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COST-EFFECTIVE CONTROL OF 1080 BAIT-SHY POSSUMS

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Abstract

The brushtail possum (*Trichosurus vulpecula*), introduced to New Zealand in 1858, is a significant conservation pest and a major vector of bovine tuberculosis (Tb; *Mycobacterium bovis*). Consequently, central and local government agencies now spend more than $30 million (NZD) each year on possum management activities. The current objective of this effort is selective, sustained control to eliminate the transmission of Tb to domestic livestock (which is assumed to require a 60% reduction in possum numbers) and to protect the areas with high ranking indigenous flora and fauna that are most at risk from possums (assumed to require a 80% reduction in numbers).

Previous simulation studies have suggested that regular aerial control with bait containing sodium monofluoroacetate (1080) is the most cost-effective large-scale possum control strategy. However, there is a growing awareness that the survivors of 1080 operations can develop ‘bait shyness’. This factor can markedly alter the efficacy of future 1080 control operations but has not been considered in previous simulation studies. I, therefore, constructed a possum control simulation model to assist in identifying the most cost-effective control strategy that would achieve sustained population reductions of 60% and 80%, given bait-shy behaviour and rapid possum population recovery due to immigration.

The simulation results suggest that it is possible to achieve sustained 60% or 80% reductions in possum numbers using a 1080-based control strategy, provided reasonably large (>100 ha) areas are controlled and 90% of susceptible possums are killed in the 1080 operations. The chronic-acting toxicant brodifacoum (Talon®) will kill the majority of any non-susceptible (i.e., 1080 bait-shy) survivors and its occasional use instead of 1080 during the follow-up control phase provided the most cost-effective way of maintaining a possum population at low density. Sensitivity analysis indicated that the most important variable influencing the overall sucess of these control strategies was the maximum rate of re-colonisation following control. With the high rates of immigration that are sometimes observed in small forest reserves, it was not possible to maintain a sustained 80% reduction in numbers using any combination of toxicants. Expensive, permanent bait stations may be required to minimise the effects of immigration into these small reserves.

Introduction

Since their introduction from Australia in 1858 (Pracy 1974), brushtail possums (*Trichosurus vulpecula*) have spread and now occupy more than 90% of New Zealand’s land area, with an estimated population of 50 to 70 million (Livingstone and Nelson 1994). The possum is a significant conservation pest, killing indigenous plants, suppressing regeneration through intensive browsing (Cowan 1991), and impacting on indigenous animals through predation, disturbance and competition for resources (Innes 1994). They are also considered the most important wildlife reservoir of bovine tuberculosis (*Mycobacterium bovis*; Tb), which they spread to cattle and farmed deer. Increased levels of Tb infection in cattle and deer herds could restrict our $5 billion (NZD) export market for beef and dairy products (Livingstone and Nelson 1994). It has been estimated that such restrictions on access for meat and dairy products could cost New Zealand up to $500 million annually (Eason *et al.* 1996).

Consequently, central and local government agencies spend millions of dollars every year on possum management activities. As an example of the magnitude of these expenditures it has been estimated that approximately $30 million was spent on possum control throughout New Zealand in the 1996/97 financial year, with contributions from Vote Agriculture ($18 million; N. Hancock, pers. comm. 1998) and Vote Conservation ($12 million; K. Briden, pers. comm. 1998). This level of funding remains insufficient to control possums in all Department of Conservation (DOC) and Animal Health Board priority areas (PCE 1994) and difficult decisions must be made regarding the location of each year's control operations.

Regardless of the criteria used to determine which areas receive possum control, field managers must then make decisions concerning the most appropriate control technique. As there is only a limited amount of money available for pest control, it is important that the most cost-effective techniques are used (Warburton *et al.* 1992). Previous research investigating cost-effective control of possums has favoured the use of aerially delivered sodium monofluoroacetate (1080) bait (Barlow 1991a). This technique can significantly reduce high density possum populations over areas as large as 20 000 ha (Eason *et al.* 1994).

An over-reliance on one toxicant, however, is considered unwise for a number of reasons (Eason *et al.* 1994). One of the main reasons is that regularly controlled populations can develop behavioural mechanisms to avoid toxic bait (Hickling 1994; O'Connor and Matthews 1996). Field and pen trials have demonstrated that the majority of 1080 control survivors will develop 'bait shyness' following sub-lethal poisoning (Ross *et al.* 1997). This bait shyness is long-lived (Morgan and Milne 1997) and can render 1080 'follow up' maintenance control ineffective (Hickling 1994). Accordingly, possum control strategies need to incorporate other control techniques such as bait station ground control with alternative, slower-acting possum toxicants (four other possum toxicants are currently registered). This paper extends previous possum modelling work (e.g. Barlow 1991a; Hickling 1995) by developing a new possum bioeconomic model that incorporates 1080 bait shyness and the chronic-acting brodifacoum toxicant (marketed as Talon®). Brodifacoum cereal bait is the only registered possum toxicant that has the ability to kill 1080 bait-shy possums in the field.

Methods

This section is divided into three sub-sections, with the first detailing the mathematical equations used in the model. The second defines the model parameter values and the third sub-section provides empirical justification for these parameter values.

Equations

The basic model (Figure 1) was written in the Microsoft Excel for Windows 95© (Version 7.0) spreadsheet package and uses the following equations for changes in density of the total population (T), susceptible sub-population (S) and the shy of acute acting toxicant bait sub-population (A):

Susceptible sub-population:

$$\frac{dS}{dt} = (S + I + (Tr_m(1 - (T/K)^{\theta})) + L) * (1- C_1\delta_1 - C_2\alpha_2) \qquad (1)$$

Shy of acute-acting toxicant bait sub-population:

$$\frac{dA}{dt} = A(1 - \mu\text{-}\varphi) + C_1(1 - \alpha_1) * (S + I + (Tr_m(1 - (T/K)^{\theta})) + L) - C_2\alpha_2A(1 - \mu\text{-}\varphi) \qquad (2)$$

Total population:

$$T = (S + A) \qquad (3)$$

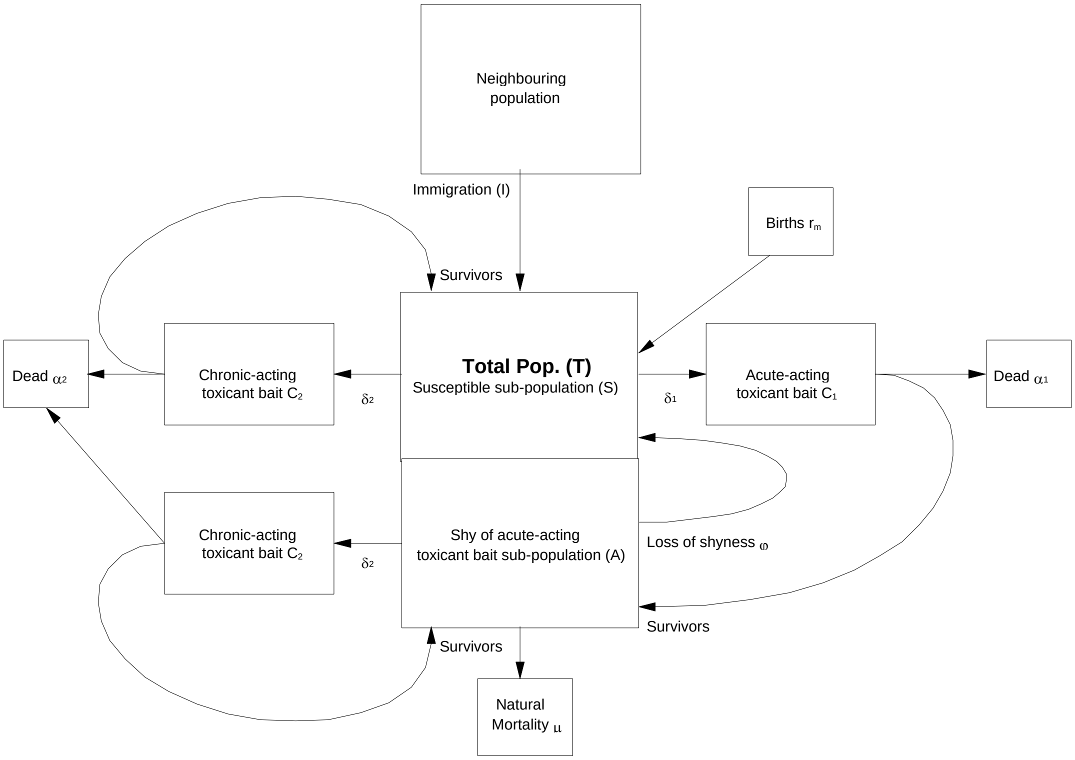

Figure 1: Flowchart for a computer simulation of possum population responses to a toxic baiting strategy employing acute, and chronic-acting toxicants. The total population (T) is made up of two sub-populations; one susceptible to poisoning (S) and one shy of acute-acting toxicant bait (A). See Table 1 for an explanation of the variables.

Model variable definitions and values

The modelling simulation was set up to estimate the total possum population (T) at 12 month intervals. The values in the table below are, therefore, per annum estimates that have been derived from various pen and field trial studies.

Table 1: Variable definitions and values used in a computer simulation of possum population responses to a toxic baiting strategy employing acute and chronic-acting toxicants.

	Definition	**Value**
S	Density of possums susceptible to poisoning	per ha
A	Sub-population of possums shy of acute-acting toxicant bait	per ha
I	Number of immigrants from neighbouring population	per ha
T	Total possum population in controlled habitat	per ha
L	Number of possums losing acute-acting toxicant bait shyness	per ha
C_1	Acute toxicant control activity	0 - 1
C_2	Chronic toxicant control activity	0 - 1
M	Maximum migration rate (possums/ha/yr)	1.2
r_m	Rate of intrinsic increase for controlled possums/year	30%
K	Carrying capacity for controlled possums/ha	10
μ	Natural mortality rate/year	10%
θ	Shape parameter for possum population growth curve	3
δ_1	Percentage of population exposed to acute-acting toxicant bait	100%
δ_2	Percentage of population exposed to chronic-acting toxicant bait	100%
α_1	Percentage of population killed by acute-acting toxicant bait	80-90%
α_2	Percentage of population killed by chronic-acting toxicant bait	75-80%
φ	Acute-acting toxicant bait shyness period decay/year	17%
C	Cost of control operation	$/ha
t	Number of years since start of simulation	1-10
I	Discount rate	10%
a	Size of the control area	ha

Biological growth

The biological growth of the possum populations was modelled using a rightwards peaked θ-logistic equation (Gilpin *et al.* 1976). Ecological studies investigating population dynamics suggest that New Zealand brushtail possum populations are regulated by density-dependent mortality, intensifying near carrying capacity (Barlow 1991b). This implies that the possum population growth curves are asymmetrically, rightward peaked (Barlow and Clout 1983).

Intrinsic growth rate/year

Possums have a significant birth pulse in autumn and sometimes a smaller one in spring, which is referred to as double breeding (Batcheler and Cowan 1988). Empirical estimations of r_m vary from a low of 20% (Hickling and Pekelharing 1989) to 59% (Keber 1985). Most of the values used in previous possum modelling simulations have been in the range of 20-30%, with variation dependent on the habitat. Possum control is most likely to occur in favourable habitat adjacent to farmland. Barlow (1991b) modelled the epidemiology of Tb in a population of non-exotic forest dwelling possums using a value of 20%, however, he suggests that 30% may be a more appropriate value to use for a population near the forest pasture margin in farmland/scrub habitat, where double breeding is more likely to occur.

An important consideration is the impact of extremely low population densities on overall breeding success. Cowan (1992) investigated the breeding success of females during the eradication of possums from Kapiti Island. This study indicates that even after the population had been reduced to near extinction there was only a slight increase in the percentage of females double breeding. This research suggests that the value of 30% is still appropriate, even when the population had been significantly reduced following control. Clout and Gaze (1984) suggest that the level of fecundity is influenced by the condition of the forest. With well-established populations the condition of the forest discourages double breeding and influences younger possum breeding success.

Natural mortality rate/year

The natural mortality (μ) parameter is required for possums that have moved into sub-population A, following control with 1080 (Figure 1). Previous modelling estimates for this value range from 10% (Barlow 1987) to 20% (Spurr 1981). The value of 20% was derived from an empirical study conducted on a well-established population near carrying capacity. Other population studies suggested that this value is more likely to be 10% when the population is at low-moderate densities (Spurr 1981). This value has also been adopted by other possum population modellers investigating the impact of control on the dynamics of a possum population (Barlow 1987; Barlow and Clout 1983; Clout and Barlow 1982).

Carrying capacity

Estimated values for carrying capacity (K) vary from fewer than 1 possum/ha in unfavourable scrubby farmland to over 25 possums/ha in blocks of favourable indigenous podocarp forest adjacent to pasture on the West Coast, South Island (Clout and Gaze 1984; Cowan 1991). In this model the control population is assumed to be located in favourable farmland/scrub habitat. Population studies suggest that this type of habitat often supports dense populations (Brockie *et al.* 1987; Coleman *et al.* 1980; Green and Coleman 1986) for which previous modelling simulations have used an upper value of 10 possums/ha.

Theta

A value for θ was obtained from an empirical study monitoring population recovery following a major poisoning operation. The area controlled was considered suitably large enough to minimise the effect of immigration on the subsequent increase in numbers. The results of this study suggest that a θ value of 3 most accurately models possum recovery in an area of indigenous forest (Hickling and Pekelharing 1989). As mentioned above this implies a rightward peaked growth curve. Such a shape assumes that possum populations are regulated at high densities by factors such as the availability of food and den sites (Barlow 1991b). Analysis of the age structure of various possum populations, near carrying capacity supports this assumption with evidence that the survival rates of all possums decline at high densities (Brockie *et al.* 1981).

Possum movement

The movement of small mammals between adjacent parcels of habitat has been widely investigated by population ecologists. It is hypothesised that dispersal of some species is governed by within-group competition for resources, such as den space, and between-group exchange of individuals through migration (Hestbeck 1982). This is referred to as a ‘social-fence’ which opens and closes depending on the population densities in the parcels of habitat.

A mathematical model of the social-fence, which has been adapted and applied to bioeconomic models investigating optimal control of beavers (Huffaker *et al.* 1992) and the spread of bovine Tb by the brushtail possum (Barlow 1993), is as follows:

$$\frac{dI}{dt} = \mathrm{M}\left(1 - \frac{\mathrm{T}}{\mathrm{K}}\right) \tag{4}$$

This equation assumes that when the density in the controlled area is low possums will migrate from the relatively densely populated non-control (neighbouring) area up to a maximum migration rate (M). The equation also assumes that dispersing possums are of breeding age and equal sex ratio. Both assumptions are consistent with the field data which has demonstrated that control areas are rapidly recolonised by a high proportion of adult possums (Keber 1985) of both sexes (Clout and Efford 1984; Green and Coleman 1984).

Maximum migration rate (per ha)

An estimate for M was derived from a number of empirical studies. In a total removal experiment possums began re-colonising a 24 ha pine plantation (Kinleith Forest, North Island) within 1 month of the control operation. After 1 year the density was 1.6 possums/ha which was 55% of the original population (Clout and Efford 1984). In another total removal experiment a 12 ha area in the Orongorongo Valley (1 200 ha) was re-colonised by 12 possums after 1 year (Barlow 1993). In an experiment in the South Island, possums were removed from a block (125 ha) of indigenous forest in Westland. The pre-control density was 10.7 possums/ha and 3 years later this population was back to 26% of the pre-control density (Green and Coleman 1984). In a more recent study 255 possums (90% kill) were removed from swamp and willow habitat (23 ha) in the Hawkes Bay (North Island). Five years later the population had recovered to 136 which is 5.9 possums/ha (Cowan *et al.* 1997). These studies suggest that the maximum rate of possum migration, under a variety of conditions is approximately 1.2 possums/ha/yr.

Efficacy of possum control operations using acute, and chronic-acting toxicants

Current possum toxicants

There are currently five toxicants registered for the control of possums in New Zealand, which can be categorised by the speed of onset of poisoning symptoms. Acute-acting toxicants (e.g., 1080) are fast acting and a lethal dose is usually consumed in a single feed (Buckle 1994). Consequently, these toxicants have the potential to quickly knock down a high density pest population using small amounts of toxic bait. The fast onset of toxicosis, however, means that any animals consuming sub-lethal doses are likely to associate cause and effect. Affected animals will then usually refuse to consume poisoned food on subsequent occasions and are referred to as being bait shy (Buckle 1994). The advantage of chronic-acting toxicants (e.g., brodifacoum) is that the delayed onset of symptoms helps to prevent the animal from associating symptoms with the bait so that it is less likely to become bait shy. The disadvantage is that animals generally require multiple- feeds of these toxicants to ingest a lethal dose. These compounds are, therefore, usually more expensive in terms of quantities of bait consumed (particularly when the population density is high) and labour costs. Chronic-acting toxicants can also pose a risk to non-target species due to the persistence of these compounds in the food chain. Due to the bait costs and secondary poisoning risks, subacute and chronic-acting toxicants are not usually used in aerial control operations on the mainland. For example, cholecalciferol is registered for use only in bait stations (Thomas *et al.* 1996).

Percentage of population encountering and consuming bait (Bait station operations)

Bait station spacing is the most important factor influencing the number of possums encountering bait (Table 2).

Table 2: Proportion of possums eating from bait stations at various station spacings.

Bait station spacing (m)	Possums eating bait (%)	Source
50	100%	Hickling *et al.* (1990)
100	93%	Thomas (1994)
101-150	95%	Thomas *et al.* (1996)
200-300	79%	Thomas and Fitzgerald (1994)
301-600	50%	Thomas and Fitzgerald (1994)

These field trials suggest that with a bait station spacing of 50-150 m approximately 95-100% of possums should encounter bait. This reduces to 80% with 300 m spacing and to 50% with 600 m spacing.

For this simulation I assumed that with a non pre-fed 100 m bait station spacing or a pre-fed 150 m bait station spacing, all possums encountered a bait station.

Percentage kill (Alternative toxicants)

The primary toxicant considered in the modelling was 1080. The two main factors influencing 1080 bait station operational success are the toxicant concentration and the availability of non-toxic prefeed (Table 3).

Table 3: Estimated kill achieved in bait station control operations using 1080 cereal bait; *n* indicates the number of separate field operations monitored.

1080 concentration (% wt./wt.)	Prefed	Spacing (m)	Kill (%)	Source
0.08%	No	50-100	45%	Thomas *et al.* (1996)
0.08%	Yes	100	58% (*n*=2)	Thomas and Hickling (1995)
0.08%	No	100	56% (*n*=6)	Henderson and Morriss (1996)
0.15%	Yes	100	98%	Thomas (1994)
0.15%	No	100	100%	Thomas *et al.* (1996)
0.15%	No	100	87% (*n*=3)	Henderson and Morriss (1996)
0.15%	No	100	75%	Henderson *et al.* (1997)
0.15%	No	150	75% (*n*=2)	Thomas *et al.* (1997)
0.15%	Yes	100	98%	Thomas and Meenken (1995)
0.15%	Yes	150	99% (*n*=2)	Thomas *et al.* (1997)
0.5%	No	100	93%	Thomas (1992)

These figures suggest that a 90% kill of susceptible possums should also be used for bait station control simulations using 0.15% concentration 1080 bait with non-toxic prefeed. Without prefeed a value of 80% is appropriate, especially when using a bait station spacing of greater than 100 m (Thomas *et al.* 1996).

The alternative toxicant considered was brodifacoum. The main factor influencing brodifacoum bait station operational success is the baiting regime (Table 4). In a pulse baiting regime toxic bait is only available for several days every 2-3 weeks whereas, with a saturation baiting regime, the bait stations are kept topped up (Thomas *et al.* 1996).

Table 4: Estimated kill achieved in bait station control operations using brodifacoum cereal bait; *n* indicates the number of separate field operations monitored.

Brodifacoum concentration (% wt./wt.)	Baiting regime	Prefed	Spacing (m)	Kill (%)	Source
0.002%	Pulsed	No	N/A	52%	Thomas *et al.* (1996)
0.002%	Pulsed	No	100	56%	Eason *et al.* (1994)
0.002%	Pulsed	No	100	59%	Henderson *et al.* (1994)
0.002%	Saturation	No	100	85% (*n*=2)	Henderson *et al.* (1997)
0.002%	Saturation	No	100	89% (*n*=2)	Morriss and Henderson (1997)
0.002%	Saturation	No	N/A	78%	Thomas *et al.* (1996)
0.002%	Saturation	No	100	78%	Henderson *et al.* (1994)

These figures suggest that a 80% kill value should be used for bait station control simulations using 0.002% concentration brodifacoum bait and a saturation baiting regime.

The other registered toxicants (cyanide, cholecalciferol and Pindone®) were not modelled. The subacute-acting cholecalciferol toxicant was not considered because 1080 is more cost -effective and has a higher control efficacy (Henderson *et al.* 1994). The acute-acting cyanide and chronic-acting Pindone® toxicants were not considered because of previous poor field efficacy (Eason *et al.* 1993; Warburton and Drew 1994).

Development of bait shyness

Shyness is a generic term indicating avoidance of a bait or poison. There are actually several mechanisms which can reduce an animal's tendency to consume a lethal dose of a toxic bait (O'Connor and Matthews 1996). Previous research suggests the most likely mechanism used by possums to avoid toxic bait is a conditioned food aversion (Hickling 1994). This is a learned behaviour which is generally induced by a sub-lethal dose of an acute or subacute-acting toxicant (Buckle 1994).

Acute and -acting toxicant bait shyness

Pen trials have demonstrated that the majority (>60%) of possums will develop an aversion (hereafter referred to as bait shyness) following a sub-lethal dose of 1080, cyanide or cholecalciferol (O'Connor *et al.* 1998; O'Connor and Matthews 1996). These pen trials also demonstrated that possum bait shyness is long lived (>24 months) and has the potential to dramatically effect the efficacy of frequent control operations (Morgan *et al.* 1996a). The most striking example of this comes from Mapara Forest (North Island) where aerial 1080 possum kills declined from 79% to 32% and then to 0%, during three annual operations (Warburton and Cullen 1993).

Recent field trials have investigated the efficacy of various possum toxicants for maintenance control, following initial control with an acute or subacute-acting toxicant. In these field trials sub-standard bait was deliberately used in the initial control operation to generate a high number of bait-shy survivors (Table 5).

Table 5: Kill rate for bait station control operations using acute and subacute-acting toxicants for initial and maintenance control (Henderson *et al.* 1997).

Initial control	Kill (%)	Maintenance control	Kill (%)
0.8% Cholecalciferol	63%	0.08% 1080	0%
0.8% Cholecalciferol	46%	0.4% Gliftor[1]	0%

0.08 % 1080	56%	0.8% Cholecalciferol	0%
0.08 % 1080	75%	0.4% Gliftor	0%
Cyanide Paste	75%	0.8% Cholecalciferol	0%

[1] An unregistered acute-acting toxicant being trialed by Landcare Research (N.Z.) Ltd.

These field trials suggest that the survivors of initial control, using either an acute or subacute-acting toxicant, are all bait shy and cannot be killed in subsequent (within 1-3 months) maintenance control operations using similar acting toxicants.

Acute and subacute-acting toxicant bait shyness period decay

An estimate of the rate of acute/subacute bait shyness degradation (φ) was derived from field trials and two long term pen trials conducted by Landcare Research (N.Z.) Ltd at Lincoln (South Island) and the Animal Behaviour and Welfare Centre (ABWC) at Ruakura (North Island). Both pen trials ran for 24 months and produced quite similar results. In the Landcare Research trial 71% of sub-lethally dosed (1080) possums remained bait shy after three months, 63% after 12 months and 57% after 24 months (Morgan and Milne 1997). In the ABWC pen trial 80% of sub-lethally dosed (cyanide) possums were bait shy 1 month later and 60% after 24 months (C. O'Conner, pers. comm. 1998). These data suggest that the number of bait-shy possums will decrease by approximately 40% over 2 years with most of the reduction occurring in the first 12 months.

The data in Table 5 indicate that immediately following control with an acute or subacute toxicant, all survivors are bait shy and cannot be controlled using similar acting toxicants. The long term pen trials indicate that the number of bait-shy possums will decrease over time with the greatest reduction in the first 12 months. This relationship is best modelled using an exponential decay equation (Equation 5). Using this equation the maximum rate of bait shyness degradation occurs in the 1st year (17%) and then slows over the remaining 9 years (Figure 2). This type of equation has been used by other researchers to model the rate of degradation of pesticide residue in soil (Feder and Regev 1975).

$$\frac{dL}{dt} = (A\varphi) \qquad (5)$$

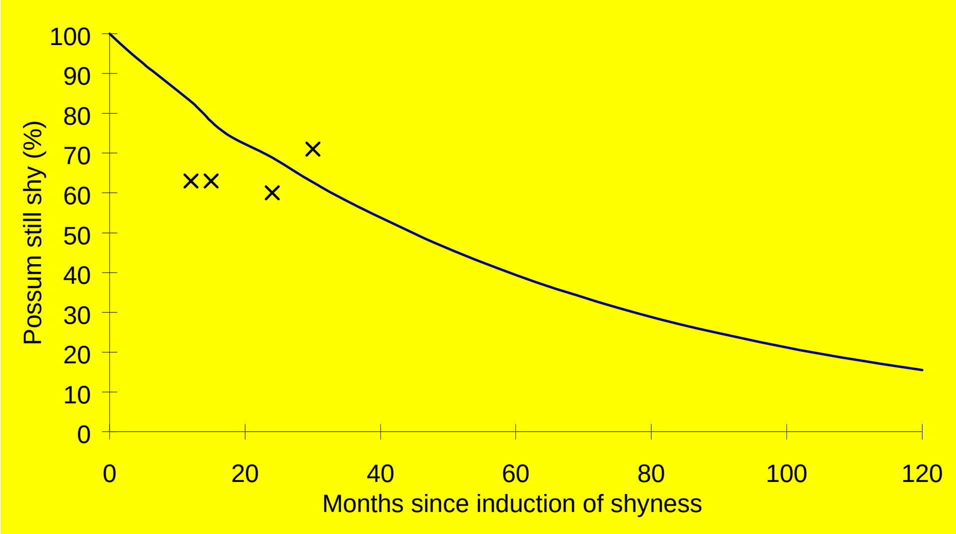

Figure 2: Continuous line is the estimated decline of possum 1080 bait shyness following a sub-lethal dose; x are actual estimates of cyanide and 1080 bait shyness levels, derived from various pen and field trial studies (references in text).

Chronic-acting toxicant bait shyness

Field trials have investigated the effectiveness of the chronic-acting brodifacoum toxicant for maintenance control (within 1-3 months), following initial control operation with an acute or subacute-acting toxicant. Again sub-standard bait was deliberately used in the initial control operation to generate a high number of bait-shy survivors (Table 6).

Table 6: Kill rate for bait station control operations using acute and subacute-acting toxicants for initial control and a chronic-acting toxicant for maintenance control (Henderson *et al.* 1997).

Initial control with acute toxicant	Kill (%)	Maintenance control	Kill (%)
0.6% Cholecalciferol	55%	0.002% Brodifacoum	74%
0.6% Cholecalciferol	55%	0.002% Brodifacoum	79%
0.08 % 1080	51%	0.002% Brodifacoum	88%
0.15 % 1080	75%	0.002% Brodifacoum	60%

These field trials indicate that the majority of survivors following initial control can be killed using brodifacoum. This hypothesis is also supported by a recent possum pen trial where researchers were unable to detect any brodifacoum bait shyness following sub-lethal doses of 0.05 and 0.1 mg/kg body weight (O'Connor *et al.* 1998).

Economics of control

1080-bait stations

Estimation of 1080 bait station costs is complex because there are numerous control variables such as bait station spacing, use of non-toxic prefeed and severity of the terrain which influence the number of bait stations that can be serviced each day. Prefeeding is a technique currently recommended for 1080 bait station control (Thomas *et al.* 1997). It is speculated that prefeeding lures additional possums to the stations that otherwise might not have found them (Thomas *et al.* 1996). Prefeeding is currently not recommended for aerial control operations as a sowing rate of 5 kg/ha delivers up to 900 lethal baits/ha (Morgan *et al.* 1997) and all possums are likely to locate bait.

1080 bait stations costs were calculated with a bait station spacing of 150 m (Table 3) with a 3 week prefeed regime (Hickling *et al.* 1991). Without prefeed a tighter 100 m bait station grid is recommended (Thomas *et al.* 1997). The number of visits to the bait stations was assumed to be six (with one visit to install the feeder, three visits to fill it with 2 kg of prefeed and then keep it topped up, one visit to deliver 0.5 kg of 1080 bait and one final visit to take away the station and uneaten toxic bait).

In ‘easy’ terrain one field worker can service 20 bait stations per day. As each station is visited six times this means it would take this field worker 6 days to service 20 bait stations for the entire control operation; or 1 day to service 3.3 bait stations. With 150 m spacing each bait station controls an area of 2.25 ha, therefore, approximately 7.5 ha can be controlled at the cost of 1 workday.

Using a flat wage rate of $144.00 per day total control labour costs came to $19.20/ha ($144/7.5 ha). This flat wage rate is the average value of three rates paid by DOC for contract labour in 1996 (M. Thomas, pers. comm. 1998). Added to this was bait costs of $4.62/ha (non-toxic $4.27 and toxic $0.35; Thomas *et al.* 1996) and a bait station cost of $1.00/ha (Thomas *et al.* 1996). Based on these figures the total 1080 bait station control cost came to $24.82/ha.

Brodifacoum-bait stations

Brodifacoum bait station costs were calculated with a bait station spacing of 100 m with no prefeeding (Table 4). Prefeeding is currently not recommended for brodifacoum bait station control (Thomas *et al.* 1997). Brodifacoum is a chronic-acting toxicant with delayed poisoning symptoms such that the toxic bait acts like non-toxic prefeed with most possums consuming a lethal dose before the onset of toxicosis. Analysis of brodifacoum bait consumption indicates that possum activity at bait stations peaks after 5 weeks, but bait should be available for a further 15 weeks to achieve a high kill (Henderson *et al.* 1997). Based on this it was assumed that the bait stations need to be replenished with 2 kg of brodifacoum bait every 6 weeks. Accordingly, the number of visits to the bait stations was assumed to be five (with one visit to install the feeder, one visit to fill bait station with 2 kg of brodifacoum, two visits to top up stations and one final visit to take away the station and uneaten toxic bait).

With easy terrain one field worker can service 20 bait stations per day. As each station is visited five times this means it would take this field worker 5 days to service 20 bait stations for the entire control operation; or 1 day to service four bait stations. With 100 m spacing each bait station controls an area of 1 ha. Therefore 4 ha can be controlled at the cost of 1 workday. Using the same flat wage rate total control labour costs were $300/ha.

As brodifacoum is a chronic-acting toxicant most possums may take several weeks to die after consuming a lethal dose (Eason *et al.* 1993). During this time possums will continue to eat additional bait and individuals can consume more than one kg of bait prior to death (Henderson *et al.* 1994). Field trials investigating the cost of brodifacoum bait eaten/ha indicated that with a moderate-high population density possums will consume a total of $27.00 of bait/ha (6 kg or around 600 g per possum). At low-moderate densities they consume a total of $9.00 of bait/ha (2 kg or around 400 g per possum) (Henderson *et al.* 1997). Using these figures and a bait station cost of $2.30/ha, total brodifacoum bait station control costs came to $47.30/ha when the possum population density was low-moderate and $65.30/ha when the density was moderate-high.

Discount rate

The cost of the aerial and ground control simulations were discounted using Equation 6 to determine the net present value of the different control strategies. A standard has developed in New Zealand whereby a discount rate of 10% has been typically used for government-funded projects (Forbes 1984). This standard has generally been used in previous possum control modelling simulations (Barlow 1991a; Warburton *et al.* 1992) and has been adopted in this model.

$$\sum_{t=0}^{T} \frac{C}{(1+i)^{t}}$$

(6)

Time frame of the simulation

Previous possum models have run for 5 (Barlow 1993), 8 (Barlow 1991a), 12 (Hickling 1995) and 28 years (Pfieffer 1994). Hickling 1995), who was the first to investigate the implications of behavioural resistance on the efficacy of 1080 control operations, argued that a 10 year period is the minimum required to gauge the effectiveness of multiple-poisoning campaigns on a possum population.

Simulation objectives

The objective of each control simulation was to reduce the possum population to below the target population density in year 1 and then to maintain the average population below this density for the remaining 9 years.

Two target population densities were used in the simulations: either 40% of pre-control carrying capacity (for elimination of Tb); or 20% of pre-control carrying capacity (for protection of conservation values).

Results

Sustained 60% kill using 1080 in bait stations

The most cost-effective strategy was 4 yearly 1080 control with an accumulated discounted cost of $53/ha (Table 7) . Brodifacoum was not required as the frequency of 1080 control did not generate significant numbers of bait-shy survivors.

Table 7: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill using 1080 in bait stations.

Strategy	Average density/ha	Accumulated discounted cost/ha
90% 1080 kill every 3 years	3.28	$68
90% 1080 kill every 4 years	**3.96**	**$53**
90% 1080 kill every 5 years	4.92	$50

Sustained 80% kill using 1080

The most cost-effective strategy was 2 yearly 1080 control with a one-off brodifacoum operation in year 2. Following the brodifacoum operation, regular 1080 control held the population in check by killing most of the immigrants and new recruits. The accumulated discounted cost of this strategy was $131/ha and maintained an average population density of 2.03 possums/ha (Table 8). This was considerably more expensive than the sustained 60% kill using 1080 ($53/ha; a 147% cost increase) as maintenance control was regularly required to limit population recovery.

Table 8: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using 1080 and brodifacoum in bait stations.

Strategy	Average density/ha	Accumulated discounted cost/ha
8 years 1080 - 90% kill	1.98	$135
2 yearly 1080 - 90% kill **1 year brodifacoum - 75% kill**	**2.03**	**$131**
3 yearly 1080 - 90% kill 2 years brodifacoum - 75% kill	2.24	$140

Sensitivity Analysis

Impact of bait shyness

The main novel feature of this bioeconomic model was that the survivors of 1080 control became bait shy. As detailed in Chapter 2, most previous control simulations have overlooked this issue (but see Hickling 1995). Pen trial studies have ascertained that the majority of possums will become bait shy following a sub-lethal dose of 1080, cyanide or cholecalciferol (Morgan and Milne 1997; O'Connor *et al.* 1998; O'Connor and Matthews 1996) and this bait shyness can be long-lived (2-5 years; Henderson *et al.* 1998). In the field this long-lived bait shyness has the potential to significantly reduce the efficacy of subsequent maintenance control operations, particularly when the control frequency is annual or biennial (Bradfield and Flux 1996; Hickling *et al.* 1991). For this simulation I calculated the most cost-effective strategies for sustained control (60% and 80% kill) without bait shyness. I then re-ran these simulations with bait shyness activated to ascertain its influence on the average population density and the accumulated cost of control.

Sustained 60% kill

Bait shyness had negligible effect on the strategies that aimed to achieve a sustained 60% kill, as there were not sufficient numbers of bait-shy survivors to significantly decrease the efficacy of 4 yearly control (Table 9). This result is similar to Hickling’s (1995) conclusion, which suggested that learned bait shyness has minimal effect on 1080 control operations if they are run at greater than 3-4 year intervals.

Table 9: Average possum density/ha of possum control strategies attempting to achieve a sustained 60% kill using 1080 in bait stations, with and without bait shyness.

Target kill	Strategy	Average density/ha		Percentage increase
		Without bait shyness	With bait shyness	

Sustained 60% kill using 1080	4 yearly 1080 - 90% kill	3.94	3.96	0.5%

Sustained 80% kill

Bait shyness did have a significant effect on the strategies that aimed to achieve the sustained 80% kill (Table 10). To achieve the target density of 20% with bait shyness, field managers would need to schedule brodifacoum control operations to target the bait-shy survivors (see Table 8).

Table 10: Average possum density/ha of possum control strategies attempting to achieve a sustained 80% kill using 1080 in bait stations, with and without bait shyness.

Target kill	**Strategy**	**Average density/ha**		**Percentage increase**
		Without bait shyness	**With bait shyness**	
Sustained 80% kill using 1080	2 yearly 1080 - 90% kill Year 8 additional 1080 - 90% kill	1.97	2.31	17%

The cost of scheduling these brodifacoum operations to kill the bait-shy survivors significantly increases the accumulated cost of control (Table 11), which demonstrates the need to include bait shyness in the modelling simulations. It also highlights how important it is for field managers to consider bait shyness when formulating possum control strategies, particularly for those attempting to achieve a >80% sustained population reduction.

Table 11: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using 1080 and brodifacoum in bait stations, with and without bait shyness.

Target kill	**Accumulated discounted cost/ha**		**Percentage increase**
	Without bait shyness	**With bait shyness**	
Sustained 80% kill using 1080	$101	$131	30%

[1] These control strategies are detailed in Tables 8 and 10

Impact of an unsuccessful initial 1080 operation

When toxic bait is correctly prepared and delivered, possum populations can be reduced by up to 95% (Morgan 1990). However, control efficacy can vary and an unsuccessful operation with an acute-acting toxicant will generate a large number of bait shy survivors (Table 5). For this simulation the initial 1080 operation kill was reduced to 60%. This meant that 40% of the starting population survived initial control and were 1080 bait shy.

Sustained 60% kill

The unsuccessful initial 1080 operation had a notable effect on the success of future 1080 control due to the large population of 1080 bait-shy survivors. The most cost-effective strategy was to revert to 2 yearly 1080 control (Table 12). This strategy had an accumulated discounted cost of $88/ha and maintained an average population density of 3.90 possums/ha. This is notably more expensive than the sustained 60% kill ($53/ha; a 66% cost increase) when there were no unsuccessful initial 1080 operations.

Table 12: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill using 1080 and brodifacoum in bait stations, following an initial unsuccessful 1080 operation.

Strategy	Average density/ha	Accumulated discounted cost/ha
Initial 1080 - 60% kill 4 yearly 1080 - 90% kill 1 year brodifacoum - 75% kill	3.99	$115
Initial 1080 - 60% kill **2 yearly 1080 - 90% kill**	**3.90**	**$88**
Initial 1080 - 60% kill 4 yearly 1080 - 90% kill	5.64	$53

Sustained 80% kill

The influence of an initial unsuccessful 1080 operation meant it was not possible to achieve a sustained 80% kill using only 1080. The most cost-effective strategy was immediate one-off brodifacoum control to target the 1080 bait survivors. This was followed by annual 1080 control and an additional brodifacoum operation in year This strategy kept the population in check by killing most of the immigrants and new recruits at an accumulated discounted cost of $219/ha (Table 13). This is also notably more expensive than the sustained 80% kill ($131/ha; a 67% cost increase) when there were no unsuccessful initial 1080 operations.

Table 13: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using 1080 and brodifacoum in bait stations, following an initial unsuccessful 1080 operation.

Strategy	Average density/ha	Accumulated discounted cost/ha
Initial 1080 - 60% kill 5 years brodifacoum - 75% kill 4 years 1080 - 90% kill	1.95	$236
Initial 1080 - 60% kill **2 years brodifacoum - 75% kill** **7 years 1080 - 90% kill**	**1.98**	**$219**
Initial 1080 - 60% kill 1 year brodifacoum - 75% kill 8 years 1080 - 90% kill	2.09	$205

Effect of population recovery due to increased and decreased rates of migration

The estimate for the maximum rate of migration was based on the results of four empirical studies conducted in a variety of habitats, however, other field trial studies have indicated that rate of migration varies in different control sites. For example, in five small forest reserves (14-135 ha), the possum populations increased by approximately 4 possums/ha/yr following brodifacoum and leg-hold trapping (Thomas *et al.* 1995). In contrast, Hickling and Pekelharing (1989) considered that immigration did not significantly contribute to the population recovery that they recorded in a >10 000 ha control area.

If the absolute rate of possum migration is assumed proportional to the length of the boundary of the control block, then the migration rate per unit area (M) will be related to the area of the control block (a) as follows:

$$\mathrm{M} \propto \frac{1}{\sqrt{a}} \tag{7}$$

In previous simulations I assumed that the hypothetical control block (assumed to be 1 000 ha in size) had a M = 1.2 possums/ha/yr. Using this formula I obtained estimates for the maximum rate of possum migration into smaller (100 ha) and larger (10 000 ha) control areas (Table 14).

Table 14: Estimated maximum rate of possum migration in various sized control areas.

Control area size (ha)	Estimated maximum rate of migration (possums/ha/yr)
100	4.0
1 000	1.2
10 000	0.4

Using these values I then varied the maximum rate of migration in the simulation model to assess the impact of area size on the cost-effective control strategies detailed in the results section.

Sustained 60% kill

Changing the maximum rate of migration had a significant affect on the number of control operations required to achieve a sustained 60% kill (Table 15). With high migration, control was almost required every year to limit the rapid population recovery. This strategy had an accumulated cost of $135/ha, which was significantly more expensive than the simulation using a migration rate of 1.2 possums/ha/yr ($53/ha; a 155% cost increase). With low migration, 1080 control was only required every 7 years and this was significantly cheaper than the simulation using a rate of 1.2 possums/ha/yr ($53/ha; a cost decrease of 28%).

Table 15: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill using 1080 in bait stations, with high and low rates of possum migration.

Target kill	Strategy	Average density/ha	Accumulated discounted cost/ha
Sustained 60% kill with high migration	8 years 1080 - 90% kill	3.98	$135

Sustained 60% kill with low migration	7 yearly 1080 - 90% kill	3.88	$38

Sustained 80% kill

With high migration, it was not possible to achieve a sustained 80% kill using any combination of toxicants (Table 16). With low migration 1080 control was only required every 3 years to achieve a sustained 80% kill, and this was significantly cheaper than the simulation using a migration rate of 1.2 possums/ha/yr ($131/ha; a cost decrease of 48%).

Table 16: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using 1080 in bait stations, with high and low rates of possum migration.

Target kill	Strategy	Average density/ha	Accumulated discounted cost/ha
Sustained 80% kill with high migration	Annual 1080 - 90% kill	3.44	$168
Sustained 80% kill with low migration	3 yearly 1080 - 90% kill	1.99	$68

Conclusions

A previous possum modelling paper suggested that one of the most cost-effective strategies for eliminating Tb possums was widespread aerial poisoning with 1080 every 6 years (Barlow 1991a). In that model the target population density for disease elimination was about half of the uncontrolled population density. The results from the current model indicate that, in the presence of density-dependent possum migration and 1080 bait shyness, more intensive control (e.g., every 4 years) is required to achieve a similar (60%) sustained population reduction.

A sustained 80% kill could be achieved using only 1080, however, the most cost-effective strategy used brodifacoum as well, as this has the ability to kill the 1080 bait-shy survivors. The model indicated that it was only necessary to use brodifacoum once, immediately after the initial 1080 operation. This strategy reduced the combined susceptible (S) and shy (A) sub-populations to below the target population density. Regular control with 1080 then maintained the average population below this density by killing the majority of new recruits and immigrants.

The sensitivity analysis identified two parameters that significantly influenced the ability of a previously successful control strategy to achieve a sustained kill. The first was the kill rate of the initial 1080 control operation; the model indicated that it was still possible to achieve target population densities provided additional control operations were scheduled. The inclusion of these additional operations, however, had a notable effect on overall control cost. For example, an unsuccessful 1080 operation increased the cost of a sustained 60% kill by $35/ha (a 66% cost increase). As detailed in the methods section there are many reasons why a control operation can fail. These results stress how important it is for field managers to ensure all bait is probably prepared, particularly for initial control when the population density is high. As demonstrated by the model, a high population density of bait-shy possums is expensive to control using brodifacoum bait.

The second parameter that had a significant influence over the success of a control strategy was the maximum rate of migration. The model indicated that with a high migration rate (4 possums/ha/yr) it was no longer possible to achieve a sustained 80% kill using any combination of toxicants. The maximum rate of migration used in the base model (1.2 possums/ha/yr) was derived from four empirical studies investigating population recovery in a variety of habitats. Some of these study sites were small (12-24 ha) and some (e.g., the Orongorongo Valley site) were surrounded by very favourable possum habitat. These data suggest that the higher rate of migration is exceptional and a rate of 1.2 possums/ha/yr is more typical, particularly in the moderate-large forest stands (cf. Hickling and Pekelharing 1989). Therefore, it seems important that field managers gauge the rate of population recovery, using pre-control population monitoring, before scheduling ongoing maintenance control operations. Without this information managers may make incorrect decisions regarding the frequency of control work required to achieve target population densities. If population recovery rates are high, due to rapid re-colonisation, field mangers may need to reassess the benefits of possum control work in that area. Field trial studies in small forest reserves, with rapid population re-colonisation, has demonstrated that a >80% sustained kill is achievable but requires a solid commitment to funding with expensive ($80/ha) permanent bait stations (Thomas *et al.* 1995).

In conclusion, there are four key outcomes from the modelling simulations. First, bait shyness had a significant effect on the frequency of control required to achieve a sustained population reduction. Future possum control modelling simulations should include bait shyness, particularly when modelling intensive control (e.g., >80% sustained kill). Second, it was possible to achieve both target population densities using currently available possum toxicants. This is an important result as biological control techniques may not be available in the near future (Gregory *et al.* 1996). Third, none of the control strategies were heavily reliant on brodifacoum. From an ecotoxicological perspective, minimising the use of brodifacoum, in favour of 1080, is desirable as brodifacoum is best avoided if there are concerns regarding the primary and secondary poisoning of non-target species (Eason and Spurr 1995). Finally, the control simulations indicate that learned behaviours such as bait shyness and enhanced neophobia should not be a major control problem, provided 1080 control efficacy is at least 90% (particularly in the initial 1080 control operation) and alternative, slower-acting toxicants such as brodifacoum bait are used occasionally (only required for the sustained 80% kill). To consistently achieve a 90% 1080 kill field managers need to: i) use bait of high palatability (R. Henderson, unpubl. data); ii) ensure bait has the correct toxicant concentration (Henderson and Morris 1996); iii) ensure bait is of adequate size (Frampton *et al.* in press); iv) use GPS navigation equipment to ensure total bait coverage in aerial operations (Morgan *et al.* 1996b); and v) use non-toxic prefeed in bait station ground control operations (Thomas 1998). This strategy should ensure that few, if any, possums are sub-lethally poisoned (Henderson *et al.* 1998).

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