Review Article

Managing and eradicating wildlife tuberculosis in New Zealand

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Abstract

Tuberculosis (TB) due to *Mycobacterium bovis* infection was first identified in brushtail possums (*Trichosurus vulpecula*) in New Zealand in the late 1960s. Since the early 1970s, possums in New Zealand have been controlled as part of an ongoing strategy to manage the disease in livestock. The TB management authority (TBfree New Zealand) currently implements three strategic choices for disease-related possum control: firstly TB eradication in areas selected for eradication of the disease from livestock and wildlife, secondly Free Area Protection in areas in which possums are maintained at low densities, normally along a Vector Risk Area (VRA) boundary, and thirdly Infected Herd Suppression, which includes the remaining parts of VRA where possums are targeted to minimise the infection risk to livestock. Management is primarily through a range of lethal control options. The frequency and intensity of control is driven by a requirement to reduce populations to very low levels (usually to a trap-catch index below 2%), then to hold them at or below this level for 5–10 years to ensure disease eradication.

Lethal possum control is implemented using aerial- and ground-based applications, under various regulatory and operational constraints. Extensive research has been undertaken aimed at improving the efficacy and efficiency of control. Aerial applications use sodium fluoroacetate (1080) bait 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, a potassium cyanide-based product) and traps. In the last 5 years there has been a shift from simple possum population control to the collection of spatial data on possum presence/absence and relative density, using simple possum detection devices using global positioning system-supported data collection tools, with recovery of possum carcasses for diagnostic necropsy. Such data provide information subsequently used in predictive epidemiological models to generate a probability of TB freedom.

The strategies for managing TB in New Zealand wildlife now operate on four major principles: firstly a target threshold for possum population reduction is defined and set, secondly an objective methodology is applied for assessing whether target reductions have been achieved, thirdly effective control tools for achieving possum population reductions are used, and fourthly the necessary legislative support is in place to ensure compliance. TBfree New Zealand's possum control programme meets these requirements, providing an excellent example of an effective pest and disease control programme.

KEY WORDS: *Disease control, livestock, management, pest control, strategies, tuberculosis (TB), possum, Trichosurus vulpecula, wildlife*

Introduction

In New Zealand, and a number of other countries, tuberculosis (TB) due to *Mycobacterium bovis* infection has become established in one or more wildlife hosts capable of independently maintaining the disease. The host or suite of hosts differs between countries and in New Zealand is uniquely centred on an introduced marsupial, the brushtail possum (*Trichosurus vulpecula*). Possums were introduced to New Zealand from Australia in 1858 to establish a fur trade (Clout and Ericksen 2000). With natural spread and subsequent human relocations, possums now occupy virtually all vegetated habitats in the North and South Islands of New Zealand from the coast to high mountains, including extensive rugged forest lands, farmland and semi-urban habitats (Clout and Ericksen 2000). Before possums were acknowledged as a wildlife vector of TB in 1971 (Davidson 1976) they had already been recognised as a significant conservation pest, causing major vegetative damage and even canopy collapse in some indigenous forest types, and selectively removing palatable forest understorey species such as fuchsia and mistletoe (Payton 2000). Organised possum population control began in the 1950s and continues to the present day as a means of curtailing possum impacts on indigenous forests and biodiversity values in priority conservation areas.

Following their confirmation as TB hosts, possums were also controlled for TB management purposes to prevent, or at least reduce, the potential transmission of disease to farmed livestock, predominantly cattle (beef and dairy) and red deer (Davidson 1976). TB was first identified in wild possums in 1967 (Ekdahl *et al.* 1970),

AHB	Animal Health Board
DOC	Department of Conservation
GPS	Global positioning system
TB	Tuberculosis due to *Mycobacterium bovis*
TCI	Trap-catch index
VRA	Vector risk area

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and subsequently identified in possum populations in 32 geographically discrete areas of New Zealand – referred to as Vector Risk Areas (VRA) which in total amounted to 10.6 million hectares (~38% of New Zealand's land area) in 2012/13. A VRA is a defined geographical area where TB is established in a wildlife maintenance host (Livingstone *et al.* 2015).

The importance of possums as a cause of TB in cattle, and the effectiveness of intensive lethal control as a way of managing this problem, were both demonstrated soon after TB was first identified in possums. As early as 1972, in the Buller South district of the West Coast region of the South Island, control of possum populations sympatric with *M. bovis*-infected beef and dairy herds resulted in an immediate and significant reduction in herd infection (Livingstone *et al.* 2015). This identified a strong causal link between TB in possums and livestock infection, and demonstrated that killing possums was highly effective in breaking that link. Subsequent findings of TB infection in cattle herds related to possums in a number of discrete areas (Adlam 1977) further confirmed possums as the main wildlife vector of the disease. As a consequence, a programme of possum population control was instigated in and around areas where TB in possums was found.

Subsequent epidemiological modelling and empirical data since the 1970s have indicated that TB can be eradicated from possum populations by reducing and maintaining their numbers at low densities for approximately 5 years (Barlow 1991a; Caley *et al.* 1999; Ramsey and Efford 2005), which is usually achieved by large-scale lethal control (as discussed later). Together with testing and movement control policies for livestock (Buddle *et al.* 2015), possum control has been the critical element that has led to a 95% reduction in the number of infected cattle and deer herds, from a peak of 1694 in June 1994 to 66 in June 2012 (Livingstone *et al.* 2015).

Because tuberculous possums and possum control are problems exclusive to New Zealand, unique solutions had to be developed that took into account this species' biology in a non-native country, including TB epidemiology, available control technology and its effects on indigenous non-target species, and the regulatory requirements and public expectations regarding large-scale pest control. Moreover, special consideration was required with regards to the practical aspects of pest control over the vast areas of New Zealand's steep forested landscapes, throughout which possum population control was required. Since 1991 the Animal Health Board (AHB; now TBfree New Zealand) funded research to improve the management of TB in New Zealand and to help achieve the goals of the National Pest Management Plan for Bovine Tuberculosis (Livingstone *et al.* 2015). The practices of possum control have been underpinned by both operational trials and specific research projects aimed at improving the strategic application and effectiveness of control programmes (i.e. intensity, frequency and spatial scale of control), and the more specific tactical application of operational practices (i.e. bait sowing rates, trapping methodology, outcome monitoring, and target specificity).

This paper reviews the main strategic, tactical and operational practices that have developed over the past three decades for reducing or completely eliminating TB in possums in particular, but also for disease surveillance in other wildlife species, e.g. ferrets (*Mustela furo*) and feral pigs *(Sus scrofa)*, that are involved in the epidemiology of TB in New Zealand.

Strategic options

In the broadest terms, the strategic options for pest and disease management are to do nothing, to reduce pest density or disease prevalence and maintain it at some level that is acceptable, or to eliminate the pest or disease completely from an area and prevent its reinvasion. All three options are applied in New Zealand to wildlife TB management.

Historically, because of limited funds, possum control was mainly applied on or near farmed areas that had the worst or most intractable livestock TB problems. Successive amendments to the National Pest Management Plan, along with associated increases in funding for possum control, provided the ability to firstly define and contain the spread of infected possums, secondly develop extensive conjoined areas of possum control within VRA where possums could be maintained at low densities, thus reducing the risk of TB in possums migrating within the area under control as well as minimising their contact with cattle and deer, and thirdly eradicate TB from the possum population in a few small VRA by maintaining possum densities at low levels.

In July 2011, the latest amendment to the National Pest Management Plan was implemented, with an objective to eradicate TB from a minimum of 2.5 million hectares of VRA by 2026 (Anonymous 2012a), based on annual funding capped at the same level as for 2002/03. To achieve this objective, approaches to possum control had to be refined, with funding prioritised on the basis of strategic choices for particular VRA or parts of VRA. The ability to prioritise areas has evolved over time as technical and control capabilities have improved, in line with improved understanding of possum ecology and TB epidemiology.

Three strategic choices are currently used to guide disease-based possum control: firstly TB eradication in those parts of selected VRA that together make up a minimum of 2.5 million hectares, TB is required to be eradicated from the possum population, with a probability of freedom of ≥0.95; Secondly Free Area Protection in those areas where possums are maintained at low densities, normally along a VRA boundary (buffer) to prevent TB in possums migrating and establishing infection in the adjacent Vector Free Area. Buffers vary in width from 5–15 km depending upon the extent and type of possum habitat within the buffer and adjacent non-controlled areas; thirdly Infected Herd Suppression, including the remaining parts of VRA where possums are targeted to minimise the probability of TB in possums infecting cattle and deer. The level of control is designed to ensure that the national annual *M. bovis* infected herd period prevalence remains <0.04%. The Infected Herd Suppression areas include farms adjacent to some relatively large areas of forest where possums are unmanaged under current resource availability.

For TB management, and disease management generally, the strategic options of suppression in perpetuity or eradication tend to overlap in practice, because both aim to reduce the reproductive rate of the disease to below 1.0 and hold it there (Anderson and May 1979). The principle difference is that where local eradication is the goal, a large surrounding area must also be free of disease to prevent reinvasion, whereas with suppression such separation is not required.

Tactical options

There have been three possible tactical options for managing TB in New Zealand wildlife that have received research consideration: wildlife population reduction through lethal control, including harvesting (Coleman and Livingstone 2000), wildlife reproductive control (Cowan 2000) and vaccination of wildlife against TB (Barlow 1991a). During the 1990s, these options were examined on a theoretical basis using population- and individual-based simulation models (Barlow 1991b, 1993, 2000a; Ramsey *et al.* 2002) to determine their relative effectiveness in possums, when used either singly or in combination. Barlow (2000b) summarised the findings and predictions of these models for each of the options, while Ramsey and Efford (2010) published the predictions of a more sophisticated individual-based spatial model to evaluate the same approaches, both individually and in combination. Although the models predicted that integrating culling with either fertility control and/or vaccination of possums could provide cost-effective alternatives to sole reliance on lethal control, neither fertility control nor vaccination has developed to the stage that they are available for operational application despite considerable research effort and expenditure. For detailed coverage of the New Zealand research underpinning development of possum vaccines and fertility control tools, the reader is referred to the relevant sections of recent review articles by Cross *et al.* (2011), Waters *et al.* (2012) and Buddle *et al.* (2013). Overall, lethal control remains the only viable option available for managing *M. bovis* infection in New Zealand wildlife.

The initial modelling of a lethal control strategy predicted that if possum populations were first reduced by 75% (knockdown) and then maintained below 40% of the population carrying capacity (maintenance), TB could be eliminated within 10 years, provided there was no immigration of *M. bovis*-infected possums during this time (Barlow 1991a). These predictions have generally been supported by field studies where both TB prevalence and relative possum abundance have been monitored (Warburton 1996; Caley *et al.* 1999), although in practice possum densities may have been held at lower densities than required by model predictions. Further modelling (Ramsey and Efford 2005) suggested that if possums were reduced to and maintained below a trap-catch index (TCI) of fewer than two possums captured per 100 operational trap-nights (2%), and provided there was no immigration of tuberculous possums, TB could be eliminated within 5 years. A comparison of different TCI targets also suggested that 2% would be the most cost-effective (Ramsey *et al.* 2008). That is, maintaining possums merely below a TCI of 5% would eventually eliminate the disease, but it would take longer, and the extra costs of extended control would exceed the costs of maintaining possums below 2% for a shorter period of time.

The concept of an initial knockdown operation to reduce the possum population from its uncontrolled state to a TCI target of 2% or below, followed by annual maintenance control to hold the possum population at or below a required TCI is followed in practice for TB control. The precise intensity and frequency of the lethal control applied varies depending on the strategic aims of the operation, i.e. TB Eradication, Free Area Protection or Infected Herd Suppression. The criteria differentiating these three classifications, and the different approaches applied for wildlife management to each, are described in detail in Supplementary Information 1.[1]

Operational practices

Aerial operations

Aerial poisoning is restricted to the use of the metabolic toxin sodium fluoroacetate (1080), incorporated into bait at 0.15% w/w (or occasionally at 0.08%), but never >0.2% w/w as concentrations above this can result in detection and consequent avoidance by possums (Henderson and Frampton 1999). Aerial operations can cover large areas of forest, e.g. up to 85,000 hectares have been treated in one operation (Coleman *et al.* 2006), and with several aircraft sowing bait simultaneously such operations can be completed in one or two days. Given high efficacy, aerial baiting is generally the most cost-effective option for controlling possums over extensive and rugged areas of forest that are difficult to traverse efficiently on foot, and in some situations it is the only practicable option.

Aerial control has been underpinned by extensive research aimed at increasing percentage kills of such operations, and reducing per hectare costs, as well as addressing non-target and welfare impacts, user safety and ensuring operational reliability. Other research has aimed to gain a better understanding of, and address public concerns related to, the impacts of 1080 on the environment and possible residues in water (Eason *et al.* 2011; Northcott *et al.* 2014).

When aerial 1080 operations were first used in the 1960s and early 1970s, they produced variable results, with the estimated percentage of possums killed from 18 operations and 15 trials averaging only 69% (Batcheler 1978). Subsequent research examining bait quality (Batcheler 1982; Frampton *et al.* 1999), bait acceptance (Morgan 1982) and bait distribution (Morgan 1994) changed operational best practice, and kills exceeding 85% were then consistently achieved (Coleman *et al.* 2006). This and other research led to the development of bait-quality standards that addressed issues such as toxin concentration, bait palatability, moisture content, bait hardness, and bait storage (Henderson *et al.* 1999). As part of current best practice, all aircraft sowing 1080 baits must use global positioning systems (GPS) to enable the pilot to disperse bait along lines at the required spacing, and to enable operational staff to audit the flight paths to ensure all of the operational area is treated and that bait has not been sown outside the designated control boundaries. In addition, all aerial 1080 operations undertaken for TBfree New Zealand must meet its standard operational procedures (Anonymous 2012b).

Most aerial 1080 operations currently utilise helicopters to deploy bait. To reduce aerial control costs, the use of fixed-wing aircraft as an alternative to (or in tandem with) helicopter application is being assessed. Available aerial top-dressing aircraft can carry one tonne of bait, have an hourly operational cost similar to helicopters, but sow at twice the speed. Initial trials using 1 kg/ha of non-toxic bait and 0.5 kg/ha of 1080 baits, applied in strips by fixed-wing aircraft, obtained a similar reduction in possum density as standard helicopter broadcast baiting (Nugent *et al.* 2012). However, fixed-wing aircraft require an airstrip for loading bait, and if this is distant from the application area, then cost savings relative to helicopter use may be lost.

Improving operational efficacy by the use of pre-feeding

To ensure possum populations are reduced consistently to very low levels, aerial baiting operations now routinely include a

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single application of non-toxic pre-feed baits (i.e., the same bait type as for the toxic application, but without 1080) to increase subsequent toxic bait consumption and overcome any bait aversion (Henderson and Frampton 1999). If possums are pre-fed before aerial application of 1080 baits, on average more possums are killed than if there is no pre-feeding (Coleman *et al.* 2006). The value of pre-feeding is also supported by a range of pen and field-based research trials (Henderson *et al.* 1999; Nugent *et al.* 2011a).

While possum control is the primary focus of TB-related animal pest control operations, aerial baiting with 1080 can have significant impacts on populations of other invasive predatory species such as ship rats (*Rattus rattus*) and, secondarily, stoats (*Mustela erminea*) (Murphy *et al.* 1999). These impacts in turn can generate either beneficial or adverse outcomes for conservation of indigenous fauna, especially birds and some large invertebrates, of which rats and stoats are significant predators. In some forest types, ship rats have been observed to increase in number to higher levels than they were before control, potentially posing increased predation pressure on native fauna (Ruscoe *et al.* 2011). To offset this risk it is desirable to achieve high rat mortality as part of the control operations to ensure any benefits are maximised. High rat kills can be achieved by non-toxic pre-feeding prior to poison deployment (Nugent *et al.* 2011a), which is an additional justification for this practice. Rat (and consequently stoat) numbers can also increase significantly during years when native beech forest seeding is synchronised (masting events), so control operations for TB in possums are aligned with conservation management needs to generate benefits for indigenous species which are at high risk from rat and stoat predation, especially in these mast years. Such applications of 1080 can result in increased abundance of native birds (Powlesland *et al.* 1999; O'Donnell and Hoare 2012).

Providing sufficient 1080 bait to kill all possums

Current best practice aerial baiting strategies are designed to ensure possums will encounter at least a single toxic bait carrying a lethal dose. To this end, 12 g baits containing 0.15% w/w 1080 are distributed as uniformly as possible across the target area generally at an application rate of 2 kg bait/hectare, equivalent to one bait per 60 m^2. Baits are applied using helicopters with underslung sowing buckets which can broadcast bait across swaths up to 220 m wide, or along much narrower "trickle-fed" paths where accuracy is crucial. The aim when broadcasting baits is to achieve a uniform distribution of baits across the control area with no gaps in bait distribution large enough to prevent any possums from encountering bait.

In practice, baits often fragment at various stages of their operational-cycle (e.g. bagging, transport, storage, handling, loading, sowing, and partially eaten baits) and because fragmented baits are not of uniform size and weight, they tend to be unevenly distributed, with heavier baits distributed more towards the outside and lighter baits towards the middle of the application swath (Nugent *et al.* 2011a). Therefore bait density needs to be sufficiently high so that possums which do not find a whole bait will still find and eat a lethal dose from several bait fragments before the onset of toxicosis (within about 30–40 minutes) at which point further bait intake ceases; sublethally poisoned possums will be likely to avoid bait in the future. While an overall bait density of 2 kg of bait/hectare largely meets this need, control efficacy could be increased (with possibly lower sowing rates) through development of bait types less prone to fragmentation, but still palatable to possums. Research and development work is in progress towards such bait improvements.

Investigation into the extent of bait fragmentation and its effect on bait quality (Nugent *et al.* 2011b) together with bait density and the influence this has on probabilities of possums encountering lethal quantities of bait, has led to the testing of alternative bait distribution patterns including strip and cluster sowing (Nugent and Morriss 2010, 2011; Nugent *et al.* 2012). Sowing baits within a relatively narrow strip or in clusters ensures baits are at high density where they occur which in turn ensures that sufficient quantities of toxic baits are readily available for possums to encounter and eat a lethal dose before toxicosis sets in, irrespective of bait fragmentation, and at possibly lower overall application rates. In strip and cluster sowing, the control area is first strip-sown with non-toxic pre-feed before the application of toxic bait in strips or clusters, along the same GPS guided lines recorded from pre-feeding. Possums exposed to pre-feed increase their searching behaviour for a period of several weeks; thus, provided aerial cluster or strip sowing of toxic bait occurs within this time period, there is a high probability that possums will find a strip or cluster of baits in sufficient quantity to avoid problems of only encountering a bait fragmentation and therefore a sublethal dose (Warburton *et al.* 2009). Recent research on strip and cluster sowing methodology suggests that relative to broadcasting, bait sowing rates can be significantly reduced without loss of effectiveness, especially where possum density is relatively low (Nugent and Morriss 2010, 2011). Use of these new sowing options could significantly reduce the amount of bait needed to be sown, and the amount of 1080 being applied to the environment. However, further work is still required to improve consistency of possum kill (for all habitat types currently subject to broadcast aerial sowing) while reducing bait application rates and costs.

Minimising the impacts of 1080 baits on non-target species

Because 1080 is a relatively broad-spectrum poison, care must be taken to avoid adverse effect on valued non-target species. There is some history of such adverse effects, and mitigation of them over time. From the 1960s to 1980s, 1080 was often applied to chopped carrot bait for aerial application. As the chopped carrot bait was not routinely screened to remove chaff (small fragments of carrot containing 1080), bird deaths, especially New Zealand tomtit (*Petroica macrocephala*) and robin (*Petroica longipes*) were commonly recorded (Harrison 1978; Spurr and Powlesland 1997). Subsequent refinement of 1080 best practice (Morgan 2004), with the now much greater use of cereal pellets, has resulted in operations that pose little risk to non-target native bird species (Spurr and Powlesland 1997; Powlesland *et al.* 1999, 2003). More recent surveys of bird populations, especially of threatened species such as kiwi (*Apteryx spp.*) and kaka (*Nestor meridionalis*), have used radio-tags to track individual birds and monitor mortality, and this has provided more robust information on the risks that 1080 operations pose to birds (Veltman and Westbrooke 2011) with general reassurance that such risks are low.

A recent exception was the death of seven of 17 radio-tagged kea (*Nestor notabilis*) killed during a 1080 operation in 2008, although it was believed these birds may have been habituated to scavenging refuse and therefore may have been more willing to seek and consume cereal pellets (J Kemp,[2] pers. comm.). In

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[2] J Kemp, Department of Conservation, Nelson, NZ.

response to these deaths, the Department of Conservation (DOC) has monitored 89 radio tagged kea through seven subsequent aerial 1080 operations with no further deaths recorded. Following the original kea deaths, DOC (and latterly TBfree New Zealand) carried out limited trials on captive kea comparing the birds' relative acceptance of two different types of cereal bait, namely RS5 and No. 7 pellets (Animal Control Products Ltd, Whanganui, NZ) (Blyth 2011). As a result of these trials, DOC now requires all 1080 operations within kea range to use RS5 baits which were less preferred by kea and which are more readily detoxified by rainfall. Additionally, trials testing anthraquinone and d-pulegone as added repellents in cereal pellets resulted in an 88.7% reduction in bait consumption by kea (Orr-Walker *et al.* 2012). Although these repellents appear to be effective at repelling kea, research is now underway to assess their effects on the acceptability of baits to possums and ship rats (Cowan *et al.* 2013), as well as understanding the volatility of d-pulegone and its impact on repellency effectiveness (M Crowell[3], pers. comm.).

Aerial 1080 baiting operations can also cause mortality in wild deer, although at apparently highly variable rates. To mitigate the impacts of this on commercial or recreational deer hunting recent research has led to development of a deer repellent (Epro Deer Repellent; Epro Ltd, Taupo, NZ) aimed at reducing deer mortality while not reducing the percentage kill of possums or ship rats (Nugent *et al.* 2004; Morriss *et al.* 2006; Morriss and Nugent 2008). Results indicated that deer deaths can be reduced by about 90% when using the repellent, with no measurable reduction in either possum or ship rat kills (Morriss *et al.* 2003; Speedy 2005; Morriss and Nugent 2008). However, inclusion of the repellent in 1080 cereal bait doubles the bait price, which effectively reduces the area over which possum control can be applied under a fixed budget (Morriss and Nugent 2009). Nevertheless, in 2011/12, it was used in about half of the aerial 1080 operations carried out by TBfree New Zealand. Conversely, in situations where TB is present in both the possum and wild deer populations, it may be beneficial to allow or even maximise by-kill of deer from a 1080 operation targeted at possums, because this will reduce the time-frame to eradicate TB from the wild animal population (Barron and Nugent 2011).

Risks to dogs and livestock are managed through public notification, poison warning signs and communication with land users in the vicinity of the operations. Dogs are particularly susceptible to 1080 poisoning, with a stated lethal dose of <0.1 mg/kg bodyweight (Goh *et al.* 2005). In New Zealand this risk is mostly through the consumption of 1080-poisoned possum carcasses. Although research has attempted to identify a potential antidote for dogs, to date this has been unsuccessful (Goh *et al.* 2005). For livestock, trials assessing the effectiveness of deer repellent on bait to minimise the risk to sheep and cattle have indicated that the compound works effectively for sheep but not for cattle (Morriss and Nugent 2009).

Animal welfare impacts of 1080

The use of 1080 also raises animal welfare concerns, with arguments that possums and other target and non-target animals suffer unacceptable levels of pain and distress following poisoning with 1080 (Sherley 2007). Others have argued that, on the basis of possums' physiological and behavioural responses and the duration of effects, 1080 poisoning is not unduly inhumane (Twigg and Parker 2010). The behaviour of animals after 1080 intoxication has been investigated to assess its relative humaneness. To determine the welfare impacts of 1080, the behaviour of eight experimentally poisoned possums was assessed in a controlled study (Littin *et al.* 2009). Half of the animals displayed abnormal appearances and postures 1 hour 50 minutes after consuming baits, seven of the eight animals exhibited retching, and three vomited, over a 27-minute period (these symptoms starting 2 hours 53 minutes after dosing). Lack of coordination began 3 hours 37 minutes after dosing, with possums then spending most of the time until death prostrate and showing spasms and tremors; mean time to death was 11 hours 26 minutes (Littin *et al.* 2009). In comparison to other available vertebrate toxic agents (none of which are registered for aerial application), the welfare impacts of 1080 are ranked as moderate, intermediate between cyanide (mild) and anticoagulants (severe) (Fisher *et al.* 2010).

Although 1080 use does have a welfare cost, it is the only vertebrate toxin currently registered for aerial application on the main islands of New Zealand and therefore its use continues to be necessary if possums and other mammalian pests are to be managed cost-effectively over large areas. It is important that any pest control that involves killing sentient animals is carried out within a strategy that has wide social acceptance, along with well-based confidence that its objectives and benefits are necessary, measurable and achievable (Warburton and Norton 2009). Additionally, the most humane control method available that is also suitable for purpose should also be selected. The strategy and operational procedures of TBfree New Zealand are considered to meet all the necessary requirements for a robust and defendable pest management programme (Warburton and Norton 2009).

Effects of 1080 baits on water quality

Recent reviews have highlighted the issues regarding the potential toxicity of 1080 in the environment (Eason *et al.* 2011; Wright 2011), and public concerns of 1080 and water generate considerable scrutiny of aerial 1080 operations. Aerial 1080 baiting operations require regulatory approval, and water monitoring may be a condition of the approving agency e.g. post-application testing of water flowing from the application area. As a result of these requirements, our own toxicology laboratory (Landcare Research, Lincoln, New Zealand) tested 2,639 water samples between 1990 and August 2012, collected from areas after aerial applications of 1080. There was no detectable 1080 in 96.7% of these samples using gas chromatography with a lower detection limit of 0.1 ppb. Concentrations of 1080 in the remaining 3.3% (n=88) samples ranged from 0.1–9 ppb. Of the total samples taken, 887 (34%) were from water used for human or stock drinking supplies, and four of these contained detectable 1080 residues at 0.1 ppb (one sample) or 0.2 ppb (three samples). None of these, however, exceeded the New Zealand Ministry of Health's provisional maximum acceptable level for drinking water of 3.5 ppb (Anonymous 2008). Since 2008, the Environmental Protection Authority (formerly the Environmental Risk Management Authority) has released annual reports on the aerial use of 1080, which contain specific operational details and water monitoring results. The data cited above are incorporated into the overall figures reported by the Environmental Protection Authority.

Review of use of aerial 1080 control

In response to public concerns about, and opposition to, 1080 use for vertebrate pest control, the Environmental Risk Management

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[3] M Crowell, Department of Conservation Technical Advisor, NZ.

Authority carried out an extensive reassessment of 1080 in 2007, and concluded that the benefits of using 1080 outweighed the adverse effects, and that any adverse effects of using 1080 could be managed adequately, provided it was applied following standardised best practice. Some new controls were imposed on aerial application of 1080 to make it safer, including mandatory use of GPS guidance of aircraft, post-operational reporting, and several requirements related to signage and notification (Anonymous 2007). The review assessed the technical risks but Green and Rohan (2012) suggested that to address community concerns improvements in engagement with relevant parties were needed, and building dialogue and collaboration with key communities was required.

The reassessment by the Environmental Risk Management Authority provided support for ongoing use of 1080, but it did not quell continued opposition, and some members of parliament called for a moratorium on its use. As a consequence, in 2011, the Parliamentary Commissioner for the Environment carried out an extensive review of the use of 1080 in New Zealand including alternatives, and concluded "It is my view, based on careful analysis of the evidence, that not only should the use of 1080 continue (including in aerial operations) to protect our forests, but that we should use more of it" (Wright 2011).

Other research has investigated the fate of 1080 in the environment once it has been deployed in bait form, assuming it has not been consumed by a pest, and shown that 1080 can leach from baits (Suren 2006), but that it is readily degraded in soils at ground temperatures over 5°C (Northcott *et al.* 2014). Further, of the 1080 that typically leaches from baits following rain, less than 1% is subsequently found in surface water where it could feasibly pose a risk for terrestrial animals (Srinivasan *et al.* 2012).

Ground-based operations

Because of the risk posed to livestock, and especially to farm dogs, from uneaten 1080 baits and carcasses poisoned with 1080, aerial application of 1080 baits cannot be used for controlling possums over farmland, unless dogs and livestock can be removed until baits and/or possum carcasses are detoxified, with the latter taking some months. Nor can aerial application of 1080 be carried out near dwellings, residential areas or other areas with high unrestricted public access and use. Consequently, possum control in such areas mostly relies on ground-based methods including traps and poisons. Most of these control operations target possum habitat on farms ranging from isolated trees and shelter-belts, to patches of scrub, forested gully systems, plantation forests, and areas of remnant indigenous forest that might be several hundred hectares in area. In order to reduce the prevalence of TB in livestock, ground-based methods must effectively reduce the local relative possum abundance to below 2% TCI Under a performance-based contract system for delivering possum control (see below), contractors for ground-control work select tools, and develop strategies for applying them, in order to maximise the probability they will meet TCI targets. In the three years from 2011–2013, the mean TCI achieved from all recorded performance contracts were 0.65, 0.46, and 0.4% respectively, considerably better than the contracted TCI targets of 2%. Additionally, 93% of about 200 performance-based operations contracted each year achieved their targeted TCI on their first post-control monitor, with the small percentage of failed contracts requiring extra work and re-monitoring to determine if the target had been achieved (data sourced from unpublished metadata in the VectorNet database, TBfree New Zealand Ltd, Wellington, NZ). These results indicate that ground-based contractors are routinely achieving the reductions required to eliminate TB from wildlife and protect livestock.

In practice, as for the stages already described for aerial operations, there are three main stages of ground-control operations, but in this case each is linked to contract-specifications (these are described in detail in Supplementary Information 2[4]). The operational specifications for ground-based control contracts vary depending on the stage of control, and costs vary considerably. Additionally, because ground-based contracts are typically carried out on farmland, the actual area of possum habitat treated is often much less than the total area contracted. On some highly developed farmland (e.g. dairy farms) <10% of the total area might be actual possum habitat that receives control. Consequently, the cost of ground control when expressed as $/total hectare can be misleading especially when compared to the cost of aerial control, where the total area and treated habitat area are the same. The costs for the various contract options for 2011–2013 are shown in Table 1. These show that the more intensive coverage required by detection surveys during the eradication phase increases the cost compared with straightforward input contracts or output control contracts, which have similar costs, but all costs can vary from year to year. However comparing costs alone assumes equal effectiveness, while operational effectiveness (i.e. percentage kill) is not measured directly, so any cost comparisons must be done cautiously. In comparing costs between ground and aerial control it must be noted that although one-off costs might be similar, ground control is typically repeated at least every second year (and often annually), whereas aerial control is generally not repeated for at least 3–5 years. Consequently, the real annual cost of ground-based control is generally greater than for aerial control.

Initial control methods

Ground-based contractors carrying out initial control generally use a potassium cyanide based product (Feratox, Connovation Ltd, Auckland, New Zealand). This encapsulated form of potassium cyanide was developed in the 1990s (Warburton and Eason 1992; Warburton *et al.* 1996) to address increasing possum shyness to the then commonly used cyanide paste (mostly sodium cyanide). The pellets are small pea-sized balls with a core of dry cyanide powder encased in a hardened resin that prevents emission of hydrogen cyanide. Each pellet contains a lethal dose of cyanide for a possum and they are usually presented mixed in a peanut butter ball. These are placed into a small biodegradable labelled bag that is stapled to a tree or fence post to be freely accessible to possums that tear open the bag, eat the peanut butter ball and when chewing on the potassium cyanide pellet, crack the casing and release the cyanide. Some contractors vary their use of potassium cyanide by placing the ball baits in fixed bait stations. Most possums lose consciousness within 7 minutes of ingestion of a potassium cyanide pellet (Gregory *et al.* 1998) and are found dead within 1–5 m of the site. Potassium cyanide is also presented in other forms such as potato starch cubes and in cereal pre-feed mixes.

Use of Feratox enables contractors to achieve high kills over relatively large areas cost-effectively. If the control target is less than

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Table 1. Mean costs of ground control of possums for four contract options, showing costs on a per total hectare (ha) and per habitat hectare (Hab ha) basis, based on data from the VectorNet database (unpublished vector database repository, TBfree New Zealand, Wellington, New Zealand). Sample sizes in brackets

	2010–2011		2011–2012		2012–2013	
	$/Total ha[a]	$/Hab ha[b]	$/Total ha	$/Hab ha	$/Total ha	$/Hab ha
Initial reduction (output-based contract)	$18.00 (1)	$38.00	N/A	N/A	$8.00 (16)	$29.00
Maintenance (output-based contract)	$8.70 (209)	$15.90	$9.70	$18.90	$7.30 (194)	$14.10
Maintenance and recovery of carcasses (input-based contract)	$4.60 (115)	$9.40	$5.60 (150)	$10.00	$7.50 (100)	$16.00
Detection, control and recovery of carcasses (input-based contract)	N/A	N/A	$14.70 (30)	$39.70	$11.20 (50)	$29.90

N/A=data not recorded.

[a] Area enclosed within the operational boundary and includes both habitat and non-habitat.

[b] Area based on the New Zealand Land Cover Database (http://www.lcdb.scinfo.org.nz) and in some areas under-represent the actual area of habitat.

5% TCI and the areas have had several years of Feratox use, most contractors also use trapping as a backup to ensure any possums that are shy of the poison bags are subsequently removed by trapping. A variety of leg-hold traps are used, with Victor No. 1 (Pest Management Services, Christchurch, New Zealand) traps being the most commonly used type. Traps are generally set using a mixture of flour and icing sugar as a visual lure and bait.

When controlling possums in larger areas of forest, and depending on the terrain, some contractors use 1080 cereal pellets, either spread onto the ground by hand or in bait stations. Where access is difficult (e.g. steep gullies and dense patches of gorse), 1080 pellets are sometimes broadcast by hand to provide a wider bait distribution. In some accessible forest areas with easy terrain, helicopters are sometimes used to sow non-toxic pre-feed pellets in GPS located strips that are then ground poisoned using 1080 pellets, Feratox or cyanide paste distributed by hand.

Maintenance control

During the initial stages of maintenance control, contractors may continue to use potassium cyanide or use more traps. Some contractors use alternative poisons, such as cholecalciferol or brodifacoum, in various types of bait stations in areas that have had several prior years of exposure to Feratox pellets and leg-hold traps.

For areas in the pre-eradication phase, all habitats must receive control to ensure there are no patches or clusters of possums left that could enable TB to persist. To ensure total coverage and sufficient intensity of control at each site, control contracts are generally changed from performance-(output) based control to input-based control, with control coverage and intensity of control being specified in the contract.

New Zealand contracting system and monitoring

The contracting system

Since about 1996 vertebrate pest control operations, especially those carried out as part of TB management, have been implemented through a competitive contract system (Warburton and Cowan 2008). TBfree New Zealand (the predominant contracting agent) typically publicises a range of control operations for competitive tender. Although price is an important selection criterion, other criteria are used, such as competence in health and safety management, relevant experience and track record, technical skills, equipment, management skills, and proposed methodology. Performance-based contracts generally have a residual TCI target to be achieved before payment is made, such as to reduce the mean relative abundance of possums to below a TCI of 2% with no individual trap-line catching more than two possums. 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 methods to achieve the contracted target density.

In areas that have already had several years of control resulting in low possum numbers, contracts are generally input-based, partly to eliminate the need for each contract to be independently monitored. 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 to all habitat (to decrease the probability that clusters of possums are missed), and recently have included the use of detection devices to better inform where trapping effort should be applied. For data recording and auditing purposes, all contractors must use GPS capable personal digital assistants to record the location of all detection devices and traps. The GPS data can then be uploaded and checked against habitat maps. Periodic audits are carried out to determine if contractors comply with contract requirements. 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, and such data are used to support TB management decisions based on probability predictions from the proof of freedom utility (see Anderson *et al.* 2015) in cases where the objective is TB eradication.

Monitoring post-operation residual possum levels

Performance contracts require the use of TCI as a standardised and reproducible method for assessing whether their control operations have successfully reduced the possum population to the contracted target density. The standardised trap-catch methodology for TCI calculations was developed in the 1990s (Warburton 1996), based on setting a defined number of randomly allocated trap lines, each containing a series of 10 consecutive leghold traps, spaced evenly throughout the habitat for three contiguous nights of fine weather. From this, for example, two possums caught over 100 trap nights would indicate a TCI of 2%. To ensure this methodology is applied in a standardised way, a national protocol (Anonymous 2011) and training courses have been developed by the National Pest Control Agencies.

The trap-catch protocol ensures the method is applied in a standardised way, but the index itself is sensitive to seasonal, habitat or density variations in possum capture (Forsyth *et al.* 2005). The post-operation possum populations being monitored are always low (i.e., TCI usually <2%), but clustering of residual possums is a concern. To assess whether the trap-catch method is effective for detecting residual possum clusters, a modelling approach was developed in the 2000s to assess the statistical limits of the protocol. Ramsey and Ball (2004) recommended that the number of trap-nights be extended from three to six and that maximum catches per trap line should be set. Setting line maxima was adopted as routine practice, but increasing trap nights from three to six has not been incorporated into New Zealand best practice methods because of cost.

Detecting possums at very low densities

Where the aim of TB control is eradication, possum densities are very low in the latter stages of pre-eradication and in the eradication phase itself (i.e. often less than 1% TCI). Consequently most traps do not catch any possums and setting them is essentially a wasted effort. To address this problem, detection devices were developed as a low-cost/low-effort way to identify any continued presence of possums and the locations of such animals, so that subsequent trapping effort could be targeted to those areas where a device had returned a positive result. This type of informed trapping was first attempted by using clumps of flour and icing sugar (Thomson *et al.* 2002), but more recently specific devices such as WaxTags (Pest Control Research, Christchurch, New Zealand) and chewcards (Connovation Ltd, Auckland, New Zealand) have been developed and used in control programmes (Thomas *et al.* 2007; Sweetapple and Nugent 2008, 2011). Where detection devices show a positive detection, from tooth mark impressions left on the device, three or four follow-up traps are set around the device for three or four nights and all captured possums are recovered for necropsy. All detection devices and trap locations have their GPS locations recorded on personal digital assistants along with the details of activities e.g., initial trap setting, trap checking. The data recorded become part of the dataset used for generating a probability of TB freedom (Anderson *et al.* 2013).

Surveillance techniques for different wildlife species

Determining the presence or absence of TB in possum populations is crucial to measuring progress towards, and achievement of, TB management plan objectives. Detecting the presence of TB in possum populations when the prevalence is very low is expensive, and can be impracticable in areas of extensive forest. Nevertheless, surveillance for the continuing presence or absence of TB from wildlife forms the current basis of next-step TB management decisions in New Zealand, by way of predictions of likelihood of disease absence derived from the probability of freedom utility (Anderson *et al.* 2015). To support this, possum carcasses infected with TB, as well as carcasses or offal from other infected wildlife, provide sources of material from which to detect potential *M. bovis* infection; this applies for a range of mammalian wildlife scavengers which are recognised as spillover hosts of TB in New Zealand and is outlined below for each species.

Possums

Where it is economical and practical, all carcasses of possums killed during the eradication phase or during surveys undertaken in Free Area Protection zones are subject to necropsy and submission of selected lymph nodes for *M. bovis* culture (Nugent *et al.* 2015a). In farmed areas where it is relatively easy to transport carcasses, possum surveys provide an economical means of direct TB surveillance, provided the density of possums is very low (relative abundance <2% TCI). However, when possum density is high, or where access is difficult, direct surveillance of possum carcasses becomes expensive, time-consuming and logistically impractical.

Currently research is being undertaken to use information from possum surveys as a means of estimating the size of the possum population in a defined area. Knowing what proportion the possum sample is of the total population enables the sensitivity of detecting TB in the possum population to be estimated, given a defined design prevalence (Martin *et al.* 2007). Prototype methodologies have been described for identifying individual possums during population estimation, some based on DNA identification (Nugent *et al.* 2003). One prototype investigation method involves using a remote system to collect individual samples of possum DNA as the capture stage, and to then cross-reference DNA extracted from samples taken from each possum killed during the survey as the recapture stage. Another prototype investigation relies on placing GPS collars on random possums caught prior to surveying to form the capture sample, and use the number of collared possums caught during the surveillance stage as the recapture sample.

Wild pigs

Where present, wild pigs provide the most sensitive and economical means of detecting TB in the possum population in extensive, rugged and forested areas (Anderson *et al.* 2015; Nugent *et al.* 2015b). Surveillance of TB using wild pigs is usually passive through hunters supplying pig heads with predilection-site submandibular lymph nodes intact, together with the GPS location of the kill sites, for subsequent necropsy. For surveys in areas where wild pigs are uncommon, captured disease-free wild pigs can be fitted with radio and GPS collars, and then released into the area of interest as bespoke disease sentinels. All data from pig surveys are used to help provide a statistical probability as to whether TB has been successfully eradicated from the possum population (Anderson *et al.* 2015).

Ferrets

Although ferrets play a role in TB dynamics in New Zealand, they are generally not sufficiently abundant to maintain the disease intra-specifically, rather there is a need for continued infection from them scavenging tuberculous carrion (Ragg *et al.* 2000). Consequently, TBfree New Zealand does not usually control ferrets, but instead carries out ferret surveys for disease surveillance purposes. Via their scavenging actions, ferrets provide a reasonably sensitive means of detecting the local presence of tuberculous possums, providing a cost-effective form of wildlife surveillance for some farmland environments, especially where feral pigs are absent. Typically, ferrets are trapped using a variety of kill and live-capture traps (Ragg *et al.* 2007) and their carcasses are supplied for necropsy, where a selection of predilection site tissues (predominantly gastrointestinal tract lymph nodes) is pooled for bacteriological culture to detect *M. bovis*.

Wild deer

In some extensive, rugged and forested areas of New Zealand, there are few or no wild pigs and ferrets are absent. In such areas, surveys of wild deer (normally red deer, *Cervus elaphus*) are used to detect the presence of TB in possums despite the low sensitivity of detection which this offers in comparison to other wildlife sentinel species (Nugent *et al.* 2015b). In most cases, deer are shot by commercial hunters who supply carcasses to deer slaughter plants, where carcasses, head and lungs are inspected for TB. Commercial meat hunters are also required to provide the locations where all wild deer are shot. If insufficient deer are being taken in this way from an area of interest to TBfree New Zealand, contract hunters are occasionally used to provide a specified number of deer from a defined area.

Other predator/scavenger species

Other introduced wildlife species can develop TB lesions that can be detected by necropsy and confirmed by bacteriological culture for disease monitoring purposes, albeit at lesser sensitivity than pigs, ferrets and wild deer. Feral cats (*Felis catus*) can occur at similar densities to ferrets in farmland environments that have high rabbit numbers, but are considerably less sensitive for detecting TB in possums. They are normally caught as a by-catch during ferret or possum surveys and have not, to date, been considered a useful surveillance species. Stoats play a similar ecological role to ferrets except they inhabit extensive forest areas. Stoat densities, however, are generally too low to provide effective surveillance of the presence of possums infected with TB. They are normally caught as a by-catch during possum surveys, although there have been some stoat-specific surveys undertaken in areas where both ferrets and pigs were absent (Warburton *et al.* 2012).

Concluding remarks

Since the early 1970s, when possums were confirmed as wildlife vectors of TB in New Zealand, the successful management of bovine TB in New Zealand has depended on the application of aerial and ground-based lethal methods to control possum populations. These methods have improved significantly over the last three decades, both in delivering cost-effective possum control and in minimising any adverse non-target and environmental impacts. The improvements in knowledge gained from ongoing research and operational experience are captured and updated in a range of technical guidelines and standard operating procedures produced by TBfree New Zealand, as well as in the National Pest Control Agencies range of best practice manuals.

The competitive performance-based contract system implemented in the mid 1990s enabled an industry of independent contractors. To be paid, contractors had to achieve target residual TCI, and this contractual requirement drove a level of innovation in possum control methodology that now supports increasingly ambitious objectives to reduce the incidence of TB, and where appropriate, eradicate the disease from wildlife. The critical pest management developments towards this outcome include the following: aerial application of 1080 baits for controlling possums over extensive areas of rugged and remote forest, at lower bait application rates and with much reduced risk to non-target species; use of ground-based control, e.g. cyanide products, other toxins and traps, for controlling possums over extensive areas of farmland with little risk to livestock, dogs, and people; a national standardised method for monitoring relative possum abundance, enabling a performance-based contract system to be implemented; and a national database and management system (VectorNet) that supports decisions on the type and extent of future control or wildlife surveillance.

The first three of these key tools continue to be improved, by incrementally fine-tuning their use, e.g. modifying distribution and sowing rates of aerial 1080 baits), through integration of new tools such as detection devices or adoption of new poisons and means of applying them. Together this has led to improvements in the effectiveness and efficiency of possum control. Application of current research and operational findings are expected to lead to further improvements in both possum control and wildlife surveillance.

The currently available suite of tools provides for cost-effective control of possums to very low and even densities (relative abundance of <1% TCI) over the whole or major parts of each VRA, including extensive areas of forests. Possum populations are now being maintained at low densities over approximately 9 million hectares of the remaining 9.9 million hectares of VRA land (PG Livingstone, unpublished data). Possum control has achieved major reductions in prevalence of *M. bovis* infection in both livestock and wildlife, and has led to eradication of TB from possum populations in 14 VRA. This success indicates that eradication of TB from possum populations in the current TB eradication areas is a realistically achievable goal, using the tools and systems currently in place.

In 2011, TBfree New Zealand's strategy changed from one of reducing the number of *M. bovis*-infected livestock herds to eradication of TB from possum populations in at least 2.5 million hectares (Anonymous 2012a). This change in focus has driven changes in the possum-control contracting industry, particularly for ground-based contractors. These contractors were originally solely focussed on possum control. Under the new strategy, although still using traps and killing possums, contractors have become collectors of data for input into the proof of freedom utility to support next-step management decisions. Thus modern contractors have to be proficient at using GPS enabled personal digital assistants to collect data on detection devices and possum capture locations, and managing these data sets as well as recovering carcasses for necropsy.

Given the costs of control, scenario modelling has indicated that it would likely take until at least 2055 for TB to be eradicated from wildlife in New Zealand (PG Livingstone, unpublished data). Research and operational innovation through adaptive management has the potential to substantially reduce the costs, and therefore the time required to achieve eradication by: (1) looking at ways of accelerating the time to confirm TB eradication, by sampling possum populations and assessing the prevalence of *M. bovis* infection in the population, and then using this information to determine the level of population control required to eradicate infection; (2) using new technologies to identify possum locations for specific targeted control e.g. aerial infrared technology; (3) exploiting new research findings on possum feeding behaviour in the design of lower cost aerial baiting operations; (4) identifying factors necessary to consistently achieve very high possum kills, thus reducing the need for repeat control effort; (5) using sampling theory to determine the probability that TB has been eradicated from possums over large areas of extensive forest, where there are few sentinel species and where the cost of sampling possums themselves would otherwise be prohibitive (Anderson *et al.* 2015). The outcomes of these new research and adaptive management objectives should become available within the next 5–7 years, which, together with outcomes of research currently being undertaken, are expected to significantly reduce the costs and time to eradicate TB, from both wild and domestic animals in New Zealand.

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