogs | 450                  | Mixed kauri-podocarp hardwood forest,                                                     | G            | Radio telemetry                          | Decrease (from secondary poisoning)                 | Secondary poisoning | All radio-tagged feral cats ( $n = 6$ ) (and one stoat and one ferret) died from secondary poisoning following initial 1080 operation.                                                                     |
| Griffiths & Barron 2016 | Ship rats, possums                                    | Mice, rats, possums, stoats, cats               | 32,000               | Sequence from pure beech (high) to mixed kāmahi-beech, to podocarp-dominated forest (low) | A            | Tracking tunnels                         | Increase                                            | Unknown             | Rats increased.                                                                                                                                                                                            |
| Innes et al. 1995       | Rats (possums in some cases)                          | Mice, possums, stoats                           | 35–3,200             | Podocarp-broadleaved forest                                                               | A + G        | Tracking tunnels                         | Increase                                            | Unknown             | Mouse-tracking rates increased 3–6 months after poisoning, peaked 7–9 months after poisoning, then declined to pre-poison levels. They were greater when ship rat control was most effective.              |
| Kemp et al. 2018        | Ship rats, possums                                    | Mice, rats, possums, stoats, cats               | 30,000               | Rimu-rātā-kāmahi forest                                                                   | A            | Tracking tunnels, possum bite mark index | Increase                                            | Unknown             | Rats increased.                                                                                                                                                                                            |
| Knight 2025 (thesis)    | Rats, possums                                         | Mice, rats, possums, cats, hedgehogs            | Unknown              | Urban                                                                                     | G            | Tracking tunnels                         | No effect                                           | Unknown             | No response of mice or hedgehogs to rat and possum control, as measured by tracking tunnels. Rat abundances were intrinsically very low (frequently below 10% RTI) and control only had a very weak effect |

| Publication              | Pest species targeted                | Pest species present                         | Area of control (ha) | Habitat type                | Control type | Monitoring method                                               | Predator response (increase / decrease / no effect) | Type of response              | Response details                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|--------------------------|--------------------------------------|----------------------------------------------|----------------------|-----------------------------|--------------|-----------------------------------------------------------------|-----------------------------------------------------|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Miller & Miller 1995     | Rats, possums (and wallabies)        | Mice, ship rats, possums, stoats (wallabies) | Unknown              | Coastal forest              | A + G        | Trap index                                                      | Increase                                            | Unknown, probably demographic | Mouse index peaked 5 months following operation, then declined to 'normal' levels.                                                                                                                                                                                                                                                                                                                                                                                          |
| Ruscoe et al. 2011       | Rats, possums                        | Mice, rats, possums, stoats                  | 900                  | Podocarp-broadleaved forest | A + G        | Capture-mark-recapture (CMR)                                    | Increase                                            | Demographic                   | Mice increased with possum and rat removal                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Sweetapple & Nugent 2007 | Rats, possums                        | Mice, rats, possums, stoats, cats            | Unknown              | Podocarp-broadleaved forest | A            | Lure disturbance, snap-back traps                               | Increase                                            | Unknown                       | A rat lure disturbance index increased nearly five-fold after possum control and remained high for up to 6 years after the 1994 poison operation. There was no snap trapping before the op, and the lure index (measured pre- and post-op) was not measured again until 4 years post-op (when the lure index was calibrated against snap trapping). It is therefore possible that events unrelated to the op may have led to the high rat numbers observed this long after. |
| Sweetapple et al. 2006   | Rats, possums (possibly some stoats) | Mice, rats, possums, stoats                  | 15,600               | Rimu-tawa forest            | A + G        | Leg-hold traps (possums), tracking tunnels (rodents and stoats) | Increase (rats); no effect (mice and stoats)        | Unknown                       | In aerial 1080 block, rat-tracking rates were significantly lower than the non-treatment in the 2–6 months after the operation, then increased to a peak 3.2-fold higher than non-treatment at 2 years after the op. The peak in mouse abundance after control occurred later in the treatment block than non-treatment, but the size of the peak was not significantly different from the non-treatment. No response observed for stoats.                                  |

| Publication                            | Pest species targeted | Pest species present                      | Area of control (ha) | Habitat type                                                         | Control type | Monitoring method                                               | Predator response (increase / decrease / no effect) | Type of response              | Response details                                                                                                                                                                                                                                                                                                                                        |
|----------------------------------------|-----------------------|-------------------------------------------|----------------------|----------------------------------------------------------------------|--------------|-----------------------------------------------------------------|-----------------------------------------------------|-------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| van Heezik et al. 2020                 | Rats, possums         | Mice, rats, possums, mustelids            | 5,100                | Exotic conifers                                                      | A            | Chew-cards                                                      | Increase                                            | Unknown                       | Mouse index doubled within 5 months post-control. Index remained high for a year and then declined and fluctuated.                                                                                                                                                                                                                                      |
| <b><i>Selective possum removal</i></b> |                       |                                           |                      |                                                                      |              |                                                                 |                                                     |                               |                                                                                                                                                                                                                                                                                                                                                         |
| Carpenter et al. (unpublished)         | Possums               | Mice, rats, possums, mustelids, hedgehogs | 25                   | Podocarp-broadleaved forest                                          | G            | Tracking tunnels                                                | Increase (rats); no effect (mice)                   | Unknown, probably demographic | Increase in ship rats within 6 months following possum control relative to non-treated blocks. No obvious mouse response.                                                                                                                                                                                                                               |
| Sweetapple et al. 2006                 | Possums               | Mice, rats, possums, stoats               | c. 3,000             | Rimu-mataī-tawa forest                                               | G            | Leg-hold traps (possums), tracking tunnels (rodents and stoats) | Increase (rats); no effect (mice and stoats)        | Unknown                       | Rats increased to 1.7–1.9 times higher than the non-treatment, 18 months after possum control. The peak in mouse abundance after control occurred later in the treatment block (6 months later than the mouse peak in non-treatment), but the size of the peak was not significantly different from the non-treatment. No response observed for stoats. |
| Wilson 2017                            | Possums               | Mice, rats, possums, mustelids, hedgehogs | Unknown              | Pasture, with pockets of indigenous shrubs/forest, and exotic forest | G            | Tracking tunnels                                                | No effect                                           | Unknown                       | Rat-tracking rate mean 10.1% (SE 0.8%). No relationship between rat-tracking rate and time since possum removal.                                                                                                                                                                                                                                        |
| <b><i>Selective stoat removal</i></b>  |                       |                                           |                      |                                                                      |              |                                                                 |                                                     |                               |                                                                                                                                                                                                                                                                                                                                                         |
| Blackwell et al. 2003                  | Stoats                | Mice, rats, possums, stoats, cats         | 1150                 | Podocarp-tawa and beech forests                                      | G            | Tracking tunnels                                                | Increase in some circumstances                      | Behavioural                   | Stoat trapping hastened rat irruption but did not increase its peak size nor significantly prolong the irruption. Effect in low phases was unclear (rats increased at one site, but no effect at another).                                                                                                                                              |

| Publication                                  | Pest species targeted                                 | Pest species present                   | Area of control (ha) | Habitat type                                                             | Control type | Monitoring method                     | Predator response (increase / decrease / no effect) | Type of response | Response details                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------------------------------------------|-------------------------------------------------------|----------------------------------------|----------------------|--------------------------------------------------------------------------|--------------|---------------------------------------|-----------------------------------------------------|------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Jones et al. 2011                            | Stoats                                                | Mice, rats, possums, mustelids         | Not applicable       | Beech forest (mouse effects) and podocarp forest (rat effects)           | A + G        | Tracking tunnels                      | N/A                                                 | Functional       | Stoats killed up to just more than 1 mouse per day, and theoretically up to 0.15 rats per day.                                                                                                                                                                                                                                                                                                                                                     |
| Walker, Kemp, Pickerell et al. (unpublished) | Stoats                                                | Mice, rats, possums, stoats, cats      | Unknown              | Beech forest with low elevation red beech, hard beech and/or rimu forest | G            | Tracking tunnels                      | Increase (except in warm Kahurangi)                 | Unknown          | Mouse-tracking rates increased with stoat-trapping effort in both regions. Ship-rat-tracking rates increased with stoat-trapping effort in cooler Kahurangi, but decreased with stoat trapping in warmer Kahurangi.                                                                                                                                                                                                                                |
| Whitau et al. 2023                           | Stoats                                                | Mice, rats, possums, stoats, cats      | Unknown              | Beech forest                                                             | G            | Tracking tunnels                      | Increase                                            | Unknown          | Rat-tracking rates were significantly higher in blocks with long-term mustelid trapping than in the single block (Rotoroa) where there was none.                                                                                                                                                                                                                                                                                                   |
| <b>Other multi-species removal</b>           |                                                       |                                        |                      |                                                                          |              |                                       |                                                     |                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| Garvey et al. 2022                           | Ferrets, cats                                         | Rats, stoats, ferrets, cats, hedgehogs | 700                  | Mixed farmland/scrub                                                     | G            | Trail cameras                         | Increase                                            | Behavioural      | Stoats not detected prior to control, detected immediately after at low densities, most common predator 6 months later.                                                                                                                                                                                                                                                                                                                            |
| Norbury et al. 2013                          | Mustelids, cats, hedgehogs (lagomorphs in some areas) | Mice, stoats, ferrets, cats, hedgehogs | 400–650              | Dry grass/shrublands, pasture                                            | G            | Live trapping (predators), CMR (mice) | Increase (Alexandra) and no effect (Macraes)        | Demographic      | Mouse response probably mediated by food supply: following predator control, mice increased (relative to non-treatment site) at the site with regular high food supply (pasture seed), enhanced by lagomorph removal, but not at the site with low/episodic food supply (masting tussock). Negative effects of predators on mouse densities in autumn. Winter mouse densities higher in shrubland than grassland, but no apparent effect of fruit. |

| Publication                          | Pest species targeted          | Pest species present           | Area of control (ha) | Habitat type                | Control type | Monitoring method                                 | Predator response (increase / decrease / no effect) | Type of response | Response details                                                                                                                                                                                                                                                                                           |
|--------------------------------------|--------------------------------|--------------------------------|----------------------|-----------------------------|--------------|---------------------------------------------------|-----------------------------------------------------|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Murphy et al. 1999                   | Rats, possums, stoats          | Mice, rats, possums, stoats    | 8,577                | Podocarp-broadleaved forest | A            | Tracking tunnels                                  | Increase                                            | Unknown          | Significant increase in mouse tracking 3–9 months after the poison operation.                                                                                                                                                                                                                              |
| Walker, Kemp & Elliott (unpublished) | Rats, possums, stoats          | Mice, rats, possums, stoats    | Unknown              | Most habitat types          | A            | Tracking tunnels                                  | Increase                                            | Unknown          | Consistent increase in mouse tracking 6 months after operations, which ended within 18 months post-op for most regions but continued for up to 3 years at some sites. Ship rat increases occurred 1 to 2 years after operations, with much larger and somewhat longer-lasting increases in warmer regions. |
| Innes et al. 2004                    | Rats, possums, mustelids, cats | Rats, possums, mustelids, cats | 350                  | Podocarp-broadleaved forest | G            | Tracking tunnels (rats), leg-hold traps (possums) | Increase                                            | Demographic      | Possum capture rate reduced from c. 25% before control to <10% after. Rat tracking initially reduced from 40% to zero after 1080, but recovered over c. 3 years to approximately original levels. Rats remained at lower relative abundance in the non-treatment area.                                     |