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MODELLING THE COST-EFFECTIVENESS OF WALLABY CONTROL IN NEW ZEALAND

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ABSTRACT: Bennett's wallaby (*Macropus rufogriseus*) was introduced to South Canterbury in New Zealand's South Island in 1974. The species rapidly increased in numbers, and by the 1940s had increased to levels where it had become a significant agricultural pest. In 1947, a coordinated wallaby control program employing teams of shooters commenced. However, wallaby numbers stayed high, and it was not until the early 1960s when aerially sown 1080 baits were used that a significant reduction in wallaby numbers was achieved. However, the need to de-stock areas prior to application of the baits prompted farmers to demand control by shooting teams rather than poison in order to achieve ongoing control. Wallaby control in South Canterbury is managed under a Regional Pest Management Strategy, relying on shooting as the primary form of control, but using aerially distributed 1080 baits and 1080 gel applied to broadleaf foliage to a limited extent when and where necessary. Wallabies are continuing to expand their range into the central alpine region adjacent to South Canterbury where they are becoming a conservation threat on public lands. In this study, we re-analyzed 13 years of detailed hunting return data in order to derive a synoptic model of wallaby population growth relative to density and prevailing rainfall. We also estimated cost-effectiveness models for control employing shooting teams, aerially distributed 1080 baits, and 1080 gel applied to foliage. We then explored the cost-effectiveness of alternative strategies for wallaby control by combining the models predicting wallaby population growth with those predicting variation in the cost-effectiveness of available techniques. The implications of this study for ongoing wallaby control for mitigation of agricultural and conservation impacts are discussed.

KEY WORDS: Bennett's wallabies, control strategies, cost-effectiveness, hunting, poison, population modelling

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INTRODUCTION

Bennett's wallabies (*Macropus r. rufogriseus*) were introduced from Tasmania into the Hunters Hills, South Canterbury, New Zealand in 1874, and over the following 50 to 60 years, they increased in number and range, eventually occupying about 350,000 ha of grazing and conservation lands (Warburton and Sadleir 1990). The wallabies currently inhabit four adjacent ranges of hills averaging 1000 m in altitude with high points reaching 2000 m. Most of their range is undeveloped tussock grassland (*Chionochloa* spp.) with remnant forest restricted to the wetter eastern side of their range. There is evidence that the wallabies may be expanding their range westward toward the central alps of the South Island.

By the 1940s Bennett's wallabies had increased to levels where they were perceived to be having a significant impact on agricultural production. In 1947, a coordinated wallaby control program employing teams of shooters with dogs was commenced. However, wallaby numbers stayed high, and it was not until the early 1960s when the use of aerially sown 1080 baits commenced that a significant reduction in wallaby numbers was achieved (Warburton 1986). As a result of these reductions, farmers were able to increase domestic animal stocking rates and became reluctant to de-stock areas to allow repeated application of poison baits. Farmers argued that shooting teams should again be deployed in order to capitalize on reductions in wallaby abundance achieved by aerial baiting operations. In response to these demands, the South Canterbury Wallaby Board was established in 1971, and a team of shooters using a pack of dogs to flush wallabies from cover became the primary control method in areas occupied by livestock. In areas that were not regularly stocked (typically unimproved forest or scrub land), either aerial 1080 or 1080 gel placed on palatable foliage was used as the control method. The Wallaby Board was funded by the Canterbury Regional Council through rates (a levy) levied from urban and rural landowners throughout the Canterbury region.

In 1993, the legislation governing the control of animal and plant pests in New Zealand was changed [Biosecurity Act (1993)] to place the onus for funding pest control on the beneficiary of that control. This meant that if the benefits accruing from wallaby control were exclusively private, individual landowners would have to fund all control on their lands. It was only where the benefits of accruing from Regional Council intervention to control wallabies could be shown to outweigh the benefits of individual intervention, or where wallabies were having a significant impact on conservation values, that a Regional Pest Management Strategy (RPMS) would be developed and funded through more broadly-based rates.

In developing a RPMS, a Regional Council must satisfy various requirements of the 1993 Act, one of which is that the most cost-effective control strategies are employed. Although a RPMS was developed for Bennett's wallabies, there was little information available allowing the most cost-effective control options to be identified. Warburton (1990) assessed the costs and effectiveness of using 1080 gel placed on palatable foliage. He found that in forested areas where suitable (palatable) leafed vegetation was present, the low cost ($NZ7.90 ha^{-1}) and high kills (91%) achieved by the technique meant it was highly cost-effective. However, in the open snow tussock grasslands that characterize the majority of the range currently occupied by wallabies, there is insufficient leafed vegetation for 1080 gel to be effectively deployed. In these areas it remains unclear which of the two alternative control techniques (aerial 1080 poison or hunting with dogs) is more cost effective. In this paper we develop a model of wallaby population dynamics in order to evaluate the cost and effectiveness of the three techniques available for wallaby control.

METHODS

Population Dynamics

Wallaby kill records for South Canterbury between 1979 and 1991 were analyzed to assess the effect prevailing wallaby density and rainfall had on rates of change in wallaby abundance. For each year, the farms on which wallabies were officially controlled were recorded along with the hours that hunters spent on each farm and the number of wallabies killed. The measure Ln kills hr^{-1} was used as a linear index of wallaby density, assuming that kill rates would approach maximum levels asymptotically (Choquenot et al. 1999). Where kill rates could be estimated for an individual property over sequential years (t), the annual instantaneous rate of increase for wallabies (r) was calculated from:

$$r = \text{Ln Kills hr}^{-1}_{t} - \text{Ln Kills hr}^{-1}_{t-1} \qquad \text{Eq. 1}$$

Estimated of r were regressed on Ln Kills hr^{-1}_{t-1} and cumulative rainfall for the calendar year in which this kill rate was estimated. Rainfall data were collected at Rocky Gully, a farm central to those for which the kill records were obtained. While the actual month in which wallabies were killed was not recorded, we assumed that rainfall in the year leading up to the period over which r was estimated would provide a useful index to seasonal conditions at that time.

We used the results of the regression analysis to estimate the parameters of a simple, weather-driven logistic model of wallaby population dynamics. The model had the form:

$$r = r_m(1 - N/K)(bRF) \qquad \text{Eq. 2}$$

where r is the instantaneous rate of change in wallaby population density, r_m is the maximum instantaneous rate of increase realized when wallaby density is very low, N is prevailing wallaby density, K is the ecological carrying capacity for the wallaby population, and b is a function determining the effect cumulative rainfall over the previous 12 months had on r.

Modelling Wallaby Control

A function linking the per capita cost of killing wallabies by hunting with dogs ($ kill^{-1}) to their density (WD) was derived from data in Warburton and Frampton (1991). The function had the form:

$$\$\ \text{kill}^{-1} = (c_{max} - c_{min})e^{-dWD} + c_{min} \qquad \text{Eq.3}$$

where c_{max} and c_{min} are the maximum and minimum costs of killing a wallaby by hunting with dogs, respectively, and d is hunting efficiency, describing how quickly costs increase at low wallaby densities. Estimates of the cost and efficacy of 1080 poison distributed on carrot bait by helicopter or applied in paste to palatable vegetation were derived from data in Warburton (1990) and Warburton and Frampton (1991).

To investigate how the cost of wallaby control varied for hunting with dogs and the two distribution techniques used for 1080, we constructed a stochastic simulation model based on Equations 2 and 3, and estimates of the cost and efficacy of poisoning obtained from previous studies. The model predicted variation in wallaby density for 100 years of simulated annual rainfall, with the average (731 mm) and standard deviation (90.85) taken from long-term records for the township of Fairlie adjacent to Bennett's wallaby range in South Canterbury. Instantaneous annual change in wallaby density was a random draw from a normal distribution of r with mean equal to the solution of Equation 2 and standard deviation equivalent to observed variation in r not explained by wallaby density or rainfall. The cost of hunting wallabies with dogs was estimated from the required density of kills to reduce the population from current density to a given target density, accounting for variation in $ kill^{-1} with wallaby density using Equation 3. All simulations commenced with wallaby density at K, and control implemented in year 5. Variation in costs ($ ha^{-1} year^{-1}) and effectiveness (average wallabies ha^{-1}) were estimated as the average of 1,000 runs of the model as the frequency with which each technique was applied was varied. For the two poisoning techniques, the frequency of application was varied from two to ten in one year increments. For hunting with dogs, the frequency of application was varied from two to five years in one year increments, with target densities for the residual wallaby population (i.e., the density of wallabies where hunting stops) set at 0.01, 0.025 0.05, 0.1, and 0.15 wallabies ha^{-1}.

RESULTS

Population Dynamics

Variation in r with Ln (Kills hr^{-1}_{t-1}) is shown in Figure 1. Both prevailing wallaby density and rainfall accumulated over the previous 12 months contributed significantly to variation in r (Table 1). Variation in r not accounted for by density and rainfall was equivalent to a standard deviation around the regression of 0.43.

Table 1. Summary of the regression of the instantaneous rate of change in wallaby abundance (r) on an index of wallaby density (Ln Kills hr$^{-1}_{t-1}$) and rainfall accumulated over the previous 12 months.

$R^2=0.43$, F-value=43.67, P-value<0.001

Effect	Coefficient	t-value	P-value
Intercept	-0.556	-4.80	<0.001
Ln Kills hr$^{-1}_{t-1}$	0.410	-9.19	<0.001
Rainfall	0.0003	2.08	0.039

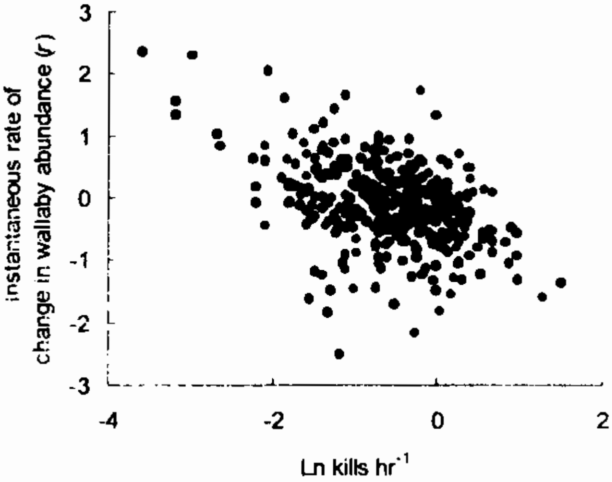

Figure 1. Variation in instantaneous rate of change in wallaby abundance (r) as a function of Ln kills hr^{-1}, a measure of wallaby density.

Modelling Wallaby Control

The maximum instantaneous rate of increase (r_m) for wallabies was estimated from the lowest observed value for Ln Kills hr$^{-1}_{t-1}$ (-3.178) using the regression summarized in Table 1 (r_m=0.75). Ecological carrying capacity for wallabies (K) was estimated using the equation derived by Freeland (1990):

$$\text{Log}_{10}K(\text{n ha}^{-1})=4.196+0.75\ \text{Log}_{10}\ \text{bodyweight(gms)} \qquad \text{Eq. 4}$$

Warburton and Sadlier (1990) estimated an average body weight of 13 kg for Bennett's wallabies, corresponding to K=0.142 wallabies ha^{-1}. Because K will by definition be the wallaby density where r averages 0, the ratio between 0.142 and the value of Ln Kills$^{-1}_{t-1}$ that gives r of 0 (0.82 from the regression in Table 1) can be used to convert values of Ln Kills$^{-1}_{t-1}$ to wallaby densities. Hence, the relationship between wallaby density, rainfall, and r was:

$$r=0.75(1-n/0.142)+(0.0003\,RF) \qquad \text{Eq. 5}$$

Ricker models based on this relationship for three levels of rainfall are shown in Figure 2. The function linking wallaby density to the per capita cost of killing wallabies by hunting with dogs in shown in Figure 3, and the efficacy of cost of distributing 1080 poison on carrot bait by helicopter and in paste on palatable vegetation are summarized in Table 2.

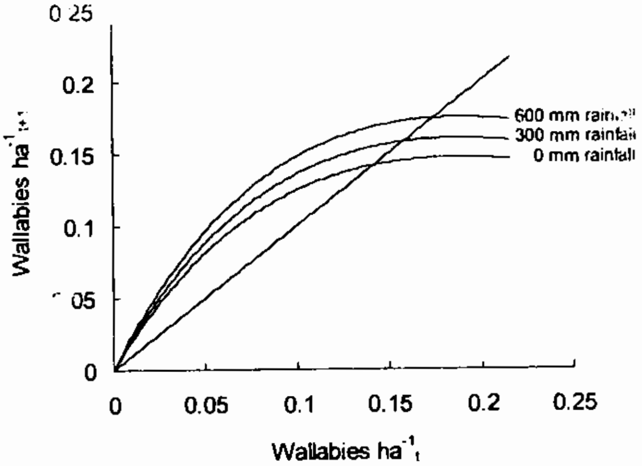

Figure 2. Ricker models for wallaby population in South Canterbury, relating wallaby density in one year (n_t) to density in the following year (n_{t+1}) for three different levels of preceding rainfall (cumulative rainfall over the previous 12 months). The straight line denotes population equilibrium.

Examples of predicted variation in wallaby density in the absence of control, and when controlled using hunting with dogs to a target density of 0.01 wallabies ha^{-1} at frequencies of five and two years are shown in Figure 4. Average cost and effectiveness of the control strategies employing hunting with dogs are summarized in Figure 5. For target densities greater than 0.1, control did not achieve any real reduction in average wallaby density, regardless of how frequently control was undertaken. Average control costs increased exponentially for lower target wallaby densities, leading to a concomitant decline in cost-effectiveness on a unit reduction in wallaby density basis. Not surprisingly, imposing control every two years held wallabies at the lowest densities relative to target densities for control, but also incurred the highest control costs.

Table 2. Cost and efficacy of 1080 poisoning for wallaby control using two distribution techniques. Estimates are taken from Warburton (1990) and Warburton and Frampton (1991).

	Method of 1080 Distribution	
	Cereal Bait Distributed by Helicopter	In Paste Applied to Palatable Vegetation
Cost ($\$ha^{-1}$)	21.0	7.9
Efficacy (% Kill)	70.0	90.0

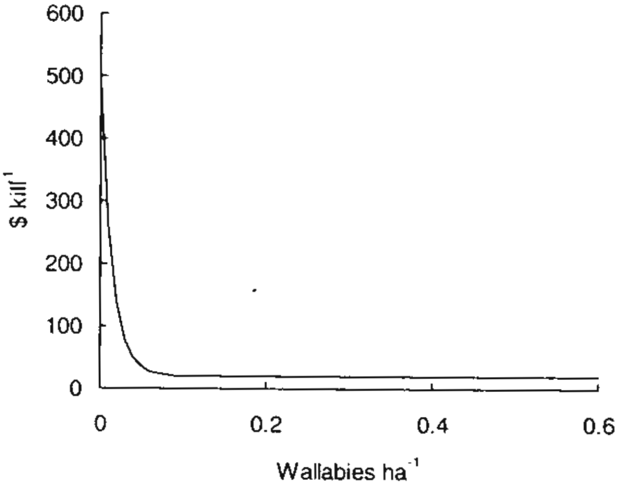

Figure 3. Variation in the per capita cost of killing wallabies using hunting with dogs as a function of their density. The relationship is adapted from Warburton and Frampton (1991).

Average cost and effectiveness of the control strategies based on 1080 poisoning are summarized in Figure 6. In contrast to hunting with dogs, cost and effectiveness declined approximately linearly with decreasing frequency for both systems of 1080 delivery. This difference reflects the fact that while the cost of hunting increases exponentially at lower wallaby densities, poisoning programs have fixed costs and fixed average efficacy. Of the two delivery systems, 1080 gel was both cheaper and more effective (see Table 2). Hence, for a given level of expenditure 1080 gel reduced average wallaby density more than 1080 applied from the air. Similarly, reducing the frequency of application for both techniques led to a much more marked decline in average cost for aerial application of 1080 than for 1080 gel.

DISCUSSION

Wallaby Population Dynamics

The effect prevailing density had on instantaneous rates of change in wallaby density (*r*) suggest that factors limiting wallaby populations in South Canterbury increase their influence as wallaby density increases. Limiting factors that could operate to regulate animal populations in this manner include: social mechanisms that reduce reproduction or survival through some form of spacing behavior; density-dependent predation or infection with parasites or pathogens; and competition for food or water. The absence of obvious predators and the positive effect rainfall had on *r* suggest the most likely limiting factors are social interaction, food and parasites, or pathogens. Herbivorous mammal populations regulated by competition for food resources typically show a curvilinear relationship between *r* and density because of the implicit lag between a change in density and a subsequent change in per capita food availability (Caughley 1976). The relationship between *r* and wallaby density in the data we had available appeared linear (Figure 1), although the scatter in these data may have obscured any subtle curvature in the relationship. A linear relationship would lend support to an instantaneous effect of increasing wallaby density on *r*, which would more typically reflect population regulation through social mechanisms.

The maximum rate of increase estimated for the population (r_m=0.75) is considerably higher than would be predicted from average wallaby bodyweight using the relationship estimated for herbivorous mammals by Caughley and Krebs (1983) (r_m=1.5 bodyweight$^{-0.36}$=0.60). However, the estimates of r_m used by Caughley and Krebs (1983) were for populations of mammals within their indigenous range. Freeland (1990) found that for introduced populations of mammalian herbivores, density at carrying capacity was higher for given bodyweights than it was for the same species within their indigenous range. He argued that outside of their indigenous range, herbivores could attain higher densities at carrying capacity because the food resources they utilized had not evolved defenses specific to offtake by these herbivores. If maximum rates of fecundity and survival for herbivores is also influenced by evolved anti-feedant defenses, maximum rates of increase for introduced herbivore populations could be expected to be higher than for populations within their indigenous range.

Cost-effectiveness of Wallaby Control

The assessment of hunting with dogs was more complex than that for either of the 1080 poisoning techniques. This is because in addition to deciding the appropriate frequency for applying hunting, managers must decide when to halt each hunting operation. This means that while a given reduction in wallaby density will correspond to some minimum frequency for poisoning operations, there may be several alternative ways of achieving the desired reduction using hunting with dogs.

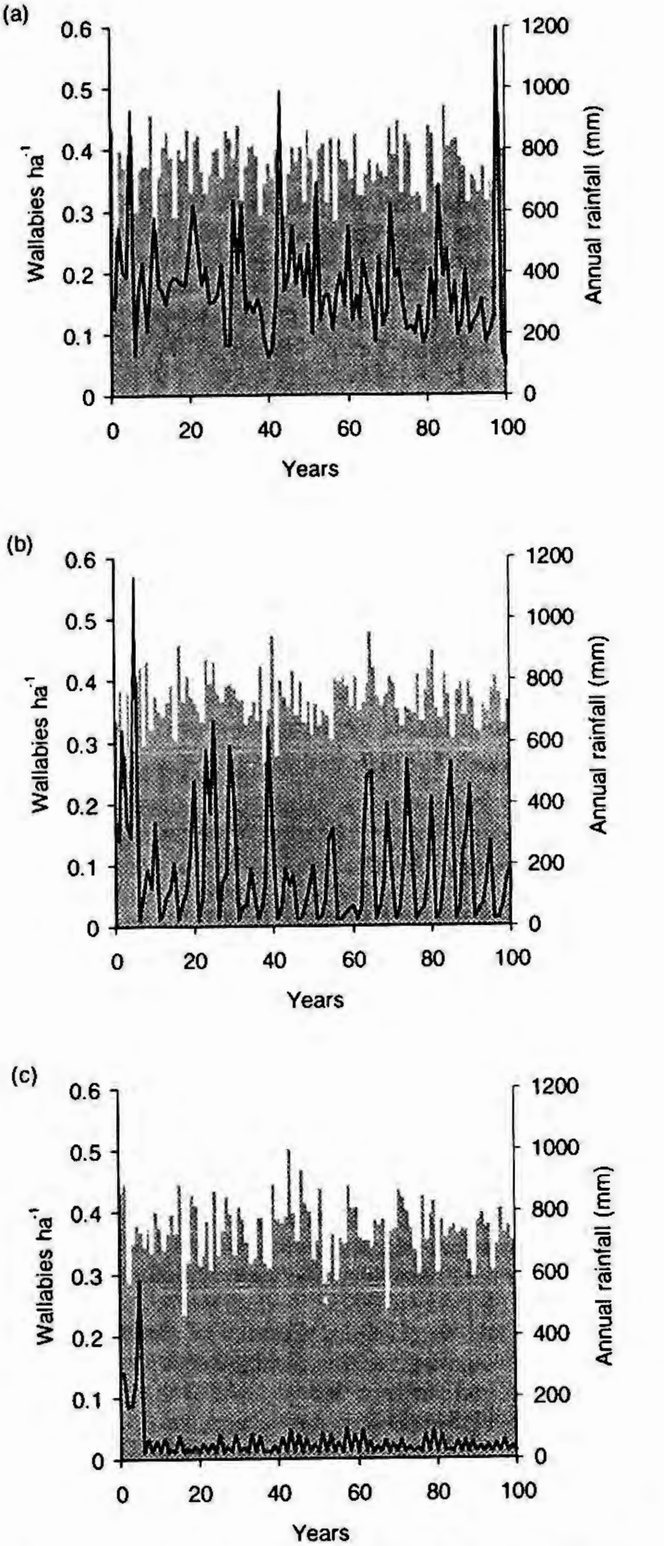

Figure 4. Variation in predicted wallaby density over 100 years of simulated rainfall (shown as gray bars) assuming: a) no wallaby control; b) control by hunting with dogs to a density of 0.01 wallabies ha^{-1} every five years; and c) control by hunting with dogs to a density of 0.01 wallabies ha^{-1} every two years.

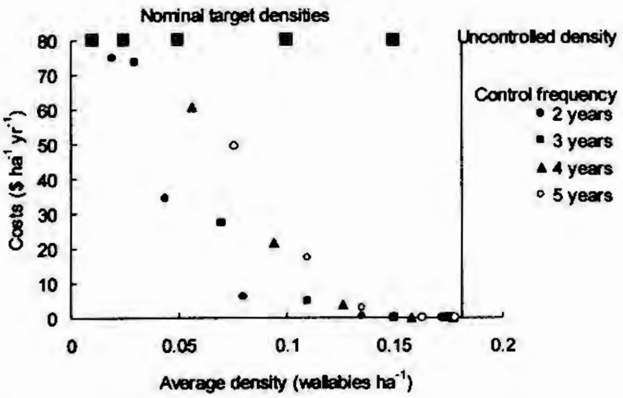

Figure 5. Predicted average cost and effectiveness of different wallaby control strategies employing hunting with dogs. Control strategies are defined by the target density for control (i.e., the density at which control ceases, indicated by the gray boxes at the top of the figure) and the frequency with which hunting is undertaken (two to five years). Averages are from 1,000 iterations of a 100-years stochastic model of wallaby population dynamics and control (see text for details). Wallaby density is the average density following initiation of control in year 5 of each simulation. The uncontrolled density of wallabies is indicated by the dashed line.

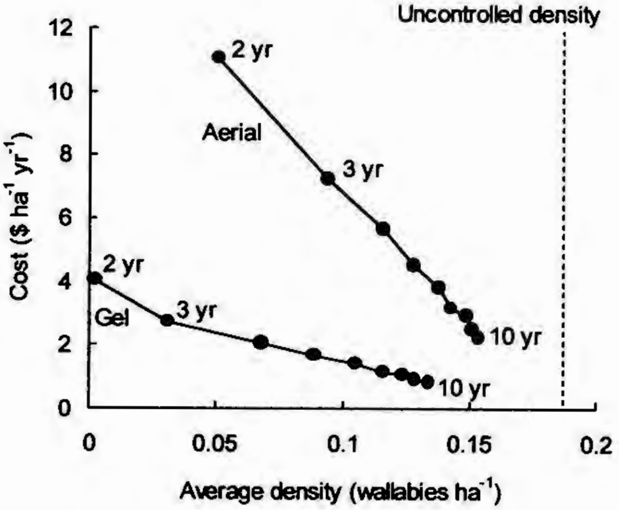

Figure 6. Predicted average cost and effectiveness of wallaby control employing two methods for 1080 distribution at different frequencies. Averages are from 1,000 iterations of a 100-years stochastic model of wallaby population dynamics and control (see text for details). Wallaby density is the average density following initiation of control in year 5 of each simulation. The uncontrolled density of wallabies is indicated by the dashed line.

For example, if the aim of wallaby control was to reduce average wallaby density to 0.5 of *K* (i.e., 0.071 wallabies ha^{-1}), the minimum frequency of control employing aerial 1080 and 1080 gel would be two years and four years, respectively. In contrast, the hunting with dogs could be used to achieve the specified reduction in wallaby density by either: 1) controlling wallabies to a target density of 0.05 wallabies ha^{-1} every two years; or 2) controlling wallabies to a target density of 0.025 wallabies ha^{-1} every four years. However, if the average annual costs associated with each strategy are estimated (Table 3), differences in the cost effectiveness of the four alternative approaches become obvious. The use of 1080-gel every four years is by far the most cost effective option of achieving the required reduction, followed by hunting to 0.05 wallabies ha^{-1} every two years, which is almost three times as expensive. Aerial application of 1080 every two years is perhaps double the cost of hunting at the same frequency, while halving the frequency of hunting but reducing the target density for hunting to 0.025 wallabies ha^{-1} massively elevates costs. This elevation is due to the exponential increase in the cost of finding and killing wallabies at low density (Figure 3).

Modelling has enabled the costs of each of the three control options to be determined given any selection of application frequency. Thus, for areas of forest that have vegetation suitable for applying 1080 gel, this control method is by far the most cost-effective option. Even so, pest managers will still have to consider other constraints that will impact on their decisions such as possible non-target impacts and the imposition placed on farmers to clear poison areas of stock.

In the open snow tussock grasslands that characterize the majority of the range currently occupied by wallabies, where there is no vegetation suitable for using 1080 gel, the modelling has indicated that hunting with dogs, at a frequency of two years, provides the most cost-effective control option for these areas. However, the choice will depend on the post-control density required to protect the agricultural or conservation values. The lower this density is, the higher the cost will be for the hunting option. Thus, when pest managers have to make choices between various control options as a requirement for developing a Regional Pest Management Strategy, population modelling can be a useful tool to determine the most cost-effective options given a range of different scenarios.

Table 3. Estimated minimum average cost of holding wallaby density below 0.5 *K* (0.071 wallabies ha^{-1}), using 1080 applied from the air, 1080 applied to palatable vegetation in a gel, hunting to a target density of 0.05 wallabies ha^{-1}, and hunting to a target density of 0.025 wallabies ha^{-1}.

Technique	Target	Required Frequency (Years)	Cost (\$ha^{-1}yr^{-1})
Aerial 1080	—	2	11.03
Gel 1080	—	4	2.06
Hunting (1)	0.050	2	5.85
Hunting (2)	0.025	3	27.33

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