Manaaki Whenua
Landcare Research

MILESTONE REPORT TO OSPRI

Project Code and Title	CON10528 TB NPMP Review Foundation
Research Leaders	Graham Hickling and Bruce Warburton
Milestone #3	Investigation into any potential changes in science underpinning case for eradication
Value of Milestone: $14,600	**Completion Date:** 14/08/2024

Summary

- As preparation for the 2025 NPMS TB Plan review, Manaaki Whenua Landcare Research (MWLR) was asked by OSPRI to identify any changes in the science underpinning the 2016 TB Plan's eradication objectives and approach. This was done by reviewing literature on eradication science and vector biology and comparing the findings with the principles outlined in the 2016 TB Plan.
- *Vector biology:* The past decade has seen new contributions on possum demography, movement, habitat use and response to control. These studies have improved our understanding of these topics but remain broadly consistent with the extensive previous research that was the foundation for the 2016 TB Plan. We did not find any significant new studies on the biology of other TB hosts and vectors on the New Zealand mainland.
- *Vector epidemiology:* A limited number of epidemiological studies have been published on New Zealand wildlife in the past decade. As with the biological studies, these have largely reinforced our existing understanding of wildlife-livestock transmission in this country. Internationally, several studies have highlighted a growing contribution of wild deer to TB dynamics. Wild deer densities in NZ have increased markedly in the past decade, however very few livestock herds and few possum populations remain infected with TB, which greatly reduces opportunities for spillover to wild deer relative to the situation in countries such as Ireland.
- *Biocontrol*: No new biocontrol research targeting TB vector fertility, postnatal development, or hormonal control of lactation or immunity were identified. Several new studies on potential gene drive technology for possums and other predators have been published, however no such drive exists as yet, social license to deploy one before 2055 seems unlikely, and once deployed a drive would take many years to propagate through the national possum population.
- *Vaccination:* Oral delivery of BCG vaccine to possums and other wildlife reservoirs will induce protection and could be used to vaccinate these species at scale. Nevertheless, the impediments to vaccine-based control identified in the lead-up to the 2016 TB Plan (lack of a registered vaccine product for possums and the high expense of vaccine delivery relative to lethal control methods) remain.
- *New tools in the eradication toolbox:* New Zealand's TB eradication objectives probably can be met using existing pest control tools, provided social licence for those tools is maintained. In

contrast, the Predator Free 2050 initiative seems unlikely to succeed without new tools, including genetic technologies:

1. there are no short-term prospects for an alternative toxin with similar efficacy to 1080 that also satisfies demands for species-selectivity, lack of residues, and humaneness. Some new target-generalist toxins are being investigated, with some now registered for control of possums in situations where use of 1080 is not feasible;
2. as control efforts progress towards final TB possum eradication, the challenge of effectively targeting the remaining bait- and toxin-shy survivors (Allsop et al. 2017) will intensify. Various research directions are being pursued to address this problem, including improved lures, baits, and bait-switching techniques;
3. by-kill of valued non-target species such as deer and kea threatens social licence for aerial 1080 operations. Bait additives that repel deer but not possums have been developed in the past decade; aversion techniques to protect kea have also had some success.
4. various efforts are underway to design multi-kill traps, however modelling suggests that at low possum density it may be more cost-effective to simply deploy several cheap single-kill traps at each trapping site. AI-enabled kill traps that can discriminate target vs. non-target species will be available soon and will assist the TB eradication programme in priority areas where the presence of valued non-target species prohibits conventional trapping. Wireless-monitoring of trap networks may reduce the cost of operating live-traps (e.g., leghold traps) but seem unlikely to provide cost-savings for kill traps as their checking frequency is primarily governed by the need to refresh bait; development of long-life baits could help address this issue.

- *Eradication strategies:* Recent field data support the 2016 TB Plan's assumption that the TB persistence threshold in possums is somewhere above a 5% ground-set Residual Trap Catch Index. Latham and Nugent (2016) found that far fewer TB possums are being detected than would be expected given disease managers' subjective assessments of TB freedom in possums, suggesting that managers have been overly cautious.
- *Eradication tactics:* Aerial 1080 control is achieving much higher kills than the 90% value assumed by Proof of Freedom scenario modelling, suggesting the potential for future cost savings. Tactics to successfully combat bait shyness are available. Ground control operations are meeting their targets overall, with more cost-effective ground control tactics gradually emerging. However, there are programme risks associated with gaps in ground control in inaccessible areas and also from indicative data that TB-infected vectors sometimes move longer-than expected distances, including across buffer zones. As eradication efforts proceed, the importance of tactics to target bait-shy and trap-shy individuals will increase.
- *Monitoring/surveillance:* Several recent studies have sought to improve monitoring of post-control wildlife populations and/or the persistence of TB-infected individuals therein. Of these, Nugent et al.'s (2017) Survey-then-Control (StC) surveillance proposal may have the most potential to provide future cost savings for the TB Programme.
- *Eradication feasibility*: A recent analysis of herd breakdown rates by Hone (2023) concluded that while New Zealand is on a pathway to biological eradication of TB, that target will not be reached by 2055. The arguments presented in that study require further discussion.
- If the goal of Predator Free 2050 (PF2050) were achieved on schedule, the programme would obviously provide an enormous boost towards achievement of the TB Plan's objectives. However, PF2050's schedule for nationwide predator eradication may be unrealistic and at the very least is

highly contingent on continuation of funding. Other than leveraging PF2050's short- to medium-term investment in new control tools, reliance of TB vector managers on PF2050 outcomes would represent a risk to the TB programme.

- *Social licence:* Loss of social licence for deployment of 1080 presents an ongoing risk to the TB Plan's milestones that is unlikely to be reduced by further biophysical science on the topic. Social science may be able to help. Public support for the use of 1080 declined from the 1990s to 2000s but we did not see evidence of further change over the past decade. Concerns over Covid-19 drew attention away from the 1080 debate but that effect is likely temporary.

1. Introduction

As preparation for the 2025 NPMS TB Plan review, Manaaki Whenua Landcare Research (MWLR) was asked to identify any changes in the science underpinning the 2016 TB Plan's eradication objectives and approach. This was done by reviewing post-2015 literature on vector biology and eradication science and comparing it with the principles outlined in the 2016 Plan Review identify i) new developments that might impact the prospects for TB eradication, and ii) new findings that could contribute to advancing the TB programme's timeline for achieving its eradication milestones. The focus of the review was on new science relating to vector biology, epidemiology and control, with a briefer look at biocontrol, vaccines and social science.

2. Background to the 2016 TB Plan's three eradication objectives

When the Biosecurity (National Bovine Tuberculosis Pest Management Plan) Order 1998 was amended in 2009, it included provision for a large-scale proof of concept that TB could be eradicated from farmed cattle and deer, and also the wildlife species that act as reservoirs and vectors of the disease. This proof of concept, in conjunction with other new scientific research, was intended to inform subsequent TB Plan reviews.

For the first of the two proof of concept trials – in the 160 km^2 heavily forested Hokonui Hills Vector Risk Area – Nugent and Livingstone (2015) provided strong evidence that TB had indeed been eradicated. In the second trial – in a 1,200 km^2 area in the Hauhungaroa and Rangitoto ranges – vector control resulted in TB infection in possums disappearing from many areas where it was previously prevalent, together with dramatic reductions in TB prevalence in pigs and deer (Nugent et al. 2014). Consequently, in their 2015 submission to the Minister, the TB Plan Review Plan Governance Group (PPG) concluded that 'in light of the progress to date, and expected new technical and management developments, eradication is now considered both feasible and economically justifiable'. The PPG consequently recommended that the aims of the TB Plan should target eradication of TB from New Zealand at an earlier date and at a lower cost than previously proposed. Specifically, the PPG recommended replacing the strategy of 'rolling back and containing the disease' with a strategy of 'active eradication' in livestock and wildlife (Kelly 2015).

The key changes proposed by the PGG were to:

- extend the term of the Plan to 30 June 2055, with new objectives and staged milestones;
- adopt a more cost-effective approach to vector control;
- adopt a more targeted, risk-based approach to livestock testing, including bringing farmed deer TB testing within the Plan;

- change the compensation policy to allow variable amounts of compensation (0-100% fair market value) to incentivise better herd management practises and encourage improved NAIT reporting of farm-to-farm livestock movements.

Associated with these proposed changes was a recommendation for a significant drop in funding, from $80 million p.a. to $65 million for the first two years, followed by an average of $60 million per annum for the next 13 years. Annual funding requirements were expected to 'quickly fall away' thereafter (Kelly 2015).

3. The 2016 TB Plan's objectives (excerpted from the PPG's 2015 Proposal)

TB freedom in livestock by 2026 - cattle and deer herds would be largely free of TB infection by 2026, with potentially a very small number of isolated breakdowns which will require mopping up.
TB freedom in possums by 2040 - this would be the point of 'statistical freedom' of disease from possums, where there is confidence, at an acceptable level of certainty that the disease is absent from possums which are then no longer able to infect livestock. A 'faster' eradication option, aiming to reach this objective by 2035, was also considered by the PPG but was judged to be less cost-effective (Anon. 2015).

TB freedom in all wildlife by 2055 - complete biological eradication of TB from New Zealand, whereby TB is considered eradicated from all wildlife, would take a further 12 – 15 years after the declaration of TB freedom in possums and will involve low level monitoring and verification, and the very occasional mop-up of residual or previously undetected infection.

4. Summary of the scientific foundations for the 2016 TB Plan's objectives

The key scientific propositions underpinning the 2016 TB Plan and its three eradication objectives are reviewed in three unpublished reports prepared in the lead-up to the 2016 Plan Review:

Caley P. 2015. *A review of science underpinning eradication of bovine TB from New Zealand*. Unpublished report to TB Free New Zealand.

Ferguson I & Hellström J. 2015. *Review of the science undertaken for the purpose of managing Bovine Tuberculosis in New Zealand.* Unpublished report to the TB Plan Review Plan Governance Group.

Nugent G & Livingstone P. 2015. *Evidence supporting the technical feasibility of eradicating entrenched bovine tuberculous (TB) infection from wildlife in forested areas of difficult operational terrain.* Unpublished report to the TB Plan Review Plan Governance Group.

Below, we summarize these propositions.

TB Freedom in livestock: Because *Mycobacterium bovis* affects more than one region, a key proposition of the 2016 Plan is that TB is unlikely to be successfully eradicated without significant use of central government and industry resources. Although TB is the 'pest' managed by the TB Plan, it was recognised that achieving the plan requires large-scale possum control and a range of disease control and surveillance measures targeting livestock and other wildlife species. Specific propositions included:

- control measures need to extend well beyond individual farms irrespective of land ownership, land use, or regional boundaries;
- nationally consistent regulations, disease control records and information systems are essential for management of in-herd infection and to prevent herd-to-herd infection;
- evidence of residual infection in herds not derived from recent possum transmission (Ferguson and Helstrom 2015) implies a need for more attention to individual animal movements;
- in areas free of wildlife TB, current herd management tools are effective but will need to become more stringent as the programme progresses towards eradication (Ferguson and Helstrom 2015);
- next-generation DNA typing schemes based on whole genome sequences of *M. bovis* will provide improved information for tracing the origin and spread of infections;
- the systems for diagnosis and management of TB in domestic cattle and deer herds represent best practice (Caley 2015) but should continue to be improved, particularly with regards to test specificity (Ferguson and Hellstrom 2015).

TB freedom in possums: In the lead-up to the 2016 TB Plan review, the ecology, epidemiology, and management of the TB in possums and other New Zealand wildlife up to the mid-2010's were summarised in a series of nine reviews in a special issue of the New Zealand Veterinary Journal (references in Caley 2015). Key scientific propositions emerging from these studies regarding the contribution of possums to the spread and maintenance of TB included:

- most transmission among wild animals is thought to occur directly between infected and susceptible individuals (Palmer 2013);
- infection by environmental contamination is possible (Courtenay et al. 2006) but is not a significant contributor to TB persistence on New Zealand farmland;
- possums are true maintenance hosts in which TB will persist indefinitely if they are left unmanaged (Morris and Pfieffer 1995) -- eradication of TB from possums therefore requires reducing the rate of transmission between possums;
- the rate of transmission between possums is density dependent, so reducing the density of susceptible individuals will eventually result in local eradication of TB from possums (Caley et al. 1999);
- reducing the density of susceptible possums could in principle be achieved through vaccination; however, no registered vaccine product is likely to become available for use in possums in the next decade.
- large scale aerial delivery of vaccine would be prohibitively expensive relative to lethal control methods (unless the latter methods were blocked by lack of social licence);
- research on alternatives to 1080 is progressing slowly and it remains uncertain whether these alternatives will be any more acceptable to the public;
- extensive research on the environmental and public health effects of 1080 indicates that 1080 is broken down relatively rapidly in the environment but it is recognized that this information

has had limited effect on public concerns ‘because many of those concerns are not evidence-related’ (Ferguson and Hellstrom 2015);

- biological or reproductive controls are potential future alternatives to use of toxins or vaccines, however biological, social and legislative hurdles have stalled this research for the foreseeable future;
- eradication of TB from a possum population relies on reducing the population below the density threshold (KT) at which infectious contacts between possums maintain the reproductive rate of the disease at or above 1.0.
- based on the relationship between a modified Residual Trap Catch Index (RTCI) and the mean area-wide prevalence of TB in possums in central North Island forests, Nugent (2005) concluded that KT in those forests is > 10% RTCI;
- typical RTCI targets of 1-2% set by TBFree New Zealand in the 2010s correspond to possum population densities well below the disease persistence threshold
- a <2% RTCI target is achievable over large areas using current technology (over the period 2007 - 2014, 86% of 6393 of RTCI assessments were <2% and 99% were <5%; Livingstone and Nugent 2015);
- infected possums are often spatially clustered, so RTCI targets need to specify maximum allowable catches per line as well as overall area averages (a consequence of this requirement is that the mean reductions achieved by contractors are often well below the overall target; Livingstone and Nugent 2015).
- achieving RTCI targets currently relies heavily of the use of compound 1080 and so may require sufficient social licence to be ensure that 1080 will remain available in the long term (Ferguson and Hellstrom 2015).
- new control technologies (as distinct from refinement of existing technologies) may in future provide vector control cost efficiencies, although Ferguson and Helstrom (2015) cautioned that few such studies had provided useful results to date.

TB freedom in other wildlife: many mammals other than possums, including humans, are susceptible to infection with *Mycobacterium bovis*. Propositions underpinning the 2016 TB Plan relating to these species included:

- most mammal species are ‘spillover’ hosts that can become infected (from another species), but do not readily pass on the disease;
- spillover host status has been demonstrated for feral pigs and wild deer in large-scale field studies (Nugent et al. 2011) – consequently, neither of these species are considered able to independently maintain TB at then-current densities in the wild in New Zealand (Nugent et al. 2014);
- recreational and commercial hunting are probably helping to prevent wild pigs and wild deer from acting as maintenance hosts in parts of New Zealand;
- long distance movement of live pigs or pig carcasses by hunters, with subsequent release or discarding of the head, has the potential to obscure determination of whether TB has been eradicated from the local possum population;

- low levels of TB found in deer in some Vector Control Zones (VCZs) could be explained by residual possum-to-deer infection or by limited deer-to-deer transmission, either of which could delay elimination of TB from the deer population;
- sika deer (*Cervus nippon*) and fallow deer (*Dama dama*) can attain locally high densities, which will increase the the risk of intra-specific TB transmission. Caley (2015) cautioned that control of these species, if needed, would be feasible technically but challenging politically;
- ferrets are spillover hosts in most of New Zealand, but in areas where ferret densities are extremely high TB may decline only slowly even if eliminated from other species, so ferrets should be targeted in such areas;
- Little empirical data on TB dynamics in host species complexes is available. Although modelling of such systems has produced mixed conclusions, Caley (2015) concluded that that these complexes were unlikely to prevent eradication of TB.

Declaration of TB Freedom: The process for declaring VCZ's 'free' of TB involves calculating P_{free} for the area using a spatially-explicit 'Proof of Freedom' (POF) model (Anderson 2010, Anderson et al. 2013, 2015). Estimates of P_{free} – based on modelling the control history and the TB surveillance data collected -- contribute to the 'case for revocation' prepared by Area Disease Managers for each VCZ under consideration. Final determination on revocation of a VCZ's VRA status is largely based on the output of the POF utility, with the specified P_{free} for declaring TB freedom currently set at 0.95. Qualitative historical factors, such as the location of the VCZ, the status of its immediate neighbours, and the financial consequences of making a false declaration, are also considered.

Propositions underpinning this POF process included:

- that the spatially explicit possum-TB model (the Spatial Possum Model; Ramsey and Efford 2010; Barron 2012) that underpins the POF modelling process uses valid design assumptions and fixed parameter values;
- that VCZ-specific parameters in the model (e.g., which areas are considered to be possum habitat or not) are also valid;
- that surveillance evidence that TB is indeed absent from a possum population will be available (this can include examination of 'sentinel' species such as deer, pigs, and ferrets);
- that there is spatial independence of wildlife surveillance sampling in different years (if samples are only collected from the same portion of the VCZ each year, POF calculations may overestimate the probability of eradication; Caley 2015);
- that additional 'assurance phase' surveillance data may become available once VRA status has been revoked, to help increase confidence in TB absence.

5. New science (since 2015) that could have implications for the 2016 TB Plan's eradication objectives

In this section we survey eradication science and vector biology research emerging over the past decade, highlighting findings relevant to the 2026 TB Plan's eradication milestones.

Vector biology

The past decade has seen new contributions on possum demography, movements and responses to control. While these findings have improved our understanding of the species' biology, they largely reinforce the extensive past literature that provided a foundation for the 2016 TB Plan. We are not aware of relevant new studies on the ecology of other potential TB vectors.

Most demographic data for possum populations used for parametrizing models has come from short-term cross-sectional studies (the long-term Orongorongo Valley study being the notable exception). Jackson et al. (2019) contributed new longitudinal data (August 1989 to August 1994) for a high density, high fecundity possum population at Castlepoint in the Wairarapa. They concluded that a shortage of dens providing protection from weather, rather than food supply, was limiting the population.

Richardson et al. (2017) investigated the relationship between possum home range size and population density in the Orongorongo Valley. Males had larger ranges than females and range size increased with decreasing population density. The authors suggest this pattern will increase the ability of TB to persist despite control and suggest that where possible older male possums should be targeted for control, as these may be the primary drivers of disease transmission.

Similarly, Margetts et al. (2020) experimentally investigated the effect of population density reduction on home-range size of possums at three sites in Canterbury; possums at high density (7/ha) increased their ranges sizes after control (2X for males and 1.3X for females) whereas possums at low density (1.5/ha) did not. O'Malley (2023) found that possums range size and stability can vary substantially between individuals (partially based on sex, with males typically having larger and less stable ranges) and cautioned that individuals with very small ranges could be missed by conventional ground control.

Cook et al. (2020) reaffirmed past studies showing that rivers inhibit possum movement and home range expansion, which supports operational practice that aligns eradication boundaries with rivers to delay possum reinvasion after control. Similarly, Veale et al. (2021) used genetic relatedness measures to demonstrate that (with two exceptions) possums captured on the true left of the Wanganui River were separated from those on the true right. The exceptions (two possums captured on the true left that were most closely related to possums from the true right) were captured within 350 m of the only bridge in the study area.

Forsyth et al. (2018) used data from a large-scale biodiversity monitoring program to identify variables predicting nation-wide abundances of possums. Possum abundances were negatively related to humidity, stem density, tree cover density, slope, elevation and distance to pasture/crop, and increased with food plant species and *Weinmannia racemosa* cover. Nevertheless, the most significant predictor of abundance was the site's control history.

Shepherd et al. (2018) updated Ramsey and Efford's (2010) Spatial Possum Model, extending it to represent all individuals in a national population of up to 40 million possums in habitat types mapped at a finer spatial scale than the original model. A prototype interface for interactive web-based presentation of the model's predictions was also provided. Their publication includes analysis of several hypothetical scenarios, including incursions of possums, and reinvasion of large areas cleared of possums. Although not addressed in their publication, the model also includes code for disease dynamics (M. Barron, pers. comm.).

Pattabiraman et al. (2022) analysed genetic structure of possums on the Kenepuru Peninsula. Despite there being few individuals of intermediate fur colour, no restrictions to gene flow or assortative mating were evident -- the implication being that reinvasion is to be expected following population reduction. Bond et al. (2024) have shown that a single gene controls possum fur colour: one or two functional copies regulates melanin and produces agouti grey fur, whereas two copies of the non-functional gene sets melanin to maximum and turns the fur black.

Paterson et al. (2021, 2022) documented low possum densities in urban forest and residential areas in Dunedin City. Modelling the feasibility of eradicating possums from Otago Peninsula, close to the city, she concluded that although the urban isthmus would act as a landscape barrier, this barrier alone would fail to prevent repopulation.

Vector epidemiology

A limited number of epidemiological studies of New Zealand have been published in the past decade. As with the ecological studies, these have mostly reinforced our existing understanding of wildlife-livestock transmission patterns in New Zealand. Several international reviews relevant to wildlife vectors of TB have highlighted a growing contribution of wild deer to TB. This latter result should be interpreted cautiously in the New Zealand context – while it is true that wild deer densities here have increased markedly in the past decade, very few livestock herds and few possum populations remain infected with TB, greatly reducing opportunities for spillover to deer relative to countries such as Ireland.

In a multi-year Orongorongo Valley field study (described in Rouco et al. 2014), researchers measured home range size and overlap in four separate possum populations in the Orongorongo Valley over three field seasons, with a subset of the possums fitted with proximity-logging radio collars. Rouco et al. (2018) constructed social networks from these possums' data to investigate whether the higher TB prevalence typically seen in male possums is a consequence of males having more frequent close contacts with conspecifics. The data indicated, however, that adult female possums had similar contact rates to males. Tobajas et al. (2024) analysed home range overlaps from the same study and found that overlaps were significantly associated with age class, with 66% of overlaps occurring between adults, 30% between adults and juveniles, and only 3.4% between juveniles. Adult males had significantly higher numbers of overlaps than expected, while adult and juvenile females had significantly less.

Members of each collared subpopulation were deliberately infected with a strain of bovine TB different from strains found naturally in the area and the spread of the introduced strain through the population was monitored. Merry (2021) constructed an individual-based model of the movements and interactions of a group of possums, including a stochastic transmission model, with the aim of comparing the model's predictions to the Orongorongo field data on TB spread. However, very few secondary infections were recorded in the field study (Rouco et al. 2016), either because infected possums were not found or because the disease was spreading slowly, and this prevented the researchers from estimating transmission parameters from the field data.

Whole genome sequencing (WGS) of *M. bovis* is providing insights into transmission dynamics in multi-host systems. For example, Crispell et al. (2020) applied the method *to M. bovis* sampled from infected cattle, deer and badgers in County Wicklow, Ireland. Cattle and deer there shared highly similar *M.*

bovis strains, suggesting that transmission is now occurring between the two species, perhaps as consequence of increasing wild deer abundance. Kelly et al. (2021) subsequently reported positive correlations between deer density and cattle TB-breakdowns in Ireland. The correlation between Sika deer density and herd breakdowns was particularly strong in County Wicklow.

Earlier New Zealand studies employing WGS (Crispell et al. 2017, Price-Carter 2018) similarly concluded that *M. bovis* strain similarity between cattle and wildlife indicated ongoing transmission between these species, however the dominant direction of spread could not be determined from their WGS data. The authors noted that for routine surveillance, the resolution gained by using WGS data must be weighed against increased costs (which is decreasing as sequencing technology continues to improve).

Thomas et al. (2021) undertook a systematic review of 124 articles on methods for diagnosis of tuberculosis in wildlife and assessed factors that can affect test performance. The review concluded that post-mortem examination and culture are useful and the widely used methods for disease surveillance, however diagnostic tests based on cellular and humoral immune response detection are gaining importance for wildlife TB diagnosis.

Ferreira et al. (2023) conducted a meta-analysis of studies to define and quantify direct and indirect wildlife-cattle interaction rates in the context of TB transmission. Given that indirect interaction rates (i.e. via contaminated environments and asynchronous overlap in space-use) were 154 times higher than direct interactions, they recommended that more attention should be paid to indirect them, particularly as indirect interactions increase significantly with increasing wildlife density.

Conteddu et. al (2024) reviewed 532 multi-host bovine TB studies to identify trends in species publication focus, methodologies, and 'One Health' approaches. The authors recommend combining well-designed empirical data collection with mathematical and simulation modelling to provide advice for policymakers and managers; this represents a vote of confidence for the approach taken in New Zealand by OSPRI and previous TB programme managers.

Wildlife biocontrol

Chand and Cridge (2020) and Chand et al. (2023) review studies that have explored interference with fertility, interference with postnatal development, and hormonal control of lactation or immunity as potential avenues for achieving biocontrol – no new initiatives relevant to the timeframe of the TB Plan were identified. Several studies on the potential for gene drive technology to target possums and other predators have been published in the past decade (e.g. Esvelt and Gemmell 2017; additional references in Chad and Cridge 2020) but no such drive as yet exists for possums, it is unlikely that there would be social license to deploy one before 2055, and any such drive would take many years to propagate through the national possum population. MacDonald et al. (2020) document concerns over the ethics, environmental impacts and feasibility of containing a possum gene drive within New Zealand.

Wildlife vaccines

Buddle et al. (2018) reviewed the efficacy and safety of BCG vaccine for control of TB in wildlife as well as for livestock. Oral delivery of BCG vaccine to possums and several other wildlife reservoirs has been shown to induce protection and so could be a practical means to vaccinate these species at scale. Nevertheless, the impediments to a vaccine-based control programme identified in the lead up to the 2016 TB Plan (i.e., lack of a registered vaccine product for possums and the anticipated high expense of vaccine delivery relative to lethal control methods) still apply.

Vaccine strategies continue to be explored internationally. For example, in Northern Ireland a 100 km^2 area was subjected to a test and vaccinate or remove (TVR) badger intervention over a 5-year period (Menzies et al. 2020). A total of 824 badgers were live-trapped and 1412 BCG vaccinations were administered. Preliminary results indicated a statistically significant downward trend in the proportion of test positive badgers.

In England, Defra announced in 2021 that badger culling is to be replaced by vaccination as a means of managing the spread of TB between badgers and cattle. Participatory workshops carried out with farmers across a range of English TB risk areas revealed that vaccination scenarios were unpopular with farmers, who were sceptical that vaccinating badgers would achieve sufficient protection against TB for cattle (Chivers et al. 2022). Nevertheless, a small-scale (unreplicated, uncontrolled) vaccination trial initiated by farmers in Cornwall reduced TB test-positivity in badgers in an 11 km^2 area from 15% to 0% over 4 years, by which time farmer enthusiasm for vaccination had increased (Woodroffe et al. 2024).

New tools in the eradication toolbox

Warburton et al. (2017) reviewed recently developed and close-to-market pest management tools and identified 15 key research priorities that would support improvement of those tools. Murphy et al. (2019) reviewed techniques being discussed or developed to support the Predator Free 2050 initiative and concluded that new tools (possibly based on genetic technologies) would be required for the initiative to succeed. Beausoleil et al. (2016) developed a systematic approach to evaluating and ranking the relative animal welfare impacts of toxins and other wildlife control methods.

Alternative toxins: The number of vertebrate pesticides registered globally has declined in recent decades but New Zealand – through government and industry investment, research effort and practical expertise – has bucked this trend and has retained some important toxin registrations whilst also registering new compounds with improved safety profiles (Eason et al. 2017). Ross and Eason (2021) review over 260 new research and review publications on 1080 from the preceding decade.

Despite this extensive 1080 research, public concerns over the use of 1080 remain and a wide-ranging research effort to develop alternative toxins – including those with potentially higher species specificity – is ongoing. Warburton et al. (2022) concluded, however, that there is no short-term prospect for obtaining an alternative toxin with similar efficacy to 1080 that will also satisfy demands for species-selectivity, lack of residues, and humaneness. Promising avenues for the development of species-specific lethal toxicants include genome mining of target pest species; gene editing to develop nonlethal technologies is another possibility. Both approaches have medium- to long-term time horizons and will require considerable funding for research.

In the shorter term, some new target-generalist toxins are becoming available for ground control of possums in situations where use of 1080 is not feasible. For example, a combination of diphacinone and cholecalciferol has proven effective against possums in pilot trials and has a better risk profile than second-generation anticoagulant rodenticides such as brodifacoum. Approval of this new bait by the New Zealand Environmental Protection Agency was granted in 2018, with final registration obtained from the Ministry of Primary Industries in 2019 (Eason et al. 2019). Data are not yet available on the operational efficacy of this toxin combination.

Baits and lures: Various studies are providing incremental improvements in our ability to attract possums and other pests to toxins and control devices. For example, Jackson et al. (2016) report that increasing protein content of baits enhances their attractiveness to possums. Mockett (2017) identified five semiochemicals that were more attractive to possums than standard lures. Waters et al. (2017) showed that a new combined olfactory and visual lure increases possum interaction rates with Chew Cards.

As control efforts progress towards final TB possum eradication, the challenge of effectively targeting bait- and toxin-shy survivors (Allsop et al. 2017) will intensify. Fisher et al. (2017) undertook field trials to develop quantitative markers of bait uptake that could provide insights into why some possums survive 1080 baiting. Nugent et al. (2020) and Warburton et al. (2020) demonstrated that switching bait type (smell, texture, and appearance) is effective at overcoming learned aversion to cereal pellets. Brewer et al. (2023) have propose incorporating 1080 in a small pill within a larger bait as a method to avoid triggering bait shyness (possums will either receive a full dose of 1080 or will be simply pre-fed if they fail to ingest the pill). Godfrey et al. (2023) demonstrated that 'observer' possums can learn how to extract a food reward from a puzzle device by watching a 'demonstrator' possum in an adjacent pen; if this kind of social learning information can also occur with aversive stimuli (such as traps and toxic baits), this could spread behavioural resistance to control.

Methods to protect non-target species: There has been growing concern among the hunting community that aerial 1080 control results in by-kill of non-target deer; these perceptions threaten social licence for the method. Pinney et al. (2021, 2022) detected by-kill of white-tailed deer in the Dart Valley/Routeburn in 2014. Malham et al. (2019) found no evidence of negative effects of aerial 1080 operations on deer in a South Westland study, however Morriss et al. (2020) subsequently reported that the majority of 26 aerial operations reviewed had moderate or high impacts on deer populations. Morriss et al. (2020) monitored trends in deer abundance on poisoned and unpoisoned areas on Molesworth Station to assess recovery of deer numbers after an unintended deer by-kill in 2017.

This growing awareness of deer by-kill prompted recent research to develop and evaluate 1080 bait formulations that repelled deer (Morriss and Nugent 2018, 2019) but not possums (Morriss and Arrow 2020). A field evaluation in 2021 demonstrated that Prodeer 1080 cereal bait has high control efficacy against possums, with no by-kill of deer detected in that trial (Morriss and Gormley 2022).

Aerial 1080 operations also threaten native kea (Kemp et al. 2019). Nugent et al. (2020) tested the effect of three candidate kea-repellent compounds on bait palatability for possums and concluded that the formulations did not pose a major threat to the level of possum control efficacy required for TB possum control. (The study did not however evaluate the efficacy of the repellents for kea.)

Nicholas et al. (2020) fed mock 1080 baits containing an emetic to captive kea and showed that the birds developed a learned aversion that lasted through at least six interactions with such baits. Yockney et al. (2022) used trail cameras to monitor 11 sites in the Wanganui catchment, Westland, where a pair of carcasses (mostly tahr paired with either a goat, deer or pig carcass) and 1.5 kg of anthraquinone-laced kea-repellent non-toxic cereal bait were left out for kea. No instances of kea eating anthraquinone-laced bait were recorded and there was no decrease in kea visit rates to the sites after aerial 1080 baiting of the catchment. Carcass attractiveness, inferred from relative interaction rates, was approximately 100 times that of the anthraquinone cereal bait.

Traps and trapping networks: Increased availability of robust, weather-proof electronics has supported the development of new traps with multiple-kill capability (e.g., Blackie et al. 2016). Although more expensive to purchase than traditional single-kill devices, multi-kill traps are promoted as being more cost-effective because they require less checking. However, when possum populations are at low density it is unclear that it is more cost-effective to use fewer multiple-capture traps rather than adding more single-capture traps. Warburton and Gormley (2015) used an individual-based spatially explicit modelling approach to address this question and concluded that for possums at a simulated density of 0.5/ha, 98% of individuals could be captured with only a single-kill trap at each trapping site. When simulated possum density was increased to 3/ha, having three single-kill traps per site would have caught 97% of possums. The authors conclude that the most cost-effective strategy will often be to deploy multiple single-capture per site, rather than investing in fewer, more expensive, multiple-capture traps.

AI-camera enabled kill traps, currently under development, will have the capability of arming or disarming contingent on whether they detect a target or non-target species. Although expensive, these traps could assist the TB eradication programme to control possums in high-priority areas where the presence of valued non-target species prevents deployment of conventional traps or toxic baits.

Warburton (2017) investigated the value of wireless monitoring of large-scale trap networks and concluded that a network that signals when traps were sprung could provide cost savings for live-capture trap networks (e.g., leg-hold traps) which currently require daily inspection but that the benefits were much less clear for kill trap networks (which can be inspected less frequently). Indeed, if checking frequency is primarily governed by the need to refresh bait, wireless monitoring is unlikely to provide cost-savings. Long-life bait dispensers, such as the ZIP Motolure, might address this but we are not aware of any published evaluation of such devices as yet.

Various new kill-trap designs have been brought to market in the past decade. Such traps are typically tested for their killing performance relative to the National Animal Welfare Advisory Committee (NAWAC) trap-testing standard (NAWAC 2019), which requires that 10 of 10 possums be rendered irreversibly unconscious within a 3-minutes of capture. (If a trap renders all captured animals irreversibly unconscious within 3 minutes, but with some or all in >30 seconds, then the trap qualifies as a Class B trap for welfare performance; if all 10 animals are rendered irreversibly unconscious within 30 seconds, the trap qualifies as a Class A trap.) Traps generally go through several design iterations before achieving a NAWAC standard (e.g., Morriss 2022).

It is important to recognize that NAWAC standards address animal welfare rather than operational efficacy. Some recent traps designs met AWAC welfare standards but have proven to be ineffective under field conditions (e.g., Sweetapple and Nugent 2020). Other new kill-trap designs have performed well in the field (e.g. Yockney et al. 2020).

There also have been research efforts to improve the effectiveness of existing trap designs. For example, Warburton et al. (2022) compared the capture rate of four alternative leg-hold trap sets (i.e. double sets, covered traps, hazed traps, enlarged trigger plates) but found no improvement relative to standard NPCA-recommended sets. However, lure placed on the ground encircling the trap achieved a 33% increase in capture rate relative to the NPCA-recommended method of placing the lure behind the trap.

Johnstone et al. (2023) showed that the residual possum population in a heavily trapped forest reserve in North Canterbury consisted of a disproportionate number of shy individuals that refused to interact with the deployed traps. In subsequent pen trials, it was found that switching trap designs could help target these shy individuals.

Eradication strategies

Nugent et al. (2018) provide an overview of New Zealand's current POF strategy for eradication of TB. Several potential approaches for further optimizing the allocation of management resources, especially for places where existing methods are impractical are discussed (e.g. the use of livestock as sentinels). Gormley et al. (2018) describe a decision-support framework that enables expected costs of wildlife surveillance to be predicted, with stopping rules implemented to help minimize costs.

Factors that will influence these stopping rules are discussed. Sinclair et al. (2023) provide an update to Nugent et al.'s (2018) POF strategy overview.

Latham and Nugent (2016) compared the probabilities of TB freedom assigned to individual Vector Control Zones (VCZs) by Area Disease Managers (ADMs) in 2015 against the outcomes of surveys for TB possums conducted within those VCZs for the period 2011−2015. Far fewer TB possums were detected than expected given the ADMs' subjective assessments of TB freedom in possums. The authors suggest that ADMs are adopting a precautionary approach that is resulting in over-expenditure on control and/or surveillance. Implications of these findings for the Technical Specifications are discussed in Milestone 5.

Nugent et al. (2017a) identified multiple focal sites where TB possums had been found since 2000, surveyed possum abundance at 17 of those sites, and then trapped and necropsied a high proportion of possums at the seven highest-density sites to determine whether TB had persisted despite possum control. These findings support the TB Plan's assumption that the TB persistence threshold in possums is somewhere above a 5% ground-set RTCI and suggest that cases of apparent TB persistence in possum populations many years after possum control may be due to substandard control.

Nugent et al. (2017b) assessed the feasibility of implementing a Survey-then-Control (StC) approach for declaring TB freedom at a large scale, using the Hauhungaroa Range as a case study. The authors conclude that while the StC approach is feasible, the best tool for confirming TB freedom is evidence confirming a near-total possum kill has been achieved.

Eradication/control tactics

New Zealand's pest managers have decades of experience with control tactics for possums and other potential TB vectors. Research on tactics over the past decade has provided some incremental gains in control effectiveness and has emphasised the importance of responding to increasing behavioural resistance (trap and bait 'shyness') among survivor animals in intensively controlled areas.

The percentage kill achieved by aerial 1080 control operations is not usually monitored, however kill estimates available since 2015 have consistently been higher than the 90% assumed by the Spatial Possum Model (e.g., 99% kill in the Hauhungaroa Ranges; Nugent et al. 2017). References to these studies, and implications of >90% kills for POF modelling and the TB Plan's objectives, are discussed in Milestone 5.

The Spatial Possum Model's predictions assume that control is applied uniformly so that pockets of infected possums are not missed by the control effort. This risk, which was highlighted by the original Hohotaka 'maintenance control' proof of concept (Caley et al. 1999), has been addressed in part by the adoption of GPS technology to monitor aerial operators' flight paths and bait flow.

Potential lack of uniformity of ground-based control, particularly in areas considered inaccessible, remains a risk for the TB Plan's objectives. Gormley et al. (2021) speculated that gaps in ground control associated with steep gorges may have contributed to the recent Hawkes Bay TB outbreak, although movement of infected vectors (pigs) from an adjacent uncontrolled area was an alternative possibility. Similarly, ongoing herd breakdowns in northern Westland have been linked to deep-forest reservoirs of TB beyond the areas subjected to possum control (and beyond the distance possums would have been expected to travel to farmland if low-density buffers between deep forest and farmland were maintained (Sweetapple et al. 2021, Veale et al. 2021).

Several changes to OSPRI's Technical Specifications to help reduce these risks associated with ground control are proposed in Milestone 5. Meanwhile, Morley et al. (2017, 2024) discuss initial trials on the use of uncrewed aerial systems (‘drones’) to deploy bait pods into gullies and other inaccessible terrain.

García-Díaz et al. (2019) assessed how 13 covariates describing landscape, habitat patch and possum population features influence the recovery time of post-control possum populations. Recovery to a density threshold of 2 possums/ha was fast in all patches, usually < 2 years, with the speed strongly dependent on habitat availability and patch area.

Nugent et al. (2021) tested a range of ground-based tools (leg-hold trapping, kill trapping, cyanide poisoning, and ground-based 1080 poisoning) for their relative effectiveness in providing possum carcasses for necropsy (TB surveillance) and for reducing possum density (control). Leg-hold trapping for three nights delivered 1.0 kills/ha, Goodnature A12 self-resetting traps killed no possums, single-kill Sentinel kill traps checked after 2 and 30 days killed 0.6 possum/ha, Feratox pellets in bait stations resulted in 0.7 kills/ha, and ground-laid 1080 poison in bait stations resulted in recovery of 0.1 kills/ha. The methods varied in how many carcases could be recovered for necropsy.

It is well-recognised that sublethal poisoning of possums and other pests exposed to fragmented or degraded toxic baits can generate long-lasting bait aversion (see Allsop et al. 2017 for a review). The risk to the TB Plan is that survivors of intensive aerial 1080 poisoning campaigns might be no longer susceptible to control, however Nugent et al. (2019, 2020) demonstrated that a ‘dual 1080’ approach that switched to a different bait type for the second 1080 application could effectively target survivors of the first application. The authors also suggest that pre-feeding with the different bait type may be most effective if it is conducted before the possums are exposed to any form of 1080 bait. Nichols et al. (2021) report >99% kill of possums using this ‘dual 1080’ approach.

Cook and Mulgan (2022) claimed success in eliminating possums from an unfenced >10,000 ha study site in the Perth river valley, Westland, using aerial 1080 control and mop-up efforts that were aided by mountains and rivers that helped protect the area from possum reinvasion. The 11-month mop-up phase used a motion-activated camera network, traps equipped with automated reporting and a possum search dog. The claim that elimination was achieved over the full area has been questioned, however, as detection devices were located in less than half of the study area (Barron et al. 2023).

Gormley et al. (2020) modelled field data from a fixed network of predator traps in Hawkes’ Bay to investigate whether similar numbers of predators could have been captured using less traps. During the maintenance phase of trapping, the simulations suggested that with 75% of traps removed from the network, approximately 75% of the fully tally of predators would still have been captured. If the proportion captured needed to be maintained above 90%, 25% of traps could have been removed.

Wilson (2022) and more recently Johnstone et al. (2023) have shown that possums in areas subjected to intensive predator control are shyer and more hesitant towards novel objects, and thus less likely to interact with traps and detection devices. Switching device types is a partial solution to this problem. O’Malley (2023) investigated possum encounters and interactions with three trap designs (legholds, Sentinels and AT220s) following population reduction. Trap ‘openness’ (the extent the animal needs to enter an enclosed space) had a strong impact on interaction rates, with possums rarely entering closed-design traps. Encounter and interaction rates were relatively low, which implies that long periods (> 100 days) may be required to remove all individuals from sparse trapping grids.

Monitoring/surveillance

Various recent studies (listed below in order of chronology) have sought to improve the reliability and cost-effectiveness of monitoring post-control wildlife populations and/or the pprevalence of TB-infected individuals therein. Of these, Nugent et al.'s (2017) Survey-then-Control (StC) surveillance proposal has perhaps the most potential to provide cost saving for the TB Plan.

Nugent et al. (2017a) undertook modelling and a field trial to investigate the optimal deployment of possum survey effort to attain a desired level of TB surveillance sensitivity. The authors recommend a stratified approach with low intensity detection in all areas plus systematic trapping in high density areas. They also trialled a feral pig sentinel surveillance programme and concluded that the current POF modelling process probably understates individual pig detection capability while overstating the spatial coverage of the surveillance pigs provide.

Anderson et al. (2017) describe a spatially explicit model that uses livestock surveillance data to strengthen predictions of *M. bovis* infection freedom, given negative wildlife reservoir surveillance results.

Forsyth et al. (2018) investigated the relationship between leg-hold trap-based indices of possum occupancy and abundance versus two cheaper alternatives (wax tags, chew cards). Median possum abundance index values estimated from traps were lower than those estimated from wax tags and chew cards in forest, but similar to those from wax tags in non-forest. The authors recommend chew cards as the better of the two options for replacing for trap-based monitoring.

Nugent et al. (2019) assessed the feasibility of modelling the risk of TB persistence in possums based an empirical assessment of whether even and very low post-control possum density had been achieved by past control. (The motivation for the approach is to reduce the need for possum-TB surveillance data in difficult-to-work areas.) The researchers concluded that the approach was indeed useful but cautioned that the longer the period between the final control and the density assessment, the more likely it is that evidence of variation in control efficacy will become obscured by population recovery and possum re-aggregation.

Sweetapple and Nugent (2020) assessed various methods for detecting and removing possums from extreme-low-density populations. In such cases, survivor possums become highly spatially aggregated, with large areas of unoccupied habitat between aggregations. This suggests detection-targeted control (DTC) will often be more cost-effective than area-wide control. The authors suggest that detection transects spaced at 500-m intervals, with devices placed every 50 m, will adequately map the distribution of most possum populations, although extreme-low-density populations may require more intensive surveys with reduced transect and/or device spacing. A multi-stage detection strategy that starts with wide transect intervals (c. 2 km) followed by more intensive targeted surveys could be cost-effective for surveys of these populations.

Ross (2021a) reviewed New Zealand initiatives to use AI techniques for sorting and classifying images of possums and other animal pest species. Use cases range from real-time, on-device applications (for example, to enable traps to discriminate between target and non-target species) to improved analysis of large volumes of images gathered from camera monitoring networks (e.g., Martin and Glen 2022). The review noted that AI camera research to date has been somewhat uncoordinated and a more strategic approach is needed.

Ross (2021b) assessed the effectiveness of a new thermal camera with AI recognition as a tool for detecting possums at very low densities following control. The thermal cameras had higher detection rates than chew cards and PIR trail cameras and greater ability to record animal behaviour around monitoring and control devices. They are, however, more expensive than other monitoring methods so their cost-effectiveness has yet to be determined.

Glen et al. (2023) reviewed ways in which dog-handler teams can contribute to active detection and control of possums and other predators by combining the dogs' ability to detect animals with their handlers' ability to mount a rapid response.

Estimates of the probability of an animal being detected by a surveillance device for a given amount of survey effort are critical for models estimating pest density or probability of pest eradication. Vattiato et al. (2023) review and summarize capture-recapture and home-range studies reporting estimates of detectability for possums and nine other New Zealand mammal pests.

Lu et al. (2024) compiled information on the volatile organic compounds (VOCs) emitted by possums and other predators in New Zealand and provide a brief overview of VOC detection techniques. The authors conclude that further research in this field has potential to enhance biomarker detection technologies for monitoring predator eradication efforts.

Eradication feasibility

If the goal of Predator Free 2050 were to be achieved on schedule, that programme would obviously provide an enormous boost towards achievement of the TB Plan's objectives because the key TB vector would have been eliminated from the New Zealand mainland. However, the spatial scale of the proposed predator eradication is two orders of magnitude larger than any previous eradication success, which may not be realistic (Linklater and Steer 2018) and is highly contingent on unresolved questions relating to interactive effects, the requirement for new tools, and overcoming social and bioethical challenges (Peltzer et al. 2019). Indeed, prospects for the initiative are uncertain as continuation of adequate funding is far from guaranteed. Moreover, while PF2050 has caught the imagination of the public, within the conservation community there is debate as to the wisdom of so much focus on predators at the expense of other threats to New Zealand's biodiversity, such as rising ungulate populations (Leathwick and Byrom 2023). Palmer and McLauchlin (2023) report that 'many people are thinking through the potential implications – positive and negative – if PF2050's targets are not reached'. Other than leveraging PF2050's short- to medium-term investment in new control tools, reliance of TB vector managers on PF2050 outcomes would represent a risk to the TB programme.

Latham and Nugent (2016) report that far fewer TB possums are being detected during possum surveys than would be expected given ADMs' subjective assessments of TB freedom in possums, which suggests that more of New Zealand may be free of TB in possums than is believed by disease managers. Conversely, Hone (2023) examined the number of livestock herds with at least one positive reactor versus annual costs associated with disease and vector control and concluded that the data do suggest New Zealand is on a pathway to biological eradication of TB, but not by 2055. The merits or otherwise of Hone's argument are discussed by Barron in Milestone 1.

Taking an international perspective, Gortázar et al. (2023) note that although many industrialized countries have reached 'Officially Tuberculosis Free' status, infection of cattle with *M. bovis* still occurs in most countries. They suggest that rather than focusing on certain animal species regarded as maintenance hosts, the problem should be viewed as one of 'complex maintenance communities where several wild and domestic species and the environment all contribute to pathogen maintenance'. They recognize, however, that the fundamental TB control paradigm of testing and culling, movement control and slaughterhouse inspection is not fully implemented in many countries because these measures are considered too expensive or ethically unacceptable.

More (2019) reviewed the recently stated commitment of the Irish government to eradicate TB from their country by 2030. He concluded that there was 'robust' evidence – based on national and international experience and a modelling study – to suggest that then-current strategies plus badger vaccination would not be sufficient to achieve the 2030 eradication target. He advocated additional measures focussed on addressing TB risks from wildlife, implementing additional risk-based cattle controls, and enhancing industry engagement. TB Scientific Working Group (2024) concurred with More (2019) that additional measures will be needed for TB eradication in Ireland and that a more regionalized eradication approach within an overall strategic framework was needed.

Social licence

Gormley and Corner (2018) reviewed the role of stakeholder values in influencing TB eradication strategies in several countries including Ireland and New Zealand. They noted that stakeholder involvement increases with the complexity of the epidemiology, and that similar groups of stakeholders may agree to a set of control and eradication measures in one region only to disagree with the same measures in another.

Loss of social licence for deployment of 1080 presents an ongoing risk to achieving the TB Plan's milestones, although Caley (2015) suggested that it should be technically feasible to achieve biological eradication of TB without the use 1080, albeit with increased costs and longer timeframes. Public support for the use of 1080 declined since the 1990's (Russell 2014) but we did not find evidence for further shifts in attitudes over the past decade. Anecdotally, concerns over handling of the Covid-19 outbreak seems to have drawn attention away from the 1080 debate, but that is probably temporary.

Kaine and Wright (2022) investigated how attitudes and involvement affected support for pest control methods, using the distribution of 1080 baits to control rats and possums as a case study. The results indicate that different communication strategies are needed for individuals with low vs high involvement in reducing pest populations and that those with low involvement will be particularly susceptible to misinformation through social media. Similarly, MacDonald et al. (2021) demonstrated that underlying beliefs affect respondent opinions about gene drives and species-specific toxins, and that public engagement strategies should acknowledge and respond to this range of beliefs.

Dickie and Fabien (2023) surveyed the attitudes of young adult New Zealanders towards mammalian predator control in 2017. Relative to the general public, a higher proportion of respondents viewed introduced predators as a threat. The majority viewed aerial distribution of poison negatively and there were ethical concerns over all current methods for pest control. The respondents were 'cautiously open' to the future use of gene editing and gene drives.

Chand and Cridge (2020) review New Zealand's Predator Free 2050 initiative as a case study of the range of tactics deployed, or proposed to be deployed, to achieve large-scale vertebrate pest control. They note that social opposition to many of these tactics 'is not always reflective of the underlying science'. Continued reference to historical arguments by groups opposing methods such as 1080 highlights the importance of proactive communication strategies when introducing new technologies, as early mistakes can significantly hinder later use.

Palmer et al. (2020) provide a perspective on how Māori views on new pest control technologies can be recognised. The Treaty relationship between government and Māori demands attention to rangatiratanga (autonomy for Māori) and tikanga (Māori customary protocols). Māori participants in the study, when asked for their perspective on issues of consent and social licence, indicated a preference for processes based upon rangatiratanga.

7. Conclusions

The majority of science findings reviewed above help to refine, but do not significantly challenge, the foundations of the 2016 TB Plan. Findings that further warrant attention during formulation of the next plan include the following:

- Percentage kills being achieved by aerial 1080 control of possums are generally much higher than the 90% value assumed by the current POF process;
- Far fewer TB possums are being detected during possum surveys than would be expected given ADMs subjective assessments of TB freedom in possums, suggesting managers are being overly precautionary;
- Incomplete coverage of inaccessible habitats during ground control operations poses a risk that clusters of infected possums will survive control;
- Nugent et al.'s (2017) Survey-then-Control (StC) surveillance approach has potential to provide cost savings.
- Nugent et al.'s (2019) proposal that possum density assessment/modelling be adopted as an alternative to estimating TB freedom in possums in areas where TB-possum surveillance is prohibitively expensive also warrants consideration.
- There are indications that infected possums in deep forest sometimes move further than expected to farmland, including across buffer zones;
- Wild deer numbers have increased significantly over the past decade, but there has been no new research to address whether these high populations may pose a risk to the TB plan's objectives;
- Similarly, rabbit populations in some parts of the country have rebounded after past suppression by rabbit haemorrhagic disease virus. There has been no new research to shed light on whether these populations are supporting large ferret populations that could delay progress towards TB eradication.
- Hone's (2023) conclusion that the TB programme is tracking towards biological eradication of TB, but not by 2055, requires further discussion.
- The potential loss of social licence for 1080 remains a risk, but one best addressed by social scientists and communication specialists. Concerns are not science-based and so are unlikely to be addressed by further bio-physical research.

8. References

Allsop SE, Dundas SJ, Adams PJ, Kreplins TL, Bateman PW, Fleming PA. 2017. Reduced efficacy of baiting programs for invasive species: some mechanisms and management implications. Pacific Conservation Biology 23(3):240-57.

Anderson DP, Gormley AM, Bosson M, Livingstone PG, Nugent G. 2017. Livestock as sentinels for an infectious disease in a sympatric or adjacent-living wildlife reservoir host. Preventive Veterinary Medicine 148:106-114.

Anon. 2015. National Bovine TB Plan Review Options Analysis. TB Plan Review Plan Governance Group.

Arnold ME, Courcier EA, Stringer LA, McCormick CM, Pascual-Linaza AV, Collins SF, Trimble NA, Ford T, Thompson S, Corbett D, Menzies FD. 2021. A Bayesian analysis of a test and vaccinate or remove study to control bovine tuberculosis in badgers (Meles meles). PloS one 16: e0246141.

Barron M, Anderson DP, Norbury G, Warburton B. 2023. Comment on Cook, B.; Mulgan, N. Targeted Mop up and Robust Response Tools Can Achieve and Maintain Possum Freedom on the Mainland. Animals 2022, 12, 921. Animals 13(11):1840.

Blackie H, MacKay J, Barrett B, Inder S, MacMorran D, Bothwell J, Clout M, Eason C. 2016. A novel device for controlling brushtail possums (Trichosurus vulpecula). New Zealand Journal of Ecology 40(1):60-4.

Bond DM, Veale A, Alexander A, Hore TA. 2024. Coat colour in marsupials: genetic variants at the ASIP locus determine grey and black fur of the brushtail possum. Royal Society Open Science 11(7):240806.

Brewer K, McWhorter TJ, Moseby K, Read JL, Peacock D, Blencowe A. 2023. pH-Responsive polymer implants for the protection of native mammals: Assessment of material properties and poison incorporation performance. Polymers 15:878.

Buddle BM, Vordermeier HM, Chambers MA, de Klerk-Lorist LM. 2018. Efficacy and safety of BCG vaccine for control of tuberculosis in domestic livestock and wildlife. Frontiers in veterinary science 5:259.

Beausoleil NJ, Fisher P, Littin KE, Warburton B, Mellor DJ, Dalefield RR, Cowan P. 2016. A systematic approach to evaluating and ranking the relative animal welfare impacts of wildlife control methods: poisons used for lethal control of brushtail possums (Trichosurus vulpecula) in New Zealand. Wildlife Research 43(7):553-65.

Caley P. 2015. A review of science underpinning eradication of bovine TB from New Zealand. Unpublished report to TB Free New Zealand.

Caley P, Hickling GJ, Cowan PE, Pfeiffer DU. 1999. Effects of sustained control of brushtail possums on levels of Mycobacterium bovis infection in cattle and brushtail possum populations from Hohotaka, New Zealand. New Zealand Veterinary Journal 47(4):133-42.

Chand RR, Nimick M, Cridge B, Rosengren RJ. 2023. Investigating the Contribution of Major Drug-Metabolising Enzymes to Possum-Specific Fertility Control. International Journal of Molecular Sciences 24(11):9424.

Chand RR, Cridge BJ. 2020. Upscaling Pest Management From Parks to Countries: A New Zealand Case Study. Journal of Integrated Pest Management 11(1):8.

Chivers CA, Maye D, Lenormand T, Enticott G, Tomlinson S. 2022. Exploring farmer attitudes towards the vaccination of badgers against bovine tuberculosis. Report to Defra. 33pp.

Cook B, Mulgan N, Nathan H. 2021. Rivers as obstacles to home range expansion by the brushtail possum. New Zealand Journal of Ecology 45(1):1-6.

Cook B, Mulgan N. 2022. Targeted mop up and robust response tools can achieve and maintain possum freedom on the mainland. Animals 12(7):921.

Conteddu K, English HM, Byrne AW, Amin B, Griffin LL, Kaur P, Morera-Pujol V, Murphy KJ, Salter-Townshend M, Smith AF, Ciuti S. 2024. A scoping review on bovine tuberculosis highlights the need for novel data streams and analytical approaches to curb zoonotic diseases. Veterinary Research 55(1):64.

Crispell J, Zadoks RN, Harris SR, Paterson B, Collins DM, de-Lisle GW, Livingstone P, Neill MA, Biek R, Lycett SJ, Kao RR. 2017. Using whole genome sequencing to investigate transmission in a multi-host system: bovine tuberculosis in New Zealand. BMC genomics 18:1-2.

Crispell J, Cassidy S, Kenny K, McGrath G, Warde S, Cameron H, Rossi G, MacWhite T, White PC, Lycett S, Kao RR. 2020. Mycobacterium bovis genomics reveals transmission of infection between cattle and deer in Ireland. Microbial genomics 6(8):e000388.

Dickie L, Medvecky F. 2023. The attitudes of young adults towards mammalian predator control and Predator Free 2050 in Aotearoa New Zealand, Australasian Journal of Environmental Management 30:2, 170-187.

Eason CT, Shapiro L, Ogilvie S, King C, Clout M 2017. Trends in the development of mammalian pest control technology in New Zealand. New Zealand Journal of Zoology 44(4): 267305.

Eason C, Shapiro L, Eason C, MacMorran D, Ross J. 2020. Diphacinone with cholecalciferol for controlling possums and ship rats. New Zealand journal of zoology 47(2):106-20.

Esvelt KM, Gemmell NJ. 2017. Conservation demands safe gene drive. PLoS Biol 15(11): e2003850.

Ferguson I & Hellström J. 2015. Review of the science undertaken for the purpose of managing Bovine Tuberculosis in New Zealand. Unpublished report to the TB Plan Review Plan Governance Group.

Ferreira EM, Duarte EL, Cunha MV, Mira A, Santos SM. 2023. Disentangling wildlife–cattle interactions in multi-host tuberculosis scenarios: systematic review and meta-analysis. Mammal Review 53(4):287-302.

Fisher P, Brown S, Warburton B, Forrester G. 2017. Rapid TB freedom through achievement of near-zero possum density: Part 1: quantitative bait marker trial and microencapsulation for bait formulation. Contract report R-10776-01 to TBfree New Zealand.

Forsyth DM, Ramsey DS, Perry M, McKay M, Wright EF. 2018. Control history, longitude and multiple abiotic and biotic variables predict the abundances of invasive brushtail possums in New Zealand forests. Biological Invasions 20(8):2209-25.

Forsyth DM, Perry M, Moloney P, McKay M, Gormley AM, Warburton B, Sweetapple P, Dewhurst R. 2018. Calibrating brushtail possum (Trichosurus vulpecula) occupancy and abundance index estimates from leg-hold traps, wax tags and chew cards in the Department of Conservation's Biodiversity and Monitoring Reporting System. New Zealand Journal of Ecology 42(2):179-91.

García-Díaz P, Anderson DP, Lurgi M. 2019. Evaluating the effects of landscape structure on the recovery of an invasive vertebrate after population control. Landscape ecology 34:615-26.

Glen AS, Garvey PM, Innes J, Buchanan F. 2023. What can wildlife-detection dogs offer for managing small mammalian predators? Wildlife Research 51: WR23068.

Godfrey EJ, Cameron EZ, Hickling GJ. 2023. Social learning in a nocturnal marsupial: is it a possum-ability? Biology Letters 19(1):20220460.

Gormley AM, Anderson DP, Nugent G. 2018. Cost-based optimization of the stopping threshold for local disease surveillance during progressive eradication of tuberculosis from New Zealand wildlife. Transboundary and Emerging Diseases 65(1):186-96.

Gormley AM, Warburton B. 2020. Refining kill-trap networks for the control of small mammalian predators in invaded ecosystems. Plos one 15(9):e0238732.

Gormley AM, Hickling GJ, Warburton B. 2021. An investigation of the 2019-2021 Hawke's Bay bovine TB ouTBreak. Manaaki Whenua-Landcare Research Contract Report LC4057 for OSPRI.

Gormley E, Corner LA. 2018. Wild animal tuberculosis: stakeholder value systems and management of disease. Frontiers in veterinary science 5:327.

Gortázar C, De la Fuente J, Perelló A, Domínguez L. 2023. Will we ever eradicate animal tuberculosis? Irish Veterinary Journal 76(Suppl 1):24.

Hone J. 2023a. Are predictions of bovine tuberculosis-infected herds unbiased and precise? Epidemiology & Infection 151:e165.

Hone J. 2023b. Diminishing returns in bovine tuberculosis control. Epidemiology & Infection 141(7):1382-9.

Jackson M, Hartley S, Linklater W. 2016. Better food-based baits and lures for invasive rats Rattus spp. and the brushtail possum Trichosurus vulpecula: a bioassay on wild, free-ranging animals. Journal of Pest Science 89:479-88.

Jackson R, Pfeiffer DU, Porphyre T, Sauter-Louis C, Corner LA, Paterson BM, Morris RS. 2019. Ecology of a brushtail possum (Trichosurus vulpecula) population at Castlepoint in the Wairarapa, New Zealand. New Zealand Journal of Ecology 43(2):3375.

Johnstone KC, Garvey P, Hickling GJ. 2024. Invasive mammal control selects for trap-recalcitrant behaviour and personality. Biological Invasions 26:549-64.

Justus W, Valle S, Barton O, Gresham A, Shannon G. 2024. A review of bovine tuberculosis transmission risk in European wildlife communities. Mammal Review 54:325–340.

Kaine G, Wright V. 2022. Attitudes, Involvement and Public Support for Pest Control Methods. Conservation 2(4):566-86.

Kelly DJ, Mullen E, Good M. 2021. Bovine tuberculosis: the emergence of a new wildlife maintenance host in Ireland. Frontiers in veterinary science 8:632525.

Kemp JR, Mosen CC, Elliott GP, Hunter CM, van Klink P. 2019. Kea survival during aerial poisoning for rat and possum control. New Zealand Journal of Ecology 43(1):1-1.

Latham MC, Nugent G. 2016. Evaluating assessments of TB freedom in possums: How close are we? Landcare Research Contract Report LC268313pp.

Leathwick JR, Byrom AE. The rise and rise of predator control. 2023. New Zealand Journal of Ecology 47(1):1-5.

Linklater W, Steer J. 2017. Predator Free 2050: A flawed conservation policy displaces higher priorities and better, evidence-based alternatives. Conservation Letters 11(6):e12593.

Lu Z, Whitton R, Strand T, Chen Y. 2024. Review of Predator Emitted Volatile Organic Compounds and Their Potential for Predator Detection in New Zealand Forests. Forests 15(2):227.

MacDonald EA, Balanovic J, Edwards ED, Abrahamse W, Frame B, Greenaway A, Kannemeyer R, Kirk N, Medvecky F, Milfont TL, Russell JC. 2020. Public opinion towards gene drive as a pest control approach for biodiversity conservation and the association of underlying worldviews. Environmental Communication 14(7):904-18.

MacDonald EA, Edwards E, Balanovic J, Medvecky F. 2020. Underlying beliefs linked to public opinion about gene drive and pest-specific toxin for pest control. Wildlife research 48(1):30-7.

Malham J, Elliott GP, Walker S. 2019. No evidence of negative effects of aerial 1080 operations on red deer (Cervus elaphus) encounters and sightings in South Westland forests. New Zealand Journal of Ecology 43(2):1-9.

Margetts BI, Ross JG, Buckley HL. 2020. Measuring home-range changes following density reduction of Australian brushtail possum. The Journal of Wildlife Management 84(1):185-92.

Martin B, Glen A. 2022. Artificial intelligence for vertically oriented cameras. Contract report LC4190 to Hawke's Bay Regional Council. 17pp.

McLean LR, Nichols MM, Taylor AH, Nelson XJ. 2022. Memory retention of conditioned aversion training in New Zealand's alpine parrot, the kea. The Journal of Wildlife Management 86(5):e22221.

Menzies FD, McCormick CM, O'Hagan MJ, Collins SF, McEwan J, McGeown CF, McHugh GE, Hart CD, Stringer LA, Molloy C, Burns G. 2021. Test and vaccinate or remove: methodology and preliminary results from a badger intervention research project. Veterinary Record 2021: e248:1-12.

Merry S. 2021. Quantifying the effect of individual heterogeneity in epidemic spread on a network. MSc Thesis, University of Canterbury. 197pp.

Mockett L. 2017. Testing the behaviour of Australian brushtail possums (Trichosurus vulpecula) to candidate semiochemicals from conspecifics' urine. PhD dissertation, Open Access Te Herenga Waka-Victoria University of Wellington.

More SJ. 2019. Can bovine TB be eradicated from the Republic of Ireland? Could this be achieved by 2030? Irish veterinary journal 72(3):1-10.

Morley CG, Broadley J, Hartley R, Herries D, MacMorran D, McLean IG. 2017. The potential of using unmanned aerial vehicles (UAVs) for precision pest control of possums (Trichosurus vulpecula). Rethinking Ecology 2:27-39.

Morley CG, Solaris P, Quinn GO, Ross KE, Peterson BJ. 2024. Precision pest control using purpose-built uncrewed aerial system (UAS) technology and a novel bait pod system. Drone Systems and Applications 12:1-3.

Morriss G. 2019. Testing the palatability of weathered Orillion deer-repellent bait on farmed red deer. Report R-10823 to OSPRI. 8pp.

Morriss G, Gormley A. 2022. Operational scale field testing of the efficacy of deer repellent Prodeer 1080 possum bait in Hawkes Bay. Report LC4100 to OSPRI. 15pp.

Morriss G, Arrow J. 2020. Testing the effect of three deer repellent concentrations on the palatability of PCR cereal baits to possums. Report LC3732 to OSPRI. 15pp.

Morriss G, Yockney I, Howard S, Nugent G 2020. Comparison of deer abundance and rates of increase (2018–2020) in 1080-poisoned and unpoisoned areas on Molesworth Station. Report LC3728 to OSPRI. 12pp.

Morriss GA, Parkes JP, Nugent G. 2020. Effects of aerial 1080 operations on deer populations in New Zealand. New Zealand Journal of Ecology 44(2):1-8.

Morriss G. 2022. Pen testing the kill efficacy of the Hammerforce trap when used for capturing possums. Report LC4225 to OSPRI. 6pp.

Morriss G, Nugent G. 2018. Impact of aerial 1080 baiting with and without Epro deer repellent on a red deer and tahr population in Otago. Landcare Research Contract Report LC3383. 20pp.

Morriss G, Yockney I, Nugent G. 2019. Operational-scale field testing of Pestex® deer repellent 1080 cereal bait. Manaaki whenua – Landcare Research Contract Report LC3622. 18pp.

Morris MC. 2020. Predator free New Zealand and the 'War' on pests: Is it a just war? Journal of Agricultural and Environmental Ethics 33(1):93-110.

NAWAC 2019. NAWAC Guideline 09: Assessing the welfare performance of restraining and kill traps. https://www.mpi.govt.nz/dmsdocument/8521-nawac-guideline-09-assessing-the-welfare-performance-of-restraining-and-kill-traps (accessed 14/8/2024).

Nichols M, Nathan H, Mulgan N. 2021. Dual aerial 1080 baiting operation removes predators at a large spatial scale. New Zealand Journal of Ecology 45(1):1-10.

Nichols M, Bell P, Mulgan N, Taylor A. 2020. Conditioned aversion in kea to cereal bait: A captive study using anthraquinone. Applied Animal Behaviour Science 230:105077.

Nugent G, Clayton R, Warburton B, Day T. 2020. Dual 1080 bait switching for killing cereal-bait-shy possums. New Zealand Journal of Ecology 44: 3403.

Nugent G, Gormley AM, Anderson DP, Crews K. 2018. Roll-back eradication of Bovine Tuberculosis (TB) from wildlife in New Zealand: concepts, evolving approaches, and progress. Frontiers in Veterinary Science 5: 277.

Nugent G, Livingstone P. 2015. Evidence supporting the technical feasibility of eradicating entrenched bovine tuberculous (TB) infection from wildlife in forested areas of difficult operational terrain. Unpublished report to the TB Plan Review Plan Governance Group.

Nugent G, Morriss G.A. Warburton B. 2019. Attempting local elimination of possums (and rats) using dual aerial 1080 baiting. New Zealand Journal of Ecology 43: 3373.

Nugent G. Sweetaple P, Yockney I, Barron M, Latham MC. 2014. Progress towards eradication of TB from wildlife in the Hauhungaroa Ranges. Contract report LC1806 to OSPRI. 67pp.

Nugent G, Sweetapple P, Yockney I, Morriss G. 2017. TB freedom in possums in the Hauhungaroa Range: A large-scale test of a new surveillance approach. Landcare Research Contract Report LC2842. 41pp.

Nugent G, Sweetapple P, Yockney I. 2021. Achieving TB freedom in deep forest without aerial 1080: Concept and comparison of potential field methods. Manaaki Whenua – Landcare Research Contract Report LC3944. 33pp.

Nugent G, Sweetapple P, Yockney I, Whitford J. 2017. Towards better parameter values and surveillance systems for the wildlife TB freedom framework. Contract report LC2733 to OSPRI. 48pp.

Nugent G, Whitford J, Brown S, Howard S, Morriss G. 2020. What concentrations of potential kea repellents in 1080 bait least affect possum and rat control efficacy? Report LC3835 to OSPRI. 30pp.

Nugent G. Whitford J, Gormley A (2019) Freedom without TB surveillance: can aerial control and density monitoring be enough? Landcare Research Contract Report LC3606. Prepared for TBfree New Zealand

Nugent G, Yockney IJ, Cross ML, Buddle BM. 2018. Low-dose BCG vaccination protects free-ranging cattle against naturally-acquired bovine tuberculosis. Vaccine 36(48):7338-44.

O'Brien DJ, Kao RR, Little RA, Enticott G, Riley SJ. 2023. The Road Not Traveled: Bovine Tuberculosis in England, Wales, and Michigan, USA. One Health Cases 2023: ohcs20230028. 14pp.

O'Malley TD. 2023. Rat and Possum Dynamics in an Eradication Landscape: Novel Tools, Movement Patterns and Device Interactions (Doctoral dissertation, ResearchSpace@ Auckland).

Palmer S, Mercier OR, King-Hunt A. 2020. Towards rangatiratanga in pest management? Māori perspectives and frameworks on novel biotechnologies in conservation. Pacific Conservation Biology 27(4):391-401.

Pandey A, Feuka AB, Cosgrove M, Moriarty M, Duffiney A, VerCauteren KC, Campa III H, Pepin KM. 2023. Wildlife vaccination strategies for eliminating bovine tuberculosis at the wildlife-livestock interface. bioRxiv 25:2023-06.

Pattabiraman N, Morgan-Richards M, Powlesland R, Trewick SA. 2022. Unrestricted gene flow between two subspecies of translocated brushtail possums (Trichosurus vulpecula) in Aotearoa New Zealand. Biological Invasions 24(1):247-60.

Patterson C. 2020. Predicting Possums: Modelling reinvasion of the common brushtail possum (Trichosurus vulpecula) within a New Zealand urban centre. PhD dissertation, University of Otago, Dunedin.

Patterson CR, Seddon PJ, Wilson DJ, van Heezik Y. 2021. Habitat-specific densities of urban brushtail possums. New Zealand Journal of Ecology 45(2):1-9.

Patterson CR, Lustig A, Seddon PJ, Wilson DJ, van Heezik Y. 2024. Eradicating an invasive mammal requires local elimination and reduced reinvasion from an urban source population. Ecological Applications 34(3):e2949.

Peltzer DA, Bellingham PJ, Dickie IA, Houliston G, Hulme PE, Lyver PO, McGlone M, Richardson SJ, Wood J. 2019. Scale and complexity implications of making New Zealand predator-free by 2050. Journal of the Royal Society of New Zealand 49(3):412-39.

Pinney KA, Ross JG, Paterson AM. 2021. White-tailed deer (Odocoileus virginianus) carcass survey following an aerial 1080 operation, Otago, New Zealand. New Zealand Journal of Zoology 48(2):147-58.

Pinney KA, Ross JG, Paterson AM. 2022. Assessing EDR and a novel deer repellent for reducing by-kill of white-tailed deer (Odocoileus virginianus), during aerial 1080 operations. New Zealand Journal of Zoology 49(3):199-214.

Price-Carter M, Brauning R, De Lisle GW, Livingstone P, Neill M, Sinclair J, Paterson B, Atkinson G, Knowles G, Crews K, Crispell J. 2018. Whole genome sequencing for determining the source of Mycobacterium bovis infections in livestock herds and wildlife in New Zealand. Frontiers in Veterinary Science 5:272.

Ramsey DS, Efford MG. 2010. Management of bovine tuberculosis in brushtail possums in New Zealand: predictions from a spatially explicit, individual-based model. Journal of Applied Ecology 47(4):911-9.

Richardson KS, Rouco C, Jewell C, French NP, Buddle BM and Tompkins DM. 2017. Investigating brushtail possum (Trichosurus vulpecula) home-range size determinants in a New Zealand native forest. *Wildlife Research* 44: 316-323.

Ross J. 2021a. The use of AI in New Zealand for the sorting of images and classification of animal species. Contract Report to Landsdowne Ventured Ltd. 29pp.

Ross J. 2021b. Detecting possums at very low densities following control. Contract Report to OSPRI. 36pp.

Ross J, Eason C. 2021. Sodium fluoroacetate (1080) in relation to its use in New Zealand revisited: A 2021 review. Contract report LINX1801 for Envirolink. 77pp.

Rouco C, Whitford J, Nugent G, Tompkins D, Richardson K, Jewell C, French N, Buddle B. 2016. Detection of TB in possums by possums. Contract report LC2053 to TBfree New Zealand. 23pp.

Rouco C, Richardson KS, Buddle BM, French NP, Tompkins DM 2016. Sex difference in the survival rate of wild brushtail possums (Trichosurus vulpecula) experimentally challenged with bovine tuberculosis. Research in Veterinary Science 107: 102-105.

Rouco C, Jewell C, Richardson KS, French NP, Buddle BM, Tompkins DM. 2018. Brushtail possum (Trichosurus vulpecula) social interactions and their implications for bovine tuberculosis epidemiology. Behaviour 155(7-9):621-37.

Russell JC. 2014. A comparison of attitudes towards introduced wildlife in New Zealand in 1994 and 2012. Journal of the Royal Society of New Zealand 44: 136–151.

Shepherd JD, Gillingham S, Heuer T, Barron MC, Byrom AE, Pech RP. 2018. Multi-scale dynamic maps for the management of invading and established wildlife populations: brushtail possums in New Zealand. Wildlife Research 45(4):336-43.

Sinclair J, New D, Neill M. 2023. Bovine TB in New Zealand–journey from epidemic towards eradication. Irish Veterinary Journal 76(Suppl 1):21.

Sweetapple P, Nugent G. 2020. Refining detection and control tools and strategies for ground-based eradication of large-scale, low-density possum populations. Contract report LC3819 for Predator Free 2050. 40pp.

Sweetapple P, Howard S, Nugent G. 2021. TB prevalence in possums vs altitude on the West Coast: Implications for possum TB surveillance. Contract Report LC4087 for OSPRI. 20pp.

TB Scientific Working Group, Griffin, J., Breslin, P., Good, M., Gordon, S., Gormley, E., Menzies, F., More, S., Ring, S. and Wiseman, J., 2024. Can a regional approach be applied to achieve eradication of bovine tuberculosis in Ireland? Food Risk Assess Europe FR-0017.

Tobajas J, Richardson KS, French NP, Buddle B, Jewell C, Tompkins DM, Rouco C. 2024. Home range overlaps of the brushtail possum (Trichosurus vulpecula): implications for disease transmission. European Journal of Wildlife Research 70(4):78.

Thomas J, Balseiro A, Gortázar C, Risalde MA. 2021. Diagnosis of tuberculosis in wildlife: a systematic review. Veterinary Research 52(1):31.

Vattiato G, Binny RN, Davidson SJ, Byrom AE, Anderson DP, Plank MJ, Carpenter JK, James A. 2023. Detectability of ten invasive mammal pests in New Zealand: a synthesis of spatial detection parameters. New Zealand Journal of Ecology 47(1) 3552.

Veale A, Sweetapple P, Nugent G. 2021. How far might possums spread TB on the West Coast? Implications for OSPRI's possum control strategy. Contract Report LC4047 to OSPRI. 28pp.

Warburton B. 2017. Economic assessment of using wireless monitoring for managing large-scale trap-networks. Landcare Research Contract Report LC2915 for Hawke's Bay Regional Council. 10pp.

Warburton B, Gormley AM. 2015. Optimising the application of multiple capture traps for invasive species management using spatial simulation. PLoS ONE 10(3): e0120373. doi:10.1371/ journal.pone.0120373.

Warburton B, Brown S, Nugent G. 2020. Bait switching for dual 1080. Manaaki Whenua – Landcare Research Contract Report LC3868. 14pp.

Warburton B, Eason C, Fisher P, Hancox N, Hopkins B, Nugent G, Ogilvie S, Prowse TA, Ross J, Cowan PE. 2022. Alternatives for mammal pest control in New Zealand in the context of concerns about 1080 toxicant (sodium fluoroacetate). New Zealand Journal of Zoology 49(2):79-121.

Warburton B, Morriss G, Howard S. 2022. Increasing the capture rates of brushtail possums in Victor# 1 leg-hold traps. New Zealand Journal of Zoology 49(2):122-8.

Waters J, Fraser D, Adams NJ, Blackie H, MacKay J 2017. Increasing possum interaction rates with Chew Cards using new formulation lures. New Zealand Journal of Zoology 44(2):1–8.

Wilson A. 2022. Behavioural variation due to selection pressures in brushtail possum (Trichosurus vulpecula) populations in Otago, New Zealand. MSc thesis, University of Otago. 47pp.

Woodroffe R, Astley K, Barnecut R, Brotherton PN, Donnelly CA, Grub HM, Ham C, Howe C, Jones C, Marriott C, Miles V. 2024. Farmer-led badger vaccination in Cornwall: Epidemiological patterns and social perspectives. People and Nature 3:10691.

Yockney I, Young L, Morriss G, Howard S. 2022. Wanganui Kea Mitigation. Report 118337 to OSPRI. 6pp.

Yockney I, Morriss G, Nugent G. 2020. Assessing the efficacy of the self-resetting AT220 trap for possum control and quantifying TB freedom. Milestone report R-2021-01 to OSPRI. 8pp.