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Minimising number killed in long-term vertebrate pest management programmes, and associated economic incentives

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Abstract

*Management of invasive vertebrate species often requires the use of lethal control tools such as toxins, traps, or shooting. However, because these pest species are sentient and have the capacity to suffer, the application of such tools raises concerns about welfare impacts. To address such concerns, research, policy and regulation have focused most often on the welfare impacts (humaneness) of the tools at the individual animal level (ie the 'quality' of the impact) with no attempt to assess welfare at the population level (ie the 'quantity' of the impact). Because control programmes often target large numbers of animals, we suggest that when the welfare costs of pest control operations and strategies are being evaluated, the numbers of individuals involved should be considered in addition to the intensity and duration of individual suffering. We explore this concept using a modelling framework and three New Zealand case studies (brushtail possums [*Trichosurus vulpecula*], ship rats [*Rattus rattus*], and Bennett's wallabies [*Macropus rufogriseus*]) to assess the extent to which typical control strategies used by land managers influence the numbers of animals killed. We test whether a predicted relationship between numbers killed and position on the population growth curve holds across these scenarios, and identify whether it would be economically viable for end-users to adopt more welfare-friendly control strategies (ie those that kill fewer individuals to achieve the required management outcomes) for these pest species, or whether some form of incentive would be required. Computer modelling showed that for four simulated brushtail possum control strategies, the number of animals killed on a 1,000-ha area over 30 years ranged from approximately 13,000 to 26,000. Similarly, for two ship rat control strategies, numbers killed over a 20-year period were 977 for an aerial strategy versus 1,517 for a ground-based strategy. For both species, the strategies that killed fewest animals generally also cost the least. For Bennett's wallabies, because farmers only carry out control for production benefits, the control strategy they are most likely to select would result in the highest number of wallabies killed. To reduce the number of wallabies killed while allowing farmers to achieve some production benefits, farmers would need to receive some additional financial benefit. The concept of welfare incentive then raises questions such as 'what willingness is there to pay for increased welfare' and 'to what extent can reducing control costs substitute for incentive payments in reducing numbers killed?'*

Keywords: *animal welfare, Bennett's wallaby, brushtail possum, control strategies, economic incentives, ship rat*

Introduction

Management of invasive species often requires the use of lethal control tools such as toxins, traps, or shooting (Arjo *et al* 2009; Adam *et al* 2010; Patergnani *et al* 2010). Because these animals are sentient, and therefore have the capacity to suffer (Gregory 2004), the application of such management to vertebrate species raises welfare concerns about the tools used and their consequent welfare impacts (Mason & Littin 2003; Littin *et al* 2004). To address such concerns, research, policy and regulation have focused most often on the welfare impacts (humaneness) of the tools used (Warburton *et al* 2000; Shivik *et al* 2005). Efforts to mitigate welfare impacts have thus been focused at the individual animal level (ie the 'quality' of the impact). However, for pest control there is also a population dimension to welfare (ie the 'quantity' of the impact), with large numbers of animals frequently targeted and the total welfare 'cost' of control programmes often being very high. Assessing and managing welfare costs of pest control operations and strategies thus needs to take into account not only the intensity and duration of individual suffering, but also the numbers of individuals involved.

The total cost of a pest control operation can be represented as:

$$WC_{Total} = (WC_{TL} \times N_{TL}) + (WC_{TSL} \times N_{TSL}) + (WC_{NTL} \times N_{NTL}) + (WC_{NTSL} \times N_{NTSL})$$

where, WC = welfare cost, $_{TL}$ = target individual lethal (ie killed), $_{TSL}$ = target individual sub-lethal (ie recover from sub-lethal poison dose, or injured), $_{NTL}$ = non-target individual lethal, $_{NTSL}$ = non-target individual sub-lethal, and N = number of individuals affected. Because sustained pest control is essentially an exercise in sustained-yield harvesting, the prediction can be made that the number of individuals to be killed depends on the population dynamics of the target species and the point on the population growth curve where control is applied (Caughley 1977). In general, if populations are sustainably controlled close to zero or close to carrying capacity (ie furthest from the population growth curve point of inflexion — typically close to half the carrying capacity — where growth rates are usually greatest), one would expect the number of individuals to be killed to be minimised. In contrast, if populations are sustainably controlled where growth rates are greatest, one would expect the number of individuals to be killed to be maximised (Getz & Haight 1989). This point, the maximum sustainable yield (MSY), is the goal of many fisheries' managers (Maunder 2002).

Pest managers have several control strategies they can apply (Shea 1998; Choquenot & Parkes 2001; Sabo 2005; Parkes *et al* 2006; Baxter *et al* 2008). These include: i) eradication; ii) removal of a fixed proportion of a population annually or at some fixed time period; iii) removal of a fixed number of individuals annually or at some fixed time period; or iv) removal of a fixed proportion of the population once a trigger level has been reached. Research to-date has focused on optimising strategies in terms of minimising financial costs while still achieving the desired management outcome (Choquenot & Parkes 2001; Parkes *et al* 2006; Baxter *et al* 2008). No attention has been paid to assessing which strategies might achieve management outcomes while minimising the number of pest animals killed or injured. In this paper, we use a modelling framework and three New Zealand case studies (brushtail possums [*Trichosurus vulpecula*], ship rats [*Rattus rattus*], and Bennett's wallabies [*Macropus rufogriseus*]), to assess the extent to which typical control strategies applied by land managers influence the numbers of animals killed. We specifically test whether the predicted relationship between numbers killed and position on the population growth curve holds across these scenarios, and identify whether it would be economically viable for end-users to adopt more welfare-friendly control strategies (ie those that kill fewer individuals for the required management outcomes) for these pest species, or whether some form of incentive would be required.

Brushtail possums are a major pest in New Zealand impacting on a range of conservation values and acting as the main wildlife vector of bovine tuberculosis (TB; Coleman 1988; Cooke *et al* 1995). About NZ$100 million are spent annually controlling possums over approximately nine million hectares. Control methods include aerial application of the toxin 1080 and ground application of poison baits and traps (Montague & Warburton 2000; Morgan & Hickling 2000). Control is generally applied on a per hectare basis and therefore costs are fixed irrespective of the number of animals killed. Ship rats are a major threat to New Zealand's avian biodiversity and, like possums, are also killed primarily using aerial application of 1080 baits (often in conjunction with possum control). However, unlike possums, rats have a variable and often high reproductive rate depending on prevailing food availability. In New Zealand's beech (*Nothofagus* spp) forests, rat numbers may irrupt to very high numbers after periodic masting events, so conservation managers now try to predict population irruptions and carry out pre-emptive rat control (Innes *et al* 1999; Elliot & Suggate 2007). As with possums, costs of rat control operations are usually dominated by fixed costs. Bennett's wallabies are a localised conservation and farm production pest in the Canterbury region of the South Island, with control being the responsibility of the landowners (mostly sheep farmers). Although this species has been controlled using aerial and ground application of poisons, most management is carried out by shooting (Warburton 1990). Consequently, control costs are dominated by variable costs because the cost per individual shot increases as wallaby density declines (Choquenot & Warburton 2006).

Materials and methods

Assessments and comparisons of the welfare costs of different control strategies for possums and rats were carried out using non-spatial population models simulated in the software package Modelmaker 4.0 (ModelKinetix, Buckinghamshire, UK), and for wallabies in Microsoft Excel®.

Possums

For managing TB, possum control strategies have been developed using both mathematical models (Barlow 1991) and empirical testing (Caley *et al* 1999). Barlow (1991) recommended an infected population be reduced to below 50% of its carrying capacity followed by maintenance control for at least eight years to eliminate the disease. Subsequent modelling by Ramsey and Efford (2005), using a spatially explicit individual-based model (Ramsey & Efford 2010), indicated that if possum abundance was reduced to a 2% trap-catch (ie two possums captured from 100 trap-nights) then TB would fade out from the population after 6–7 years. The general strategy employed by the Animal Health Board (AHB), the body that manages the National Pest Management Strategy for TB in New Zealand (AHB 2001), follows this recommendation (Knowles *et al* 2005).

To assess how choice of management strategy affects the number of possums killed, we modelled the MSY scenario (50% initial reduction from habitat carrying capacity (K = 10 possums ha^{-1}), followed by annual control maintaining the population at this level; Figure 1[a]), and three alternative management strategies; ii) 90% initial reduction from K, followed by repeat control whenever the population reached 50% of K (Figure 1[b]); iii) 90% initial reduction from K, followed by low intensity annual control maintaining it at that level (Figure 1[c]); and iv) 90% initial reduction from K, followed by maintenance control every 4 years (Figure 1[d]). Possum population growth was simulated on a yearly basis by a theta logistic function:

$$N_{t+1} = N_t e^{r(1-Nt/K)\theta}$$

where N_t is the number of possums at time t, r is the instantaneous rate of population growth, and θ is a shape parameter (Barlow & Clout 1983). Typical operational control costs and percentage kills were used to model control efficacy and costs (Table 1).

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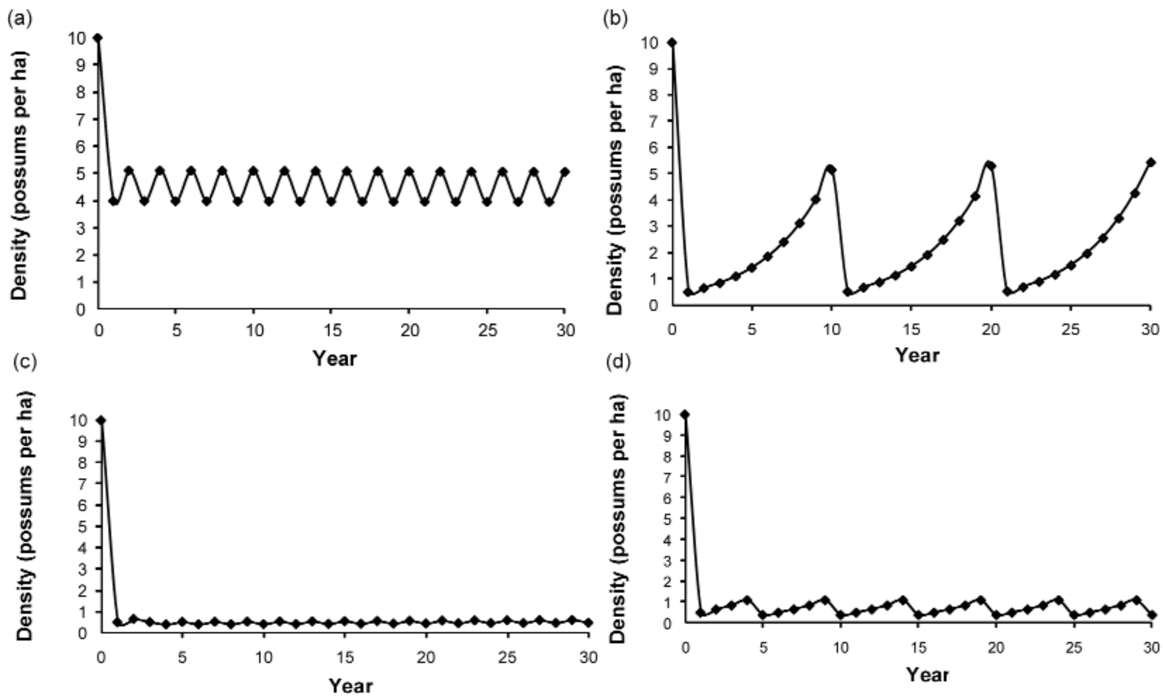
Figure 1



The four possum control strategies modelled, showing initial population reductions and maintenance control intensity and frequency (see text for details). Control was applied each time the population is shown to decline.

Table 1 Parameters and values used to model four possum control strategies. Strategies 1 to 4 are described in the text.

	Strategy			
Parameter	**1**	**2**	**3**	**4**
Carrying capacity (starting density)†	10	10	10	10
Yearly rate of increase (*r*)‡	0.3	0.3	0.3	0.3
Percent kill (initial reduction from *K*)	50%	90%	90%	90%
Percent kill (maintenance control)	30%	80%	25%	55%
Cost of initial control	NZ$30	NZ$30	NZ$30	NZ$30
Cost of maintenance control	NZ$25	NZ$15	NZ$15	NZ$25
Threshold (possums ha^{-1})	5	5	NA	NA

† Efford (2000), ‡ Barlow and Clout (1983).

Ship rats

Control of ship rats is generally carried out by DOC to minimise the damage to threatened species and, to be effective, at least for some species, rat abundance needs to be reduced to levels of less than about 5% as indexed by tracking rates (Innes *et al* 1999). In beech forests, rat abundance is characterised by periodic irruptions driven by seed-masting events that occur on average every 5 years (Wardle 1984; Innes 1990). We used the rat sub-model of the vertebrate pest community model presented in Tompkins and Veltman (2006) to simulate rat populations on a monthly basis and assess two control strategies: one that used aerial control immediately before each rat population irruption, and one that applied ground-based bait station control during the bird-breeding season (Figure 2).

The rat sub-model consists of four discrete stages, adult rats (R_A) and three juvenile age classes (R_{J1}, R_{J2} and R_{J3}), with one month spent in each juvenile class by growing rats (Innes 1990):

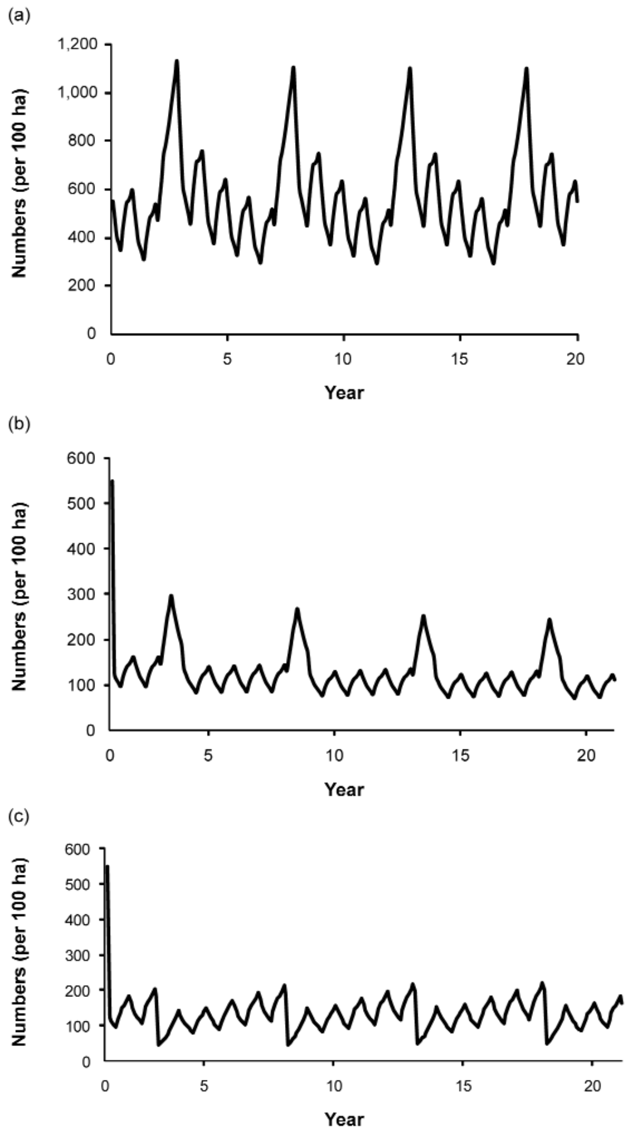
$$\frac{dR_{J1}}{dt} = \lambda_R \theta_R R_A - R_{J1}$$

$$\frac{dR_{J2}}{dt} = \gamma_{JR} R_{J1} - R_{J2}$$

$$\frac{dR_{J3}}{dt} = \gamma_{JR} R_{J2} - R_{J3}$$

$$\frac{dR_A}{dt} = \gamma_{JR} e^{-a_R R_A} R_{J3} - (1-\gamma_{AR}) R_A$$

Figure 2



Modelled ship rat numbers over time, with periodic mast-driven population irruptions, under three scenarios: (a) no control; (b) annual ground-based control during bird breeding seasons; and (c) aerial control prior to irruption.

Table 2 Parameter values used to model two ship rat control strategies and their sources in the literature. All rates are per individual per month.

Symbol	Parameter	Value		
		Non-mast	Mast	Refs
λ_R	Breeding rate	0.3	0.45	1, 2
θ_R	Breeding season	Oct–Mar	May–Feb	1.2
γ_{JR}	Juvenile survival	0.9	0.9	3
γ_{AR}	Adult survival	0.93	0.93	4
a_R	Intraspecific density-dependence	4.76×10^{-4}	4.76×10^{-4}	5

References: [1] Daniel (1978), [2] Innes (1990), [3] Blackwell *et al* (2001), [4] Daniel (1972), [5] Tompkins and Veltman (2006).

where, λ_R is the number of juvenile rats produced per adult rat during each month of the breeding season (denoted by the logic switch θ), γ_{JR} and γ_{AR} are the monthly juvenile and adult rat survival rates, respectively, and e^{-aR} denotes density-dependence such that juvenile recruitment into the adult class decreases with increasing adult population size. The parameter values used in the model are listed in Table 2. Aerial control was applied a month prior to a predicted rat population irruption at a cost of NZ$26 per hectare, and the ground control was applied for a period of 6 months over the bird breeding season at a cost of NZ$5 per hectare per month.

Bennett's wallabies

In 1993, changes in legislation governing the management of pests on private lands in New Zealand (ie the Biosecurity Act 1993) placed the onus for funding control onto the beneficiary, mainly farmers. Farmers, however, are mostly only concerned about the abundance of wallabies when they have a significant impact on farm production, and they generally only spend money and effort on control when the benefits outweigh the costs. The simulation model of Choquenot and Warburton (2006) was used to determine the number of animals that are sustainably killed for any given residual density. The model was a simple, weather-driven, stochastic model of wallaby population dynamics of the form:

$$r = r_m(1 - N/K) \times (b\mathrm{RF})$$

where r is the instantaneous rate of change in wallaby density, r_m is the maximum instantaneous rate of increase, N is the prevailing wallaby density, K is the carrying capacity of the habitat (0.142 wallabies ha^{-1}; Choquenot & Warburton 2006), and b is a function determining the effect of cumulative rainfall (RF) over the previous 12 months on r. A function linking the per capita cost of killing wallabies by hunting (NZ$ per kill to wallaby density (N) was derived from data in Warburton and Frampton (1991). The function had the form:

$$\text{\$ per kill} = (c_{max} - c_{min})^{e\text{-}dN} + c_{min}$$

where c_{max} and c_{min} are the maximum and minimum costs, respectively, of killing a wallaby by hunting and d is hunting efficiency, describing how quickly costs increase as wallaby density declines (see Choquenot & Warburton 2006). To determine the economic benefits gained from control, we used a ratio of wallabies to stock units of 0.2 (ie 1 wallaby = 0.2 dry stock equivalents) and a dry stock unit economic value of NZ$40. Results are expressed on a per control operation basis (ie cost or kills ha^{-1} operation^{-1}).

Results

Possums

The number of individuals killed varied considerably between strategies (Figure 3). Strategy 3 (ie an initial 90% kill followed by annual maintenance control) killed least animals, estimated as ~13,000 from a 1,000-ha area over 30 years and less than half the number killed by strategy 1 (~26,000 killed). As predicted by harvesting theory, the two strategies (1 and 2) that maintained the population around 50% of K killed more animals than the two (3 and 4) that maintained population numbers close to zero (Figure 3).

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The costs of each control strategy also varied considerably, with strategy 3 having a cumulative cost more than twice that of the other three strategies (Figure 4).

Ship rats

Aerial control applied immediately prior to each rat population irruption killed about 40% fewer individuals than ground-based bait control applied annually during the bird breeding season (Figure 5). Over a 20-year period, the total numbers killed by the aerial strategy versus the ground-based strategy were 977 and 1,517 per 100 ha, respectively. The cumulative costs of the two strategies also differed markedly but, unlike the possum strategies, the rat control strategy with the lower number killed (aerial control prior to irruption) also had the lower cost (Figure 6).

Bennett's wallabies

As the target density at which the wallaby population was maintained declined from *K* (ie from 0.142 animal ha^{-1}), the cumulative number of individuals killed increased until the target density was about 60% of *K*, and then declined (Figure 7). Control cost increased almost linearly with declining density, reflecting the increasing difficulty, and therefore time, in finding and shooting individual wallabies. As wallaby density declines, farmers obtain some production benefits by increasing stock units. However, because control costs continue to increase as wallaby density declines in our model, there is a predicted negative economic benefit to the farmer (= loss) once the residual density reaches about 0.1 wallaby ha^{-1}, below which the net benefit declined rapidly (Figure 8).

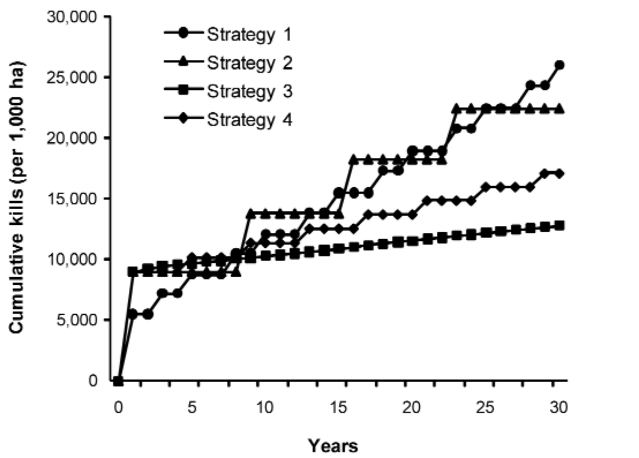
Discussion

Possums

The four simulated possum-control scenarios tested related to possum management for TB eradication. The disease models used initially to predict control targets suggested that possums needed to be held at or below 50% of *K* and maintained at that level for several years (Barlow 1991). In contrast, the more recent model of Ramsey and Efford (2005) suggests that TB can be eradicated more quickly if possum abundance is held at a 2% trap-catch index (approximately 0.5 possum ha^{-1}; Ramsey *et al* 2005). The simulations conducted here show that if managers apply the Ramsey *et al* (2005) strategy then the number of animals killed in the long term is much lower than if they apply the Barlow (1991) strategy (Figure 3). However, with the control tools and frequency of application required to maintain possums at the low densities of the Ramsey strategy, the yearly cost per hectare of this strategy is predicted to be very high compared with the other options (Figure 4).

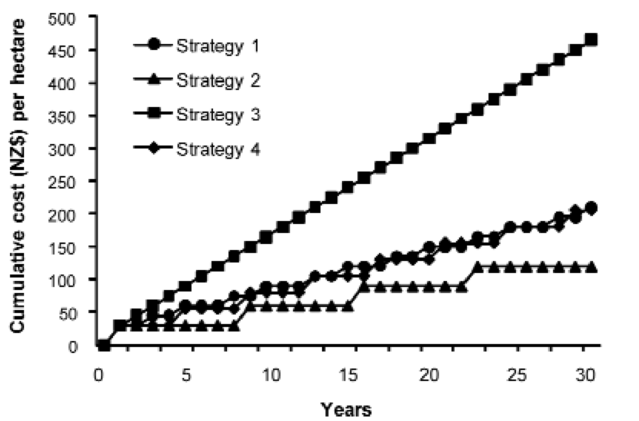
For the purpose of TB eradication, however, managers only need to apply possum control until the disease is eradicated, and modelling shows that if possum abundance is held at very low levels then the disease is eradicated more quickly (Ramsey & Efford 2005). Consequently, for TB eradication, the duration of control needed to achieve the required goal also needs to be taken into account when comparing the

Figure 3



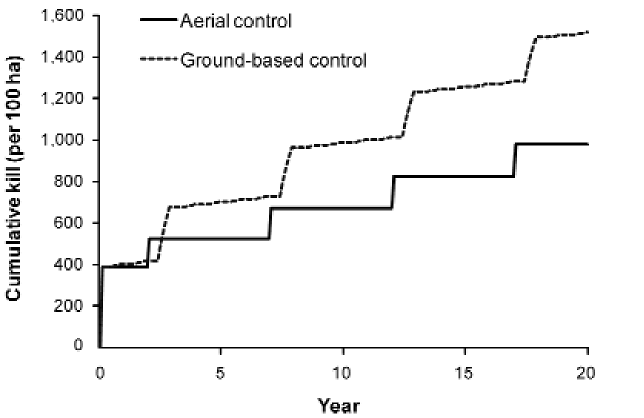
Cumulative kill per 1,000 ha of four possum control strategies: (1) 50% initial reduction from *K*, followed by annual control maintaining the population at this level; (2) 90% initial reduction from *K*, followed by repeat control whenever the population reached 50% of *K*; (3) 90% initial reduction from *K*, followed by low intensity annual control maintaining it at that level; (4) 90% initial reduction from *K*, followed by maintenance control every 4 years.

Figure 4



Cumulative cost of the four possum control strategies simulated (see text for strategy descriptions).

Figure 5



Cumulative numbers of ship rats killed by aerial control applied immediately prior to rat population irruptions versus ground-based bait control during the bird breeding season.

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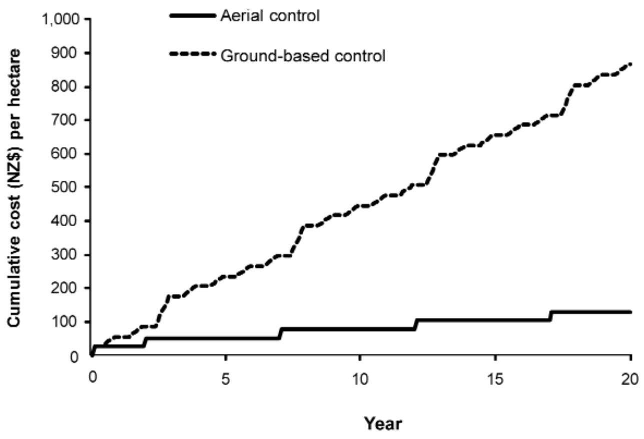
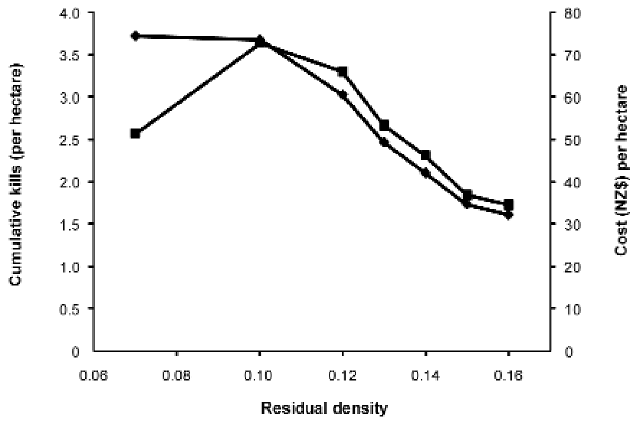
Figure 6



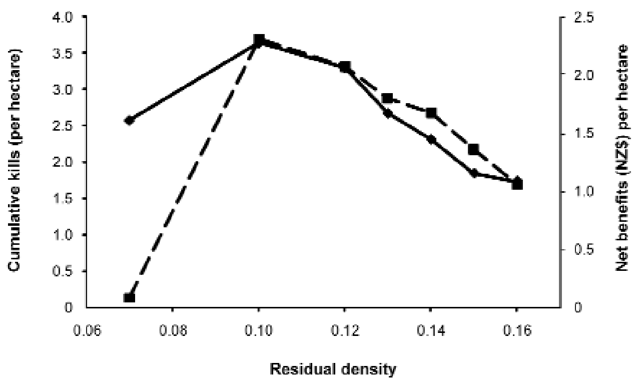
Cumulative costs of two ship rat control strategies simulated (see text for strategy descriptions).

Figure 7



Predicted changes in the cumulative kill (squares) and control cost (diamonds) of Bennett's wallabies as the residual density that the population is sustained at declines from *K* (ie 0.142 wallaby ha^{-1}).

Figure 8



Predicted changes in the cumulative kill (diamonds) and net benefits (squares) of Bennett's wallaby control as the residual density that the population is sustained at declines from *K* (ie 0.142 wallaby ha^{-1}).

financial and welfare costs of different strategies (this contrasts with possum control for conservation protection, which requires ongoing control). The Ramsey and Efford (2005) control strategy (ie maintaining possums below a 2% trap-catch using annual maintenance control; strategy 3 in Figures 3 and 4) is predicted to eradicate TB from wild possum populations within 7 years. In our model, this would result in approximately 10,000 possums being killed per 1,000 ha, at a total cost of about NZ$150 per hectare. In contrast, the Barlow (1991) strategy (ie an initial 50% kill followed by annual maintenance control at half *K*; strategy 1 in Figures 3 and 4) is predicted to take at least 20 years to eliminate TB, resulting in a predicted 18,000 possums killed per 1,000 ha also at a cost of about NZ$150 per hectare. The strategy of an initial 90% kill and then repeated aerial control every 4 years (strategy 4 in Figures 3 and 4) also provides a low cost and low kill outcome, while the strategy of a 90% initial kill followed by repeat control whenever the populations reaches 50% of *K* (strategy 2 in Figures 3 and 4) had the lowest financial cost of all simulations, but a welfare cost as high as that of strategy 1.

Ship rats

Of the two ship rat control strategies simulated, the aerial control option timed by predicted population irruptions was predicted to kill fewer animals in the long term (Figure 5). This option also had a considerably lower cost in the long term (ie < NZ$200 per 100 ha over 20 years) than the alternative strategy (ie > NZ$800 per 100 ha over 20 years). Consequently, there are very strong economic incentives for applying the rat-control strategy that results in the least animals killed (Figure 6). Unfortunately, mast prediction and therefore rodent irruption prediction are currently relatively imprecise (Monks 2007), and so such ideal outcomes will not be achieved routinely until such predictions become more robust.

Bennett's wallabies

Management of wallabies differs from that of possums and rats in that control is generally applied by individual farmers and for solely economic reasons. Consequently, the level of control applied in our simulations was interpreted relative to the net benefits farmers could achieve from reducing wallaby numbers and increasing livestock stocking rates. Since wallaby control costs increase as wallaby numbers decline, and control costs impact directly on production benefits, our model simulations suggest that farmers are only likely to apply sufficient control to reduce wallaby numbers to about 50–60% of *K* (Figures 7 and 8). If farmers reduce wallabies to levels well below 50% of *K*, they are likely to incur significant opportunity costs (being unlikely to allocate additional expenditure for wallaby control just to achieve a welfare benefit). This is unfortunate since control to about 50–60% of *K* was predicted to result in the greatest number of individuals being killed.

Welfare impact of control and pest species carrying capacity

As Caughley (1977) pointed out, sustained pest control is essentially equivalent to sustained harvesting. In the harvesting paradigm, the goal is often to achieve the maximum sustained yield (MSY). However, in pest control, from an animal welfare perspective, the goal is to achieve the desired outcome with minimal welfare cost. This includes both minimising the harm to individuals and minimising the number of individuals involved (ie minimising the sustained kill — 'MSK'). The modelling of various control strategies across three vertebrate pest species here upheld the predictions of MSY theory: the predicted number of animals killed in long-term control programmes depended largely on the density at which pest populations were maintained in relation to *K*. That is, strategy 1 for possums (Figure 3), ground-based annual control of rats (Figure 5) and intermediate control effort for wallabies (Figure 7), holding the populations closest to 50% of *K* of all the strategies simulated for each species, resulted in the greatest numbers of individuals predicted to be killed for each species in the long term. This paper focuses on the numbers of animals killed, but managers, when deciding between competing strategies, must also take into account the relative welfare impacts of the tools that might be used in each strategy. For example, when controlling possums using aerial application of baits, the poison sodium fluoroacetate (1080) is used, but when carrying out ground-based control, foothold traps, cyanide poison, or anticoagulant poison baits in bait stations might be used. Consequently, managers will be challenged with how to weigh the welfare costs of the tools relative to the numbers of animals killed. That is, is it better to kill more individuals with lower welfare impact tools or fewer individuals with higher welfare impact tools?

Economic incentives to minimise the number of animals killed

The level at which pest populations are maintained should be guided by the relationship between the pest density and the impact they have on the resource needing protection (Choquenot & Parkes 2001; Hone 2007). Most optimisation of pest control has focused on minimising financial costs (Baxter *et al* 2006; Tompkins & Ramsey 2007; Baxter 2008; Drucker *et al* 2010) and, for similar cost reasons, land managers generally will neither reduce pest densities any lower than is necessary nor increase the frequency of control any higher than is necessary. The numbers of animals killed by competing strategies are very rarely, if at all, considered when managers identify those strategies that might also deliver the best long-term population welfare outcomes. The approach taken in this paper is the first theoretical treatment of the topic and shows that, irrespective of the target density, there are competing strategic options for different pest species that may result in different numbers of animals killed and have different costs.

For some simulated control strategies (eg strategies 3 and 4 for possums, and the aerial-control strategy for rats) the lowest kills and least financial costs align. The Animal Health Board applies strategies 3 and 4 to possum control for TB eradication in New Zealand, the former in areas of farmland where possum habitat is patchily distributed, and the latter over large areas of intact forest. So, although one of the AHB's strategies (ie annual maintenance control) could be very expensive, because it is time limited by successful disease eradication it delivers very cost-effective management of TB in possums with the least animals killed. Consequently, the economic incentives support the application of the MSK-type strategies. However, for other control strategies (eg for wallabies) the lowest kills and least financial costs do not align. In this case, to reduce the number of wallabies killed while allowing farmers to achieve some production benefits, farmers would need to receive some additional financial benefit. The concept of welfare incentive then raises questions such as 'what willingness is there to pay for increased welfare?' and 'to what extent can reducing control costs substitute for incentive payments in reducing numbers killed?' These questions do not currently get asked and, for them to be asked, pest control managers need to be made aware that they have choices not only to select strategies that minimise financial cost (Baxter 2007), but also to reduce the number of animals killed in long-term pest control programmes. One approach to increasing awareness of these issues among pest managers would be to integrate such questions and decision-making into an adaptive management framework that addresses wider ethical questions about pest control (Warburton & Norton 2009).

References

Adam G, Drucker AC, Glenn P, Edwards B, William K and Saalfeld B 2010 Economics of camel control in central Australia. *The Rangeland Journal 32*: 117-127. http://dx.doi.org/10.1071/RJ09046

Animal Health Board 2001 *Bovine Tuberculosis National Pest Management Strategy 2001–2013*. Animal Health Board: Wellington, New Zealand

Arjo WM, Shwiff S and Kirkpatrick K 2009 Short-term evaluation of two integrated pest management programs for mountain beaver (*Aplodontia rufa*). *Crop Protection 28*: 703-709

Barlow ND 1991 Control of endemic bovine Tb in New Zealand possum populations: Results from a simple model. *Journal of Applied Ecology 28*: 794-809. http://dx.doi.org/10.2307/2404208

Barlow ND and Clout MN 1983 A comparison of 3-parameter, single-species population models, in relation to the management of brushtail possums in New Zealand. *Oecologia 60*: 250-258. http://dx.doi.org/10.1007/BF00379528

Baxter PWJ, McCarthy MA, Possingham HP, Menkhorst PW and McLean N 2006 Accounting for management costs in sensitivity analyses of matrix population models. *Conservation Biology 20*: 893-905. http://dx.doi.org/10.1111/j.1523-1739.2006.00378.x

Baxter PWJ, Sabo JL, Wilcox C, McCarthy MA and Possingham HP 2008 Cost-effective suppression and eradication of invasive predators. *Conservation Biology 22*: 89-98. http://dx.doi.org/10.1111/j.1523-1739.2007.00850.x

Blackwell GL, Potter MA and Minot EO 2001 Rodent and predator population dynamics in an eruptive system. *Ecological Modelling 25*: 227-245. http://dx.doi.org/10.1016/S0304-3800(01)00327-1

Caley P, Hickling GJ, Cowan PE and Pfeiffer DU 1999 Effects of sustained control of brushtail possums on levels of *Mycobacterium bovis* infection in cattle and brushtail possum populations from Hohotaka, New Zealand. *New Zealand Veterinary Journal 47*: 133-142. http://dx.doi.org/10.1080/00480169.1999.36130

Caughley G 1977 *Analysis of Vertebrate Populations*. Wiley-Interscience: London, UK

Choquenot D and Parkes J 2001 Setting thresholds for pest control: how does pest density affect resource viability? *Biological Conservation 99*: 29-46. http://dx.doi.org/10.1016/S0006-3207(00)00186-5

Choquenot D and Warburton B 2006 Modelling the cost-effectiveness of wallaby control in New Zealand. *Wildlife Research 33*: 77-83. http://dx.doi.org/10.1071/WR05008

Coleman JD 1988 Distribution, prevalence, and epidemiology of bovine tuberculosis in brushtail possums, *Trichosurus vulpecula*, in the Hohonu Range, New Zealand. *Wildlife Research 15*: 651-663. http://dx.doi.org/10.1071/WR9880651

Cooke MM, Jackson R, Coleman JD and Alley MR 1995 Naturally occurring tuberculosis caused by *Mycobacterium bovis* in brushtail possums (*Trichosurus vulpecula*) II. Pathology. *New Zealand Veterinary Journal 43*: 315-321. http://dx.doi.org/10.1080/00480169./1995.35912

Daniel MJ 1972 Bionomics of the ship rat (*Rattus r. rattus*) in a New Zealand indigenous forest. *New Zealand Journal of Science 15*: 313-341

Daniel MJ 1978 Population ecology of ship rats and Norway rats in New Zealand. In: Dingwall PR, Atkinson IAE and Hay C (eds) *The Ecology and Control of Rodents in New Zealand Nature Reserves* pp 145-152. Department of Lands and Survey: Wellington, New Zealand

Drucker AG, Edwards GP and Saalfeld WK 2010 Economics of camel control in central Australia. *The Rangeland Journal 32*: 117-127. http://dx.doi.org/10.1071/RJ09046

Efford M 2000 Possum density, population structure and dynamics. In: Montague TL (ed) *The Brushtail Possum: Biology, Impact and Management of an Introduced Marsupial* pp 47-61. Manaaki Whenua Press: Lincoln, New Zealand

Elliott GP and Suggate R 2007 *Operation Ark Three Year Report*. Department of Conservation: Christchurch, New Zealand

Getz WM and Haight RG 1989 *Population Harvesting: Demographic Models of Fish, Forest, and Animal Resources*. Princeton University Press: Princeton, USA

Gregory NG 2004 *Physiology and Behaviour of Animal Suffering*. Universities Federation for Animal Welfare Series. Blackwell Science: London, UK

Hone JM 2007 *Wildlife Damage Control*. CSIRO: Collingwood, Victoria, Australia

Innes JG 1990 Ship rat. In: King CM (ed) *The Handbook of New Zealand Mammals, 1st Edition* pp 206-225. Oxford University Press: Auckland, New Zealand

Innes JG, Hay R, Flux I, Bradfield P, Speed H and Jansen P 1999 Successful recovery of North Island kokako *Callaeas cinerea wilsoni* populations, by adaptive management. *Biological Conservation 87*: 201-214. http://dx.doi.org/10.1016/S0006-3207(98)00053-6

Knowles GJE, Hunter M and Rush A 2005 The eradication of bovine tuberculosis from infected wildlife populations: a New Zealand scenario. *Proceedings of the 11th Wildlife Damage Management Conference* pp 1-11. 16-19 May 2005, Lincoln, New Zealand

Littin KE, Mellor DJ, Warburton B and Eason CT 2004 Animal welfare and ethical issues relevant to the humane control of vertebrate pests. *New Zealand Veterinary Journal 52*: 1-10

Mason G and Littin KE 2003 The humaneness of rodent pest control. *Animal Welfare 12*: 1-38

Maunder MN 2002 The relationship between fishing methods, fisheries management and the estimation of maximum sustainable yield. *Fish and Fisheries 3*: 251-260. http://dx.doi.org/10.1046/j.1467-2979.2002.00089.x

Monks A 2007 Climatic prediction of seedfall in *Nothofagus, Chionochloa* and *Dacrydium cupressinum*. *DOC Research & Development Series 276*. Department of Conservation: Wellington, New Zealand

Montague T and Warburton B 2000 Non-toxic techniques for possum control. In: Montague TL (ed) *The Brushtail Possum: Biology, Impact and Management of an Introduced* Marsupial pp 164-174. Manaaki Whenua Press: Lincoln, New Zealand

Morgan D and Hickling G 2000 Techniques for poisoning possums. In: Montague TL (ed) *The Brushtail Possum: Biology, Impact and Management of an Introduced Marsupial* pp 143-153. Manaaki Whenua Press: Lincoln, New Zealand

Parkes JP, Robley A, Forsyth DM and Choquenot D 2006 Adaptive management experiments in vertebrate pest control in New Zealand and Australia. *Wildlife Society Bulletin 34*: 229-236. http://dx.doi.org/10.2193/0091-7648(2006)34[229:AMEIVP]2.0.CO;2

Patergnani M, Gras LM, Poglayen G, Gelli A, Pasqualucci F, Farina M and Stancampiano L 2010 Environmental influence on urban rodent bait consumption. *Journal of Pest Science 83*: 347-359. http://dx.doi.org/10.1007/s10340-010-0304-7

Ramsey D and Efford M 2005 Eliminating Tb: results from a spatially explicit stochastic model. *Landcare Research Contract Report LC0405/118*. Landcare Research: Lincoln, New Zealand

Ramsey DSL and Efford MG 2010 Management of bovine tuberculosis in brushtail possums in New Zealand: predictions from a spatially explicit, individual-based model. *Journal of Applied Ecology 47*: 911-919. http://dx.doi.org/10.1111/j.1365-2664.2010.01839.x

Ramsey D, Efford M, Ball S and Nugent G 2005 The evaluation of indices of animal abundance using spatial simulation of animal trapping. *Wildlife Research 32*: 229-237. http://dx.doi.org/10.1071/WR03119

Sabo JL 2005 Stochasticity, predator-prey dynamics, and trigger harvest or non-native predators. *Ecology 86*: 2329-2343. http://dx.doi.org/10.1890/04-1152

Shea K 1998 Management of populations in conservation, harvesting and control. *Tree 13*: 371-374. http://dx.doi.org/10.1016/S0169-5347(98)01381-0

Shivik JA, Martin DJ, Pipas MJ, Turman J and Deliberto TJ 2005 Initial comparison: jaws, cables, and cage-traps to capture coyotes. *Wildlife Society Bulletin 33*: 1375-1383. http://dx.doi.org/10.2193/0091-7648(2005)33[1375:ICJCAC]2.0.CO;2

Tompkins DM and Ramsey D 2007 Optimising bait-station delivery of fertility control agents to brushtail possum populations. *Wildlife Research 34*: 67-76. http://dx.doi.org/10.1071/WR05109

Tompkins DM and Veltman CJ 2006 Unexpected consequences of vertebrate pest control: Predictions from a four-species community model. *Ecological Applications 16*: 1050-1061. http://dx.doi.org/10.1890/1051-0761(2006)016[1050:UCOVPC]2.0.CO;2

Warburton B 1990 Bennett's wallaby. In: King CM (ed) *The Handbook of New Zealand Mammals, 1st Edition* pp 44-51. Oxford University Press: Auckland, New Zealand

Warburton B and Frampton C 1991 Bennett's wallaby control in south Canterbury. *Forest Research Institute Contract Report No. FWE91/59*. Landcare Research: Christchurch, New Zealand

Warburton B and Norton B 2009 Towards a knowledge-based ethic for lethal control of nuisance wildlife. *Journal of Wildlife Management 73*: 158-164. http://dx.doi.org/10.2193/2007-313

Warburton B, Gregory NG and Morriss G 2000 Effect of jaw shape in kill-traps on time to loss of palpebral reflexes in brushtail possums. *Journal of Wildlife Diseases 36*: 92-96

Wardle JA 1984 *The New Zealand Beeches: Ecology, Utilization and Management*. New Zealand Forest Service: Wellington, New Zealand