

Predicting the efficacy of virally-vectored immunocontraception for managing rabbits

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Abstract: Models were developed to examine the efficacy of immunocontraception as an alternative control method for pest rabbits. The models simulated the dynamics of rabbit populations structured by age and sex, and helped identify the benefits of an integrated pest management strategy that includes immunocontraception and lethal control. Virally vectored immunocontraception (VVIC) using a sterilising myxoma virus reduced the long-term density of rabbits. However, our models indicated that the efficacy of VVIC is much less than using lethal methods of management currently available (e.g. poison baiting). Nevertheless, in areas where lethal control cannot be used, a sterilising strain of myxoma may be a useful tool for rabbit management, but competition between sterilising and non-sterilising strains will reduce the overall efficacy of VVIC. Regardless of how effective poisoning is at reducing rabbit numbers, the benefits in terms of increased pasture availability and wool growth may not outweigh the costs incurred by a poisoning campaign. In our analysis the most cost-effective control remains natural epizootics of myxomatosis since they do not incur a cost to the landholder. There is likely to be some small additional benefit to releasing a sterilising strain of myxoma, and landholders may need to supplement this with baiting under some circumstances (e.g. above average breeding season or areas where myxomatosis occur infrequently).

Keywords: Bioeconomic analysis; cost-effectiveness analysis; fertility control; myxoma; *Oryctolagus cuniculus*; pest; rabbit.

Introduction

Nigel Barlow was a pioneer of the use of predictive models and their practical application to investigate the effectiveness of virally-vectored immunocontraception (VVIC) for the management of vertebrate pests (Barlow, 1994, 1997, 2000; Barlow *et al.*, 1997). Barlow *et al.* (1997) suggested that the effects of age structure on the predictions of models of fertility control would be a useful topic for future research. In this paper we have examined the effectiveness of VVIC for improving agricultural production using an age and sex structured model of a pasture–rabbit–sheep production system.

European rabbits (*Oryctolagus cuniculus*) can have a devastating impact on agricultural production and the environment (Williams *et al.*, 1987, 1995). For example, in Australia, production losses from rabbits to the sheep wool and meat industry alone are estimated at around A\$35.4 million annually (McLeod, 2004). The major means for reducing these impacts rely

mainly on the biological control agents myxoma virus (*Myxomatosis cuniculi*) and rabbit haemorrhagic disease virus (RHD), and on the use of vertebrate pesticides and habitat modification, such as warren ripping. To be effective, all of these options rely on increasing death rates, and a large proportion of a given pest population must be affected. However, pesticide resistance has also been identified in some target species (e.g. 1080 and rabbits; Twigg *et al.*, 2002) and some of these options are undergoing closer scrutiny on animal welfare grounds (Broom, 1999; Littin *et al.*, 2004). Pest management programmes need to promote an integrated approach and be flexible in their implementation of alternative options. For these reasons, the development of viable and acceptable control options for vertebrate pests needs to be ongoing.

Immunocontraception is an alternative, but yet to be fully harnessed, approach for controlling pest animals (Kirkpatrick *et al.*, 1990; Tyndale-Biscoe, 1991, 1994). Immunocontraception reduces birth rates by immunising the target animal against one of its own

reproductive hormones, gamete proteins, or other proteins essential for reproduction. Injectable immunocontraceptive agents have been used to control localised populations of a number of overabundant mammals, including wild horses (*Equus caballus*) (Kirkpatrick *et al.*, 1990, 1997; Kirkpatrick and Turner, 2002), feral donkeys (*Equus asinus*) (Turner *et al.*, 1996), African elephants (*Loxodonta africana*) (Fayrer-Hosken *et al.*, 2000) and white-tailed deer (*Odocoileus virginianus*) (Kirkpatrick *et al.*, 1997; Walter *et al.*, 2002; Rutberg *et al.*, 2004). More recently, the potential of VVIC for reducing the abundance of pest populations of wild rabbits (Robinson *et al.*, 1997), foxes (*Vulpes vulpes*) (Saunders *et al.*, 1995; Bradley *et al.*, 1997) and house mice (*Mus domesticus*) (Singleton *et al.*, 2002) has been examined. With VVIC, the antigen that induces sterility is produced by a specific genetically modified disseminating vector such as the myxoma virus (rabbits) or the cytomegalovirus (mice). However, the overall benefits of such an approach are yet to be fully explored. A realistic assessment of the efficacy of immunocontraception via a disseminating vector is one of the key requirements if VVIC is to be successfully developed for these pests. The usefulness of VVIC for broad-scale management of vertebrate pests also requires further clarification.

Here we developed models to examine the efficacy of VVIC by simulating the effects of a recombinant myxoma virus, both in the presence and absence of more traditional control strategies for managing rabbits (e.g. poison baiting and wild-type myxomatosis). The models were largely based on field-derived data (see Williams and Twigg, 1996; Twigg *et al.*, 1998a, 1998b, 2000; Twigg and Williams, 1999), and simulated the dynamics of a rabbit population structured by age and sex. We deliberately chose a trophic model that explicitly simulated the interaction of rabbits with pasture availability and the epidemiology of wild and recombinant sterilising strains of myxoma virus. The modelled outcomes were used to measure the benefits resulting from an integrated pest management strategy that included both fertility and lethal control. Finally, we comment on the feasibility of VVIC to reduce the impact of pest rabbits on agricultural production and illustrate how such models can provide useful decision-making tools that are not currently available to wildlife managers.

Methods

In our models the abundance of rabbits was limited by their food supply. The model includes the effects of mortality induced from epizootics of myxomatosis, together with competition between wild and sterilising strains of myxoma. The model includes measures

of pasture biomass to permit prediction of the benefits of reducing rabbit grazing pressure and any consequent increase in available food, which could potentially result in increased wool production. The optimal combinations of immunocontraceptive and conventional control have not been previously defined, and the models were used to examine the best combinations of these control measures to maximise effectiveness whilst minimising costs. The model does not include other trophic interactions such as predation.

We used an 'escalator boxcar train' algorithm (Goudriaan and van Roermund, 1989; de Roos, 1997) to solve the model numerically. This method can include interactions between the environment and the simulated population, an arbitrary number of physiological traits of individuals, and can easily handle continuous reproduction by the target species.

Parameter values used in the model are presented in Table 1. The table also includes descriptions of variables and parameters and, where appropriate, data sources from which parameters were derived.

Pasture growth and total standing dry matter

Monthly pasture growth was simulated using the native pasture growth model GRASP (Littleboy and McKeon, 1997), using interpolated climate data for southwestern Western Australia. The interpolated data set spanned the years 1970–2000 [which includes the period for the Twigg *et al.* (2000) study and was provided by the Data Drill Service of the Australian Bureau of Meteorology (BOM, 2004)]. The same 30-year period was used for all simulations. Total standing dry matter per month (Eqn (1)) was a function of the previous month's total standing dry matter, pasture growth and pasture offtake by herbivores (Eqns 3 and 9).

$$TSDM_{t+1} = TSDM_t + \Delta V - F_t - F_u \quad \text{Eqn (1)}$$

where $TSDM_t$ was total standing dry matter for time period t , ΔV was pasture growth, F_t was the total amount of forage consumed by rabbits (i.e. the summed functional response for all cohorts), and F_u was the total amount of forage consumed by sheep.

Table 1. Parameter and variable names, including a brief description of each parameter or variable, its value used in the model and the source of the data upon which the parameters and variables were based.

Parameter or Variable Name	Description	Value	Source
Pasture biomass			
$TSDM_t$	Total standing dry matter for time period t (kg ha ⁻¹)	(Variable)	
ΔV	Pasture growth (kg ha ⁻¹ month ⁻¹)	(Variable)	
Functional responses			
i_a	Body weight (g) of a rabbit aged a days	(Variable)	
k	Upper asymptote or growth rate (g)	1470	Dudzinski and Mykytowycz 1960; Dudzinski and Mykytowycz 1961
q	Growth rate (g day ⁻¹)	0.0232	Dudzinski and Mykytowycz 1960; Dudzinski and Mykytowycz 1961
r	Time since birth when maximum growth occurs (days)	52.6	Dudzinski and Mykytowycz 1960; Dudzinski and Mykytowycz 1961
h	Constant to convert days to months (days month ⁻¹)	30.4 (= 356/12)	
g	Maximum food intake rate (kg day ⁻¹)	0.0677	Short, 1985
j	The inverse of the pasture biomass at which a fraction ($1 - e^{-1} \approx 0.63$) of the maximum intake rate is attained	0.00725	Short, 1985
F_t	Total amount of pasture consumed by rabbits (g month ⁻¹)	(Variable)	
F_s	Consumption rate of pasture by sheep (kg day ⁻¹ kg ^{-0.75})	(Variable)	
κ	Maximum pasture intake (kg sheep ⁻¹ day ⁻¹), assuming a FFW of 40 kg	1.099	Langlands and Bennett 1973
c	Inflection point of the functional response curve (kg ha ⁻¹)	259	Langlands and Bennett 1973
FFW	Fleece free weight (kg sheep ⁻¹)	40.0	This study
Reproduction			
$B_{\theta,a,y}$	Number of births of sex θ from female rabbits of age a in month y	(Variable)	
$F_{a,y}$	The density of fertile female rabbits of age a in month y	(Variable)	
$M_{a,y}$	Age specific frequency of pregnancy of rabbits of age a in month y	(Variable)	Twigg <i>et al.</i> 1998b, 2000
E_a	Age specific litter size of rabbits of age a	(Variable)	Twigg <i>et al.</i> 1998b, 2000
b_θ	Proportion of embryos of sex θ	0.5	Twigg <i>et al.</i> 1998b
ψ	Sex ratio of newborns (male:female)	1:1	Twigg <i>et al.</i> 1998b, 2000
Survival			
$l_{a,i}$	The proportion of individuals surviving from birth to age a that are in class i (fertile or sterile)	(Variable)	Twigg <i>et al.</i> 2000
λ_i	Shape parameter of the Weibull distribution for class i . This parameter is the instantaneous death rate (rabbits month ⁻¹).	Fertile females and males: 4.50 Sterile females: 2.28	Twigg <i>et al.</i> 2000
γ_i	Scale parameter of the Weibull distribution for class i . A dimensionless parameter.	Fertile females and males: 0.447 Sterile females: 0.322	Twigg <i>et al.</i> 2000
Wool growth			
W_s	Monthly fleece growth (g sheep ⁻¹ month ⁻¹)	(Variable)	
d	Maximum fleece growth rate (g sheep ⁻¹ month ⁻¹)	0.0859	Pattie and Williams, 1967
f	Food intake rate at which a fraction ($1 - e^{-1} \approx 0.63$) of the maximum food intake rate is attained (g day ⁻¹ kg ^{-0.75} FFW)	57.9	Pattie and Williams, 1967
Immigration			
τ_f, τ_m	Immigration rates of female and male sub-adults, respectively (rabbits month ⁻¹)	0.1	Twigg <i>et al.</i> 1998a

Density dependence

DDB_x	Density dependent age specific reproductive output	(Variable)	
$DI B_x$	Density independent age specific reproductive output	(Variable)	
DDI_x	Density dependent age specific survival	(Variable)	
$DI I_x$	Density independent age specific survival	(Variable)	
ω	A dimensionless shape parameter of the logistic equation	-7.1	This study
β	A dimensionless shape parameter of the logistic equation	0.0035	This study

Epidemiological sub-model

P_i	The probability of becoming infected with strain i after n contacts with vectors	(Variable)	
δ_i	The probability of successful transmission by strain i	0.15 (both strains)	This study
n	The number of contacts each host has with vectors	10	Fenner et al. 1952
Y_t	The number of infected and infectious hosts	(Variable)	
N_t	The total number of hosts	(Variable)	
α_w	Disease induced mortality rate from infection with wild (non-sterilising) strain of myxoma	0.0417	Fenner and Ross 1994; Fenner and Fantini 1999
α_s	Disease induced mortality rate from infection with sterilising strain of myxoma	0.0417	Fenner and Ross 1994; Fenner and Fantini 1999
v_w	Recovery rate from infection with wild (non-sterilising) strain of myxoma	0.0833	Fenner and Ross 1994; Fenner and Fantini 1999
v_s	Recovery rate from infection with sterilising strain of myxoma	0.0833	Fenner and Ross 1994; Fenner and Fantini 1999
η	Proportion of females infected with the sterilising strain of myxoma virus, which recover from infection and remain fertile	0.2	This study
$S_m(a,t)$	Density of susceptible male rabbits	(Variable)	
$S_f(a,t)$	Density of susceptible female rabbits	(Variable)	
$Y_{m,w}(a,t)$	Density of males infected and infectious with the wild strain (non-sterilising) of myxoma	(Variable)	
$Y_{m,s}(a,t)$	Density of males infected and infectious with the sterilising strain of myxoma	(Variable)	
$Y_{f,w}(a,t)$	Density of females infected and infectious with the wild (non-sterilising) strain of myxoma	(Variable)	
$Y_{f,s}(a,t)$	Density of females infected and infectious with the sterilising strain of myxoma	(Variable)	
$Z_m(a,t)$	Density of immune males	(Variable)	
$Z_{f,w}(a,t)$	Density of immune females that are fertile	(Variable)	
$Z_{f,s}(a,t)$	Density of immune females that are sterile	(Variable)	

Future cost

FC	Accumulated future cost	(Variable)	
I_c	Initial cost of management	3.16	Williams and Moore, 1995
π	Inflation rate	3.5%	Australian Consumer Price Index 1985-2004

Payoff

O_N	Payoff in terms of reduced mean population size	(Variable)	
N_t^{w+s}	Population density at time t in the presence of MV and SMV	(Variable)	
N_t^w	Population density at time t in the presence of MV only	(Variable)	
O_V	Payoff in terms of increased pasture biomass	(Variable)	
V_t^{w+s}	Pasture biomass at time t in the presence of MV and SMV	(Variable)	
V_t^w	Pasture biomass at time t in the presence of MV only	(Variable)	
T	Total time over which the projection was made (years)	30	This study

Rabbit population dynamics

The dynamics of the age and sex structured rabbit population were represented by the following set of equations:

$$\frac{\partial n_f(a,t)}{\partial t} + \frac{\partial n_f(a,t)}{\partial a} = -[\mu_f(a,V) + {}_D\alpha_w(t) + {}_P\alpha(t)]n_f(a,t) + \tau_f(a^\zeta),$$

$$\frac{\partial n_s(a,t)}{\partial t} + \frac{\partial n_s(a,t)}{\partial a} = -[\mu_s(a,V) + {}_D\alpha_s(t) + {}_P\alpha(t)]n_s(a,t),$$

$$\frac{\partial n_m(a,t)}{\partial t} + \frac{\partial n_m(a,t)}{\partial a} = -[\mu_m(a,V) + {}_D\alpha_w(t) + {}_D\alpha_s(t) + {}_P\alpha(t)]n_m(a,t) + \tau_m(a^\zeta),$$

$$n_f(0,t) = \int_0^\infty m(a,V)n_f(a,t)da,$$

$$n_s(0,t) = \psi \cdot n_f(0,t),$$

$$n_f(a,0) = n_{f,0}(a),$$

$$n_s(a,0) = 0,$$

$$n_m(a,0) = n_{m,0}(a)$$

where $n_f(a,t)$, $n_s(a,t)$ and $n_m(a,t)$ were the densities of fertile females, sterile females and males at age a and time t respectively, $\mu_f(a,V)$, $\mu_s(a,V)$ and $\mu_m(a,V)$ and were the natural per capita mortality rates for fertile females, sterile females and males respectively (which were all a function of age a and total standing vegetation dry matter V), ${}_P\alpha(t)$ was the mortality rate due to poisoning, ${}_D\alpha_w(t)$ and ${}_D\alpha_s(t)$ were the mortality rates due to infection with the wild strain (non-sterilising myxoma virus, MV) and sterilising strain of myxoma (sterilising myxoma virus, SMV) respectively, $\tau_f(a^\zeta)$ and $\tau_m(a^\zeta)$ were the immigration rates of fertile females and males respectively of age a^ζ , $n_f(0,t)$ and $n_m(0,t)$ and were the densities of fertile female and male births respectively, $m(a,V)$ was the maternity function (female births per female, and ψ is the sex ratio of newborns (males/females). The initial densities of fertile females and males were given by the vectors $n_f(a,0)$ and $n_m(a,0)$. The initial density of sterile females, $n_s(a,t)$, was zero. A flowchart of the model (Figure 1) shows the steps in the execution of the code.

Functional response

To calculate the age-specific functional response of rabbits we first estimated the weight of rabbits as a

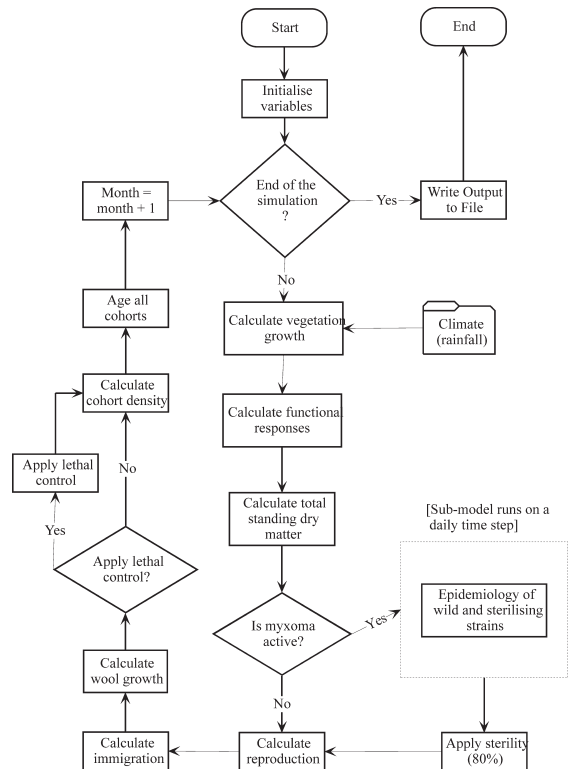


Figure 1. Flowchart of the main model.

function of age. We then used a functional response derived for rabbits (Short, 1985) that predicted food intake as a function of metabolic weight. By substituting the metabolic weight of rabbits as a function of age into the functional response equation we were able to predict food intake as a function of age.

We used previously published data on the growth rates of rabbits (Dunnet, 1956; Dudzinski and Mykytowycz, 1960) to determine body weight as a function of age. A Gompertz function was used to model this relationship (Eqn (2))

$$w_a = k \cdot \exp \left\{ -\exp \left[-q(a-r) \right] \right\} h \quad \text{Eqn (2)}$$

where w_a was the body weight (g) of a rabbit aged a days, and k (the upper asymptote, measured in g), q (the growth rate, measured in g day^{-1}) and r (the time of maximum growth, measured in days) were fitted parameters. Parameters were found by maximum likelihood, assuming normally distributed observation errors. The parameter h converted daily growth to monthly growth. We assumed that there were no differences in growth rate between the sexes.

In the absence of a functional response derived for rabbits on the pasture at the study site where the population data used in the model were collected, we used the functional response derived by Short (1985) for rabbits grazing an arid pasture (Eqn (3)). Rabbit body weight as a function of age (Eqn (2)) could be substituted into Eqn (3) and pasture consumption as a function of age could be calculated. Short's (1985) function was

$$F_r = g \cdot h \left[1 - \exp(-j \cdot TSDM) \right] \left[w_a^{0.75} \right] \quad \text{Eqn (3)}$$

where F_r was the functional response of rabbits ($\text{kg kg}^{-0.75} \text{ month}^{-1}$) per metabolic kg of body weight, w_a was body weight (kg) of a rabbit aged a days. The parameters g (the maximum food intake rate, kg day^{-1}) and j (the inverse of the pasture biomass at which a fraction ($1 - e^{-1} \approx 0.63$) of the maximum intake rate is attained) were fitted parameters (see Short (1985) for details on how these parameters were fitted). The parameter h converted daily intake to monthly intake.

Total pasture consumption per month by rabbits (F_i) was calculated by summing over all cohorts and both sexes.

Reproduction

The age- and month-specific number of births was

$$B_{\theta,a,y} = F_{a,y} M_{a,y} E_a b_{\theta} \quad \text{Eqn (4)}$$

where $B_{\theta,a,y}$ was the number of births of sex θ from

females aged a in month y , $F_{a,y}$ was the density of fertile female rabbits, $M_{a,y}$ was age-specific frequency of pregnancy, E_a was age-specific embryonic litter size, and b_{θ} was the proportion of embryos that were of sex θ . $M_{a,y}$, E_a and b_{θ} were derived from Twigg *et al.* (1998b).

Cohort survival

Using the data of Twigg *et al.* (2000), a Weibull function (Eqn (5)) was used to predict the age specific survival of fertile females, sterile females, and males

$$l_{a,i} = \exp \left[-(\lambda a_i)^{\gamma} \right] \quad \text{Eqn (5)}$$

where $l_{a,i}$ was the proportion of individuals surviving from birth to age a that were in class i (fertile female and male, or sterile female), λ is a shape parameter that describes the instantaneous death rate per unit time and γ is a dimensionless scale parameter. Parameter values were found by maximum likelihood, assuming normally distributed observation errors.

Density dependence

The functions for age-specific mortality and reproduction do not implicitly include density dependent terms. Density dependence was included by multiplying age-specific survival and reproductive output by a modifying term that was a function of pasture biomass (Eqns 6 and 7, respectively). Following the method of McCallum (1994) we used a logistic function, which had the effect of scaling survival or reproductive output. If pasture biomass was high and not limiting then survival and reproductive output were at their maximum level. But as pasture biomass declined below a threshold of about 2500 kg ha^{-1} , survival and reproductive output were reduced (L. Twigg, unpubl. data). Density dependence occurred via a negative feedback loop caused by rabbits consuming pasture, which reduced survival and reproductive output.

Pasture biomass was assumed to influence survival and reproductive output via the following logistic relationships:

$${}_{DD}B_a = {}_{DI}B_a \left[\frac{\exp(\omega + \beta \cdot TSDM_{t-1})}{1 + \exp(\omega + \beta \cdot TSDM_{t-1})} \right] \quad \text{Eqn (6)}$$

and,

$${}_{DD}I_a = {}_{DI}I_a \left[\frac{\exp(\omega + \beta \cdot TSDM_{t-1})}{1 + \exp(\omega + \beta \cdot TSDM_{t-1})} \right] \quad \text{Eqn (7)}$$

where ${}_{DD}B_a$ was age-specific reproductive output modified by the density-dependent term, ${}_{DI}B_a$ was age-

specific reproductive output unmodified by the density-dependent term, $_{DD}l_a$ was age-specific survival modified by the density-dependent term, l_a was age-specific survival unmodified by the density-dependent term and $TSDM_{t-1}$ was the previous month's total standing dry matter (pasture biomass). The constants ω and β are shape parameters of the logistic function that have no obvious biological interpretation. No data were available to estimate ω and β so values were chosen until the predicted time series provided a close fit to the observed time series. The predicted time series provided a reasonable match to the observed data (Fig.1).

Immigration

The rate of immigration was set at a constant rate of 0.1 rabbits $ha^{-1} month^{-1}$. All immigrants were 9 months old and were fertile. A preliminary sensitivity analysis indicated that while immigration of fertile rabbits was important, the results were relatively insensitive to immigration rate. The rate chosen was representative of the immigration rates observed at the study site (Twigg *et al.*, 1998a).

Epidemiological model

In the model rabbits became infected with myxomatosis in the months October, November or December. These months were chosen to mimic the pattern of myxomatosis at the field site used by Twigg and his colleagues, where mosquitoes, the main vector of myxomatosis, were mainly active in late spring or early summer (Kerr *et al.*, 1998; Twigg *et al.*, 2000).

The epidemiological model was based on the compartmental approach that is popular for studying disease dynamics in wildlife populations (Anderson and May, 1978, 1979; May and Anderson, 1978, 1979; Anderson *et al.*, 1981; Pech and Hone, 1988), and was modified to include age and sex structure.

In the model, susceptible rabbits could be infected with either MV or SMV. The probability of being infected by a strain depended on the number of contacts between hosts and vectors, the probability that a vector contacted an infectious host, and the probability that the contact resulted in successful disease transmission. Hosts either died from infection at a strain-specific rate, or they recovered. Females that recovered from infection with the wild strain remained fertile and immune for life, while females that recovered from infection with the sterilising strain became sterile and immune for life. However, some females that were infected with the sterilising strain did not respond to the immunocontraceptive agent and remained fertile (Figure 3a). These individuals were termed non-responders. Recovered males remained fertile irrespective of which strain they were infected with and remained immune for life against reinfection from

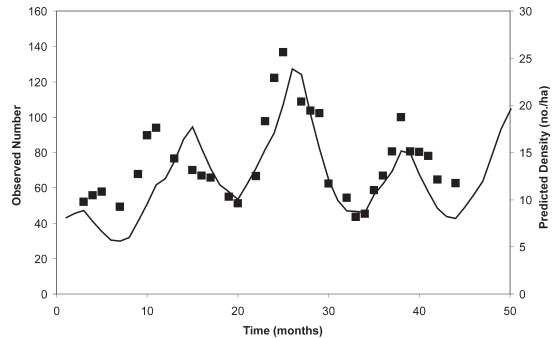


Figure 2. Observed number of rabbits captured at the study site in Wellstead, Western Australia (Twigg *et al.*, 1998b, 2000). Data are from a control site where no female rabbits were sterilised (solid squares are observed number). The continuous line is the predicted time series of rabbit density from the model. Myxomatosis epizootics were included in 3 of 4 years following the observations of Twigg *et al.* (1998b).

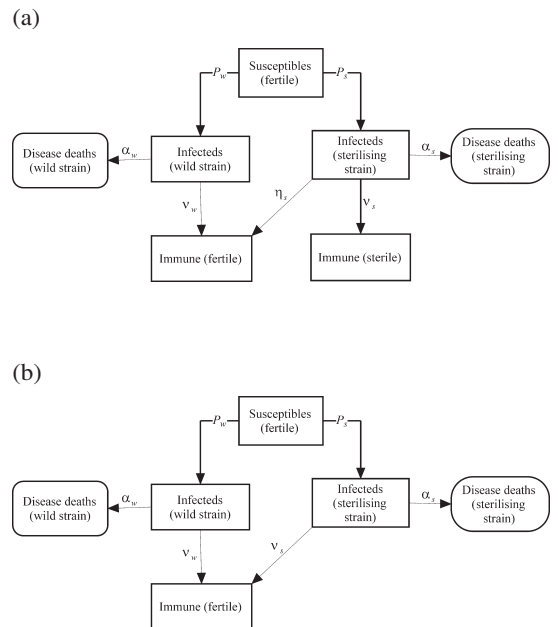


Figure 3. Flowchart of (a) female and (b) male epidemiological sub-models.

either strain of myxoma virus (Figure 3b). We did not include any effects of RHD as this would have added considerably to the complexity of the models.

The age and sex structured epidemiological model was

$$\begin{aligned} \frac{\partial S_m(a,t)}{\partial t} + \frac{\partial S_m(a,t)}{\partial a} &= -P_w S_m(a,t) - P_s S_m(a,t), \\ \frac{\partial S_f(a,t)}{\partial t} + \frac{\partial S_f(a,t)}{\partial a} &= -P_w S_f(a,t) - P_s S_f(a,t), \\ \frac{\partial Y_{m,w}(a,t)}{\partial t} + \frac{\partial Y_{m,w}(a,t)}{\partial a} &= P_w S_m(a,t) - (\alpha_w + \nu_w) Y_{m,w}(a,t), \\ \frac{\partial Y_{m,s}(a,t)}{\partial t} + \frac{\partial Y_{m,s}(a,t)}{\partial a} &= P_s S_m(a,t) - (\alpha_s + \nu_s) Y_{m,s}(a,t), \\ \frac{\partial Y_{f,w}(a,t)}{\partial t} + \frac{\partial Y_{f,w}(a,t)}{\partial a} &= P_w S_f(a,t) - (\alpha_w + \nu_w) Y_{f,w}(a,t), \\ \frac{\partial Y_{f,s}(a,t)}{\partial t} + \frac{\partial Y_{f,s}(a,t)}{\partial a} &= P_s S_f(a,t) - (\alpha_s + \nu_s + \eta_s) Y_{f,s}(a,t), \\ \frac{\partial Z_m(a,t)}{\partial t} + \frac{\partial Z_m(a,t)}{\partial a} &= \nu_w Y_{m,w}(a,t) + \nu_s Y_{m,s}(a,t), \\ \frac{\partial Z_{f,w}(a,t)}{\partial t} + \frac{\partial Z_{f,w}(a,t)}{\partial a} &= \nu_w Y_{f,w}(a,t) + \eta_s Y_{f,s}(a,t), \\ \frac{\partial Z_{f,s}(a,t)}{\partial t} + \frac{\partial Z_{f,s}(a,t)}{\partial a} &= \nu_s Y_{f,s}(a,t) \end{aligned}$$

where $S_m(a,t)$ and $S_f(a,t)$ were the density of susceptible males and susceptible females, respectively, at age a and time t , $Y_{m,w}(a,t)$ and $Y_{m,s}(a,t)$ were the densities of males infected and infectious with the wild strain and sterilising strain respectively, $Y_{f,w}(a,t)$ and $Y_{f,s}(a,t)$ were the densities of females infected and infectious with the wild strain and sterilising strain respectively, $Z_m(a,t)$ was the density of immune males, $Z_{f,w}(a,t)$ and $Z_{f,s}(a,t)$ were the densities of immune and fertile females and immune and sterile females respectively, P_w and P_s were the probabilities of being successfully infected with MV and SMV respectively, α_w and α_s were the disease-induced mortality rate of the wild strain and sterilising strain respectively, ν_w and ν_s were the disease recovery rates for the wild strain and the sterilising strain respectively, and η_s was the rate at which females infected with the sterilising strain recover from infection with the sterilising strain but do not become sterile.

Transmission of myxoma

Although rabbit fleas and mosquitoes are important transmission vectors at the localised level, mosquitoes are believed to be the main vector for transmitting the

virus between areas (Fenner and Ratcliffe, 1965; Kerr and Best, 1998; Kerr *et al.*, 1998). Consequently, we assumed that myxoma virus transmission only occurred via mosquito vectors and used a frequency dependent transmission function to calculate the probability of transmission (Thrall *et al.*, 1995). Frequency dependent transmission is thought to be appropriate for diseases that are transmitted by vectors (Thrall and Burdon, 1997; McCallum *et al.*, 2002). The probability of virus transmission was

$$P_i = 1 - \left(1 - \delta_i \frac{Y_i}{N_i} \right)^n \quad \text{Eqn (8)}$$

where P_i was the probability of becoming infected with strain i after n contacts with vectors, Y_i/N_i was the probability of vector-mediated contact with an infected host (equivalent to disease prevalence), and δ_i was the probability of successful transmission.

Overwintering of myxoma

In the epidemiological model we assumed that myxomatosis epizootics were associated with the activity of mosquito vectors only. Although we

acknowledge that fleas may play a part in disease transmission, at the Wellstead study site mosquitoes were the most important vector (Twigg *et al.*, 1998b, 2000). We assumed that myxoma virus overwintered (see Fenner and Fantini, 1999) in the rabbit population with a prevalence of 1%. It was from this infected and infective group that epizootics were initiated in the spring-summer period.

Modelled strains of myxoma

Only two strains of myxoma virus were considered in the model, although in natural populations of rabbits many strains may be active at any one time (Merchant *et al.*, 2003b). For the purpose of the model the strains were identical in their epidemiological characteristics (i.e. probability of successful transmission, mortality rate, recovery rate) except that one strain caused sterility in females while the other did not. Competition between myxoma virus strains occurs between but not within hosts, since superinfection does not occur and infection by any one strain elicits life-long cross-protective immunity against reinfection with any other strain (Fenner and Ross, 1994). Thus, competition for hosts is analogous to competition for space (*sensu* Schoener, 1983); once a rabbit is 'occupied' by a strain of myxoma it cannot be 'occupied' by any other strain.

Sheep productivity model

The benefits of the various methods of rabbit control were examined using a sheep productivity model. This model was used to estimate wool growth under various management scenarios. All sheep were assumed to be 40-kg fine-wool merino wethers. The stocking rate of sheep was held constant. Although in a natural system stocking rate is rarely constant, the important comparisons in this study were between strains of SMV and MV, and their efficacy compared with alternative control methods such as poisoning.

Sheep functional response

The modelled food intake rate of sheep was based on the food intake rate model of Langlands and Bennett (1973), derived from fine-wool merino sheep grazing a temperate pasture of mixed *Phalaris tuberosa*–*Trifolium repens*, which was similar to the pasture mix at Wellstead (Twigg *et al.*, 1998b, 2000).

The functional response of sheep was

$$F_s = \frac{\kappa \cdot 10^{(-\%TSDM)}}{FFW^{0.75}} \cdot h \quad \text{Eqn (9)}$$

where F_s was daily food intake ($\text{kg day}^{-1} \text{kg}^{-0.75} \text{FFW}$), κ was maximum food intake per day [which for a 40-kg merino sheep was assumed to be $1.099 \text{ kg day}^{-1}$, after Langlands and Bennett (1973) and Short

(1985)], $TSDM$ was total standing dry matter (kg ha^{-1}), FFW was fleece-free weight (kg), c was the pasture biomass that corresponds to the inflection point of the functional response (kg ha^{-1}) and h was a constant that converted daily food intake to monthly intake. The parameter c was found by maximum likelihood, assuming observation errors were normally distributed.

Wool growth

We derived a simple function for monthly wool growth as a function of food intake rate using the data of Pattie and Williams (1967). An inverted exponential function was fitted to the data

$$W_s = d \left[1 - \exp\left(-\frac{F_s}{f}\right) \right] \cdot FFW^{0.75} \cdot h \quad \text{Eqn (10)}$$

where W_s was fleece growth ($\text{g sheep}^{-1} \text{month}^{-1}$), and F_s and FFW are as previously defined for Eqn (9). Parameter d is the maximum fleece growth rate ($\text{g sheep}^{-1} \text{month}^{-1}$), f was the food intake rate at which a fraction ($1 - e^{-1} \approx 0.63$) of the maximum daily food intake rate per kilogram of metabolic body weight was attained ($\text{g day}^{-1} \text{kg}^{-0.75} \text{FFW}$) and h was a constant that converted daily fleece growth to monthly growth. Parameters were fitted by maximum likelihood assuming that observation errors were normally distributed.

Cost-effectiveness analysis

Cost-effectiveness analysis can be used to find the least expensive way to achieve a pre-determined threshold in animal abundance or impacts (Bicknell, 1993). It can also be used to compare methods and strategies when pest numbers need to be held under a threshold. In Australia, there have been few attempts to quantify this relationship for rabbits (Fennessy, 1966; Croft *et al.*, 2002; Fleming *et al.*, 2002) and the rabbit density damage function remains poorly defined. Therefore, it was not possible to set meaningful pest density or damage thresholds *a priori*. As an alternative, we examined a range of combinations of sterilisation and lethal control, without pre-defining a threshold against which efficacy and cost-effectiveness could be measured. Optimal control strategies were defined as those that provided the best balance between maximising efficacy and minimising cost. We assumed that epizootics of MV and SMV would spread naturally rather than by repeated deliberate releases and so bore no costs. Poison baiting, on the other hand, incurred costs.

For the purpose of determining the benefits of SMV two main comparisons were examined; poison baiting in the presence of MV only, and poison baiting in the presence of both MV and SMV. Cost-

effectiveness was examined by comparing the ratio of payoff (a surrogate for effectiveness) to the costs of poisoning.

Poison baiting

Poisoning rabbits with Compound 1080 (sodium fluoroacetate) is one of the most widely used methods of control and is an effective way of quickly reducing rabbit numbers (Williams and Moore, 1995; Williams *et al.*, 1995). A comprehensive study on the costs of controlling rabbits in temperate pastures (Williams and Moore, 1995) found that ground laying of poison baits cost about A\$7.00 ha⁻¹ in 1991. Since we were concerned with the accumulated costs of controlling rabbits between the years 1970 and 2000, we first converted this amount (A\$7.00 in 1991) to an equivalent cost in 1970 by rearranging Eqn 11, to give initial cost in terms of future cost, inflation (set at 3.5% per annum based on the average Consumer Price Index 1985–2004) and time. We calculated that in 1970 ground baiting cost about A\$3.16 ha⁻¹. We used these costs for examining cost-effectiveness. We assumed that poison baits killed 75% of each cohort.

We examined two types of baiting: threshold baiting and interval baiting. Threshold baiting involved monitoring pest population density, and initiating a baiting campaign if pest density exceeded a predetermined threshold. We examined a range of thresholds from 2.5 rabbits ha⁻¹ to 25 rabbits ha⁻¹ in increments of 2.5 rabbits ha⁻¹. The cost of monitoring was not included in the model. Interval baiting involved baiting at a predetermined time interval irrespective of the state of the system (i.e. rabbit density had no bearing on the decision of when to bait). We examined a range of intervals between baiting campaigns ranging from every 12 months to every 120 months (10 years) in 12-month increments. For comparative purposes a 'no baiting' treatment was also included, which provided a reference point against which the efficacy of baiting treatments could be measured.

Future cost

We carried out a retrospective analysis where the cost of management was accumulated (summed) over the years 1970–2000. If there were multiple costs then the accumulated future cost (*FC*) over the period *T* was simply

$$FC = \sum_{t=0}^T I_c (1 + \pi)^t \quad \text{Eqn (11)}$$

where *I_c* was the initial cost of management, π was the inflation rate, and *t* was the number of years that had elapsed.

Payoff

Hood *et al.* (2000) coined the term 'payoff' to refer to the degree of host population suppression by a sterilising virus. Their derivation was based on the earlier work of Beddington *et al.* (1978) who were interested in measuring the impact that a parasitoid had on its host. Both of these studies were interested in equilibrium population sizes in the presence and absence of a presumed limiting factor, a sterilising virus and parasitoid respectively. We modified the payoff function described by Hood *et al.* (2000) so that it was applicable to non-equilibrium populations. There were two types of payoff functions used; the first for determining the degree of suppression of host population density by the introduction of a sterilising agent (Eqn(12)), and the second for determining the degree of relief, in terms of increased pasture availability and wool growth, from the introduction of the sterilising agent (Eqn (13)).

The payoff in terms of reduced population size of rabbits was

$$O_N = \frac{1}{T} \sum_{t=1}^T \left(1 - \frac{N_t^{w+s}}{N_t^w} \right) \quad \text{Eqn (12)}$$

where *O_N* was the payoff in terms of reduced mean population size, *N_t^{w+s}* was the population size at time *t* in the presence of the MV and SMV, *N_t^w* was the population size at time *t* in the presence of MV only, and *T* was the total time over which the projection was made.

The payoff in terms of increased amount of pasture (or wool growth) was

$$O_V = \frac{1}{T} \sum_{t=1}^T \left(1 - \frac{V_t^w}{V_t^{w+s}} \right) \quad \text{Eqn (13)}$$

where *O_V* was the payoff in terms of increased pasture biomass, *V_t^{w+s}* was pasture biomass at time *t* in the presence of the MV and SMV, *V_t^w* was pasture biomass at time *t* in the presence of MV only, and *T* was the total time over which the projection was made.

Results

In the following series of analyses we examined the effect of threshold baiting on (a) rabbit density, (b) available pasture and (c) wool growth, and then examined the effect of regular baiting on these same variables. For the analyses examining rabbit density and pasture availability rabbits grazed the pasture alone, but for the analysis of wool growth the rabbits shared the pasture with sheep.

Threshold baiting

As the threshold density for triggering a baiting campaign declined, the benefits of using VVIC also declined (Fig. 4a). At low baiting thresholds there was virtually no difference between the mean densities of rabbits. As the threshold increased, the difference between the mean densities of rabbits in the presence of MV only and SMV + MV increased in magnitude. This resulted in an increase in payoff in the presence of SMV as the threshold for initiating a baiting campaign increased.

The mean total standing dry matter (available pasture) declined as the baiting threshold increased (Fig. 4b). The projected mean pasture biomass realised in the presence of MV only or in the presence of SMV and MV decreased as the threshold for baiting increased, but the difference in mean pasture biomass was small (5 kg ha⁻¹; range in pasture biomass, 1963–1968 kg ha⁻¹). The small difference in pasture availability resulted in only a small payoff. It is worth noting that if the baiting threshold was set at a low level (e.g. 2.5 rabbits ha⁻¹), the payoff from using a combination of VVIC and baiting was negligible since the effect of poisoning was much greater in magnitude than the effect of SMV. However, as the threshold was increased the payoff improved but was still relatively small.

The pattern in wool growth and payoff (Fig. 4c) was similar to the pattern for available pasture (Fig. 4b). Mean wool growth per sheep per month declined as the threshold for rabbit management increased. The projected mean wool growth realised in the presence of MV only or in the combined presence of SMV and MV decreased as the threshold for baiting increased, but the difference in mean wool growth was small (0.3 g sheep⁻¹ month⁻¹; range in wool production, 247.4 to 247.7 g sheep⁻¹ month⁻¹). This small difference resulted in a corresponding small payoff. It appeared that, as in the payoff for available pasture, the overall effect of poisoning was much greater than the effect of sterilisation by VVIC.

Regular baiting

The advantage of using VVIC declined as the interval between baiting campaigns shortened (Figure 5a). At a 12-month interval there was little difference between the mean density of rabbits in the presence of MV only or in the presence of SMV + MV. As the interval between baiting campaigns increased, the difference between the projected rabbit density with and without VVIC increased in magnitude and resulted in an increased payoff when SMV was present.

The mean total standing dry matter (available pasture) declined as the interval between baiting increased (Figure 5b). The projected mean pasture biomass realised in the presence of MV only or in the

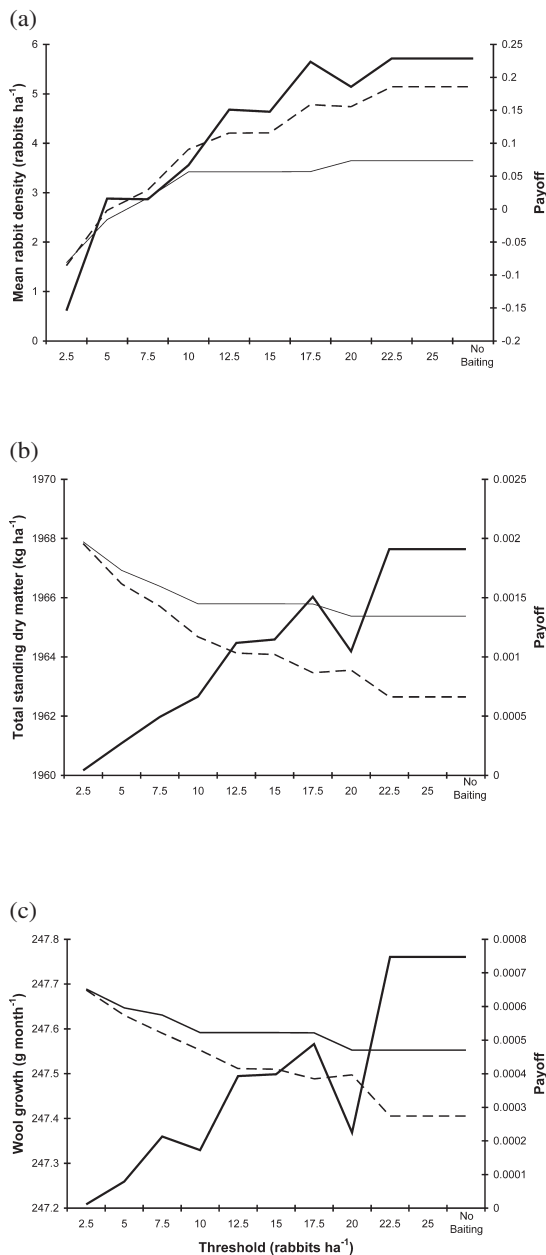


Figure 4. (a) Mean rabbit density (rabbits ha⁻¹) and payoff using a SMV achieved by varying the threshold for triggering lethal baiting campaigns. (b) Mean total standing dry matter (kg ha⁻¹) and payoff achieved by varying the threshold for triggering lethal baiting campaigns. (c) Mean wool growth (g sheep⁻¹ month⁻¹) and payoff achieved by varying the threshold for triggering lethal baiting campaigns. Thick solid lines are payoff, thin dotted lines are the presence of MV only, and thin lines are the presence of SMV + MV.

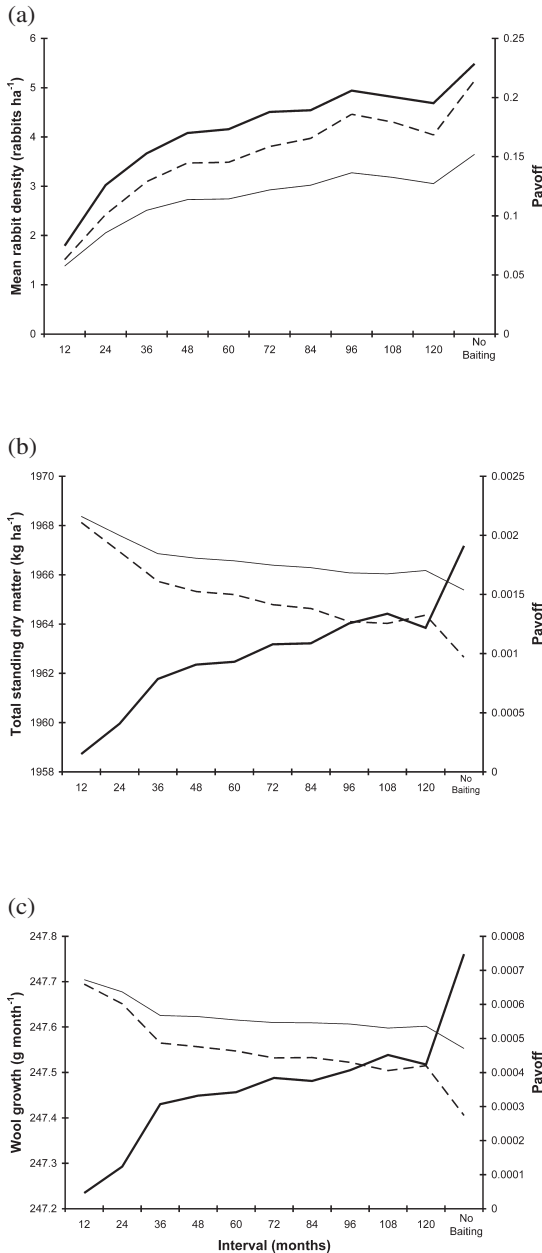


Figure 5. (a) Mean rabbit density (rabbits ha⁻¹) and payoff of using a SMV achieved by varying the interval between lethal baiting campaigns. (b) Mean total standing dry matter (kg ha⁻¹) and payoff achieved by varying the interval between lethal baiting campaigns. (c) Mean wool growth (g sheep⁻¹ month⁻¹) and payoff achieved by varying the interval between lethal baiting campaigns. Thick solid lines are payoff, thin dotted lines are the presence of MV only, and thin lines are the presence of SMV + MV.

presence of SMV and MV decreased as the interval increased, but the difference in mean pasture biomass between these scenarios was small (4 kg ha⁻¹; range in pasture biomass, 1964–1968 kg ha⁻¹). The small difference in pasture availability resulted in only a small payoff. If the interval was set at a low level, for example 12 months, the payoff from VVIC was marginal since the effect of poisoning was much greater in magnitude than the effect of SMV. However, as the interval increased the payoff from VVIC was greater, but still relatively small.

The pattern in wool growth and payoff (Figure 5c) was similar to the pattern for available pasture (Figure 5b). Mean wool growth per sheep per month declined as the interval between baiting campaigns increased. The projected mean wool growth realised in the presence of MV only or in the combined presence of SMV and MV decreased as the interval between baiting increased, but the difference in mean wool growth was small (0.2 g sheep⁻¹ month⁻¹; range in wool growth, 247.5 to 247.7 g sheep⁻¹ month⁻¹). This resulted in only a small payoff from SMV. It appeared that, as in the payoff for available pasture, the effect of poisoning was much greater than the effect of sterilisation.

Cost-effectiveness analysis

The effectiveness/cost ratio of threshold baiting increased as the threshold to initiate a baiting programme increased (Figs 6a and b). In terms of effectiveness/cost ratio, there was no apparent benefit to setting the threshold lower than about 8 rabbits ha⁻¹ since the ratio was close to zero. The effectiveness/cost ratio of interval baiting also improved as the time interval between baiting programmes increased (Figure 7a and b). However, if the management goal was cost-effective management of rabbits, then our results suggest that it was more cost effective to let natural epizootics of myxomatosis regulate rabbit populations, than to undertake either threshold or interval baiting.

A comparison of the effectiveness/cost ratio for threshold baiting and interval baiting indicates that for all payoff variables (rabbit density, available pasture and wool growth) threshold baiting was at least an order of magnitude more cost effective than interval baiting. This result reflected the reduced cost of maintaining a threshold baiting strategy, relative to the costs of interval baiting, and that the payoff for the two baiting strategies was similar.

Regardless of how effective poisoning was at reducing rabbit numbers, the benefits in terms of increased pasture availability and wool growth were unlikely to outweigh the costs incurred during the poisoning campaign. The most cost-effective control remained natural epizootics of myxomatosis, but there was also some small additional benefit from the release of SMV.

Discussion

The most obvious form of damage by rabbits is caused by their grazing. At high densities, rabbits can form a large component of total grazing pressure. At low densities rabbits can still impact upon native vegetation by consuming seedlings and rare plants (Lange and Graham, 1983; Cooke, 1987). Grazing competition occurs when the food removed by rabbits prevents other herbivores from reaching their maximum intake or restricting their dietary selection to less favourable foods. There is evidence of competition between sheep and rabbits in eastern New South Wales where sheep live weight and clean fleece weight were reduced when rabbits were maintained at a high density of 72 rabbits ha⁻¹ (Fleming *et al.*, 2002). However, wild rabbit populations are rarely maintained at such high

densities, since their dynamics are better characterised as irruptive where they reach high densities for only short periods and then crash to low density once they overexploit their food resource (Williams *et al.*, 1995). As a consequence of this irruption-crash cycle, overgrazing by rabbits is frequently short-lived and localised, and the secondary effects of food availability on primary production (e.g. sheep weight gain or wool growth) may be relatively small or short-term.

Other damaging effects of rabbits include grazing-induced changes in pasture species composition (Croft *et al.*, 2002), soil erosion (Williams *et al.*, 1995), preventing vegetation regeneration (Lange and Graham, 1983) and physically displacing native species (Calaby, 1969; Robley *et al.*, 2002). These issues could not be dealt with in the current study and remain opportunities for future research.

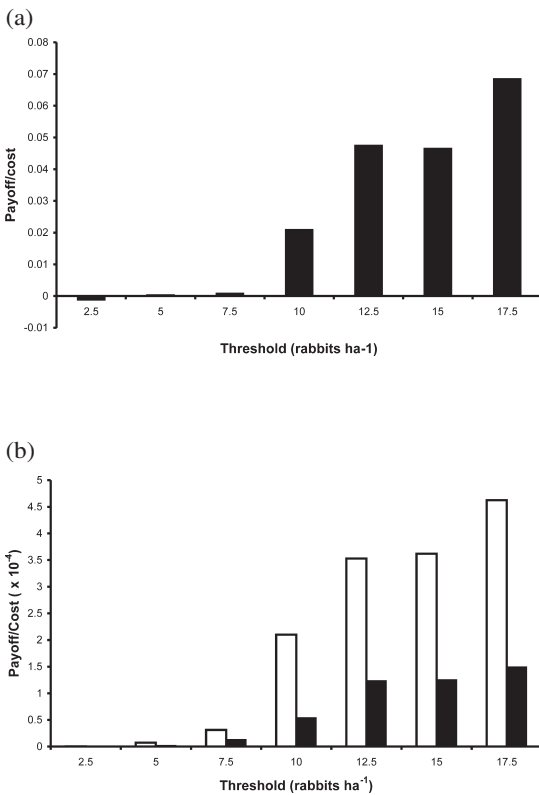


Figure 6. Cost effectiveness (payoff/cost) of (a) using VVIC and lethal control, in terms of rabbit density, of varying the threshold (rabbit density) used as a trigger for lethal baiting campaigns, and (b) in terms of available pasture (open) and wool growth (solid) of varying the threshold (rabbit density) used as a trigger for lethal baiting campaigns.

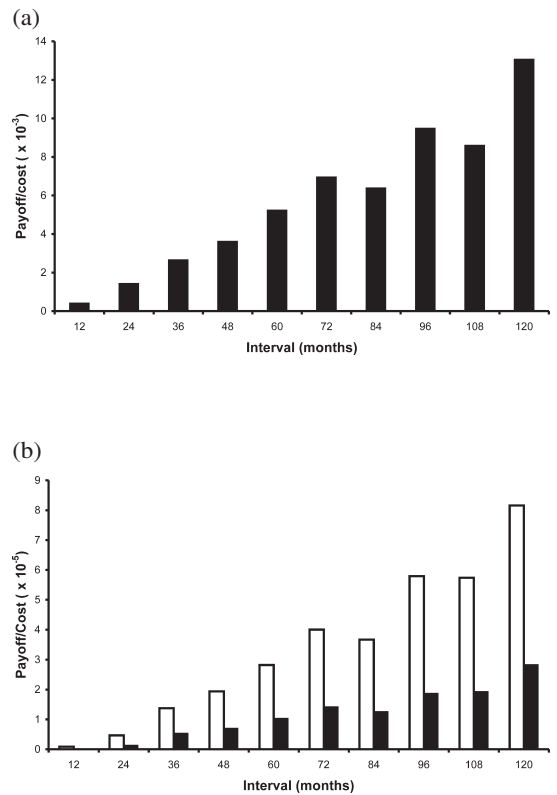


Figure 7. Cost effectiveness (payoff/cost) of (a) using VVIC and lethal control, in terms of rabbit density, of varying the interval between lethal baiting campaigns and (b) in terms of available pasture (open) and wool growth (solid) of varying the interval between lethal baiting campaigns.

Our bioeconomic analysis indicated that the benefit (measured by the payoff/cost ratio) to primary productivity from poison baiting in the presence of annual epizootics of myxomatosis is small. Lethal management, such as poisoning, warren ripping and fumigation, is expensive. Costs incurred in using these methods must be recouped through increased productivity (e.g. increased live weight, wool growth or stocking rate) or some other clearly stated performance indicator (e.g. environmental protection). In our analysis, there were only small increases in wool production associated with lethal management when annual cycles of myxomatosis were included, and our results suggest that it may be uneconomic to use poisoning in areas where myxomatosis (and/or RHD) is regularly active. This result depends on the modelled relationships between rabbit grazing, pasture growth and sheep productivity. Unfortunately, there were no data available to validate these relationships, so confidence in these findings remains equivocal. Furthermore, alternative lethal methods such as warren ripping can provide longer-term rabbit population control than poisoning (Williams and Moore, 1995) but warren ripping is not suitable for many habitats (e.g. native vegetation or rocky outcrops). Using a different method of control will affect cost-effectiveness, but unfortunately such analyses were beyond the scope of the present study. Regardless of the degree of confidence in our modelled outcomes, there is a clear need to better define the density–damage relationship between rabbit grazing and primary productivity. This relationship is currently poorly understood, and the few studies that have attempted to examine these aspects have produced equivocal results (Croft *et al.*, 2002; Fleming *et al.*, 2002).

A genetically marked, unmodified strain of myxoma has been successfully introduced into rabbit populations in eastern Australia (Kerr *et al.*, 2003; Merchant *et al.*, 2003a, 2003b). This is encouraging with respect to introducing SMV. However, the introduced strain only persisted on the study sites between 62 and 174 days, which Merchant *et al.* (2003a) hypothesised was most likely due to competition from wild-type viruses. These trials demonstrated that the success of introducing a new strain of myxoma virus may depend on the absence or low prevalence of wild strains of myxoma virus at the release site. Thus, the serology of rabbits and the prevalence of wild-types of myxoma virus would need to be determined before a deliberate release. This would all add to the cost of a release, and would make the benefit/cost ratio less favourable.

It has been suggested that VVIC will be most useful in conservation areas where habitat is highly valued and cannot be destroyed (e.g. by warren ripping)

for the purpose of managing rabbits (Williams, 1997). The results of our models suggest that VVIC using a recombinant myxoma virus will reduce rabbit densities, even in the presence of a competing strain of myxoma. However, it is not clear that this reduction in density will enable management goals to be met since the relationship between rabbit density and damage in conservation areas is poorly understood. If rabbit density must be reduced below some threshold, such as 1 to 2 rabbits ha⁻¹, as suggested by Lange and Graham (1983), to permit *Acacia* seedlings to survive and mature stands of trees to regenerate, then VVIC and myxomatosis alone are unlikely to be successful in achieving the required decrease in rabbit numbers. Again, there is a clear need to better define the relationship between rabbit density and environmental and agricultural damage.

Because it acts by decreasing birth rates, and hence the number of pest animals that need to be destroyed, immunocontraception is viewed as an ethical and, overall, a more humane method of population control than alternatives such as poisoning (Barr *et al.*, 2002). However, the decision to use the myxoma virus as the vector for the immunocontraceptive agent in rabbits is controversial due to the suffering associated with this disease (Oogjes, 1997). Myxomatosis is a lethal disease of rabbits causing conjunctivitis that can lead to temporary blindness, swelling of the head and genital region, and lesions on the body (Fenner and Ross, 1994). Infected animals can have a prolonged period of suffering before death or recovery. However, Oogjes (1997) suggests that the 'total ethical "cost" comparison' may still favour VVIC using a modified myxoma virus over other methods of population control. Nevertheless, these doubts over the use of immunocontraception would not have arisen if the sterilising agent was able to be distributed in bait or by an agent with relatively mild physiological side-effects. The issue of competition between strains may also have been minimised, at least in the first instance, if the vector chosen was not currently present in Australian rabbit populations. An immunocontraceptive bait which contains the antigen that induces the immunocontraceptive response in rabbits may also overcome the problem of acquired immunity to myxomatosis with VVIC. Given the potential efficacy of fertility control when acquired immunity to myxomatosis is not important, e.g. 70–77% reduction in mean density (McLeod *et al.*, 2004), using a bait to distribute the contraceptive agent may be a profitable opportunity for future research. However, the practicality and benefits/costs of such an approach for the broad-scale control of rabbits would require careful consideration.

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