Animal Health Board Project No. R-10677

Identifying the Optimal Frequency of Control Required to Eradicate Tb under Various RTCI Targets

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Landcare Research
Manaaki Whenua

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Summary

Project and Client

Research to determine the optimal frequency of possum control, based on residual trap-catch index (RTCI) targets, for the control of bovine tuberculosis (*Mycobacterium bovis*; Tb) in brushtail possums was undertaken using a spatially explicit, stochastic model of the dynamics of possums and Tb by Ramsey Consulting and Landcare Research for the Animal Health Board (Project R-10677), between January 2007 and August 2008.

Objectives

- Using an individual-based, spatially explicit, stochastic model of Tb in possums, identify the optimal control and monitoring frequency required to eradicate Tb from possums using RTCI targets.
- Using data from actual control histories as case studies, attempt to validate the model predictions.

Methods

The spatial model of Ramsey & Efford (2005) was used to determine the optimal frequency of control required (either aerial or ground) to eradicate Tb from possum populations. Optimisation took the form of cost/time minimisation: a search for the minimal overall cost of applying a certain control type to achieve a certain benefit (Tb eradication), in the minimal amount of time. The main method for varying control costs occurred by altering the frequency of control. Four control frequencies were simulated (1-, 2-, 3- and 5-year interval(s) between repeat controls) and predictions compared with a scenario where control was only implemented when an annual monitor indicated that the population was above the RTCI target (annual trend monitor trigger). For all simulations, the widely used threshold of 2% RTCI was set as the control target and all simulations occurred over a 10-year time horizon.

Simulation modelling covered a variety of conditions believed to possibly affect the outcome of control. The most important of these was including the effects of immigration from uncontrolled habitat by varying the size of the control area in relation to the size of neighbouring uncontrolled habitat. To facilitate this, simulation was undertaken on four artificial scenarios as well as three current operational areas from the Southland Region to mimic actual operational conditions.

For model validation, we assembled data on the control and monitoring histories from six operations within the Southland Region and compared data on actual pre- and post-control RTCI values and model predictions for the same periods. To undertake this, the model was modified so that the observed sequence of discrete control events and associated RTCI monitoring could be replicated. The model predictions of pre- and post-control RTCI were then compared qualitatively with the observed pre- and post-control RTCIs.

Results and Conclusions

For all the artificial scenarios, annual control was the fastest to achieve a 95% probability of Tb eradication but was also the most expensive. Conversely, undertaking control every

5 years was always least expensive but took the longest to achieve a 95% probability of Tb eradication. In addition, control at 3- or 5-year intervals did not always eradicate Tb within 10 years.

The total cost of achieving Tb eradication, the time taken to achieve it, and the probability of Tb escaping the control area were combined into a single index, the Cost-Effectiveness Index (*CEI*). Control frequencies that minimised *CEI* were considered to be optimal, in that they minimised the expenditure of the competing resources of cost and time and the risk of Tb spread. Calculation of this index indicated that 5-yearly intervals between controls had a much higher *CEI* than other control frequencies and, hence, was always suboptimal. Annual control, while minimising the risk of Tb spread, was not always the optimal strategy due to its high cost. Calculation of the *CEI* indicated that the optimal frequency of aerial control was once every 3 years, while for ground control the annual trend monitor trigger was the optimal strategy.

Results of the model validation showed that the 95% intervals for the mean RTCIs predicted by the model covered 56% of the observed pre-control values, while 67% of the observed post-control values were similarly covered by the prediction intervals from the model. In general the mean of the predicted RTCI values tended to be lower than the observed values, with an average discrepancy between predicted and observed values of −18% and −52% for pre- and post-control RTCI values respectively. However, the size of the discrepancy varied between operations.

Recommendations

- Undertaking possum control every year, regardless of the pre-control RTCI, is unnecessary to eradicate Tb from possums and so wastes resources that could be used elsewhere.
- Using a threshold of 2% RTCI, the models predicts that optimal frequency of aerial possum control for the eradication of Tb in possums within a single region is once every 3 years. This is predicted to minimise use of the competing resources of cost and time to achieve eradication. However, if the total funding available across all regions within a VRA (or nationally) is less than that required for triennial control, aerial control at five yearly intervals is the model favoured of the scenarios modelled because it has the lowest total funding requirement.
- Annual or biennial aerial control should only be considered if there is a high risk of Tb escaping and establishing outside the control area or when circumstances require an urgent response. For ground control, undertaking annual monitoring to decide when to apply control was the most cost-effective strategy.
- If ground control is to be used on small (1000–-3000 ha) control areas that are at risk of high immigration from surrounding habitat, then the optimal frequency of ground control is annual.
- These predictions are based on the assumption that possum control is applied evenly to the control area. To emulate even application of possum control, the use of line maxima should continue to be used as a key indicator of control performance.
- Further work needs to be undertaken on validating the spatial possum/Tb model in order to determine how well the model can predict short-term recovery rates (indexed by RTCI) following possum control.

1. Introduction

Research to determine the optimal frequency of possum control, based on residual trap-catch index (RTCI) targets, for the control of bovine tuberculosis (*Mycobacterium bovis*; Tb) in brushtail possums was undertaken using a spatially explicit, stochastic model of the dynamics of possums and Tb by Ramsey Consulting and Landcare Research for the Animal Health Board (Project R-10677), between January 2007 and August 2008.

2. Background

Frequently repeated control of farmland possum populations is seen as the best way of reducing the risk of Tb-infected possums transmitting the disease to livestock. Many areas are therefore routinely controlled every year, even when the post-control RTCIs in the previous year were well under the target. However, historical expansion of vector risk areas has increased the area needing management to more than can be controlled annually with the funding available for Tb management.

Recent modelling investigations (Ramsey & Efford 2005) have shown that Tb can be eradicated from possums within 5–10 years without control needing to be repeated each year, even allowing for errors in the Residual Trap Catch Index (RTCI) of possum abundance. Furthermore, increased control efficiencies, especially with the use of aerial control, have strengthened the proposition that annual control is no longer necessary to keep possum populations below the nominal RTCI threshold, usually 2%. Frequently repeated control is expensive and may not be the optimal use of resources to achieve Tb eradication. The aim of this research was, therefore, to determine the optimal frequency of control and monitoring required to eradicate Tb using RTCI targets, based on predictions from the spatial model of Ramsey & Efford (2005). We also used data from various operations within the Southland Region that had detailed control and monitoring histories, to compare the ‘goodness of fit’ between data from actual control operations and model predictions for those same operations, in an attempt to validate the control and RTCI monitoring modules of the model.

By determining the optimal frequency of possum control, we will be able to assess the size of the opportunity cost (if any) incurred by undertaking control of possums more frequently than necessary to achieve Tb eradication. This knowledge will enable prediction of the lowest cost approach required for local, regional, and national eradication of Tb, or, equally, for other strategies for Tb management that are being developed for the upcoming (2009) review of the National Pest Management Strategy for Tb.

3. Objectives

- Using an individual-based, spatially-explicit, stochastic model of Tb in possums, identify the optimal control and monitoring frequency required to eradicate Tb from possums using RTCI targets.
- Using data from actual control histories as case studies, attempt to validate the model predictions.

4. Methods

An existing spatially explicit, stochastic model of the dynamics of bovine tuberculosis (Tb) in possums (Ramsey & Efford 2005) was modified for this research. A brief overview of the model follows.

4.1 Ramsey & Efford model

The model simulates individual possums on a continuous-time basis, and includes their spatial location in the model ‘landscape’. Births and deaths are modelled using established parameters for these processes and the model contains a birth pulse typical of possum populations in New Zealand. Disease transmission occurs at a local scale and is based on the probability of contact between infected and susceptible individuals, determined by the distance between home range centres. Because the model is spatially explicit it has the potential to generate disease dynamics that are difficult or impossible to replicate using non-spatial models. A typical pattern of spatially explicit disease models is foci of infection, or ‘hot spots’.

The model also includes a module that simulates the RTCI monitoring process. This module is also spatially explicit and simulates the random placement of monitoring lines on the model landscape using rules that follow the established monitoring protocol (NPCA 2004) (i.e. 10 trap lines, 200 m apart, placed in habitat and trapped for 3 nights). The possum population is ‘sampled’ by the monitoring lines using the algorithm in Ramsey et al. (2005). This algorithm incorporates variation in the probability of capture, resulting in simulated RTCI estimates that incorporate sampling and process error.

Finally, the model allows the possum population to be ‘controlled’ by simulating discrete control operations that are designed to reduce the population to a specified RTCI. The efficacy of control differs according to whether the control operation is designated ‘aerial’ or ‘ground’ and varies stochastically so that occasional control ‘failures’ are incorporated into the results. Control costs can be incorporated with future control costs discounted to net present value.

4.2 Model modifications

For this project, we modified the model as follows.

We first incorporated recent information on the efficacy and costs ($/ha) of both aerial and ground-based possum control. Control efficacy (% reduction in the possum population achieved by control) was treated as a random variable, using a beta distribution (Evans et al. 2000), with parameters governed by the variation in control efficacy identified in the operational data. Each of the individual control operations simulated was required to deliver an RTCI of 2% or less. We then calculated, separately for aerial and ground control, the optimal frequency of possum control required to achieve Tb eradication. This optimisation involved identifying the control frequency that resulted in the lowest total cost of achieving Tb eradication in the minimum amount of time. Throughout this report, 'Tb eradication' is defined as the 95% probability that Tb was eradicated. This metric is similar to the notion of 'quasi-extinction' used in threatened species risk assessment, which is usually defined as the probability that a population declines below a predetermined threshold (Ginzburg et al. 1982).

Factors other than the frequency of control will affect Tb outcomes, with the most important being the rate of immigration by Tb-infected and uninfected possums from uncontrolled habitat neighbouring the control area. The importance of this depends on the relative sizes of the controlled and uncontrolled areas and whether or not they are separated by buffers in which control is undertaken. We simulated four scenarios chosen to span the large range of possible combination of these variables:

- Scenario A: A 1000-ha control area with no neighbouring uncontrolled habitat, similar to the scenarios undertaken in Ramsey & Efford (2005)
- Scenario B: A 1000-ha control area surrounded by extensive uncontrolled possum habitat and, hence, subject to high immigration pressure (Fig. 1b)
- Scenario C: A 10 000-ha control area surrounded by a strip of uncontrolled possum habitat (Fig. 1c)
- Scenario D: A 10 000-ha control area surrounded by a strip of uncontrolled habitat but assuming that Tb possums were initially no closer than 1 km from the control boundary (Fig. 1d)

The total area simulated under each scenario was 15 000 ha, and carrying capacity (K) for all scenarios was assumed to be a uniform 5 possums/ha with the transmission rate set to give a Tb prevalence of 5% at equilibrium. Tb possums initially occurred only within the control area.

In addition to these 'artificial' scenarios, three real-world scenarios were also simulated using actual operational areas from within the Southland Region (Fig. 2). Operational boundary shapefiles were obtained from Environment Southland and combined with habitat maps derived from land cover classes from the NZ Land Cover Database version 2 (LCDB2). Using GIS software, polygon outlines of each operational boundary were placed over the LCDB2 layer and used as a 'cookie-cutter' to extract land-cover types within each boundary, as well as an additional 5-km buffer area surrounding each boundary. These extracted layers were imported into the spatial model and used to define the model landscape in terms of available possum habitat. The LCDB2 cover types were each assigned a value for possum carrying capacity (K), based on estimates of uncontrolled possum density for similar habitat compiled by Efford (2000) (see Appendix 2 for the type conversions used). Possums were able to disperse in and out of the control area from the 5-km buffer area outside the operational areas that was assumed not to be subject to possum control. This process allowed us to simulate the likely dynamics of more realistic populations.

As in the artificial scenarios, we stipulated that Tb-infected possums initially occurred only within the control area. This was done to determine whether the stipulated control frequency could not only eradicate Tb from the control area, but also prevent emigration and establishment of Tb-infected possums in the neighbouring uncontrolled habitat.

Four control frequencies were simulated (1-, 2-, 3-, or 5-yearly interval(s) between repeat control) and predictions compared with a scenario where control was only implemented when an annual monitor indicated that the population was above a 2% RTCI target (annual trend monitor trigger). All simulations occurred over a 10-year time horizon. Costs included the total of control and monitoring costs and all future costs were discounted to net present value (NPV) using a discount rate of 10%. The base costs for aerial and ground control were the same as those used for the artificial scenarios. For each scenario, 500 simulations were undertaken with the probability of eradication each year calculated as the proportion of the 500 simulations where Tb became extinct in that year. Logistic linear regressions were fitted to these probabilities, with time since start of control and NPV cost fitted as independent variables. By inverting the regression, the time and the total NPV cost to achieve a 95% probability of Tb eradication could be predicted (Collett 1991).

We compared the predicted possum population outcomes for six operational areas in the Southland Region against actual monitoring data for those areas. Southland is the only region where this was feasible as it is the only region that routinely collects sufficient pre-control RTCI data needed for complete comparisons of pre- and associated post-control data. For each of the six operational areas from the Southland Region given in Fig. 2 we obtained data from 2001 to 2008 on the history of possum control, including the type of control (aerial/ground), the RTCI values (pre- and post-control), the standard error of the RTCI estimate, and the number of monitoring lines used. Not all populations were monitored every year.

Using possum habitat derived from the LCDB2 classes, the model was modified so that the observed sequence of discrete control events and associated RTCI surveys could be simulated for each operational area. The predicted pre- and post-control RTCIs were then compared qualitatively with the observed post-control and/or trend monitor RTCIs by comparing the coverage of the 95% prediction intervals around the mean RTCIs from the model with the observed values. We also calculated absolute differences between the predicted mean RTCI values and the observed values to determine whether there were any systematic biases. Although more quantitative metrics could have been used for validation, in most cases the interpretation of these is not obvious so we opted for the more intuitive qualitative comparisons.

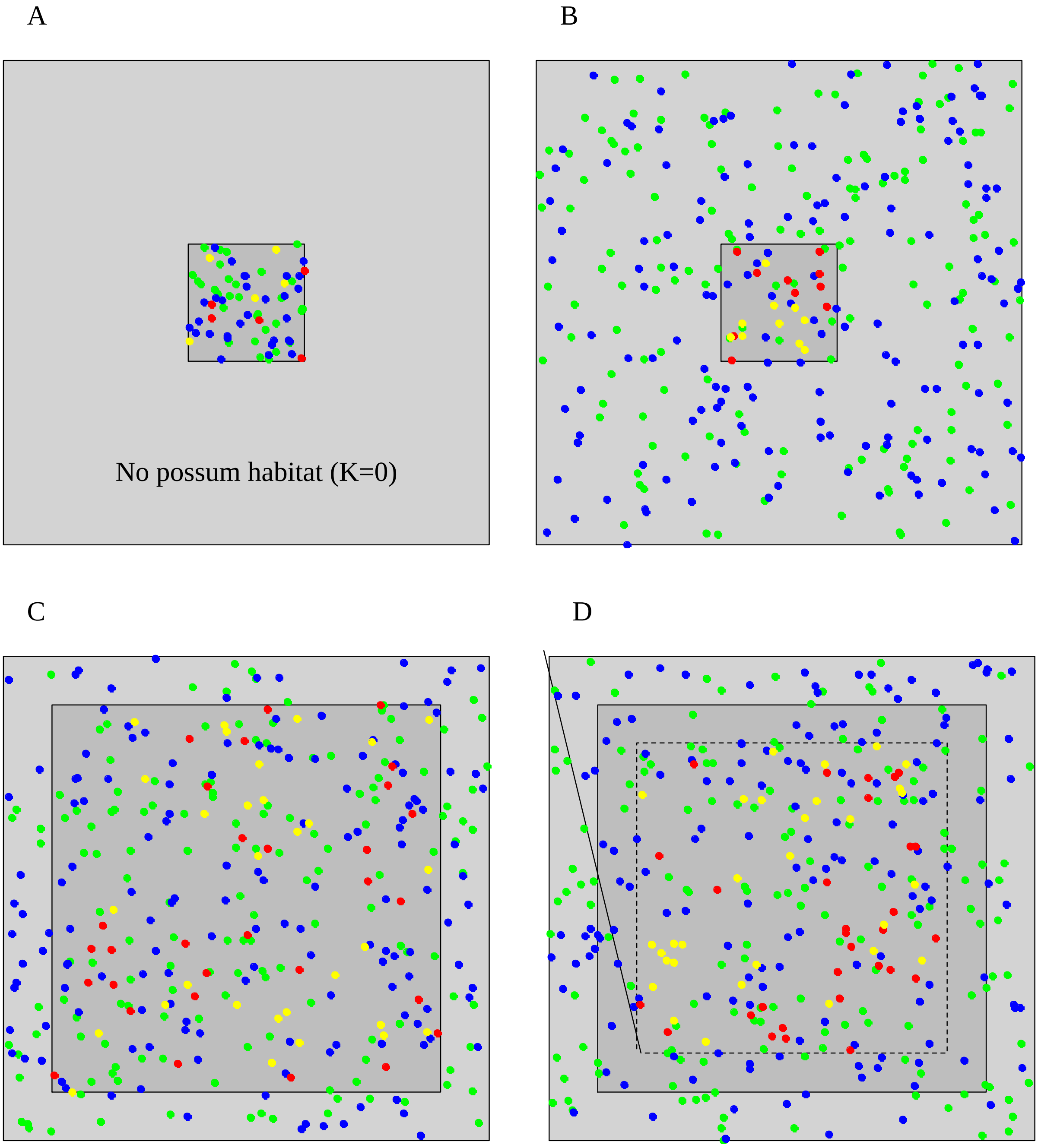

Fig. 1. Size of the artificial control areas used in the optimal possum control simulations. Light grey area = total simulation area; dark grey area = control area. (a) 1000 ha with no surrounding habitat; (b) 1000 ha with surrounding habitat; (c) 10 000 ha with surrounding habitat; and (d) 10 000 ha with surrounding habitat and a 1-km buffer between Tb-infected possums and the control boundary. Total area simulated was 15 000 ha. Blue and green dots represent susceptible possums, red and yellow dots represent Tb-infected possums. Uncontrolled density was 5 possums/ha and starting Tb prevalence was 5%.

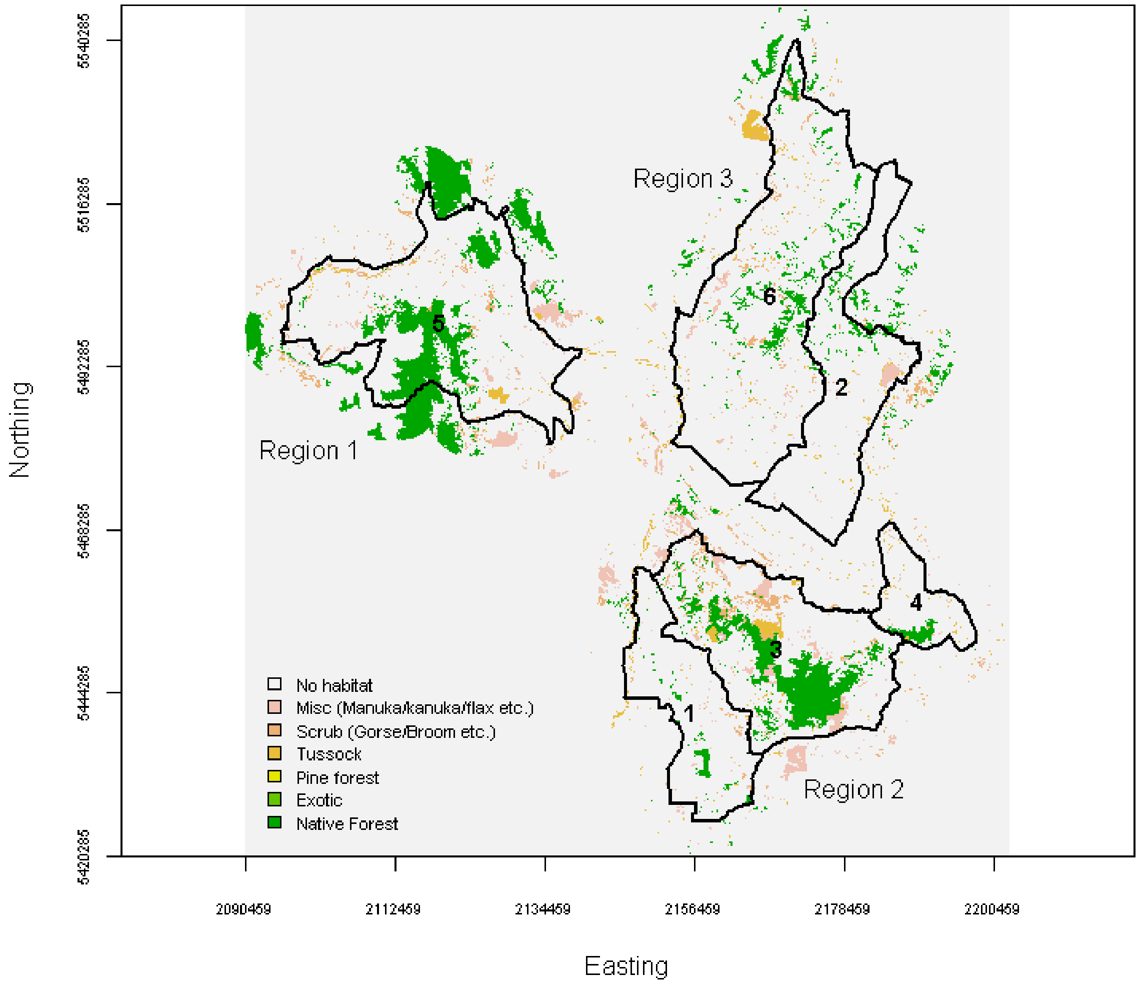

Fig. 2. Operational area boundaries from the Southland Region overlaid on possum habitat maps derived from LCDB2 cover classes. Possum habitat types were converted to values for possum carrying capacity (Appendix 2) and habitat as shown extended to include a 5-km buffer outside the outermost operational boundaries for each region. Simulations of the optimal control frequency, were done on a regional basis while individual operational areas were used for the model validation simulations. Operations included: 1 – Brown’s, 2 – Waipounamu, 3 – Hokonui #2, 4 – Hokonui #4, 5 – North Takitimu, 6 – North Southland.

5. Results

5.1 Efficacy and costs of aerial and ground-based possum control

Data from 84 operations conducted between 1997 and 2006 and with both pre- and post-control RTCI were obtained (69 in Southland, and the remainder in Hawke's Bay, Waikato, Tasman, and Canterbury). Those with pre-control RTCI values greater than 15% were classed as 'high' (initial) operations, with the remainder classified as 'low' (maintenance).

The efficacy of control (proportion killed) for each of the 84 operations was calculated as (eqn 1):

$$1 - \frac{RTC_{post}}{RTC_{pre}}.$$

The mean efficacy of control, for high and low initial population densities, is summarised in Table 1.

Table 1 Control efficacy (mean and standard deviation (SD) of % reduction in RTCI) from 84 AHB possum control operations carried out between 1997 and 2006 for aerial and ground-based control operations on populations initially at high (≥15% RTCI) or low (<15% RTCI) population densities.

Control	Population	Efficacy (%)	SD	*Nn*
Aerial	H	96	3.4	3
	L	95	5.7	11
Ground	H	85	8.2	14
	L	77	17.9	56

The cost of aerial and ground-based possum control were able to be obtained for 12 of the 84 operations. Due to the low number of operations, no attempt was made to summarise these operations based on initial population size. All pre-2006 costs were inflation-adjusted using the annual consumer price index (CPI) to 2006 dollars to facilitate comparisons (Table 2).

Table 2 Per-hectare cost ($) of aerial and ground-based possum control operations carried out between 2001 and 2006.

Control	Cost ($/ha 2006)	*N*
Aerial	$23.1	9
Ground	$31.8	3

5.2 Optimal frequency of possum control

Artificial scenarios

Annual control was the fastest to achieve Tb eradication but was also the most expensive (Tables 3 & 4). Conversely, undertaking control every 5 years was always least expensive but took the longest to achieve Tb eradication. In addition, control at 3- or 5-year intervals did not always eradicate Tb within 10 years, notably in Scenario C, the 10 000-ha control area.

The total NPV cost of control to achieve Tb eradication differed widely among the scenarios. Eradication could be achieved cheaply and quickly (within 5 years) where there was no neighbouring uncontrolled habitat, but where the control area was surrounded by uncontrolled habitat, eradication costs and times often doubled. Larger control areas were more costly to eradicate on a per-hectare basis than smaller areas, largely due to the greater chance of immigration into the control area by Tb-infected possums that had established in the uncontrolled habitat area. However, adding a 1-km buffer around the area initially containing Tb possums (Scenario D) vastly reduced the NPV cost of control and the time to Tb eradication (Tables 3 & 4), suggesting most of the Tb establishing in the uncontrolled habitat came from Tb-infected possums initially located within 1 km of the control boundary.

Under Scenarios B, C and D, Tb sometimes escaped the control area and established in the surrounding uncontrolled habitat within 10 years (Tables 5 & 6). The probability of this occurring was highest (54%) for Scenario C, under 5-yearly ground control (Table 6). Of the various fixed control intervals, the probability was always lowest for annual control for all three scenarios, indicating that annual control is the best option for Tb containment.

Imposing control both within and over 1 km around the area in which Tb-infected possums were initially contained (Scenario D) greatly reduced the probability of Tb escaping, especially with annual control, but there was still a small chance of escape. These results suggest that buffers wider than 1 km are needed to contain Tb within the area already infected.

Table 3 Accumulated cost (cost $/ha) and the number of years taken (years) to achieve a 95% probability of Tb eradication using aerial control for each of the artificial scenarios, for possum control at intervals of 1, 2, 3 and 5 years or when annual trend monitoring produced an RTCI greater than the 2% trigger level (M). Initial control was applied in year 1. Costs are discounted to 2006 values using a discount rate of 10%. Base costs for aerial control were $23/ha and $300/line for monitoring. Values are the average of 500 simulated outcomes.

	1,000 ha		1,000 ha		10 ,000 ha		10 ,000 ha	
	Scenario A		Scenario B		Scenario C		Scenario D	
Interval between control (yrs)	Cost ($/ha)	Years	Cost ($/ha)	Years	Cost ($/ha)	Years	Cost ($/ha)	Years
1	54.9	2	104.3	4	154.1	8	53.7	2
2	52.1	3	79.9	5	95.7	9	53.2	4
3	50.3	4	57.8	6	66.1	9	51.2	5
5	32.9	5	55.4	8	60.4	12	49.2	7
M	38.9	5	101.9	4	108.8	9	56.8	4

Table 4 Accumulated cost (costs $/ha) and the number of years taken (years) to achieve a 95% probability of Tb eradication using ground control for each of the artificial scenarios, for possum control at intervals of 1, 2, 3 and 5 years or when annual trend monitoring produced an RTCI greater than the 2% trigger level (M). Initial control was applied in year 1. Costs are discounted to 2006 values using a discount rate of 10%. Base costs for ground control were $32/ha and $300/line for monitoring. Values are the average of 500 simulated outcomes.

	1,000 ha		1,000 ha		10 ,000 ha		10 ,000 ha	
	Scenario A		Scenario B		Scenario C		Scenario D	
Interval between control (yrs)	Cost ($/ha)	Years	Cost ($/ha)	Years	Cost ($/ha)	Years	Cost ($/ha)	Years
1	133.4	3	219.3	5	260.7	9	156.7	4
2	103.5	4	159.8	5	172.1	10	129.4	6
3	101.2	5	124.5	6	151.5	10	105.1	6
5	98.2	6	121.0	8	127.1	11	105.2	7
M	86.4	5	212.8	5	206.7	9	130.6	5

Table 5 Probability of Tb escaping and establishing outside the control area by the end of the 10-year control horizon using aerial control for each of the artificial scenarios. Values are the mean of 500 simulated outcomes.

FrequencyInterval between control (yrs)	1,000 ha	1,000 ha	10 ,000 ha	10 ,000 ha
	Scenario A	Scenario B	Scenario C	Scenario D
1	—	0.22	0.23	0.01
2	—	0.22	0.27	0.03
3	—	0.25	0.31	0.03
5	—	0.26	0.38	0.03
M	—	0.17	0.28	0.02

Table 6 Probability of Tb escaping and establishing outside the control area by the end of the 10-year control horizon using ground control for each of the artificial scenarios. Values are the mean of 500 simulated outcomes.

FrequencyInterval between control (yrs)	1,000 ha	1,000 ha	10 ,000 ha	10 ,000 ha
	Scenario A	Scenario B	Scenario C	Scenario D
1	—	0.23	0.37	0.04
2	—	0.29	0.43	0.06
3	—	0.31	0.49	0.09
5	—	0.34	0.54	0.10
M	—	0.26	0.39	0.05

Southland regions

Model predictions of the time taken to eradicate Tb for all three Southland regions varied between 3-12 years (Tables 7 & 8). As for the artificial scenarios, costs halved as the frequency of control increased from annual to 5-yearly but this increased the time to eradication substantially. Overall the least expensive control frequency was the annual trend monitor trigger (M) but it was also among the longest to achieve Tb eradication. Costs were lowest for Region 3, but eradication times were lowest for Region 2. Region 1 was the most expensive and slowest to achieve eradication.

Collectively for these three regions, the model indicated that annual aerial control could be reasonably expected to have eradicated Tb within 3–5 years for a total discounted cost of between $71-$104 per hectare (Table 7). For annual ground control, Tb could be expected to be eradicated within 5–8 years for a total discounted cost of $151-$227 per hectare (Table 8). Under aerial control, there was a low chance of Tb spreading beyond the control boundaries (13–20% for Region 1, Table 9). However, under ground control, there would be a reasonably high chance that Tb would have spread beyond the control boundaries within 10 years (43–62% chance of spread for Region 1, Table 10).

Table 7 Accumulated cost ($/ha) and the number of years taken (Years) to achieve a 95% probability of Tb eradication using aerial control for each of the three Southland operational regions in Fig 2. Initial control was applied in year 1. Costs are discounted to 2006 values using a discount rate of 10%. Base costs for aerial control were $23/ha and $300/line for monitoring. Values are the mean of 500 simulated outcomes.

	Region 1		Region 2		Region 3	
Interval between control (yrs)	Cost ($/ha)	Years	Cost ($/ha)	Years	Cost ($/ha)	Years
1	104.2	5	70.6	3	84.5	4
2	66.7	6	66.6	5	61.4	5
3	61.6	7	48.2	6	44.1	6
5	45.6	9	45.4	8	41.2	8
M	51.5	8	35.5	9	32.9	8

Table 8 Accumulated cost ($/ha) and the number of years taken (Years) to achieve a 95% probability of Tb eradication using ground control for each of the three Southland operational regions in Fig. 2. Initial control was applied in year 1. Costs are discounted to 2006 values using a discount rate of 10%. Base costs for ground control were $32/ha and $300/line for monitoring. Values are the mean of 500 simulated outcomes.

	Region 1		Region 2		Region 3	
Interval between control (yrs)	Cost ($/ha)	Years	Cost ($/ha)	Years	Cost ($/ha)	Years
1	226.6	8	174.0	5	150.6	5
2	149.4	10	139.3	7	115.0	8
3	127.5	10	112.7	8	90.2	9
5	103.1	12	91.3	9	69.8	10
M	110.2	9	87.0	9	69.6	9

Table 9 Probability of Tb escaping and establishing outside the control area by the end of the 10-year control horizon using aerial control for each of the Southland operational regions.

Interval between control (yrs)	Region 1	Region 2	Region 3
1	0.13	0.00	0.03
2	0.14	0.00	0.05
3	0.19	0.00	0.05
5	0.20	0.01	0.07
M	0.20	0.01	0.04

Table 10 Probability of Tb escaping and establishing outside the control area by the end of the 10-year control horizon using ground control for each of the Southland operational regions.

Interval between control (yrs)	Region 1	Region 2	Region 3
1	0.43	0.00	0.09
2	0.52	0.02	0.11
3	0.54	0.01	0.15
5	0.62	0.07	0.27
M	0.47	0.02	0.15

5.3 Model validation

The observed and predicted pre- and post-control RTCIs for each operation were generally well aligned (Figs 3–8) with the 95% confidence intervals predicted by the model covering 56% of the observed pre-control values, and 67% of the observed post-control values. The mean of the predicted RTCI values tended to be lower than the observed values, with an average discrepancy between predicted and observed values of −18% and −52% for pre- and post-control RTCI values respectively. However, the size of the discrepancy tended to vary between operations. Coverage was worst for Hokonui #2 and Hokonui #4 (Figs 5 & 6) and discrepancy was worst for North Southland (Fig. 7).

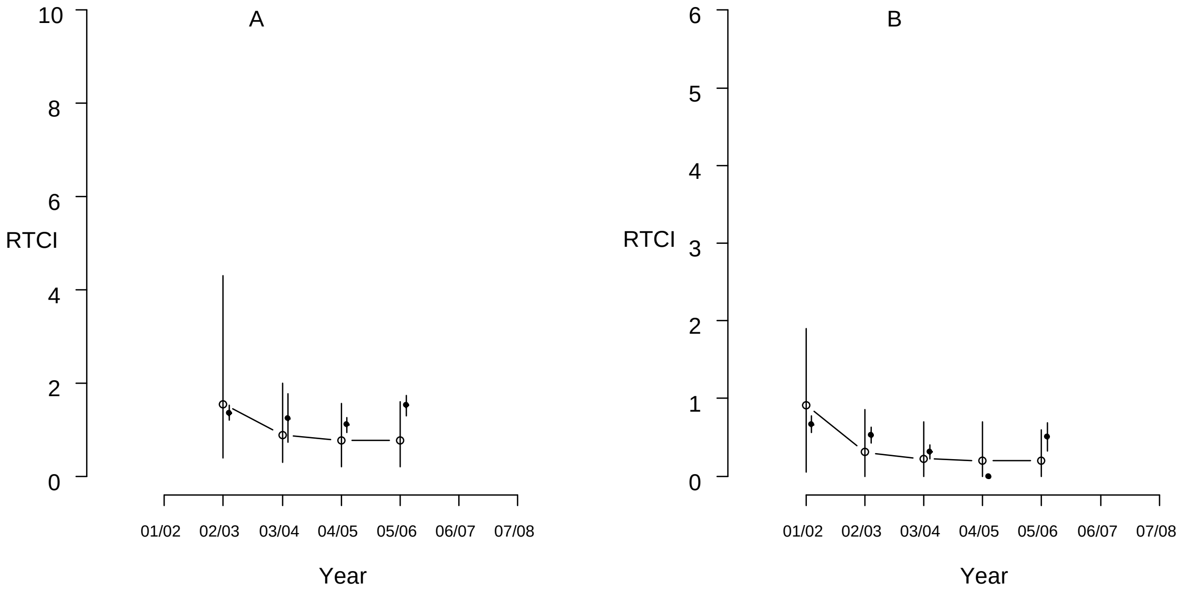

Fig. 3. Predicted vs observed values from (A) pre and (B) post-control RTCI monitoring from North Takitimu, Southland, between 2001/02 and 2007/08. Open circles = model predictions (± 95% prediction intervals); closed circles = observed data (± SE).

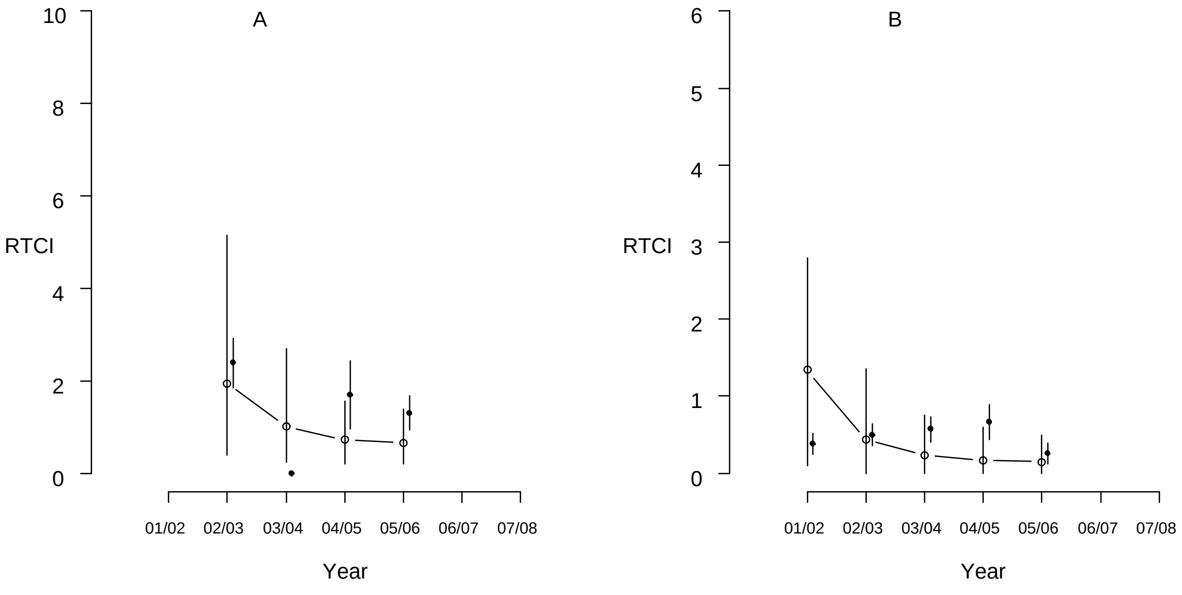

Fig. 4. Predicted vs observed values from (A) pre- and (B) post-control RTCI monitoring from Brown’s, Southland, between 2001/02 and 2007/08. Open circles = model predictions (± 95% prediction intervals); closed circles = observed data (± SE).

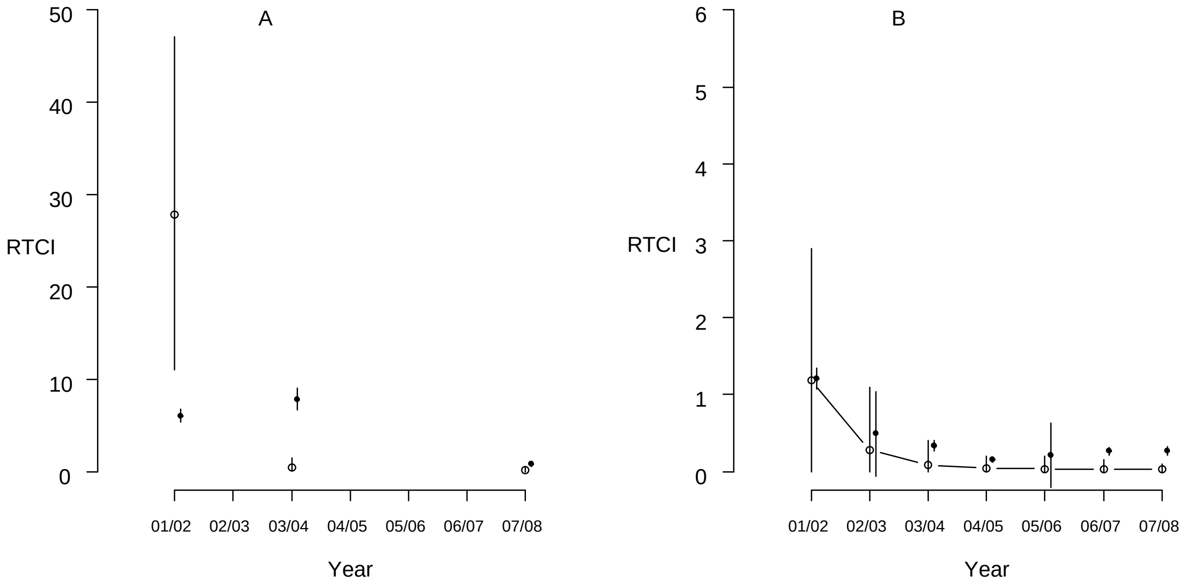

Fig. 5. Predicted vs observed values from (A) pre- and (B) post-control RTCI monitoring from Hokonui #2, Southland, between 2001/02 and 2007/08. Open circles = model predictions (± 95% prediction intervals); closed circles = observed data (± SE).

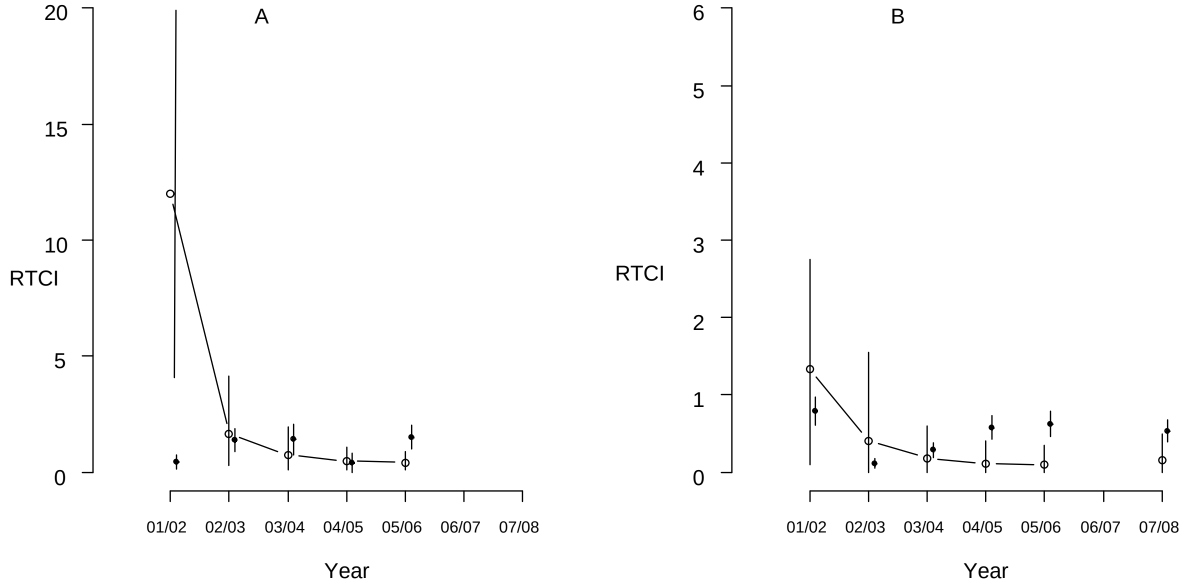

Fig. 6. Predicted vs observed values from (A) pre- and (B) post-control RTCI monitoring from Hokonui #4, Southland, between 2001/02 and 2007/08. Open circles = model predictions (± 95% prediction intervals); closed circles = observed data (± SE).

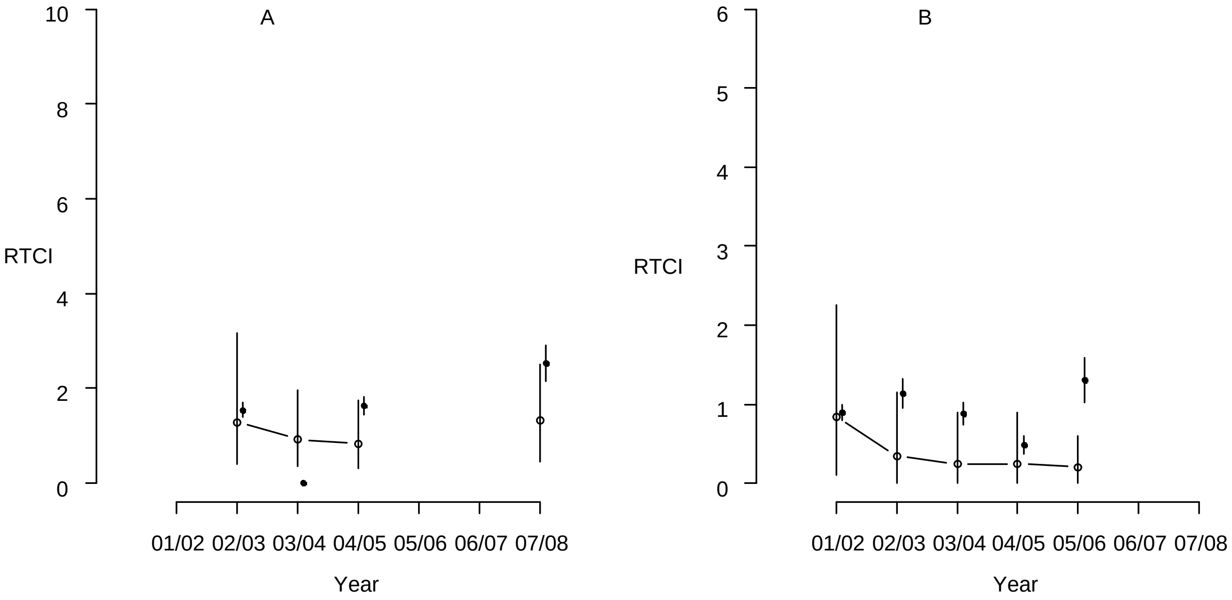

Fig. 7. Predicted vs observed values from (A) pre- and (B) post-control RTCI monitoring from North Southland between 2001/02 and 2007/08. Open circles = model predictions (± 95% prediction intervals); closed circles = observed data (± SE).

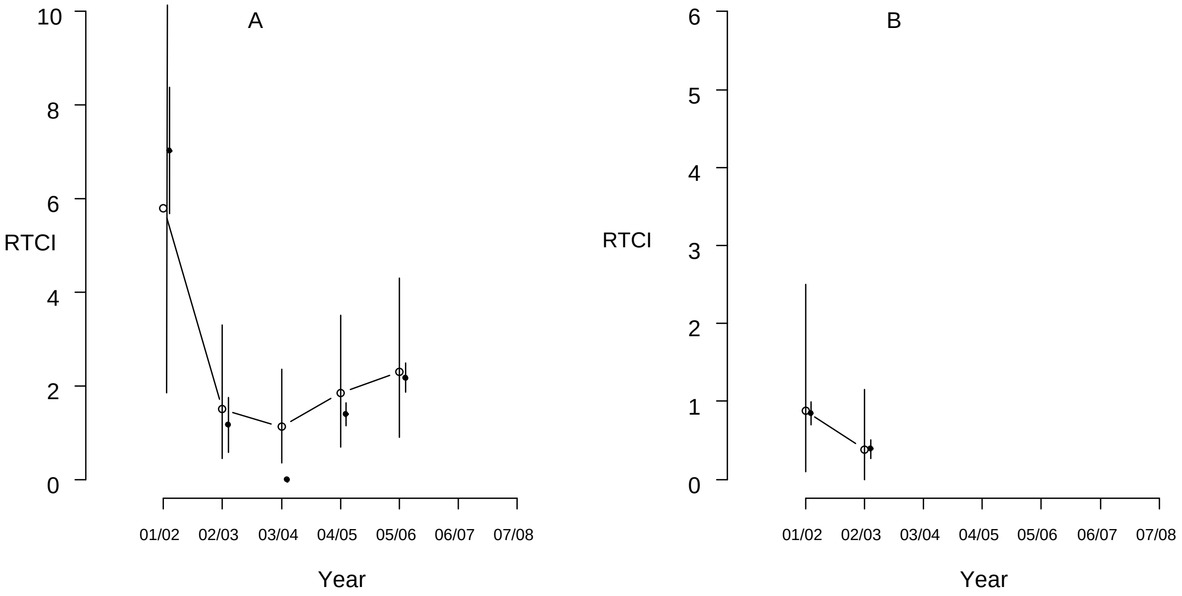

Fig. 8. Predicted vs observed values from (A) pre- and (B) post-control RTCI monitoring from Waipounamu, Southland, between 2001/02 and 2007/08. Open circles = model predictions (± 95% prediction intervals); closed circles = observed data (± SE).

6. Conclusions

Data from AHB operations conducted between 1997 and 2006 indicated aerial control reduced RTCIs by an average of 95% regardless of whether the pre-control density was high (>15% RTCI) or low (<15% RTCI). These estimates are higher than the average kill of 87% in 48 operations conducted between 1994 and 1999 (Veltman & Pinder 2001) and higher than the efficacy of aerial control given in Ramsey & Efford (2005) using data from Department of Conservation aerial operations occurring between 1996 and 2004, suggesting that the efficacy of aerial control has improved slightly. In contrast, the equivalent estimates for ground control of 85% and 77% efficacy for high and low population abundance were similar to those in Ramsey & Efford (2005). Costs ($/ha in 2006) for aerial and ground-based possum control were also similar to those in Ramsey & Efford (2005).

6.1 Optimal frequency of control

Our simulations covered both artificial and real landscapes that we consider represent a range of possibilities likely to span real-world situations. We essentially varied the suitability of neighbouring uncontrolled habitat to act as a sink for Tb possums dispersing from the control area as well as the likelihood of the same habitat acting as a future source of Tb dispersing back into the control area. This differs from the scenarios simulated in Ramsey & Efford (2005), which all assumed there was no neighbouring uncontrolled habitat.

All our artificial scenarios assumed that the neighbouring habitat was similar to that in the control area, but we varied the size of that area relative to that of the control area. In contrast, the Southland landscapes comprised a mix of habitats of varying (assumed) possum carrying capacity that each varied in size and proximity to the control boundary. Region 1 contained the highest amount of neighbouring habitat that was highly suitable for possums (i.e. native forest type) and, hence, also had the highest risk of Tb establishment beyond the control boundary. Although we assumed that the 5-km habitat buffer adjacent to all the Southland region boundaries was uncontrolled, this is rarely the case in reality. However, leaving all the neighbouring habitat uncontrolled increased the variation in model predictions and, therefore, covered conservative or worst-case outcomes.

If the assumptions in the model are correct, the simulations collectively predict that control undertaken every year or every 2 years, using a 2% RTCI threshold, should reliably eradicate Tb within the control region, within 10 years, regardless of whether aerial or ground control was undertaken and regardless of the nature and size of neighbouring habitat. While undertaking control using longer intervals was always less expensive, the predicted mean time to eradicate Tb sometimes exceeded 10 years (but never 12 years). Hence, in order to capture both the cost and time aspects of Tb eradication, we constructed an index of cost-effectiveness as:

$$CEI = NPV \times t^{(1+pe)}$$

where *CEI* is the Cost-Effectiveness Index, *NPV* is the accumulated discounted total cost (2006 $/ha) of achieving eradication, *t* is the time taken to achieve eradication, and *pe* is the probability that Tb has escaped the control area. The *CEI* penalises the accumulated cost of achieving eradication by the time taken to achieve it, with the time to eradication increasing geometrically as a function of the probability of Tb escape. The formulation of the CEI index, although *ad hoc*, attempts to penalise *NPV* by the opportunity costs related to the time spent on eradication (*t*) as well as future control costs that will become necessary due to Tb escape and spread (*pe*). It should be noted that other ways of representing these costs would lead to different outcomes than those reported here. Control frequencies with the lowest values of *CEI* represent the most cost effective strategies.

Averaging *CEI* over all the simulated aerial control strategies indicated that a 3-year interval between controls was the optimal compromise that minimised the expenditure of the competing resources of cost, time, and the risk of Tb escape (Fig. 9). However, annual control and the annual trend monitor trigger (M) were almost as cost- effective. For ground control, the annual trend monitor trigger had a lower *CEI* than the other control frequencies with next most cost effective strategy being annual control (Fig.10). For both aerial and ground control, 5-yearly intervals between control was the least cost -effective strategy due to the generally long times to achieve eradication and the associated high probability of Tb escape (Figs 9 & 10).

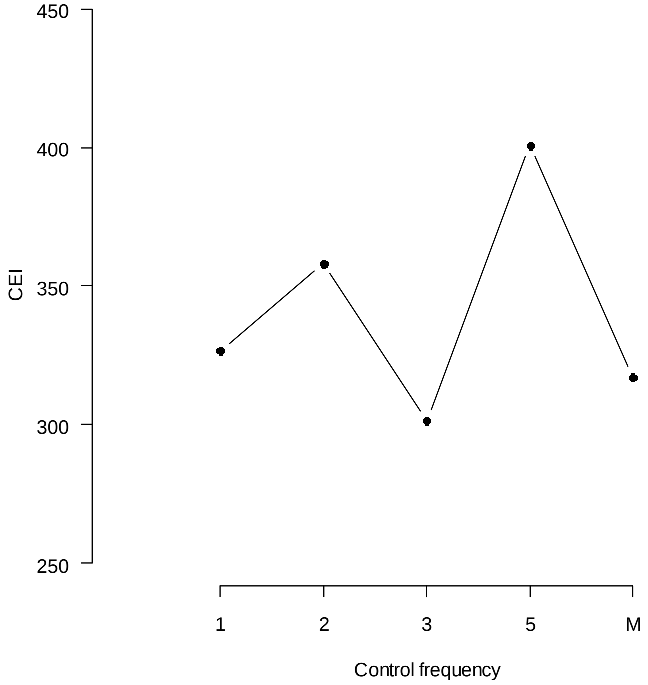

Fig. 2. Cost Effectiveness Indexs (*CEI*) for aerial possum control averaged over all scenarios for each control frequency.

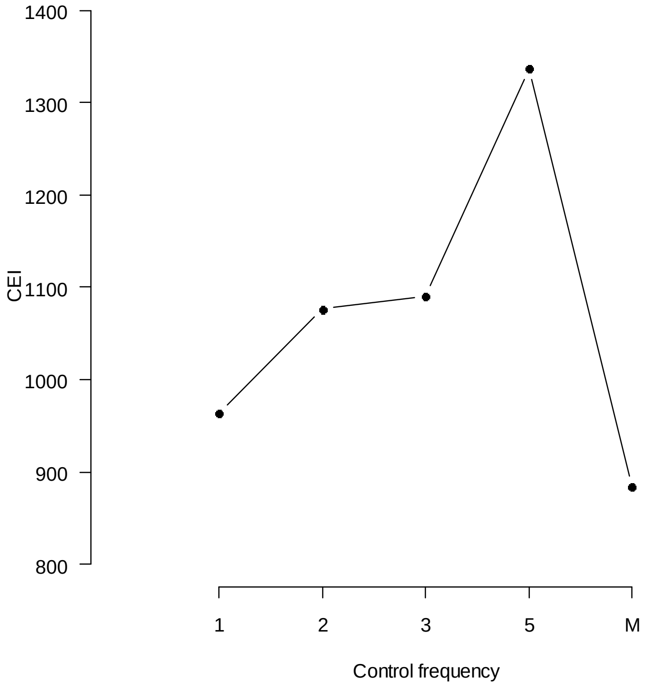

Fig 3. Cost-Effectiveness Index (*CEI*) for ground-based possum control averaged over all scenarios for each control frequency.

The optimums for individual scenarios often differed from the combined scenario averages in Figs 9 & 10. For example, for small areas subject to heavy immigration pressure (as represented by Scenario B) the optimal frequency of ground control was annual, whereas for large areas with a relatively small source of uncontrolled possums (Scenario C) it was every 2 years.

Differences in the cost of eradication between Artificial Scenario C and Scenario D, where Tb-infected possums were initially no closer than 1 km from the control boundary, indicated that most of the Tb being ‘exported’ from the control area occurred from infected possums located within 1 km of the control boundary. This supports observations on movements of clinically tuberculous possums found in Ramsey & Cowan (2003). The occurrence of Tb-infected possums near the control boundary as well as the amount, type and proximity of adjacent uncontrolled habitat had a profound influence on the probability of Tb-spread out of the control area. In the worst-case scenario where the control region was bordered by an abundance of high quality uncontrolled habitat (native forest adjacent to Southland Region 1), the probability of Tb escaping the control area and establishing in the adjacent habitat was as high as 70% for 5-yearly control and was 43% even using annual control. This implies that frequent control and wide buffers are required to completely eliminate the possibility of Tb spread.

6.2 Model validation

Validation of the possum/Tb model necessarily focused only on the monitoring and control modules of the model rather than disease transmission or population dynamics, because there are few empirical data on the latter. The key validation results for the six Southland areas are:

- Two-thirds of the post-control RTCI values from the operations were covered by the 95% predicted intervals from the model.
- Pre-control or trend monitor values from individual operations were less predictable by the model than post-control RTCI values
- Overall, the predicted RTCI values were lower than the observed ones, especially for the post-control values.

The most plausible reason for the discrepancies between predicted and observed values is that the model tended to underestimate the population recovery rate. One likely possibility for this is that within the model possum control is assumed to be applied evenly over the control area whereas in reality contractors apply control more thoroughly in some areas than others. Other possibilities are that the model underestimates the population intrinsic rate of increase. Another possible reason is that the model underestimates the amount of breeding (i.e. adult) dispersal occurring in possum populations (all young of the year are hardwired to disperse). Presently the model assumes there is a 10% chance of an adult male dispersing each year and a 5% chance for females. Increasing the rate of breeding dispersal would result in faster recovery rates in controlled areas, but there are no published or unpublished estimates of the true rate of breeding dispersal in possums.

If the discrepancies between predicted and actual RTCI values are due to the uneven application of control, then procedures to ensure even application of control should be implemented. Use of line maxima could help achieve this.

7. Recommendations

- Undertaking possum control every year, regardless of the pre-control RTCI, is unnecessary to eradicate Tb from possums and so wastes resources that could be used elsewhere.
- Using a threshold of 2% RTCI, the models predicts that optimal frequency of aerial possum control for the eradication of Tb in possums within a single region is once every 3 years. This is predicted to minimise use of the competing resources of cost and time to achieve eradication. However, if the total funding available across all regions within a VRA (or nationally) is less than that required for triennial control, aerial control at five yearly intervals is the model favoured of the scenarios modelled because it has the lowest total funding requirement.
- Annual or biennial aerial control should only be considered if there is a high risk of Tb escaping and establishing outside the control area or when circumstances require an urgent response. For ground control, undertaking annual monitoring to decide when to apply control was the most cost-effective strategy.

- If ground control is to be used on small (1000–3000 ha) control areas that are at risk of high immigration from surrounding habitat, then the optimal frequency of ground control is annual.
- These predictions are based on the assumption that possum control is applied evenly to the control area. To emulate even application of possum control, the use of line maxima should continue to be used as a key indicator of control performance.
- Further work needs to be undertaken on validating the spatial possum/Tb model in order to determine how well the model can predict short-term recovery rates (indexed by RTCI) following possum control.

8. Acknowledgements

We thank Paul Livingston for access to information on the costs and efficacy of aerial and ground-based possum control. Thanks also to Amy Rush (Environment Southland) for access to RTCI data for the Southland Region and John Gibson and Kelly Beuth for processing the LCDB2 cover types for each of the Southland operations.

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Appendix 1 Optimal control frequency simulations

Control frequencies (All control targets set at 2% RTCI)
Every year
Every 2 years
Every 3 years
Every 5 years
Trend monitor trigger – control only if annual trend monitor is >2% RTCI

All control frequencies performed for each combination of the following scenarios:

Control type
Aerial control
Ground control

Control area (total area = 15 000 ha)
No immigration (1000-ha area)
1000-ha control area
10 000-ha control area
10 000-ha control area + 1-km buffer between Tb possums and control boundary
Southland Region 1
Southland Region 2
Southland Region 3

Initial K (carrying capacity) = 5 possums/ha

Number of simulations = 500 per scenario

Control costs
Aerial: $32/ha
Ground: $23/ha

Control efficacy
Aerial
Initial: 95%, CV 10%
Maintenance: 90%, CV 20%
Ground
Initial: 85%, CV 10%
Maintenance: 75%, CV 25%

Number of monitoring lines for each control area size
1000 ha – 5
10 000 ha – 30
Southland region 1 – 100
Southland region 2 – 100
Southland region 3 – 100

Time horizon for each scenario is 10 years. Criterion is the net present cost of eradicating Tb with a specified level of confidence (set at 95%).

Appendix 2 LCDB2 cover type conversions

LCDB2 class	New class	Class key	Habitat type	K (possums/ha)
1. Built-up Area	0	0	No habitat	0
2. Urban Parkland/Open Space	0	1	Habitat other	1.0
3. Surface Mine	0	2	Scrub	3.0
4. Dump	0	3	Tussock	0.2
5. Transport Infrastructure	0	4	Pine forest	2.2
10. Coastal Sand and Gravel	0	5	Exotic	5.0
11. River and Lakeshore Gravel and Rock	0	6	Native forest	8.9
12. Landslide	0			
13. Alpine Gravel and Rock	0			
14. Permanent Snow and ice	0			
15. Alpine Grass-/Herbfield	0			
20. Lake and Pond	0			
21. River	0			
22. Estuarine Open Water	0			
30. Short-rotation Cropland	1			
31. Vineyard	1			
32. Orchard and Other Perennial Crops	1			
40. High Producing Exotic Grassland	0			
41. Low Producing Grassland	0			
43. Tall Tussock Grassland	3			
44. Depleted Grassland	0			
45. Herbaceous Freshwater Vegetation	1			
46. Herbaceous Saline Vegetation	0			
47. Flaxland	1			
50. Fernland	1			
51. Gorse and or Broom	2			
52. Manuka and or Kanuka	1			
53. Matagouri	0			
54. Broadleaved Indigenous Hardwoods	6			
55. Sub Alpine Shrubland	1			
56. Mixed Exotic Shrubland	1			
57. Grey Scrub	2			
60. Minor Shelterbelts	1			
61. Major Shelterbelts	1			
62. Afforestation (not imaged)	1			
63. Afforestation (imaged, post-LCDB1)	1			
64. Forest – Harvested	1			

65. Pine Forest – Open Canopy	4
66. Pine Forest – Closed Canopy	4
67. Other Exotic Forest	5
68. Deciduous Hardwoods	5
69. Indigenous Forest	6
70. Mangrove	0