ISSUE 27 / MARCH 2016

LANDCARE RESEARCH
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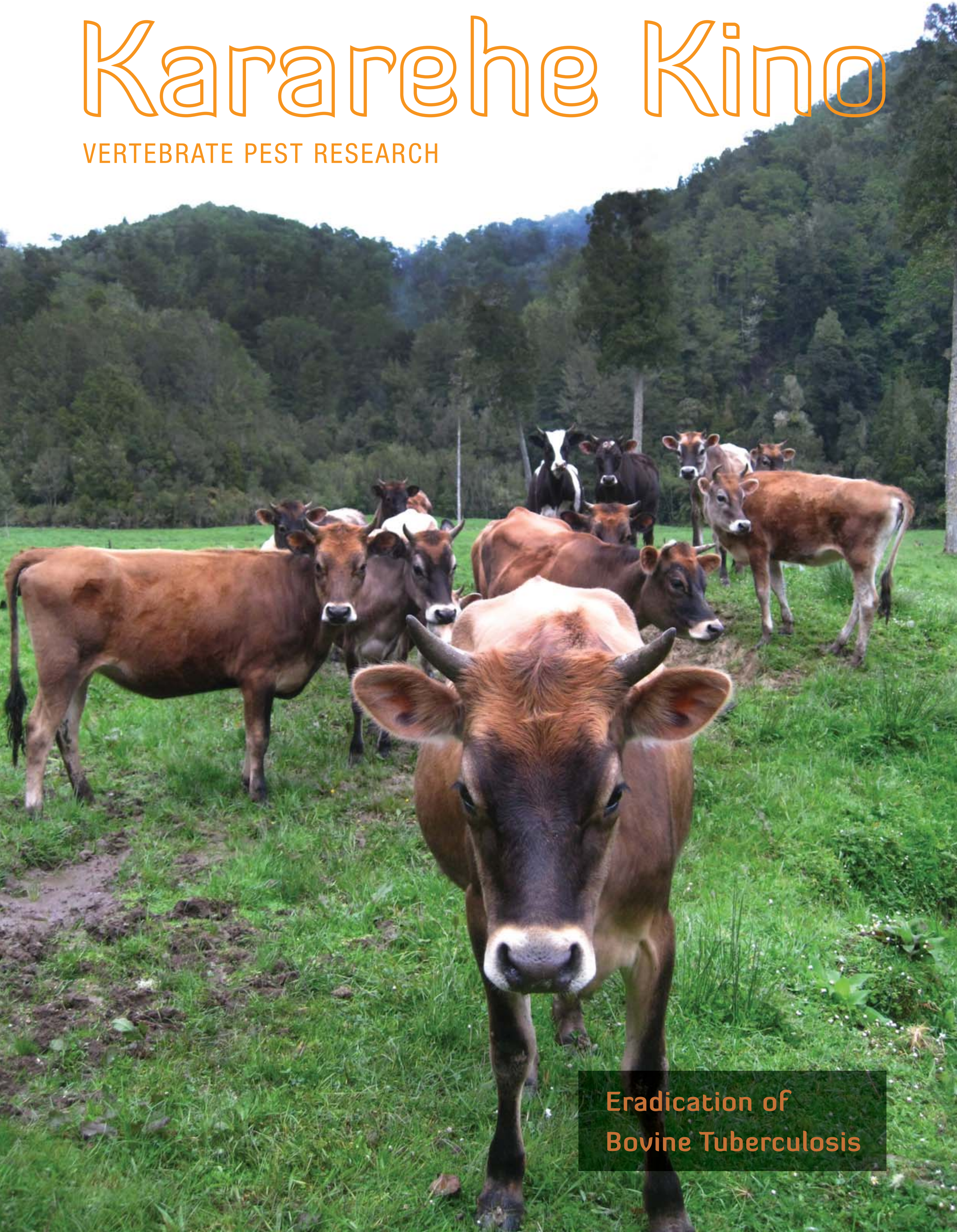
Kararehe Kino

VERTEBRATE PEST RESEARCH



Eradication of Bovine Tuberculosis

ISSN 1175-9844 (Print) ISSN 1170-3016 (Online)

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Page 2,3: Contractor using PDA – TBfree New Zealand; radio-tracking possums – Aran Proud; grazing cattle – Caroline Thomson; Hauhungaroa Range – Graham Nugent.
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Thanks to: Leah Kearns

Layout: Cissy Pan

Published by: Landcare Research
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In this issue:

Also available electronically - the newsletter can be downloaded as a pdf and individual articles in HTML format:
http://www.landcareresearch.co.nz/publications/newsletters/kararehe-kino


Caroline Thomson

Editorial

The benefits of applied research

Cattle at a feed trough near Lake Taupo.

When the results of applied research are made available to end users and beneficiaries, the impact can be profound.

Take, for example, bovine tuberculosis (TB). When I was a newly-trained veterinarian in the early 1970s, in the area where I practiced it was common for up to 60% of dairy cattle to react positively to their first caudal fold skin test (an indication of exposure to TB). More significantly, the disease was a significant disease of morbidity in young rural children who drank unpasteurised milk.

Nowadays TB is controlled under the Biosecurity Act, initially via the Animal Health Board, now OSPRI (TBfree New Zealand). Under the Act, the National Bovine TB Pest Management Plan (NPMP) must be reviewed periodically. Typically, such reviews have been undertaken every five years. However, the latest proposed plan runs for 10 years, with a recommendation to extend it beyond that time.

In early 2015 a group comprising independents (including the groups Chair), stakeholders (Federated Farmers and OSPRI) and funders (Crown, Dairy New Zealand, Deer New Zealand, and Beef & Lamb), convened the Plan Governance Group (PGG) to review the existing NPMP and recommend the adoption of the amended plan.

The proposed plan recommends, for the first time, adopting the goal of nation-wide biological eradication of TB from New Zealand. It proposes the following objectives:

1. Biological eradication of TB from New Zealand by 2055, with the key milestones of
   - TB freedom in livestock by 2026
   - Effective TB freedom in possums by 2040 (statistical freedom)
   - Complete biological eradication after 12–15 years, following low level monitoring and verification.
2. Ensuring the affected herds' annual period prevalence stays at or below 0.2% on average throughout the plan.

Over the past years there has been much excellent research targeted at TB in New Zealand, particularly on the role that possums and other feral animals play in the spread of this disease. Recently, much of that work has been published in a special issue of the New Zealand Veterinary Journal (*TB in Livestock*, published July 2015) and in this edition of *Kararehe Kino*.

The work of people such as Graham Nugent, Paul Livingstone (TBfree New Zealand), Phil Cowan, Frank Cross, Bruce Warburton, Dean Anderson and others has made significant contributions to advancing our knowledge.

The PGG, in reviewing the NPMP, faced a dilemma:

- The incidence of TB in livestock has been reduced to very low levels and, since milk is generally pasteurised and meat is cooked, was TB still a problem?
- The various funding agencies were all facing significant budgetary challenges and regional councils did not believe they should be funding at the same level as previously.
- With continued commitment, the prospect of eradication was tantalisingly close.

As part of the review process, the PGG commissioned two science reviews. The first was to answer the question 'was eradication of TB from New Zealand scientifically possible and financially feasible?' The second was to review the role of vector-to-livestock and livestock-to-livestock spread of TB, the role of livestock movements, and the feasibility of elimination of TB from the vector risk areas. Finally, when it was agreed that livestock-to-livestock spread is now significantly important, the NPMP detailed the importance of traceability through the National Animal Identification and Traceability system (NAIT), now part of OSPRI, to fulfilling the objectives of the draft plan.

When (not if) TB becomes a disease exotic to New Zealand, this country will owe a debt of gratitude to the authors of the papers in this edition of *Kararehe Kino*.

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Making TB science available to end users

The control and eradication of bovine tuberculosis (TB) from New Zealand wildlife has been based on strong scientific foundations. However, often this science has only been appreciated by a small group of TB managers and researchers. This is because the research has been widely published across scientific journals that are often (for copyright reasons) not readily available to end-users and the public, and the articles themselves are not easily comprehensible to the general public. In addition, a lot of the research is not formally published and exists only in the so-called 'grey literature' such as reports produced by various institutions and agencies, and is not easily found. Thus, the funders of the National Pest Management Plan for TB (NPMP) and their stakeholders (which includes the public) have at times found it difficult to independently assess the depth and robustness of wildlife TB science, particularly when faced with strategic choices about the future direction of the NPMP.

The opaqueness of the evidence underpinning TB control and eradication was raised as an issue during the second review of the NPMP in 2008–2009. Given that the next review was scheduled for about 2015, in 2010 Graham Nugent proposed the collation and synthesis of contemporary wildlife-related TB research into a single comprehensive and more accessible publication. TBfree New Zealand (then the Animal Health Board) strongly supported the idea, with Paul Livingstone in particular championing the cause and arranging the funding required to support the work. Although the original proposal was for a multi-chapter book, the project team soon decided on the alternative of a series of scientific papers published in an open access formal journal, as this ensured that the work would be subject to rigorous and independent peer review, and more importantly, that the published material would be accessible to everyone via the internet.

The authors for this work were assembled in 2011 and comprised 19 leading authorities on wildlife TB from seven different organisations around the world. In addition to writing and editorial input from Graham and Paul, the authors were given editorial assistance by Phil Cowan and Frank Cross and supported by the editorial team of the New Zealand Veterinary Journal (NZVJ), Petra Muellner and Fiona Rhodes. The outcome has been a 108-page Special Issue on 'TB in Wildlife' published in the NZVJ in July 2015 (available at: *http://www.tandfonline.com/toc/tnzv20/63/sup1*). With many of the contributing papers available online since late 2014 this publication has, as intended, provided the scientific information underpinning the recently-completed 2015 review of the NPMP for TB.

The NZVJ Special Issue comprises nine review, overview and research-themed papers, covering aspects of wildlife TB management such as policy and strategic practices, tactical approaches to the control of infected wildlife populations, understanding the roles of the various vector species in TB transmission, the impact of wildlife management on livestock, and the use of ecoepidemiological modelling in wildlife TB management. An important feature of the NZVJ Special Issue is that it has identified and drawn upon the 'hidden' TB science in the 'grey literature', such as previously unpublished project reports produced by Landcare Research and other institutions – these reports are not only cited, but most of them have now been made available online (*http://www.tbfree.org.nz/research-papers.aspx*).

The NZVJ Special Issue complements a related special issue on 'Dealing with TB in Wildlife' published by the international journal *Epidemiology & Infection* in 2013 (*http://journals.cambridge.org/action/displayIssue?jid=HYG&volumeId=141&seriesId=0&issueId=07*; some articles Open Access).

The special issue of this latter journal had a broader global focus and comprised mostly primary research papers rather than comprehensive reviews and overviews. New Zealand research on TB in possums and other wildlife was represented in that publication by three research papers.

As a result of evaluations based largely on the formal research presented in the NZVJ Special Issue, no concerns were raised by the high-level stakeholder group leading the 2014–15 review of the NPMP about the accessibility and robustness of the science used to evaluate alternative strategic options. They commissioned what was effectively a 'review of the reviews' that used the Special Issue as its primary feedstock, and concluded that there was enough scientific evidence to believe that eradication of TB from wildlife was feasible. Based on that, NPMP funders have had the confidence to recommend, for the first time, adoption of nationwide biological eradication of bovine TB from New Zealand as the NPMP goal.

More information on the NPMP review is found in supporting documents and general review information in the following online link: *http://tbplanreview.wix.com/tbplanreview#!supporting-documents/c1b2q*

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Controlling possums to *manage TB*

Loading 1080 bait into a sowing bucket near Inangahua.

Since the early 1970s, possums have been controlled in New Zealand as part of an ongoing strategy to manage bovine tuberculosis (TB) in livestock. The frequency and intensity of such control is driven by a requirement to reduce populations to very low levels, then to hold them at or below this level for 5–10 years to ensure the disease is eradicated.

Possum control is implemented using aerial applications of toxic bait and ground-based applications of toxic bait and traps. Both are applied under various regulatory and operational constraints. Aerial applications use bait loaded with sodium fluoroacetate (1080) at 0.15% and sown at rates of 0.5 to 2 kg/ha. Aerial control is the preferred option for controlling possums over extensive and rugged areas of forest that are difficult to access by foot. Ground-based control uses a range of toxins (primarily cyanide, as Feratox®) and light-weight traps (e.g. Victor No 1).

Although possum control tools have been available for many years, control programmes didn't make significant inroads into possum populations and into the incidence of TB in livestock until the mid 1990s, when control shifted from essentially being carried out by regional council pest control staff to a competitive contracting industry.

Possum control contracting systems

For TB management, TBfree New Zealand publicises a range of control operations for competitive tender. Although price is an important selection criterion, other criteria include competence in health and safety management, relevant experience and track record, technical and management skills, equipment, and proposed methodology. Initially, all contracts were performance-based and used an index of possum density to determine if control targets were achieved and whether contractors should be paid. Most performance-based contracts have few restrictions on what control methods can be used, and it is up to the contractor to select the most cost-effective method to achieve the contracted target density. However, before such a competitive and performance-based system could be implemented, it was necessary to have a robust, standardised, and independent monitoring system for measuring whether the contractor had achieved the contracted target reduction.

Monitoring contractor performance

A standardised trap-catch index (TCI) was developed in the 1990s by Bruce Warburton and colleagues for monitoring contractor performance. It was based on a defined number of randomly allocated trap lines, each containing 10 leghold traps spaced at 20 m and set for three contiguous nights of fine weather. From this method, for example, two possums caught over 100 trap nights would indicate a TCI of 2%. To ensure the methodology was applied in a standardised way, a national protocol and training courses were developed by the National Pest Control Agencies (*http://www.npca.org.nz/*).

From 2011 to 2013, the mean TCI achieved from all recorded performance contracts each year was 0.65%, 0.46%, and 0.4%, respectively, and was considerably lower than the contracted targets of 1–2%. Additionally, 93% of c. 200 performance-based operations contracted each year achieved their targeted TCI on their first post-control monitor, with the remaining contracts requiring extra work to achieve the desired target.

Input contracts

In areas that have had several years of performance-based control, contracts generally shift to input-based control to eliminate the cost of having to independently monitor the operation. Input contracts are essentially method-driven, with contractors being required to apply a particular control method at a prescribed intensity, such as a stipulated trap-spacing and number of trap nights. Input contracts are often used to ensure control is applied across all habitats to decrease the probability of clusters of possums being missed, and recently have included the use of detection devices, such as chewcards, to better target trapping effort.

Capturing the data

For data recording and auditing purposes, all contractors must use GPS-capable personal digital assistants (PDAs) to record the location of all detection devices and traps. These data can then be uploaded, checked against habitat maps, and used in models to determine if TB has been eradicated from possums. TBfree New Zealand has developed 'bespoke' databases (i.e. VectorNet and VectorTrax) to manage the large amounts of spatial and activity data collected by contractors. Such data are now used to support TB management decisions based on probability predictions from the 'proof of freedom' utility (viz. a computer model that generates the probability that an area is free of TB). Because of the need for these data, in the last 5 years there has been a shift from contractors simply carrying out possum control to them collecting data on possum presence/absence and collecting possum carcasses for checking their TB status.

Delivering an effective control programme

The strategies for managing TB in New Zealand wildlife operate on four major principles: (1) having a target threshold for possum population reduction that is known to result in TB being eliminated, (2) an objective methodology for assessing whether the target reductions have been achieved, (3) cost-effective control tools for achieving possum population reductions, and (4) the necessary legislative support to ensure compliance. TBfree New Zealand's possum control programme meets these requirements, and provides an example of a very effective pest and disease control programme underpinned by significant and ongoing research.

This work was funded by TBfree New Zealand.

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Contractor using a personal digital assistant while undertaking ground control of possums.

How does chronic TB affect *possum movements?*

Researcher using a handheld receiver to locate study animals, Muzzle Station, North Canterbury.

Significant new insight into the movement of possums in relation to their role as vectors of bovine tuberculosis (TB) has been revealed in recent research by Graham Nugent and his colleagues. The team now has a deeper understanding of how far possums range in forested and semi-arid habitats; how much of their range they use on a daily, weekly or monthly basis; their short-term foraging patterns; and how their movement patterns change in response to recently-depopulated buffer zones.

One thing not yet known is how TB affects possum movement patterns. In this article, we explain why this information is important, and summarise a mix of new and old data that provides fresh insight into the question. An improved understanding of possum movements will help further improve the proof-of-freedom framework now being used to declare areas free of TB. This framework relies on a Possum-TB model that assumes possums remain fully active (and in a steady-state of infectiousness) throughout the whole of the disease course. Is that likely?

Recent research suggests that the disease course in possums from infection to death – at least for artificially-infected possums – averages 18 weeks (range 6–28 weeks). It also suggests possums with late-stage disease are likely to be severely debilitated, so chronic TB <u>will</u> affect possum movements – but to what extent? Recently, Ivor Yockney and his colleagues sought to answer this question on Muzzle Station in North Canterbury, by radio-tracking wild possums fitted with GPS collars (*Fig.*). Before release, each possum was artificially infected with TB by injecting *Mycobacterium bovis* directly into their paws, an inoculation method that produces a disease pattern closely matching that seen in naturally-infected possums. Ivor, Graham and Jackie Whitford then tracked the possums over the ensuing months and eventually recovered the collars, capturing some possums along the way to chart the progress of the disease, allowing some to run close to the full course of disease before recapturing them, or simply collecting carcasses of animals that died from TB.

Analysis of this possum movement data by Cecilia Latham and Frank Cross indicated that the majority of artificially infected possums showed routine and steady-state movement behaviour for the first 8–10 weeks post-infection (*Fig. a, b*), which corresponds to the pre-clinical and early clinical stages of TB identified from earlier studies: at this time TB lesions are likely to be developing in the possums' axillary and inguinal regions but not in their lungs. Then from weeks 10–12 onwards, possum movement became progressively curtailed (*Fig. a, b),* mostly likely reflecting internal disease spread and, in particular, development of severe and increasingly debilitating lung disease. This morbidity phase lasted 2–4 weeks, before the animal died, which could be either pin-pointed to a day and time from collar downloads (*Fig. a*) or estimated from collars emitting a 'mortality signal' due to cessation of possum movement (*Fig. b*).

But not all possums followed this pattern. Some seemed to succumb to disease rapidly (*Fig. c*), while others maintained 'normal' movement behaviour for extended periods, despite developing severe disease (*Fig. d*); still others seemed to suffer few ill effects and were possibly short- or medium-term 'survivors' (*Fig. e*), something that these and other studies have shown can occasionally occur.

What this means for the role of possums in TB transmission is that the course of disease and its effects on possums is not only variable across time but also probably differs widely between individuals, and that accordingly an individual possum's infectiousness is likely to vary over time. For example, the first clinical symptom of severe disease (both artificially-induced and naturally-acquired) is that inguinal and axillary lesions rupture to release infectious material to the exterior though a sinus. Earlier work by Dan Tompkins in conjunction with Bryce Buddle of AgResearch showed that lesions at this stage can contain in excess of 10 million TB bacteria per gram of tissue, yet during this time some possums maintain full or near-full mobility, and can potentially create an infection risk over most of their home range. In contrast, another period of infectiousness is likely to occur near death (peri-mortem), when possums have developed extensive lesions throughout their lungs and viscera so are likely to be excreting enormous numbers of bacteria. By this stage, however, our results suggest they are barely moving, so the risk is geographically much more restricted. Such animals are 'sitting ducks' for both other scavenging wildlife (e.g. pigs, ferrets) and for other possums who may attack, scavenge or even attempt to copulate with them.

These results confirm that the assumptions in the current possum-TB spatial model (i.e. that infected possums present a more or less constant infection risk over their whole range for the duration of the disease course) is possibly too simplistic. We now need to complete more detailed analyses of the movement data from tuberculous possums, to explore how big an effect this new understanding has in changing the patterns of disease predicted by the Possum-TB model.

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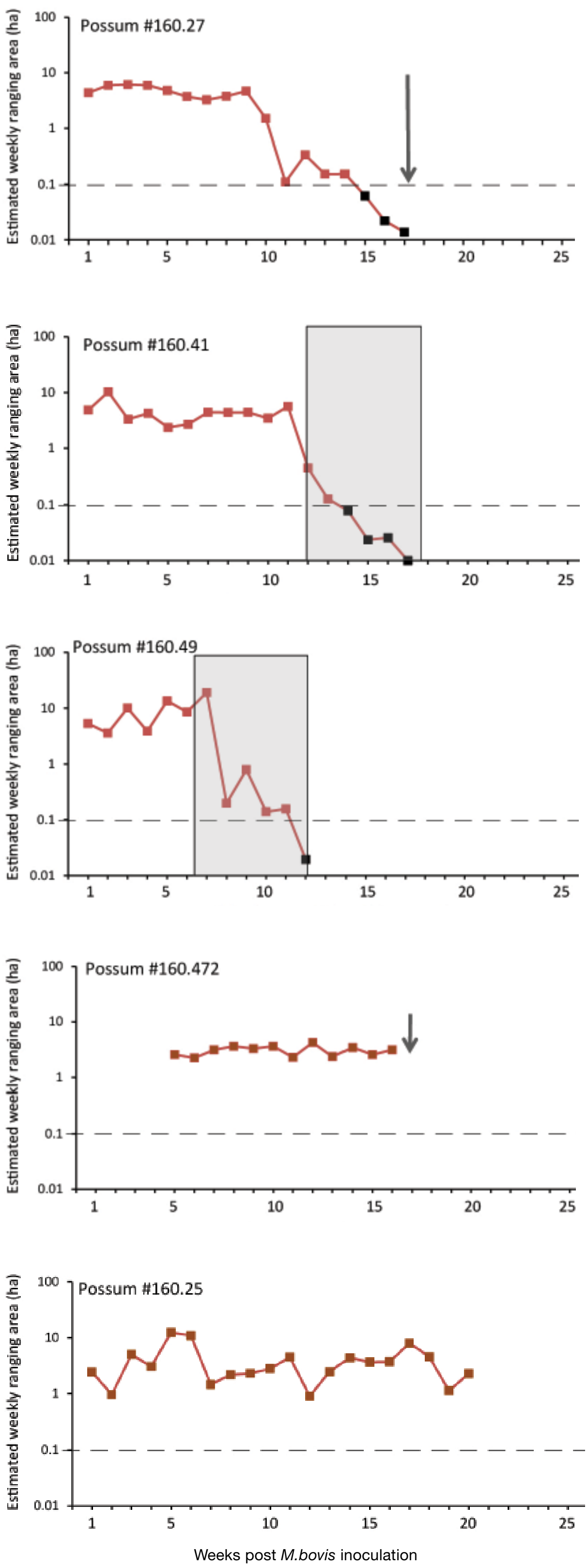

a. Possum displaying progressive reduction in range coverage from week 9 post-inoculation onwards, with download from the GPS collar indicating precise time of death (17.4 weeks, arrowed).

b. Possum displaying progressive reduction in range coverage from week 11 post-inoculation onwards, with the mortality signal indicating death between weeks 12 & 18 (shaded box).

c. Possum displaying progressive reduction in range coverage from week 7 post-inoculation onwards, with the mortality signal indicating death between weeks 7 & 12 (shaded box).

d. Possum showing no overt change in ranging behaviour up to 16 weeks post-inoculation, despite the fact that it had advanced TB. This animal was captured alive at week 16.9 (arrowed), with TB lesions in all peripheral lymph nodes plus lungs.

e. Possum showing little change in ranging behaviour up to 20 weeks post-inoculation, a time-point at which previous studies have indicated mortality probability is ~70%. This animal was still alive at week 28 (when its final telemetry fix indicated it was still moving).

Fig. *Changes in estimated weekly ranging area covered by possums as they develop clinical TB over periods of up to 20 weeks post-infection via* M. bovis *injection. Weekly ranging area estimates are in hectares and depicted on a logarithmic scale. Red symbols and lines represent time-points at which the possum was still alive; black symbols represent points below a nominal cut-off at 0.1 (grey dashed line) where the possum was most likely dead or severely moribund.*

Bovine TB infection at Karamea – why is TB persisting there?

Young dairy cows on a farm/forest margin at Karamea.

The decline of TB-infected cattle and deer herds across New Zealand from 1700 in the mid-1990s to less than 40 in 2015 is a disease management success story. However, in the Karamea district in Westland, reduction in infected herd numbers has proven harder to achieve and progress has been considerably slower than elsewhere. Despite possum control on the farmland and adjacent forest, combined with a higher than average level of herd TB testing, herd infection has persisted since the early 1970s. Landcare Research, in collaboration with Mark Neill (TBfree New Zealand) looked at both livestock- and possum-related aspects prevalent at Karamea to identify the likely causes of the continuing infection.

Herd characteristics and testing

The number of infected dairy herds at Karamea declined between 1993 and 2011, with the largest declines following aerial control operations against possums in the adjacent forest (suggesting possums were driving the infection). However, these declines were relatively short-lived. Although possum control, along with the test and slaughter programme for livestock, reduced the proportion of infected herds, it was difficult to drive the prevalence below 0.2 (i.e. 20% of herds infected). Most Karamea dairy herds are considered to be 'closed' and do not trade in livestock (i.e. cull animals are sent directly to slaughter). Purchasing stock is rare and where it does occur, most farmers buy from disease-free areas. A survey of farmers found a significant correlation between herd infection status and the use of run-off blocks generally close to forest. However, there was little evidence of a relationship between persistent infection and bush-pasture margins, offal pits, home kill, stock water systems, retention of carry-over cows, or animals sent to slaughter.

Possum distribution, abundance and infection

Possum control has been carried out periodically in the Karamea district since the 1970s and annually since 1996. In the winter of 2008, all forest adjacent to Karamea farmland from Blue Duck Creek in the south to Kohaihai in the north and extending 5–10 km into the forest interior was aerial sown with 1080 bait. In 2009 and 2010, Bruce Warburton and Jackie Whitford distributed chewcards (baited coreflute plastic that possums chew) throughout traditionally infected farms to assess the relative abundance and distribution of possums. Additionally, all possum carcasses retrieved from TBfree New Zealand-funded control operations and from the trapping that followed detection surveys were necropsied and their lymph nodes pooled for culture. In 2011, the possum interference rate on chewcards placed along the forest margin was 2.8% (192/6789), indicating very low possum numbers across all local habitats. Comparing the mean distance between captured possums and between the same number of possums when distributed randomly between all trap sites showed they were significantly aggregated, particularly on forest margins.

Between 2006 and 2011 only four infected possums were identified at Karamea, and all were from a 2006 survey of 249 possums actively screened for TB. Subsequently, a further 386 possums were sampled, but no TB was detected. However, in the winter of 2012 a control operation detected four infected possums (two with visual lesions and two identified by culture) from a sample of 50 taken in the Arapito Valley (Karamea River).

Factors predicted to be driving the continuing infection

Farmers, ecologists, veterinarians, possum trappers, and anti-1080 people all have their preferred explanation of why TB persists at Karamea, ranging from infected immigrant possums, within-herd infection, infected stoats, infected seals, and infected possums in swampy areas not being effectively controlled. However, the major contenders are possum related infection and in-herd infection. To objectively determine the factors driving the infection, Dean Anderson used livestock testing data from 2003–2011 to develop a hierarchical Bayesian statistical model to make inferences on wildlife and livestock factors influencing the probability that an individual cow on a farm is infected at a specific time. Using his model, Dean showed the probability that an individual cow is infected is best predicted by models including the proximity of the farm to forest, and whether the farm had previously been infected. Herd exposure to forest represented the risk that an infected possum would come onto a given farm, and is proportional to the farm area and its proximity to forest.

So what did the team learn about TB infection at Karamea? Herds continue to become infected, some for many years. Although some of this infection might be caused by continuing infection within herds (i.e. in cows not expressing a detectable immune response to skin or blood tests), the trapping of infected possums and model predictions suggest that the perpetuation of infection is mostly influenced by wildlife factors and by the proximity of farms to forest. As long as infected possums remain in the adjacent forest (Kahurangi National Park) there will always be the potential for new TB cases in Karamea livestock. Although possum numbers on Karamea farms are low as a result of control, eradication of the disease will require ongoing effective possum control over large areas of the adjacent forest, maintaining possum control on the farmland, and continuing herd testing.

This work was funded by TBfree New Zealand

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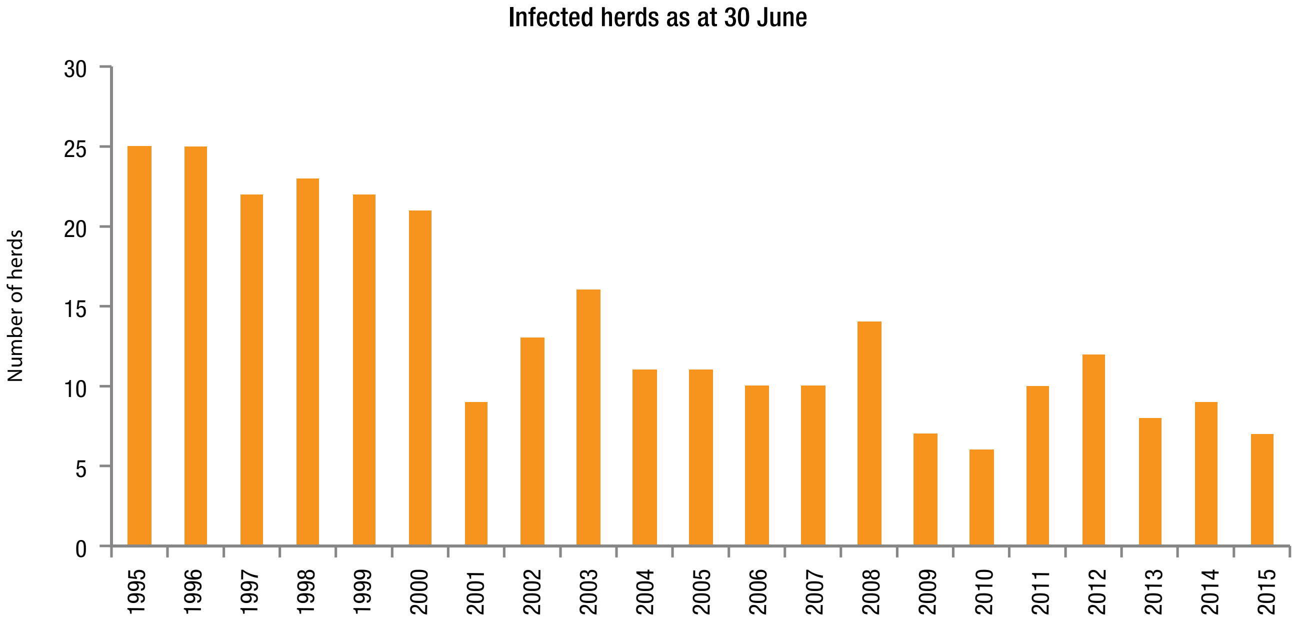

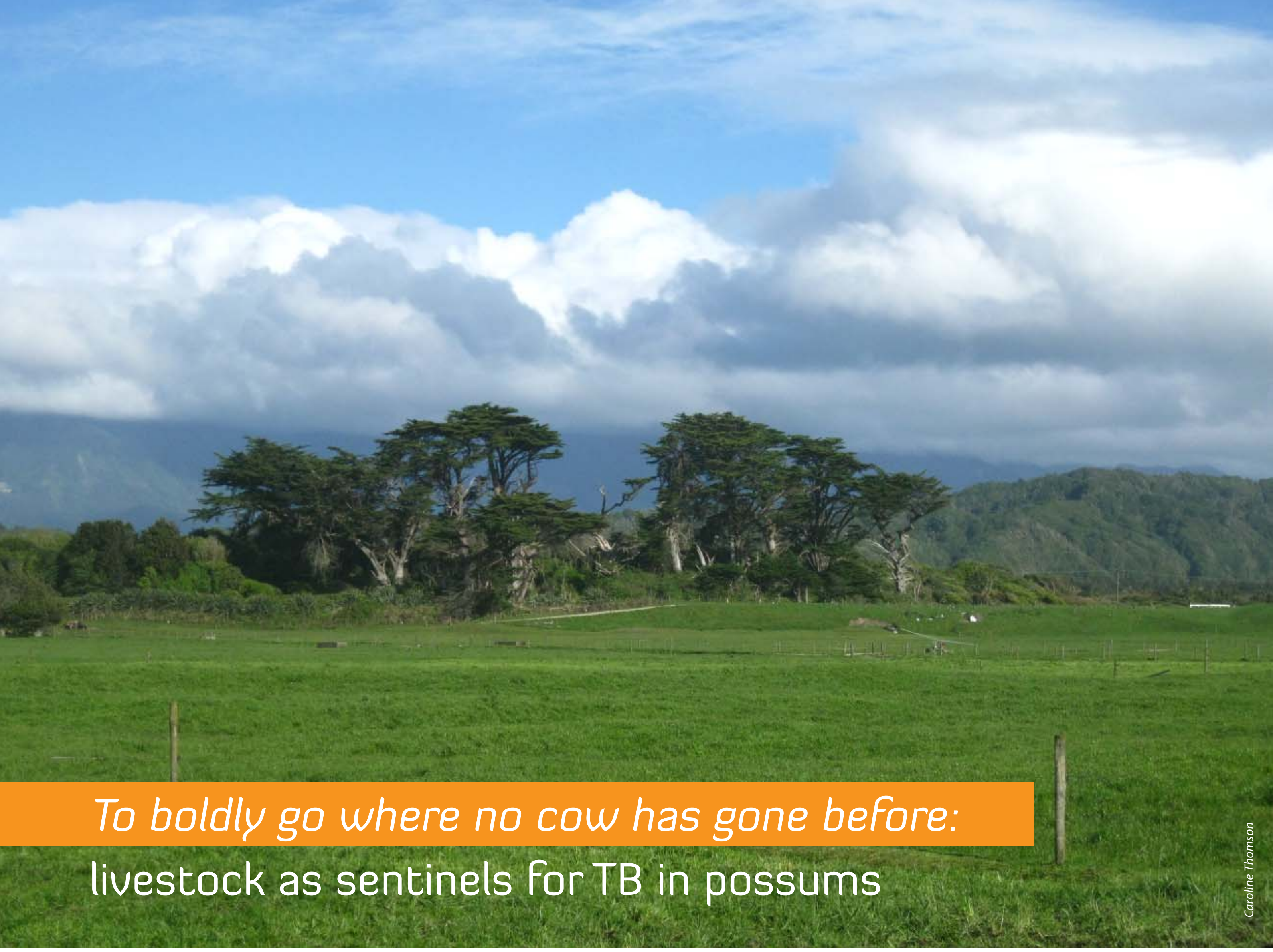

To boldly go where no cow has gone before: livestock as sentinels for TB in possums

Farm/forest margin habitat, Karamea.

Substantial research effort over several decades has gone into improving surveillance techniques for assessing the status of TB (caused by *Mycobacterium bovis*) in New Zealand wildlife. Driven by an effective collaborative feedback loop between management questions and scientific inquiry, important advances have been made in diagnostics and in understanding the behavioural ecology of host species and multi-species epidemiological dynamics (see Anderson et al. 2015 *New Zealand Veterinary Journal 63*). Diagnostics within an animal has progressed at three levels: gross lesion identification, culture techniques of mycobacteria, and genetic identification *M. bovis* strains. Possums emerged as a maintenance host, while other wildlife species were identified as spillover hosts, which do not maintain the disease but serve as useful sentinels to indicate its persistence. Research findings on movement behaviour and disease transmission rates have informed predictive modelling of TB persistence in specified wildlife control operations. All of these advances led to the increasingly frequent situation in which no TB is detected in wildlife surveys, and has created the need for a predictive tool to quantify the level of confidence in the absence of TB given no detections (Proof of Freedom Utility; Nugent 2015 in *Kararehe Kino 25*). The Utility now plays a key role in TBfree New Zealand's effort to eradicate TB from the entire country by progressively declaring vector control zones (VCZ) free of the disease. Given the very large area to survey, the high cost of possum and wildlife-sentinel surveys, and severe budget limitations, the emerging need is for a low-cost and wide-spread surveillance system.

One solution to this problem is to use livestock-TB-surveillance data to make inferences on the probability of disease absence in sympatric or adjacent-living possum populations. The disease is transmitted in both directions between possums and livestock; therefore, the absence of TB in livestock tells us something about the disease status in wildlife. While TB testing of livestock is not inexpensive *per se*, it is conducted as part of routine herd-health management and will be done in the future. Dean Anderson has developed a user-friendly tool for TBfree New Zealand disease managers to predict the probability of disease freedom in wildlife given negative livestock surveillance data. To detect TB in an infected possum population using livestock data, the following sequence of events must occur: 1) livestock must encounter infected possums and become infected themselves, 2) infected livestock are tested for TB, and 3) the test is positive. To estimate the probability of these events, the model

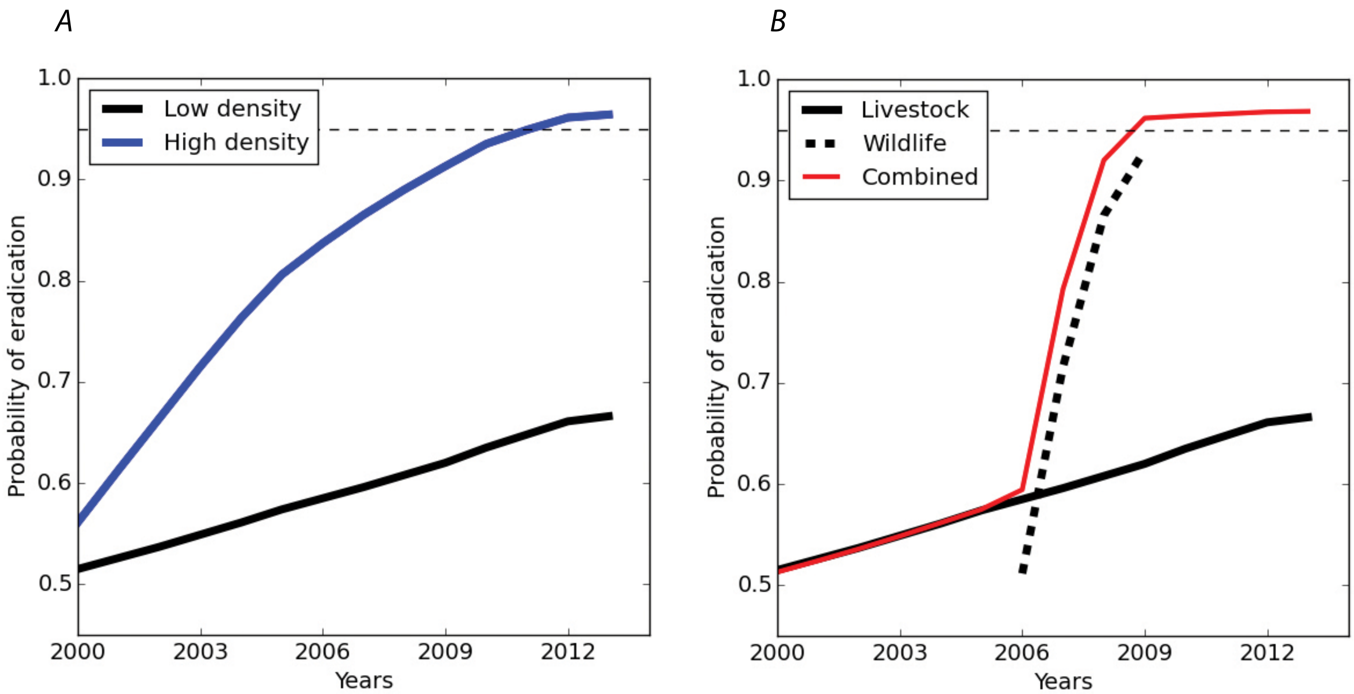

***Fig.** Results from the Livestock as Sentinels Tool trialled in a 10,000 ha VCZ using livestock testing data from 2000–2013 and wildlife data from 2006–2009. The graphs are explained in the accompanying text.*

incorporates the spatial layout of possum habitat and farms, and the number of animals tested.

To demonstrate the model, Dean applied the *Livestock as Sentinels Tool* to a 10 000-ha VCZ with livestock testing data from 37 farms from 2000 to 2013. Not all farms were surveyed in any given year. If possum control had occurred in the VCZ, population density would be expected to be low, and if infection persisted, the proportion of the area with TB possums would be low. In this low-disease-prevalence situation it would be difficult to find one of the few remaining infected animals, which results in low surveillance sensitivity and low probability of eradication (black line in *Fig. A* and *B*). If no control had occurred, possum density and TB prevalence would be high, and the surveillance would have a high sensitivity and would likely detect TB. Given that no TB was detected, the predicted probability of eradication using livestock data alone would exceed 95% (blue line, Fig. A). Importantly, in this situation, wildlife control and surveillance, and the associated costs of both could be completely avoided.

In high TB-risk areas, (i.e. where TB had been previously found), possum control and surveillance would be advisable. The *Livestock as Sentinels Tool* can be used to supplement wildlife surveillance data to decrease the time to successfully declare eradication or reduce the amount of money spent on wildlife surveillance. In the trial VCZ, wildlife surveillance data were collected from 2006–2009, and by itself never achieved the target 95% probability of eradication (dashed line, *Fig. B*). However, the combined analysis of livestock and wildlife data exceeded the target probability (red line, *Fig. B*).

Wildlife disease management is expensive and logistically complicated. The *Livestock as Sentinels Tool* takes advantage of existing data to either supplement or replace direct surveillance of wildlife disease status. The only cost is the minimal time required to acquire, process and analyse the data. The potential benefits are substantial reduction in surveillance costs and reduced time to achieve a target probability of disease eradication in wildlife. While the tool was described in the context of TB in New Zealand, it could be applied to any wildlife disease that affects regularly tested livestock.

The work was funded by TBfree New Zealand.

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Lesion resolution may contribute to TB persistence in the face of control

Recent trials to directly measure the rate at which infected possums transmit TB to uninfected possums in free-living populations have raised more questions than they have answered. While TB transmission in possums was successfully experimentally induced and monitored, the rates at which it occurred were too low to account for TB persistence based on current understanding of the disease in possums.

Past fieldwork observations led Dan Tompkins and colleagues to wonder whether infected individuals surviving for long periods of time could be the missing link. While it is generally assumed that TB infected possums survive for only a few months, there are now several documented cases of individuals surviving years of TB lesion development and resolution (*Fig.*).

Caroline Thomson

Dan discovered the existence of such possums while he was conducting a field trial to assess the efficacy of oral vaccination against the disease in 2004–6. During that trial, the team encountered a naturally infected possum that survived with periodic relapses of TB lesions for more than 2 years – far longer than the few months generally assumed. Even then, the long-surviving infected individual was euthanased at the end of the trial, rather than succumbing to disease.

Searching through the literature has revealed the occurrence of such possums in at least two other studies. In addition, a Massey University student, Ian Lugton, argued strongly in his PhD thesis in 1997 that such long-lived, infected individuals, were likely to have a median survival time after infection of more than 3 years. Also of great interest was that 90% of these long-lived individuals were male.

These observations fit the general pattern observed for TB in mammals, which is of variation among individuals in their innate resistance to the disease. To explore how such variation could influence TB persistence in possum populations, Pen Holland led a small modelling study to assess the potential influence of lesion resolution on persistence, relative to other likely sources of variation.

Pen constructed a generic contact-network model for simulating disease, loosely based on TB in possums. With this, Pen and Dan considered the effects on disease persistence of lesion resolution, in addition to the effects of spatial clustering of individuals, with those individuals being the 'most connected' in the network also being the most infectious. The latter two effects were motivated by recent evidence that suggests greater levels of TB transmission when possums are more clustered, and that adult males may play a disproportionately high role in TB transmission due to both greater contact rates with other possums and longer survival when infected.

Upon simulating Pen's model, she and Dan found that while there was no potential for the other factors to favour disease persistence, there was clear potential for the phenomenon of lesion resolution. This may thus help to explain how TB manages to

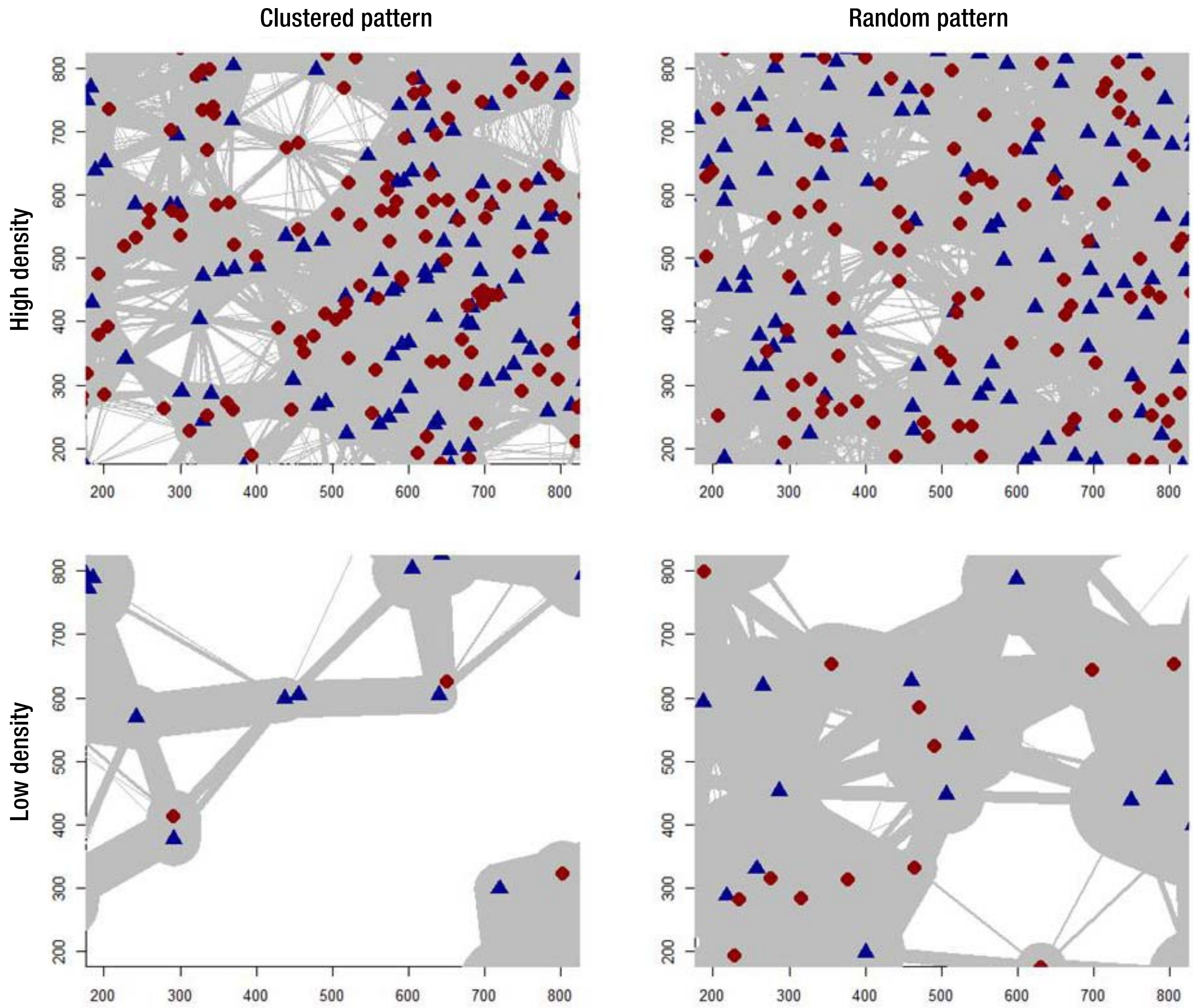

Fig. *Example networks with high and low animal density, and clustered and random spatial distribution patterns (showing the central 36 ha of the 100 ha modelled). Blue triangles are males and red circles are females, while line thickness is representative of contact rate.*

persist in possum populations even though, in reality, disease transmission among possums is at a lower rate than is generally assumed. Also, long-lived infected individuals may be one of the reasons why TB can re-emerge in controlled areas, potentially driven more by male possums (the greater dispersing sex).

We now need to gain a better understanding of the likely size and impact of long-lived, infected individuals in the real world of intensive TB possum control.

This work was funded by the Royal Society of New Zealand Marsden Fund, TBfree New Zealand, and Landcare Research.

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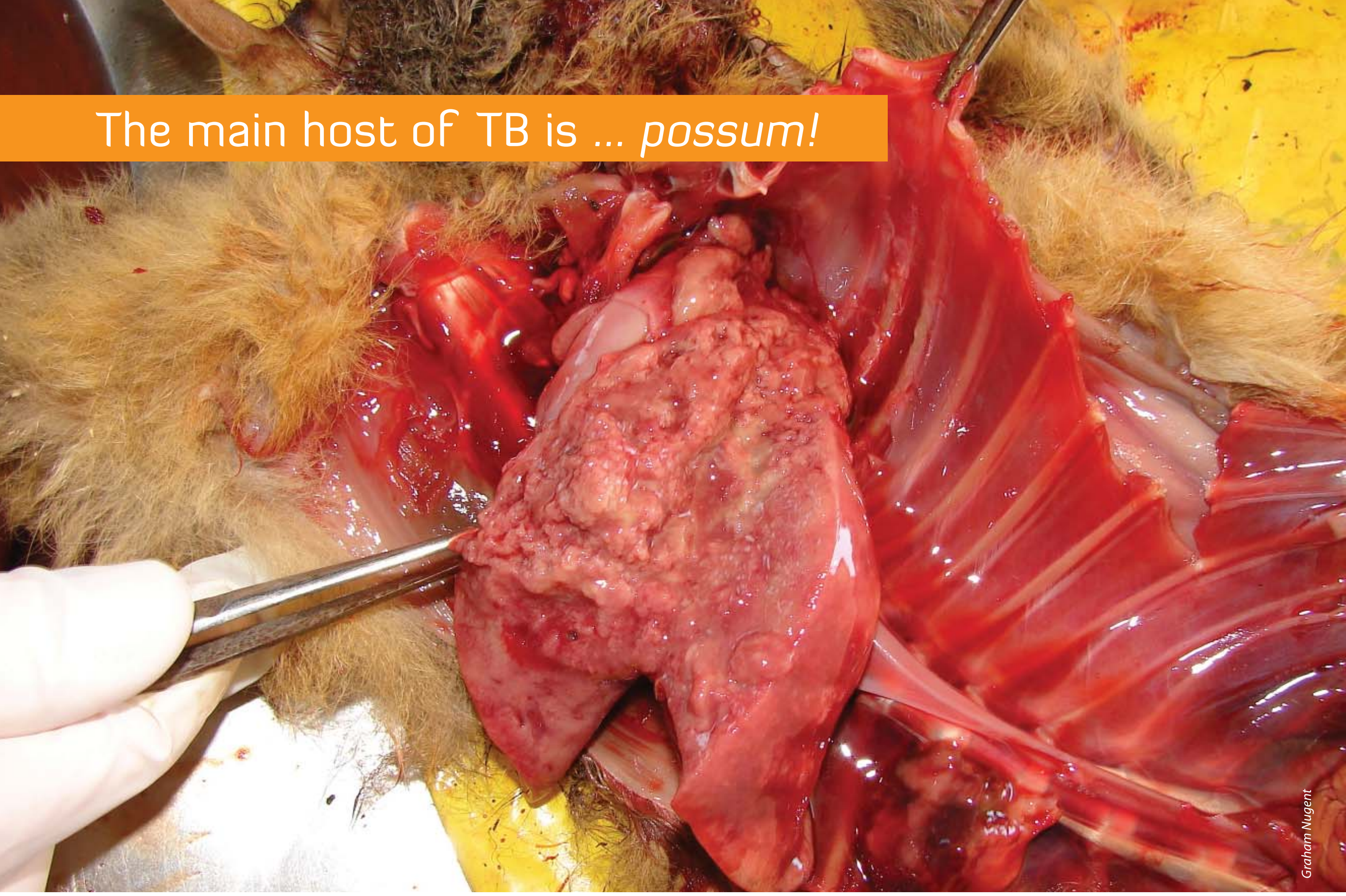
TB lesion in the inguinal lymph node of a possum.

The main host of TB is ... *possum!*



No room to breathe – the pus-filled lungs of a possum that died of TB.

It has recently been suggested (both through media and by an MP) that possums are 'not the single most important vector [of bovine tuberculosis (TB)] as official channels are fond of repeating', based on only 54 (0.04%) possums being diagnosed as infected with TB from 124 213 necropsies conducted by TBfree New Zealand over nine years[1]. In stark contrast, in their 2015 review of the role of possums as hosts of TB, Graham Nugent and his colleagues use much of the same data as strong evidence that major progress is being made in locally eliminating TB from possums and other wildlife. This necropsy data is very largely collected in 'freedom' surveys conducted in areas in which possums have long been controlled to very low densities, to confirm that there is a high probability TB has been locally eliminated from possums. By definition, such freedom surveys are not conducted in areas where TB is known or suspected to occur in the possum population. Thus, finding very few infected possums is a measure of the substantial success of the TB control strategy, not of the insignificance of possums as hosts of TB. Such surveys have been central in helping TBfree New Zealand declare over one million hectares free of infected wildlife, enabling them to stop possum control in these areas.

Nonetheless, the disparity in the inferences drawn from the same data set is thought-provoking. How strong is the evidence that possums are not only a host for TB, but also a crucially important one? Graham's 2015 review answers that question 'scientifically', but some simple historical observations are equally compelling.

Possums in some places undoubtedly do get TB (*photo*) – in the most extreme case, in 1990, Jim Coleman and colleagues found 62% of possums living in rough grazing land at Flagstaff Flat in Westland were infected. Possums usually have small home ranges, so those living more than a few hundred metres from where cattle graze seldom interact with them. Most possums that get TB die within 4–6 months, so sustained presence of TB in possums in deep forest indicates that the disease is cycling within their populations – and there are good examples of TB persisting in possums in deep forest. In the Hohonu Range in Westland, Jim Coleman and Peter Caley recorded a TB prevalence of 13% in 1973/74, falling to 3% in 1989/90, then rising to 9% in 1997, with prevalence unrelated to nearness to farmland. Likewise, in the Hauhungaroa Range in the central North Island, in 1997–2000, Graham recorded a 6% prevalence in an uncontrolled possum population in forest >3 km from farmland – higher than the 2% recorded in the wider area more than 15 years previously.

[1] http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=11459697].

While it is almost impossible to observe TB being transmitted between wild animals, there is now incontrovertible proof that possums can and do pass TB to one another. In the Orongorongo Valley in Wellington in an area away from farmland, Carlos Rouco and Dan Tompkins tracked possums known to have a unique strain of TB, and found that strain had passed to other possums that shared the same patch of forest.

It is also obvious that cattle only occasionally pass the disease to possums – possums shared rough farmland habitat with often heavily infected cattle herds during the early part of last century, but TB was not recorded in possums until the 1960s. In contrast, there is very strong historical evidence that TB passes from possums to cattle far more readily. Within a decade of TB being found to be common in some local populations of possums, possum control was applied near and on farms in which the level of TB in cattle had stayed stubbornly high despite intensive quarterly testing and culling of infected animals. Within two years of such possum control, TB in cattle had dropped to very low levels (*Fig.*), strongly implying that possum control had largely stopped TB transmission from possums to cattle. This pattern and response to control was also observed in other places in the 1980s, leaving no need for further scientific confirmation.

Thus, modern scepticism about the role of possums as vectors of TB is perhaps understandable, given the relative rarity of infection in possums nowadays, but it is misplaced. The rarity of infection in possums, and therefore the low rate at which they now pass TB back to cattle, is a measure of local eradication success – it demonstrates that TB is being progressively eliminated from possums in more and more areas. These data have been the key in convincing government and agricultural stakeholders that national eradication of bovine TB is feasible and affordable, and should be adopted as New Zealand's TB management goal. The slightly daunting aspect of the national eradication goal is that it aims to achieve a prevalence in possums that is considerably lower than 0.04% mentioned above. The goal is less than 0.000003% – less than one infected possum in 30 million (i.e. none).

The review referred to above was funded by TBfree New Zealand, and this article was funded by Landcare Research.

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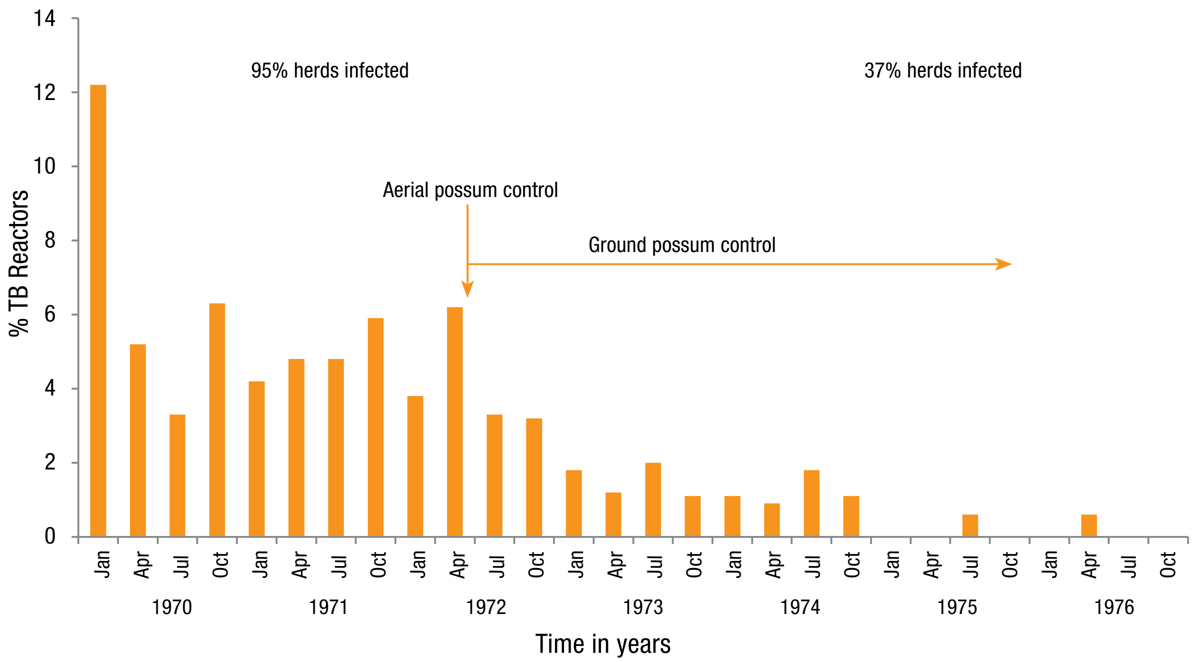

***Fig.** Ancient evidence – decline to near zero in the percentage of TB positive tests (reactors) in cattle from 40 herds in the Cape Foulwind area after initiation of possum control (reproduced with permission from Surveillance 13(3) p. 5 (http://www.sciquest.org.nz/elibrary/download/46062/Special_issue_%3A_Cattle_Tuberculosis_-_History_of_t.pdf).*

Ghost hosts:
Deer, pigs, and TB eradication

Last known deer infected with TB in the central Hauhungaroa Range. It was killed in late 2013, about 13 years after possum control was first imposed in the area.

Possums are the main wildlife vector of bovine tuberculosis (TB) in New Zealand, but pigs and deer are spillover hosts of the disease. Replicated large-scale field trials show that greatly reducing possum densities but *not* deer or pig densities results in the prevalence of TB in deer and pigs falling towards zero, albeit slowly in deer. Graham Nugent and his colleagues believe this is strong evidence that neither species can independently sustain TB in the wild under New Zealand conditions, even though they can do so under more crowded conditions on farms or overseas. Their spillover status is surprising, given that in some places the prevalence of TB in adult pigs can approach 100%, and over 50% in adult deer. The good news implicit in such spillover status is that control of pigs and deer is therefore **not** an essential component of TB eradication, so the economic and social cost of pig and deer control can be avoided. However, both species remain important in New Zealand's TB management programme.

Pigs become infected wherever they share habitat with infected possums because they readily eat carrion (including dead possums), often in large groups (*Fig. 1*), and are important for two reasons. First, they are far more wide-ranging than possums, so once infected, they have the potential to carry TB long distances, possibly to areas where there are no infected possums. For example, an uninfected radio-collared sow released in Hochstetter forest on the West Coast was killed 32 km away 15 months later, along with three of her offspring, and all four of them were infected. This is far beyond the usual pig home radius of a few kilometres. The risk is that ferrets and very occasionally possums, could scavenge on the remains of such dispersing pigs when they die or are killed, and thereby establish a new outbreak of TB. This risk is made worse by hunters transporting live or dead pigs to faraway areas and then releasing them or dumping carcass remnants in places where other wildlife can scavenge them.

Second, pigs are very good at finding and eating possum carcasses (*Fig. 1*), and are therefore cost-effective detectors (sentinels) of continued TB presence in areas where possum numbers have been greatly reduced to break the TB cycle. Like canaries, once used as an early warning system of invisible gas risk in coalmines, pigs are now frequently used to help show which areas have become free of TB. They are especially valuable in this role in large unfarmed areas where 'proving' TB absence by direct survey of low density possum populations is almost prohibitively expensive. In some contexts, surveying a single pig can be more cost-effective than setting 100 possum traps. The main drawback to using pigs as sentinels is that they are not always available. But even that problem can sometimes be overcome by releasing sentinel pigs into areas where possum surveys are impractical.

For deer, the issues are different. They interact with TB infected possums and possum carcasses far less than pigs and their usefulness as sentinels is thought to be a hundred times lower than for pigs – except where there are very few pigs, when deer surveys can sometimes be cheaper than possum surveys. Unfortunately, despite being weak sentinels, when deer become infected they can carry infection for up to 15 years. Unlike possums (which mostly die within six months of becoming infected), and much more like humans, many deer that become infected do not immediately develop full-blown tuberculosis – rather they remain latently infected until, through age or ill health, their immune system is no longer able to keep the latent infection at bay and the animal develops and dies of tuberculosis. This makes it possible for TB to be eradicated from a local possum population within as few as five years of possum control being started, but for the ghost of past infection to live on in deer for another decade after that (*Fig. 2*). The problem is that if possum control is stopped after 5–10 years, possum numbers can increase back to the levels at which

Fig. 1 Scavengers extraordinaire – trail camera images of resident and released wild pigs feeding on possum carcasses, showing how a single tuberculous possum carcass can infect a large number of pigs.

TB can persist before the last infected deer dies. This creates a tiny but not negligible risk that TB can re-establish in such possum populations and start a new epidemic. As a consequence, possum control has to be maintained for at least a decade in areas where significant numbers of infected deer were once present.

Thus, despite not being maintenance hosts in their own right, wild deer and pigs will remain an important part of the New Zealand TB control programme for its entire duration.

This article is based largely on research funded by TBfree New Zealand and the Ministry of Business, Innovation and Employment.

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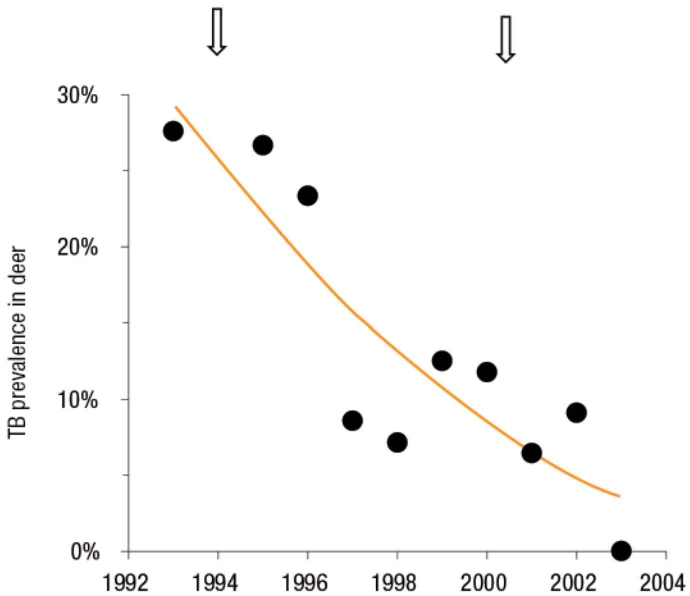

Fig. 2 Gradual decline in TB prevalence in deer in the eastern Hauhungaroa Range in the central North Island after possum control in 1994 and 2000 (arrows).

Some recent *relevant publications*

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