Review Article

Development of the New Zealand strategy for local eradication of tuberculosis from wildlife and livestock

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Abstract

We describe the progressive development of New Zealand's national strategy for control of tuberculosis (TB) in its agricultural sector over the last four decades. The strategy is globally unique, reflecting the need for effective and co-ordinated management of TB in a wildlife maintenance host, the brushtail possum (*Trichosurus vulpecula*), in addition to controlling infection in cattle and farmed deer herds. Since the early 1990s, the strategy has been developed by the Animal Health Board (AHB), formed to empower the farming industry to take the leadership role in funding of TB control, policy development and administration.

The AHB became the first non-government organisation to develop and gain acceptance by the funders (farming industry and government) of a National Pest Management Strategy (NPMS) under the Biosecurity Act 1993. A key outcome of the NPMS for TB control was the development and inclusion of very challenging objectives that provided direction for management, research and possum control. This paper describes the process whereby the NPMS was revised twice, following achievement of each successive set of strategy objectives within budget. Success was based on firstly, reorganisation of the AHB and its operational systems to achieve increased efficiency; secondly, improved efficiency through contracting possum and disease control, and thirdly research delivering effective and practical applications, while also providing a scientific basis for setting directions for future control strategies. The last revision of the NPMS was implemented in 2011, and included objectives to eradicate *Mycobacterium bovis*-infected wildlife populations over 2.5 million hectares by 2026. This ambitious objective was adopted only after extensive forecast modelling enabled stakeholders to identify and select the most cost-effective long-term solution for the management of *M. bovis*-infected possum populations.

The accomplishment of New Zealand's TB control programme, in meeting successive sets of demanding NPMS objectives, has seen a 95% decrease in the number of infected cattle and deer herds since they peaked at 1,694 in 1994, and the eradication of TB from infected possum populations from 830,000 hectares. Provided the current level of funding continues, New Zealand is positioned to achieve national eradication of TB well in advance of the 40–50-year timeline forecast 3 years ago.

KEY WORDS: *Tuberculosis, possums, wildlife, disease eradication, strategy*

Introduction

This paper, the last of the set of nine articles in this issue, documents the evolution over the last four decades of the strategic objectives, administrative structures and funding arrangements for New Zealand's national programme for management of tuberculosis (TB) in its livestock farming industry. These actions had become necessary after the disease had become widespread in wildlife, predominantly brushtail possums (*Trichosurus vulpecula*), which infected adjacent livestock. The epidemiological and ecological evolution of the TB in wildlife problem, and the progressive operational and management responses to it, are documented in the eight companion papers. Here we focus on evaluating how the programme developed and was adapted in response to its success over time. Our aim is to provide a forward-looking assessment of the factors that have been critical in moving from identification of a wildlife-related problem of TB in cattle (and later deer) herds, to damage limitation (minimising further expansion of the TB in wildlife problem), then to the current situation where the aim is for regional disease eradication from both livestock and wildlife. Further, determining the need for, and identifying the path to, national TB eradication required a means of predicting the time, effort and likely cost to achieve this, together with stakeholder involvement to derive an agreed outcome; this process is described.

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AHB	Animal Health Board
AIHP	Annual infected herd prevalence
NPMS	National Pest Management Strategy
NPMP	National Pest Management Plan
NPV	Net present value
TB	Tuberculosis
VRA	Vector risk area(s)

Initial governance of the problem of TB in possums

Governmental leadership 1972–1989

There was a long hiatus between bovine TB being made a notifiable disease in 1893 (Anonymous 1893) and the first instigation of an organised approach to curb disease, implemented by the Department (later Ministry) of Agriculture, by compulsory TB control programmes for dairy herds (1956–1961), beef herds (1970) and deer herds (1990) (Davidson 2002). The resultant livestock TB control programmes first involved diagnostic testing and slaughter of reactors, slaughterhouse surveillance and movement control. The TB programme originally focused solely on livestock, but by 1971 TB in wildlife had been identified as a source of recurrent *Mycobacterium bovis* infection for cattle (Davidson 1976). During the 1970s, the size of the known problem of TB in possums expanded rapidly in both the North and South Islands and, in response, possum control for TB purposes began in 1972 (Livingstone *et al.* 2015). The TB-related possum control programme was initially funded by government (via the Ministry of Agriculture and NZ Forest Service) and delivered through existing animal pest control infrastructures within the former NZ Forest Service and local Agricultural Pest Destruction Boards (Adlam 1977). In 1978 however, the level of government funding for possum control was reduced from approximately NZ$3 million/year to NZ$0.5 million/year (Coleman and Livingstone 2000). Such reduced funding caused cut-backs in possum control, which as a consequence facilitated expansion of the areas occupied by tuberculous possums and an increase in the number of infected herds and TB reactors (Livingstone *et al.* 2015). The resurgence of TB in livestock in the 1980s, despite ever more stringent management of the disease in livestock, prompted increased political pressure from farmer stakeholder organisations, resulting in increased government funding becoming available for possum control from 1984. By then, all control of tuberculous possum populations was being undertaken by the Agricultural Pests Destruction Council on behalf of the Ministry of Agriculture and Fisheries, with regional councils largely taking over these functions after their formation in 1989 (May 1996).

Shift to stakeholder-led governance

Following the introduction in 1956 of compulsory TB testing for dairy herds supplying whole-milk to metropolitan areas, a Town Supply Tuberculosis Committee was established. This committee comprised representatives from the Town Milk Suppliers Federation and Federated Farmers, as well as a Department of Agriculture veterinarian. The committee's purpose was to advise the Director-General of Agriculture on the views of the industry and make recommendations for financial assistance to individual farmers who suffered hardship as a result of the scheme. In 1958, in anticipation of the introduction of compulsory TB testing for all dairy herds, the committee was expanded to include a New Zealand Dairy Board representative and was renamed the National Tuberculosis Advisory Committee (Davidson 1979). In addition, district committees comprising farmer representatives and the local Department of Agriculture veterinarian were established in 1961. These Tuberculosis Advisory Committees aimed to help local farmers comply with the scheme and supported those with TB-related hardships in seeking financial assistance. In 1969, the national and district committees were expanded to include the beef industry, becoming the National Animal Health Advisory Committee and Regional Animal Health Advisory Committees, respectively (Davidson 1979).

In 1987, the government decreed that farmers were required to fund 48% of the national TB control programme through a cattle slaughter levy, and proposed that this should increase to 66.6% over 3 years (Anonymous 1987). Given they were to become the major funders, farming leaders became increasingly involved in the administration of the National Animal Health Advisory Committee, including assuming the role of chairman. Subsequent pressure from the National Animal Health Advisory Committee and its stakeholder organisations was instrumental in obtaining further increases in government funding for TB-related possum control, so that by 1989 NZ$3 million/year was again being spent for this action, the same as in 1977 (Coleman and Livingstone 2000).

In 1989, the National Animal Health Advisory Committee changed its name to the Animal Health Board (AHB). It was legally incorporated as such in 1993 (with a subsequent name change to TBfree New Zealand Ltd in July 2013). The AHB comprised representatives of its industry and government funders, initially including Federated Farmers of New Zealand (through its dairy, and meat and wool sections), New Zealand Dairy Board, New Zealand Meat and Wool Board, New Zealand Deer Farmers Association, along with the New Zealand Local Government Association and two representatives of central government.

Development of a National Pest Management Strategy for TB in wildlife

Establishment, powers and funding principles

The formal establishment of the AHB as a legal entity anticipated its intended role as a management agency under the Biosecurity Act 1993. In a major innovation, the Biosecurity Act 1993 provided for any body-corporate to propose the creation of a national pest management strategy for an unwanted organism in New Zealand's environment, such as *M. bovis*. Government approval of such a proposal was subject to rigorous tests for achievability of stated objectives, cost-benefit analysis and demonstrated acceptability to funders and affected parties. The AHB duly developed, consulted on and gained agreement from funders (farmers, industry groups, central and local government) on a 5-year National Pest Management Strategy (NPMS) for bovine TB. The NPMS proposal was submitted to Government for approval in November 1995 (Anonymous 1995) and was formally approved in 1998. This delay provided the AHB with the legal powers required to administer and enforce the NPMS.

The Biosecurity Act also introduced the principle that the costs of pest management should be met by those who benefited from the activity, and by those who, through their action or inaction, exacerbated the problem. Under the beneficiary principle, the beef, dairy and deer industries agreed to fund all livestock disease control activities, and to partly meet the costs of managing TB in possums and other wildlife, hereafter termed vector control. This term is mainly applied to controlling, monitoring and undertaking surveys of possum populations, but it also encapsulates surveillance of other wildlife as sentinels, including ferrets (*Mustela furo*), wild deer and feral pigs (*Sus scrofa*). Under the exacerbator principle, the balance of vector control costs were allocated to central and local government on behalf of public and private landowners respectively, because their lands could harbour tuberculous possum populations, thereby making it difficult to clear infection from adjacent cattle and deer herds. The NPMS enabled the collection of funds though a levy on the slaughter of all adult cattle, with further funding contributions being negotiated with dairy and deer industry sectors, and with central and local government. Despite the delay in formal approval, government funding for vector control proposed in the NPMS became available from 1 July 1995.

Evolution of objectives and amendments

The primary objective for the first 5 years of the NPMS was to prevent expansion of vector risk areas (VRA). VRA are defined as geographic areas in which TB has been confirmed present in possums, or was strongly suspected to be present in a wildlife maintenance host, based on epidemiological findings from infected cattle and deer herds. The secondary objective was to reduce the percentage of infected cattle and deer herds in both VRA and vector free areas. Vector free areas comprised all areas not classed as VRA.

There was early success in achievement of the secondary objective, with a 60% decline in infection in livestock from a peak of 1,694 infected herds in June 1994, to 666 by June 2000 (Livingstone *et al.* 2015). However, 10 new VRA emerged in the first 5 years of the NPMS, contributing to a substantial increase in total size of VRA (Livingstone *et al.* 2015).

The continued expansion of the tuberculous possum problem prompted both central government and industry to progressively and substantially increase funding for vector control, reaching NZ $33.4 million in the 2000/2001 financial year (Anonymous 2001a). This foreshadowed a major review of the NPMS with a formal amendment (the second NPMS) being proposed in 2001 (Anonymous 2001b) which was eventually approved in 2004. The major new objective of the second NPMS was to reduce the national annual infected herd prevalence (AIHP) from 1.32% in 2000/2001 (Anonymous 2001b) to no more than 0.2% by 2013. Considered extremely ambitious at that time, an AIHP target of ≤0.2% was chosen because if this was maintained for 3 years, New Zealand would meet the international standard for national classification of official freedom from TB in cattle and deer herds (Anonymous 2014b). In support of this, there was a significant increase in total NPMS funding, to ~NZ$80 million per annum in 2002/2003 (Table 1; Anonymous 2003). Funding has remained at that level since, with NZ$50–60 million per annum allocated to vector control. This increase enabled a major expansion of the area subjected to intensive vector control, which contributed to meeting the 0.2% AIHP objective. Equally ambitiously, the second NPMS aimed to prevent expansion of VRA boundaries after June 2004. This objective was achieved with only one small exception; the Rolleston Range VRA, identified in 2012 (Anonymous 2013).

By about 2005, it was clear that TB in livestock was still declining rapidly (Hutchings *et al.* 2013) and there was an increasingly strong belief among AHB staff, stakeholders and researchers that eradication of TB from wildlife was feasible. This belief was based on a number of factors. Firstly, empirical field validation had been obtained at a local level (Caley *et al.* 1999) of previous theoretical predictions (Barlow 1991) that reducing possum densities by 75%, and then maintaining them below about 40% of carrying capacity, should be sufficient to eradicate TB. There was strong operational evidence that intensive possum control had successfully eradicated TB from possum populations in 11 small VRA, including 49,000 hectares at South Kaipara Head, Auckland region (Anderson *et al.* 2015).

Table 1. Annual income and categorised expenditure (NZ$ million) for New Zealand's tuberculosis (TB) control programme, from 1985–2010. The table does not include farm-related costs associated with mustering and presenting cattle and deer herds for TB testing, or the TB testing costs paid by individual deer farmers.

	Financial Year ending June					
	1985[a]	1991[b]	1995[c]	2000[d]	2005[e]	2010[f]
Income						
Central and local Government	4.3	5.9	11.2	26.0	36.0	34.1
Levies and Industry funding	3.3	13.5	21.5	26.2	45.3	44.9
Total	7.6	19.4	32.7	52.2	81.3	79.0
Industry share (%)	43	70	66	50	56	57
Expenditure						
Operational	Nd	2.2	1.4	3.6	6.0	6.3
Disease Control	4.7	8.1	11.7	14.5	17.7	18.4
Compensation	1.8	3.5	3.5	1.2	0.9	0.5
Research	0	0.5	1.8	2.5	2.6	2.5
Vector control	1.1	4.1	14.3	30.4	54.1	51.3
Total	7.6	18.4	32.7	52.2	81.3	79.0

Nd=not determined.
[a] Data were derived for 1985 by interpolation from the primary data reported in Anonymous (1986). Allocation of funding to some categories may not exactly match with those in other years.
[b] Data from Anonymous (1991).
[c] Data from Anonymous (1996).
[d] Data from Anonymous (2000).
[e] Data from Anonymous (2005).
[f] Data from Anonymous (2010).

Equally important was reliable achievement of very low and even possum densities in rugged or heavily forested terrain (Warburton and Livingstone 2015). Notable examples of this were in the Hokonui (Southland region) and Hauhungaroa (Waikato region) Ranges (~9,000 hectares and ~80,000 hectares, respectively) where aerial poisoning, using sodium fluoroacetate (1080) preceded by two non-toxic prefeeds, had reduced indices of possum relative abundance (namely the residual trap-catch index; Anonymous 2011b) to the very low levels of <0.3% and <0.05%, respectively (Coleman *et al.* 2006).

Finally, there was increasing confidence that while wild deer, feral pigs and ferrets frequently were infected with *M. bovis,* they were largely spillover hosts in the TB cycle and were unable to sustain *M. bovis* infection independently of possums (Nugent *et al.* 2015a). This implied that possum control alone would usually be sufficient to eradicate TB from wildlife, albeit only slowly in regions where infected wild deer (in particular) were common (Barron *et al.* 2013, 2015).

At the same time, an independent review (Simpson and Hickling 2005) confirmed that the number of infected livestock herds was well below forecast, indicating better than expected progress toward the target of 0.2% AIHP by 2013. That review also argued that the strategic focus on an AIHP target had become suboptimal, because it required a thin spread of vector control funding over most areas where livestock were sympatric with infected wildlife. A more targeted approach could create opportunities for local or regional eradication, with better long-term TB control outcomes. That review, and the mounting confidence that TB could be eradicated from possums, prompted a second full review of the NPMS in the late 2000s. This second review process, described in more detail below, ran for 3 years. For the first time, it explored a full range of strategic options, from doing nothing (ceasing all management of TB) through to the most ambitious objective of national eradication of TB from both livestock and wildlife. Funders eventually accepted new objectives that included eradication of TB from possums over significant areas. An amended NPMS was proposed in September 2009 (Anonymous 2009a) and came into force on 1 July 2011. Under the Biosecurity Law Reform Act 2012, the NPMS was re-designated as the National Pest Management Plan (NPMP).

The major new objective of the NPMP was to demonstrate the feasibility of eradicating TB from possum populations in two extensive forests (these being considered to be the most challenging areas for successful TB eradication), within the broader objective of eradicating TB from possum populations from a minimum of 2.5 million hectares of VRA by June 2026. The objective of preventing VRA expansion was retained, but the AIHP target for livestock was relaxed to 0.4%, to allow vector control and surveillance efforts to be increased in the areas targeted for eradication of TB from possums, with a consequent decrease in effort in other areas.

Managing the first and second National Pest Management Strategies

During the first NPMS, the AHB had operated mainly through high-level strategic direction and policy development. It had minimal in-house operational capacity, and it out-sourced most service delivery. Management of TB in livestock was mostly out-sourced to the state-owned enterprise AgriQuality NZ, that primarily involved cattle TB testing services. Vector control services were mostly provided by regional councils, and included planning, costing and managing local vector control programmes. Field operations were initially undertaken mostly by regional council staff, but later by private contractors under independently monitored vector control contracts (Warburton and Livingstone 2015).

The AHB had also made an early commitment to evidence-based management and innovation during the first NPMS by committing NZ$2.0–2.5 million annually to research, a funding level that has been maintained since. This research was designed to improve the understanding of TB epidemiology in wildlife (including host status), cost-effectiveness and acceptability of possum control, provide better diagnostic tests for TB in cattle and deer and evaluate effectiveness of BCG vaccination in possums, cattle and deer.

The more demanding objectives and funding constraints of the second NPMS required a more efficient and capable management structure. This led to the implementation of in-house management systems and functions including a disease management information system to record herd information and manage the out-sourced TB testing programme; employment of veterinarians to manage infected herds and design the vector control programme; development of a vector management information system (VectorNet) to manage vector control contracts; and employment of staff to manage, implement and audit the delivery of the vector control programme. Systems and business processes were also re-shaped to encourage competition between providers for the remaining out-sourced activities including livestock TB testing to set specifications, requiring all TB testers to be technically accredited by the Ministry of Agriculture and Forestry, management of the compliance requirements of the disease control programme, TB diagnostic services and field vector control operations. These changes continued to provide improved managerial and technical control of the TB programme, while encouraging innovation and efficiency in the delivery of contestable disease and vector control services.

Managing and implementing the National Pest Management Plan

The fundamental change in objectives in July 2011, from controlling TB to attempting to eradicate it, required a major strategic shift in the NPMP. Operational areas for vector control were assigned to one of three categories, with each category representing a different strategic approach (Figure 1). These so-called strategic choices were firstly, eradication, where the aim was to have achieved (and declared) a 0.95 probability of TB freedom in possums by 2026, allowing high-intensity possum control and disease surveillance to be ceased in those areas; secondly free area protection, where the aim was to ensure that tuberculous possums did not spread back into the eradication areas or into

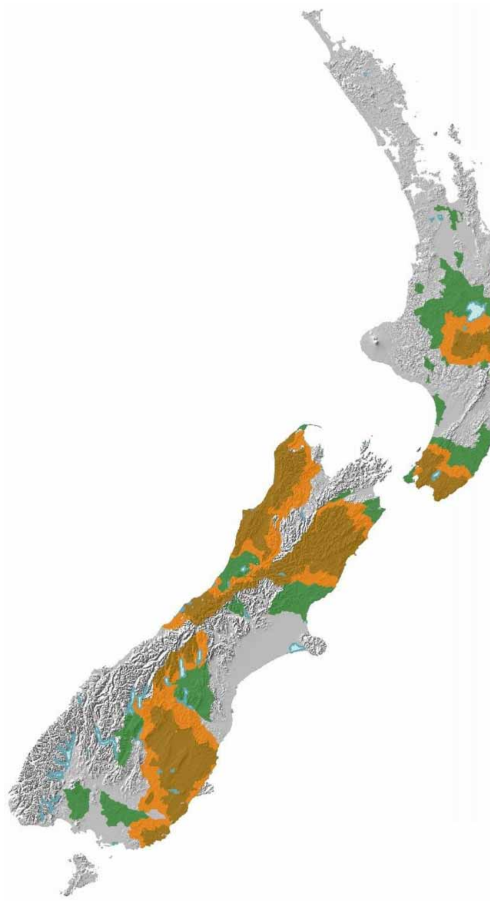

Figure 1. New Zealand's vector risk areas (VRA) categorised by the strategic choice outcomes to be achieved as part of the National Pest Management Plan for control of tuberculosis (TB). The categories were eradication (green shading) with the aim of having areas free of TB in wildlife by 2026; free area protection (orange shading) with the aim of reducing or keeping possum densities below the TB persistence threshold, thus preventing spread of TB beyond VRA or back into eradication areas; and infected herd suppression (brown shading) with the aim of keeping possums on and near farmland at a level to maintain the national annual infected herd prevalence below 0.4% (Hutchings *et al.* 2013).

the vector free areas; and thirdly infected herd suppression where the aim was to carry out sufficient possum control to maintain the national AHIP below 0.4% (Hutchings *et al.* 2013). Implementation of this overall approach required careful communication with farmers, especially in infected herd suppression areas where herd infection rates might increase over the 15 years from 2011.

Sources of funding and classes of spending for the TB control programme from 1985 to 2010 are summarised in Table 1. There were major increases between the early 1980s and the early 2000s, but since then funding has remained more or less constant, with no adjustment for inflation. From being 100% funded by government prior to 1985, the share of programme costs borne by industry has varied from 43% in 1985 to 70% in 1991, but since 2005 has remained stable at about 56%.

Expenditure on vector control increased most dramatically, from 1984 to 2005. Expenditure on disease control also increased over this period, initially reflecting increasing numbers of infected herds. Since then the number of cattle tested each year has decreased (e.g. from 5.5 million in 2002/2003 to 4.5 million in 2009/2010) but costs associated with management of infected herds increased, as did the number of samples and costs for ancillary serial and parallel diagnostic tests. Costs associated with culture of *M. bovis* and DNA analyses, together with greater use of call centres and databases for farmer communications and programme management respectively, also increased over this time period. In contrast, the annual cost of compensation payments to farmers fell from NZ$3.7 million in 1994/1995 (when there were 6,227 cattle TB reactors) to NZ$0.5 million in 2009/2010 (for 636 cattle TB reactors). An unexpected spike (to NZ$1.5 million) in 2012/2013 was caused by a large but transient increase in reactor numbers primarily as a result of within-herd transmission in a few large herds (Anonymous 2013).

Continuous improvement

Research has long underpinned both the direction and success of each NPMS iteration, as well as contributing to substantial technical, operational and management improvements (Livingstone *et al.* 2015). Along with the adoption of new technologies, better TB diagnostics and sophisticated information management systems, continued substantial improvements in the sustainability and efficiency of possum control have accelerated progress towards local eradication of TB from possums. Important recent advances have included evaluation and registration of new possum toxins for ground and possibly aerial use (Eason *et al.* 2012); development and testing of alternative aerial sowing techniques for toxic bait, resulting in incremental reductions in control costs (Nugent and Morriss 2013); work towards increasing possum interaction with traps, toxic baits and detection devices to improve efficiency of ground control (Sweetapple and Nugent 2011; Warburton and Livingstone 2015); and implementation of operational guidelines and standard operating procedures, enabling consistent performance and compliance with legal, health and safety requirements. Improvements in diagnostic techniques and methods have also contributed to more efficient management of TB test-positive cattle and deer, as well as controlling infection in herds and animals (Buddle *et al.* 2015; Livingstone *et al.* 2015).

The adoption in 2011 of local eradication objectives, has driven recent development of strategies and tools for quantitatively assessing the probability that a specific area is free of TB. Of particular note is the development of a sophisticated simulation and data modelling Proof of Freedom framework (Anderson *et al.* 2013, 2015). This has rapidly become one of the key tools for deciding when to declare TB freedom. The Proof of Freedom tool is strongly supported by other recent improvements in technology and methodology, including: the burgeoning use of handheld computers by field contractors to record the detailed geospatial data needed to target possum control and to declare TB freedom; the development of more affordable operational techniques for possum density estimation and TB status (Nugent *et al.* 2014, 2015b) and the implementation of a National Animal Identification and Tracing scheme that records livestock movements, allowing easier forward and backward tracing of TB cases, and enabling development of a risk-based TB-testing programme.

Drivers of success

The 96% reduction in the number of infected cattle and deer herds, from 1,694 in June 1994 to 72 in June 2014, highlights the success of the NPMS and NPMP in reducing the prevalence of TB in livestock. Much of that reduction occurred during the first NPMS, even though total VRA continued to expand reaching 10.5 million hectares (~40% of New Zealand) by 2004 (Livingstone *et al.* 2015). A crucial milestone in the second NPMS was achievement of the ambitious 0.2% AIHP objective 18 months ahead of schedule, with the AIHP in cattle falling from 1.1% in June 2002 to 0.19% in December 2011. For the NPMP, success will mainly be measured against the 2026 eradication objectives. After 3 years, progress is good, with TB freedom having been achieved over 830,000 hectares of VRA (Anonymous 2014a).

The major drivers of this sustained success of the NPMS fall into four groups. Firstly, robust processes of consultation resulted in agreement between stakeholders on strategic objectives, TB control methods and policies, generating a sense of partnership and ownership of the strategy, with surveys showing 85% support among farmers for the NPMS (Anonymous 2011a). This support is sustained through effective communications, most notably nowadays through a dedicated contact centre. The outcome has been durable funding agreements between industry and government, with stable funding since 2002 (Table 1) enabling long-term planning.

The second group of drivers stem from a sole agency being made responsible and accountable for developing and implementing the agreed strategy. As a single-purpose dedicated agency, the AHB was able to progressively develop in-house managerial and technical capability in key areas, such as the construction of information systems and databases, to underpin a business model in which contracting of field services, such as cattle TB testing and vector control, was conducted in a tightly controlled but highly competitive environment. This in turn drove operational innovation by contractors, leading to long-term cost savings.

A third group of drivers relate to improvements in TB management in livestock. These include more accurate diagnostic herd testing (Buddle *et al.* 2015) and DNA typing of *M. bovis* (Price-Carter *et al.* 2011) and the ability to impose increasingly tighter controls on movement of stock from infected herds and risk areas. TB management in livestock was also supported by specific industry funding agreements, such as the dairy industry topping up payments for TB dairy reactors from clear herds when they were found to be non-tuberculous at slaughter.

The final group of drivers reflect an emphasis on a science- or evidence-based approach to the development of strategy, tactics and policies for wildlife surveillance and control, through early and heavy investment in research and technology, and acceptance and adoption of research results. Major findings from investments in eco-epidemiological research included early confirmation and acceptance that possums were a major source of TB for cattle (Davidson 1976) and, later, formal confirmation of their status as maintenance hosts (Morris and Pfeiffer 1995; Caley *et al.* 1999). In addition confirmation that feral pigs, wild deer, and ferrets were largely spillover hosts meant that they did not require direct population control for TB management (Nugent 2011). This research also resulted in development and use of modelling in designing control and surveillance programmes (Barlow 1991; Ramsey and Efford 2010; Anderson *et al.* 2015). There was likewise deliberate investment in development of an affordable quantitative tool, the residual trap-catch index (Anonymous 2011b), as a measure of possum relative abundance, both for setting possum control targets and measuring the effectiveness of control operations against those targets. This provided an objective means of generating competition and excellence in performance-based contracting for possum control (Warburton and Livingstone 2015). More broadly, several lines of research and management improvement have enabled substantial improvements in cost effectiveness of possum control to be made progressively.

Development of the National Pest Management Plan: making the case for eradication

Decision-making around eradication, control or abandonment of the National Pest Management Strategy

By 2006, when the second review of the NPMS was initiated, numbers of infected herds had fallen 90% from the 1994 peak. Although undocumented, some funders questioned the continued high cost of the programme relative to the actual production losses caused by the now low levels of disease. Also, some industry stakeholders were firmly of the view that with the low AIHP, TB did not pose an ongoing risk to the export of their products. As noted above though, there was a growing realisation that large-scale eradication of TB from infected possum populations was feasible and offered prospects for greatly reduced future costs of TB control. The reviewers of the NPMS therefore developed and evaluated a full range of strategic options, recognising that an in-depth analysis of costs and benefits would be required to highlight to funding stakeholders that biological eradication of TB was both affordable and achievable.

Initially, three main strategic options were developed and evaluated. Each option was developed based on research findings, operational data and historical knowledge to predict the intensity, cost and duration of possum control required for the ~700 vector control zone (i.e. possum management units). The options were:

Eradication

The goal was biological eradication of TB from all wildlife, and hence livestock, within 30 years; the latter through continued livestock disease control methods of diagnostic screening and movement control. It was assumed that progressive local eradication of TB from wildlife within VRA, including in areas remote from farmland, would be achieved by keeping possum population densities low (≤ 2% residual trap-catch index) for at least 10 years.

Containment

The goal was to maintain the *status quo*. TB would be permitted to persist in perpetuity within wildlife within VRA, but with sufficient possum control to prevent any worsening of the prevalence of TB in livestock and also prevent any VRA expansion beyond the forecast 2010 boundaries. This was to be achieved by eradicating TB in 16 small VRA, then establishing 5–15 km wide buffer zones at the perimeters of the remaining five main VRA. Within buffer zones possum densities would be maintained at levels considered too low for long-term sustainment of TB (i.e. ≤2% residual trap-catch index) in order to contain the spread of any possums carrying infection. In the remaining VRA core areas, possum populations on and near farmland would be controlled less stringently, but still sufficiently to maintain the national AIHP at ≤0.2%.

No control or modified no control

This strategy would result in cessation of all active management of TB under a coordinated national or regional strategy, resulting in TB spreading through possum populations to eventually occupy most of New Zealand. The No control option was developed to provide an economic baseline against which the full (rather than relative) benefits of the other options could be assessed. The parameters for this option are outlined in detail in Supplementary Information 1[1]. Geographic information system mapping and a spreadsheet model were used to predict the rate of the expansion in size of VRA and the consequent increases in prevalence of TB in livestock. VRA expansion was modelled using data from the 1979–1989 period when there was little control of TB in possums. This option was subsequently modified (modified no control; detailed in Supplementary Information 2[1]) to include some possum control and TB testing, especially of dairy herds. It was considered realistic that some farmers would themselves (or with industry support) initiate some degree of TB control irrespective of the absence of any orchestrated TB management plan.

The modified no control option predicted that there would be ~2,900 infected cattle and deer herds by 2030 producing some 59,000 TB reactors annually. By contrast, under the eradication option, the number of infected herds was predicted to fall to zero within 30 years, while under the containment option the number of infected herds was predicted to fall to an asymptote of ~60 infected herds (Anonymous 2007a).

In comparing the economics of the three options outlined above, projected monetary savings from lower production losses under containment or eradication were predicted to be small, relative to the modified no control option, resulting in negative predicted net present values (NPV) for these options (Table 2). This reflected the legacy, from the previous major investment in the NPMS, of forecast low levels of TB in livestock in 2010 resulting in small production losses and little need for farmer-funded possum control. Although production losses under the modified no control option were predicted to eventually increase to very high levels, those distant future losses were discounted to near

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Table 2. Predicted outcomes from an economic analysis comparing the initial strategic options for the National Pest Management Strategy for control of tuberculosis. Total cumulative expenditure, present value (PV) costs and net present value (NPV) in NZ$ million are given for the eradication and containment options, relative to a modified no control option, over 20- and 30-year timeframes, using a 7.5% discount rate with no consideration of potential trade impacts, but inclusion of a terminal value (data from Anonymous 2007b).

	Time frame				
	20 years		30 years		
Option	Expenditure	PV	Expenditure	PV	NPV
Containment	1,260	578	1,777	626	−62
Eradication	1,433	686	1,517	696	−82

zero present values. In contrast, the containment and eradication options would both incur high initial costs, for little additional benefit relative to modified no control at 2010. This apparent economic advantage under modified no control was considered unrealistic, because it was likely that the predicted future high level of TB in livestock would generate an increasing threat to marketability of primary produce. This would eventually force a renewal of coordinated TB testing and possum control.

Over 20 years, forecast expenditure under containment was lower than for eradication (Table 2), because containment required less intense and less widespread possum control, whereas eradication required intense possum control over all 10.5 million hectares of VRA. Over 30 years, however, forecast expenditure was lower for eradication (Table 2), reflecting a decline in costs as the size of VRA fell to zero, whereas the costs of containment continued in perpetuity. More importantly, comparison of the NPV for eradication and containment suggested little difference between the two, with containment marginally favoured.

Scenario refinement: use of forecasting models to evaluate future options

When presented with the above predictions in 2007, funders initially rejected the eradication option, on the basis of significant additional short to medium-term cost, and doubts over achievability. Instead they proposed consideration of further variants, these being: a slow staged approach to eradication that avoided the need for an initial increase in funding; variants of a less stringent sustained control option with acceptance of a higher maximum national AIHP (≤1.0% of livestock herds), and a further modified no control or *Ad hoc* option (as detailed in Supplementary Information 3[2]) that included more herd testing in response to rising disease levels, and expenditure of NZ$12 million per annum on possum control.

The need to be able to directly compare these more complex options prompted the development of a forecasting model, as outlined in detail in Supplementary Information 4[2]. The initial modelling framework had assumed that TB could be eradicated from forest areas by applying three high-intensity (aerial poisoning) possum control operations at 5-yearly intervals, and from farmland by applying high-intensity annual ground control for 5 years, followed by lesser levels of risk-targeted control for the next 10 years. By contrast, newer modelling predicted that containment could be achieved by applying 2- and 5-yearly possum control in farmland and forest, respectively (in VRA buffer areas), plus 3- and 5 yearly control, on farmland and nearby forest (within 3 km) respectively, in VRA core areas for ~80% of the then current annual vector control expenditure of NZ $50 million. An iterative scenario refinement process followed, eventually resulting in comparison of four alternative NPMS scenarios for the future (Figure 2). The modelling predicted it would take 55 years to achieve national eradication if there was no initial increase in funding. However, time to eradication would fall to 40 years with a 10–15% initial funding increase (Figure 2, Anonymous 2009b). Over the 55-year period, predicted total expenditure was lowest for an option of rapid eradication and highest for an option of sustained control even though the latter had the lowest initial annual cost (Table 3). All options still had negative NPV relative to the refined *Ad hoc* option for the same reasons as above, but importantly, the NPV for the two eradication options were similar to each other, and both were less negative than the two sustained control options (Table 3). The more negative NPV values (Table 3) for the revised options, compared with the initial options (Table 2), reflected adoption of more conservative assumptions about the ease of eradication.

Based on these forecasts, funders subsequently agreed to the continuation of the NPMS, albeit with funding capped at the 2008/2009 expenditure level of NZ$81.2 million/year (Livingstone *et al.* 2009). Further modelling suggested that this would provide NZ$47 million for possum control, with about NZ$41 million of that initially required to sustain control and keep the AIHP below 0.4%, leaving NZ$6 million per annum initially available to implement a programme of progressive roll-back eradication. Funders considered that option would maintain the gains from historical investment and prevent any major worsening of the problem, as occurred in the 1980s after funding for possum control was heavily reduced. It also offered the prospect of major

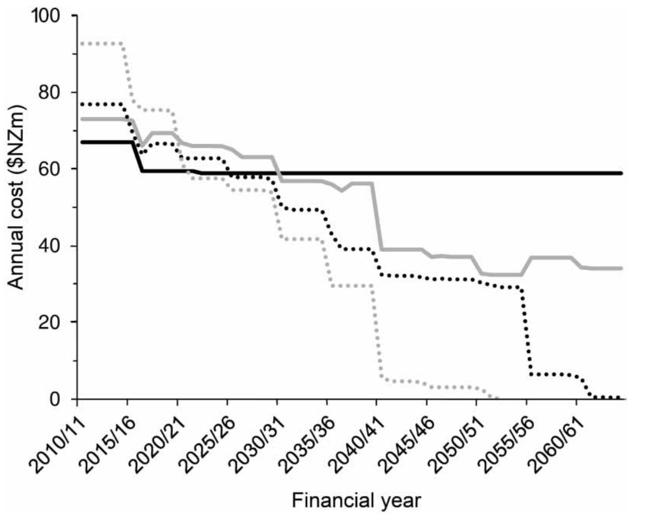

Figure 2. Predicted total annual National Pest Management Strategy expenditure for control of tuberculosis over 55 years from ~2010 for four strategic options. A baseline is provided by the sustained control option (solid black line) resulting in containment within 2010 vector risk area (VRA) boundaries, and annual infected herd prevalence <1%, compared to sustained control after rollback (solid grey line) involving implementation of sustained control after initial eradication from small VRA and "easy" parts of main VRA, and slow (dotted black line) and fast (dotted grey line) eradication scenarios, with the former not requiring an initial increase in funding levels (data from Anonymous 2009b).

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Table 3. Predicted outcomes from an economic analysis comparing four further strategic options considered for the National Pest Management Strategy. Values include national expenditure in the first year and over a 55-year-time frame, net present value (NPV) over the first 30 years relative to an *ad hoc* option, and estimated time to achieve eradication of tuberculosis. All costs are in NZ$ million, using an 8% discount rate without inclusion of a terminal value (data from Anonymous 2009b).

Option	Year 1 expenditure ($)	Total 55 year expenditure ($)	NPV over 30 years ($)	Time to eradicate (years)
Sustained control, no roll back	67	3,204	−228.5	Not achieved
Sustained control after roll-back	73	2,650	−246.7	Not achieved
Slow eradication	76.9	2,263	−128.7	45
Fast eradication	92.7	1,804	−128.8	30

reductions in future costs without requiring any increase in initial expenditure. However, funders and stakeholders required stronger proof that eradication of TB from difficult forested terrain was feasible and affordable, which shaped the eradication objectives for the NPMP outlined above. Proposed amendments to the NPMP thus included development of a Proof of Freedom framework for estimating the probability that TB had been eradicated from the possum population in a defined area (Anonymous 2009a). Submissions from funders supported the proposed changes to the strategy, but emphasised the need for further research towards more cost effective methods of possum control (Anonymous 2009c).

Agreement to continue the NPMS, despite the forecasted negative NPV, reflected industry acceptance that the risks and costs related to potential future adverse impacts on market access or product acceptability were likely to be substantial, even if not able to be quantified in current dollar terms. By supporting the proposed new NPMP objectives, which included containment of VRA and maintaining AIHP at no greater than 0.4%, funders showed they were not prepared to allow New Zealand's TB problem to regress (Anonymous 2009c, 2009d). In summary, the forecasting exercises ultimately made the case for eradication by showing it had a higher (albeit ostensibly negative) NPV than the options of sustained control or containment.

Conclusions

The introduction of the Biosecurity Act 1993 facilitated the development and implementation of an agreed strategy to control endemic TB, using a mixture of industry and government funds, and provided for that strategy to be amended twice to set and successfully meet progressively more ambitious disease control goals. Meeting the current objective of eradicating TB from possums, from a minimum of 2.5 million hectares of VRA by 2026 under a capped budget, will be a major challenge but will help determine whether it is feasible and economically rational to eradicate TB from possums throughout New Zealand. Progress in this area over the last 3 years has been encouraging, as from July 2011 TB has been adjudged newly eradicated from possum populations across an area of about 830,000 hectares (Anonymous 2014a); meanwhile further good progress has been made in implementing programmes to eradicate TB from the two "difficult case" extensive forest areas totalling ~140,000 hectares (Nugent *et al.* 2014, 2015c). There has been rapid accumulation of quantitative evidence that TB can be eradicated from possums, and possibly more cheaply than originally predicted. Most recently, the results of contemporary possum surveys, conducted over a 5-year period from 2007/2008 onwards, found that within >200 vector control zones that had been subject to 5 years or more of intensive possum control, no *M. bovis* infection was detected from among >78,000 animals necropsied (Nugent *et al.* 2015b).

There are some threats to achieving eradication. These include potential constraints on future vector control funding by stakeholders and some public opposition to aerial 1080 application. The risk of the latter currently remains offset by strong official support (Wright 2011). Therefore, as long as programme funding is maintained near current levels, we predict bovine TB could be eradicated from New Zealand well before the originally forecast date of 2055.

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