Department of Economics and Marketing
Discussion Paper No.27

An Optimal Control Model for Pest Management Under Bait-shyness

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December 1996

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ISSN 1173-0854
ISBN 1-877176-04-4

Abstract

This paper presents a dynamic bioeconomic model of vertebrate pest management which incorporates a behavioural trait in the target population known as toxin or bait avoidance. Pests who exhibit such avoidance after exposure to control operations are subsequently referred to as 'bait-shy'. Optimal control theory provides the theoretical framework for the development of the model, which is then solved using non-linear programming. The model is applied to the empirical problem of rook control in the Canterbury Region of New Zealand. The relevant decision maker in the context of this empirical problem is the Canterbury Regional Council, whose objective is to minimise the sum of discounted control costs and rook inflicted damage over time. Decisions to control rooks are made yearly. A unique contribution of this model is the inclusion of a 'bait-shy' population, which develops when birds are exposed to sub-lethal doses of control. State variables include a population of susceptible and a population of "bait-shy" rooks, and the solution procedure determines the optimal control strategy through time. Numerical results from the model, subject to specific parameter values, highlight several important aspects regarding timing and efficacy of control.

KEYWORDS

Dynamic optimisation, bioeconomics, pest control, pest management, bait-shyness.

Kathryn Bicknell and Ross Lambie are Lecturer and Masters Student, respectively, Department of Economics and Marketing, Lincoln University. Senior authorship is not assigned.

This paper was presented at the Second Annual Conference of the New Zealand Agricultural Economics Society, Blenheim, New Zealand, July, 1995.

Acknowledgement

The authors wish to thank Rob Phillips and Paul Cornelius of the Canterbury Regional Council for making time available and providing us with the necessary background information on which this study is based.

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1. Introduction

The effective control of plant and animal pests is an important economic problem for private individuals attempting to protect production values and for governmental agencies in charge of managing resources for the public. Control programmes for vertebrate pests can become compromised, however, when individuals in the target population learn to recognise the bait or toxin as harmful, and thus avoid eating lethal doses during control operations. Such learned avoidance, known as 'shyness', is now known to be a particular problem with the poison sodium monofluoroacetate (or compound 1080). Shyness could consequently have a significant impact on the success of control programmes in New Zealand, where 1080 is one of the principal toxins in the campaign against vertebrate pests.

Rooks (*Corvus frugilegus*) were introduced into New Zealand as means of controlling pasture insect pests (Flynn, 1979). Since that time, however, the birds themselves have become a major nuisance to producers of commercial crops in areas where rook densities are high and invertebrate populations are low. The objective of control authorities in Canterbury is to eradicate rooks from the region. While past efforts have been highly successful at reducing rook numbers, the heavy reliance on 1080 may mean that shyness becomes a major problem in the few birds which have survived control operations to date.

In this paper we present a dynamic optimisation model for pest control under the threat of bait-shy behaviour. Optimal control theory provides the theoretical basis for the model, which is subsequently solved using nonlinear programming. The decision maker's objective is hypothesised to be the minimisation of control costs plus pest inflicted damage. The goal of the analysis is to more fully understand the tradeoff between current control of susceptible pests, and the development of a shy population that will not consume toxic baits. The inclusion of a damage function allows the determination of an economic balance between the costs of control and the benefits of higher agricultural yields.

The paper proceeds as follows. We first provide some detail on the control of rooks in Canterbury to motivate the empirical problem and identify key features which must be captured in the theoretical model. The literature is then surveyed for evidence of previous work on similar issues. While no economic analyses of the control of bait-shy populations were uncovered, the related problem of genetic resistance to chemical pesticides and herbicides has been studied in some detail, providing guidance on how to proceed with the current analysis. A mathematical model is then presented, along with variable definitions and parameter values for the empirical application.

Results suggest that when rook densities are low, the level of damage that they inflict on surrounding agricultural values does not warrant high levels of control. This general result is reinforced by the fact that frequent control operations increase the proportion of bait-shy individuals, further escalating the cost of control. These results are sensitive, however, to the specification of the cost and damage functions. Not surprisingly a greater degree of damage is associated with earlier control efforts, and subsequently lower rook numbers. Finally, the solution procedure allowed us to explore control strategies that were 'non-optimal' in the sense that policy constraints implied a very small target population. Although the results are highly dependant on model specification and parameter values, they do begin to shed light on the tradeoffs and welfare effects of current control strategies.

2. Rooks in Canterbury: The Empirical Problem

The establishment of rooks in Canterbury began with two liberations: one in 1871 involving five birds, and the other comprising thirty-five birds in 1873 (Bull, 1957). Both of these liberations occurred in Christchurch. Although the protected status of rooks was completely removed in 1919 (Flynn, 1979), population numbers increased to between 7000 and 10,000 birds by 1947 (Bull, 1957). The successful population growth during this period was assisted by favourable changes to the rook's habitat. While the conversion of pasture to arable land reduced invertebrate food supplies, commercial crops provided rooks with a ready substitute (Flynn, 1979). The removal of scrub and bush complemented the presence of suitable nesting trees such as *Pinus radiata, Eucalyptus sp.*, and *Cupressus macrocarpa* in creating conditions that were similar to the rooks' natural habitat (Bull, 1957).

The rook diet includes invertebrates, animal flesh from scavenging and predation of other birds nestlings, walnuts, acorns, cereals (usually in stubble fields), pulses, and grasses and clovers (Coleman, 1971; Purchas, 1976). Food availability is a major determinant of the rook's diet and feeding ranges (Coleman, 1971). While invertebrates are the preferred food source, in the event of dry summers or cold winters the availability of invertebrates declines and rooks spend more time eating cereals and pulses (Coleman, 1995).

Rooks foraging on commercial crops can cause damage at all stages of plant development; planting, sprouting and maturing (Porter et al., 1994). According to Purchas (1980), rooks spend 6% of their feeding time eating newly sown or ripening crops during the summer and less than 2% during other seasons. At low population numbers the impact of rooks is therefore negligible (Coleman, 1971). As the population increases, however, significant agricultural damage can result. Rookeries are re-occupied in early spring as breeding activity increases (Coleman, 1971). Eggs are laid between the end of August and beginning of November, depending on food availability (Coleman, 1972). Although brood sizes range from 1 to 6 chicks, no more than 4 chicks fledge from any one brood (Coleman, 1972). The breeding success of rooks has been observed to range from 12% to 38% in Canterbury (Coleman, 1972), suggesting without ongoing control rook populations could become problematic.

Coordinated control efforts, which included shooting, felling nesting trees, poisoning, trapping and scaring, began in 1945 and resulted in both large numbers of rooks killed and the extension of their breeding range through the fragmentation of rookeries (Bull, 1957). In the late 1950's rook control was undertaken by the Ministry of Agriculture and Fisheries (Canterbury Regional Council, 1991). Under the Animal Pest Destruction Act 1967 rooks were declared a pest of local importance in Canterbury and responsibility for control moved to the several Pest Destruction Boards covering the region. In 1989 the Canterbury Regional Council became responsible for undertaking control programmes as part of a reorganisation of local government. Control by the Regional Council has continued under the new legislative framework provided by the Biosecurity Act 1993. The area currently affected by rooks comprises three distinct sub areas; the Canterbury Plains bounded by the Waimakariri River to the north and the Rangitata River to the south, Banks Peninsula, and Kaikoura . Under the current control regime which began in 1992 the rook population has been reduced from an estimated 5,559 birds to less than 100 at the beginning of 1996.

The past 50 years of coordinated effort has highlighted several problems associated with rook control. Rooks are very mobile pests capable of causing crop damage over large areas, and feeding ranges during the non-breeding season can extend to 20km (Coleman, 1995). Any reduction in bird numbers is therefore beneficial to an affected region. However, past experience has shown that rook control by individual farmers has been ineffective and has probably contributed to the rook problem by fragmenting colonies and shifting them into new areas (Bull, 1957; Flynn, 1979). Rooks are also prone to bait-shyness (Flynn, 1976), which can be defined as the behavioural trait, either learned or non-learned, of avoiding toxins or baits. A consequence of shyness is that control activities undertaken early in the time horizon will reduce the effectiveness of future control, particularly if future control involves similar baits and/or toxins.

The difficulties mentioned above have important implications for how the rook control problem is viewed economically. In particular, there are at least three externalities associated with rook management that provide justification for the active involvement of a centralised control authority. Firstly, a land holder independently undertaking a successful rook control operation can not exclude adjoining land holders with similar economic objectives from enjoying the benefits of lower rook numbers. It is therefore possible that adjoining land holders may become *free riders* by benefiting from control without incurring any of the costs.

The application of control technology which is ineffective at killing a large percentage of a target population will also disperse the rook population over a wider area, due to the bird's propensity to spread when disturbed. In this situation adjoining land holders who do not undertake control may face a *negative diffusion externality* through the actions of a controlling land holder. The negative diffusion externality associated with rooks has the reverse diffusion dynamics to that described for beavers by Bhat et al. (1993). In their study the externality arose from the beavers tendency to diffuse to less-densely populated habitat which resulted in a pest flow from uncontrolled to controlled land.

The third externality arising from independent rook control is also a consequence of using ineffective control methods. Birds surviving a control attempt may be more difficult to control in the future due to behavioural shyness. Such shyness effectively increases the costs for other land holders undertaking future rook control in that a proportion of the remaining population will no longer be susceptible to control attempts. It is the characteristic of bait-shy behaviour that we attempt to capture with our empirical model.

The above externalities imply that individual control is not likely to be socially optimal. The literature on the economics of pest control, where a pest has the characteristics of a common property resource, suggests that centralised control is required in order to internalise externalities and thereby achieve outcomes which are more socially optimal (Feder and Regev, 1975; Tisdell, 1982; Bhat et al, 1993). Economic justification for centralised control supports earlier recommendations from rook control experts who claimed that coordinated control was necessary for greater control effectiveness (Flynn, 1976; Purchas, 1976). The Canterbury Regional Council has responded to the need for centralised control by stating that rook control is "a highly specialised area of pest control" (Canterbury Regional Council, 1993) and prohibiting independent control activities. The Biosecurity Act 1993 provides the Council with a favourable legislative environment within which to carry out rook control activities, which include inspection and monitoring, advice and education, and service delivery. A pest management rate is used to fund these services.

3. Past Work

In a recent survey of the literature, Hone (1994) acknowledged the importance of economic analysis of vertebrate pest control activities, but discovered that very little work had been undertaken to that date. Of the economic analyses that have been carried out, a common objective seems to be the evaluation of existing control programmes using cost-benefit analysis. Two examples which illustrate this dominant view on the role of economic analysis in vertebrate pest control over the last decade are Collins et al.'s (1984) evaluation of black-tailed prairie dog control in the rangelands of South Dakota, and the evaluation by Vickery et al. (1994) of possible control methods to reduce the damage that brent geese inflict on crops in Britain. Cost benefit analysis is not restricted to evaluating large scale public control programmes. Dolbeer (1981) uses a cost benefit framework in his micro-level analysis of blackbird damage control for cornfields in Ohio.

The literature on invertebrate pest management provides the greatest contribution to the economic theory of pest control. The concept of *economic threshold,* defined as the pest density at which control measures should be initiated to avoid reaching the economic injury level, has been an integral part of this analysis following an early paper by Stern et al. (1959).

The *economic injury level* is the lowest pest density level at which economic damage would be caused.

Entomologists and economists have since developed the economic threshold concept along two distinct lines (Mumford and Norton, 1984). Entomologists have sought to use the concept to identify a "rule of thumb" for use in pest control decisions. The objective of their research is to determine the pest population level at which control should be applied. Economists, on the other hand, have used marginal analysis to identify an optimal level of pest control and hence an economically optimal pest population level. Headley (1972a: p.105) defined the optimal pest population level as "the population that produces incremental damage equal to the cost of preventing that damage".

The early development of the economic threshold concept proceeded from the simple static Headley model to include both the level and timing of control as variables (Hall and Norgaard, 1973). A dynamic formulation of the model followed, which gave rise to the notion of a variable threshold (Hueth and Regev, 1974). Shoemaker (1979) established multi-dimensional economic thresholds that took into account environmental conditions and population densities. More recent development includes the flexible threshold of Harper et al. (1994), which incorporates variable economic and production conditions together with a stochastic dynamic pest population.

No consensus exists as to which of the two approaches is more relevant to pest control decisions in the field. The entomologist's approach is perceived to provide a practical solution, while the economist's approach has been recognised as offering a more theoretically efficient solution (Mumford and Norton, 1984; Pedigo et al., 1986). Entomologist's concerns that the theoretical consistency gained from using the economist's approach would be "at the expense of biological and practical reality" (Mumford and Norton, 1984: p.172) were founded on doubts regarding the data requirements of large optimisation and simulation models (Pedigo et al, 1986). In order to reach a compromise between practicality and efficiency some studies have incorporated the entomological threshold concept within a more rigorous economic framework (Moffitt et al., 1984; Moffitt et al. 1987; Davis et al., 1992; Yu et al., 1994).

Mathematical modelling has been vital to the development of optimal pest control policies. Shoemaker (1976), for example, used dynamic programming to establish a management strategy for alfalfa weevil. Recent studies involving insect control (Harper et al., 1994), vertebrate control (Huffaker et al., 1992; Bhat et al., 1993) and weed control (Pandey and Medd, 1991; Gorddard et al., 1995) have also shown that the application of optimisation methods can produce more efficient pest control strategies. An example of the successful use of simulation methods in pest control is found in a study of horn fly control by Gordon et al. (1984).

In addition to the economic threshold concept, the pest control literature can be distinguished by the unit of analysis adopted. Most of the invertebrate pest control studies have been conducted at the farm level (Moffitt et al., 1987). This emphasis arises from a belief that improvements to decision making at this level were required in order to achieve greater aggregate effectiveness in pest management (Stern et al., 1959; Headley, 1972b; Norgaard, 1976; Norton, 1976). The use of farm level economic analysis in many pest control studies has been associated with short range spatial and temporal decision parameters (Pedigo et al. 1986). These decision characteristics, often relevant for invertebrate pest control, reflect the fact that control costs and benefits accrue largely to the individual farmer.

In some situations, however, pest control activities exhibit the characteristics of a public good. This occurs where there is non-rivalry in consumption of pest control activities and/or non-excludability from the benefits of control. In these situations independent control action is unlikely to lead to socially optimal outcomes and therefore requires some form of collective control. Applied studies recognising the public good aspect of pest control generally involve highly mobile pests. Bhat et al. (1993) used a region affected by beavers as the unit of analysis upon which to evaluate a centralised control strategy. A regional approach was also adopted by Davis et al. (1992) and Collins et al. (1984) in studies which evaluated public agency control of grasshoppers and prairie dogs respectively. With respect to avian pest control, Dolbeer (1981) highlighted the need to undertake a regional economic analysis of blackbird control in order to justify publicly funded research and management programs. The study by Vickery et al. (1994) of control methods for reducing damage caused by protected brent geese also recognises that public funding requires the inclusion of a social perspective in the economic evaluation.

While the literature reviewed provided no examples of pest control in the presence of behavioural avoidance, there are a number of papers dealing with the related issue of genetic resistance. Genetic resistance also implies a loss of control efficacy, but in this case it is due to selection pressure, and it is therefore passed on from one generation to the next. From a modelling perspective, however, both genetic resistance and behavioural avoidance are very similar.

One of the earliest papers in the published literature applying economic analysis to pesticide resistance was written by Hueth and Regev in 1974. These authors present a theoretical discrete time optimal control model in which the decision maker is hypothesised to chose a pesticide application strategy that maximises the discounted net benefits of control. Their model contains pest density, stock of susceptibility, and potential plant product as state variables. The target population's current susceptibility to chemical control is a function of susceptibility and the level of chemical input in the pervious period. These authors develop a valuable conceptual link between the development of pesticide resistance and the optimal depletion of an exhaustible resource, but they offer no empirical application for their model.

Shortly after the appearance of Hueth and Regev's study, Taylor and Headly (1975) published an alternative theoretical model of insect control in the presence of genetic resistance. The decision maker in their model also seeks to maximise the discounted net benefits of control, where benefits are a function of the pest population and costs are a function of control. The state equations which describe the composition of the insect population include three distinct sub-populations with varying levels of pesticide resistance. While they provide no empirical application of their theoretical model, these authors suggest that dynamic programming could be used as a solution procedure once parameter values have been estimated.

Regev et al.(1983) were among the first to present an empirical application to complement their general theoretical model of insect control under pesticide resistance. Their regional model, closed to outside migration, featured a centralised decision maker seeking to maximise discounted profit from a given crop. Following Hueth and Regev (1974), their state variables include pest density and the stock of pesticide resistance. The decision maker controls the system by choosing the level of pesticide application and the optimal time to switch from cropping to the next most profitable alternative. Perhaps not surprisingly, switching time is found to be sensitive to the profitability of land use alternatives. Their empirical model is specified in discrete time and solved using non-linear programming. Results suggest that a central control agent who ignores resistance tends to use more chemical insecticide, thereby increasing the degree of resistance in the pest population. The authors also compare the results of their centralised optimal control model to those which emerge from a model in which resistance is recognised, but the decision maker is hypothesised to be a private individual who does not believe that they can affect the level of resistance in the pest population. Results of this comparison suggest that private decision makers will use less pesticides early in the time horizon, implying a larger total pest population but a slower development of resistance.

Gorddard et al. (1995) more recently presented a dynamic optimisation model for weed control under herbicide resistance, in which a non-chemical control alternative is shown to have a major impact on the optimal herbicide strategy. State variables in their model include the density of susceptible and non-susceptible weeds, and control activities involve either chemical or non-chemical control, as well as the number of years to continue cropping. Results suggest that the presence of genetic resistance to chemicals lowers the net benefits of cropping, and prompts an earlier switch to non-cropping alternatives. The introduction of non chemical control implies a higher net present value for the objective function due to lower herbicide dosages early in the time horizon, and more time spent cropping if resistance is present. Non-chemical control is therefore a key management tool for delaying resistance, but cost considerations imply that it will not be chosen if resistance is not present.

The literature reviewed above provides invaluable guidance on how behavioural avoidance can be incorporated into an empirical model of vertebrate pest control. The need for centralised control, resulting from the economic consequences of the spatial characteristics of rooks, suggests the adoption of a regional level of analysis. In addition the population and behavioural dynamics in the rookery imply that control activities applied in one time period will impact the effectiveness of control in the future. The rook control problem is therefore fundamentally dynamic in nature.

In the following section a bioeconomic model of the rook control problem is developed within an optimal control framework. There are several reasons why optimal control is considered most suitable for this empirical problem. The rook control problem can be captured in a model of low dimension, permitting the application of optimisation techniques. Apart from the interaction between rook population growth and crop yields, and bait-shyness and control, we can abstract away from complex ecosystem dynamics. The solution procedure also provides interesting economic information through the determination of shadow values. Finally, non-linear equations such as rook population growth can be handled directly by optimal control.

4. Empirical Model

The objective of this empirical model is explore the implications of learned avoidance (shyness) on the effectiveness of the rook control programme in Canterbury. The study focuses on temporal dynamics and does not explicitly incorporate spatial dynamics. The region, which is confined to the susceptible area between the Rangitata and Waimakariri Rivers, contains several rookeries which cause crop damage approximately in proportion to their aggregate population size. The Council's objective is taken to be the minimisation of the sum of discounted control costs and rook inflicted damage costs over time (eq. 4.1). Decisions to control rooks are made on an annual basis. Control activities are applied directly to the rookery and the effect of any control activity is assumed to impact the rook population after that year's breeding season. Definition of the variables and parameter values used in the model are contained in Table 1.

4.1 Objective Function

The rook control model is represented mathematically as follows,

(4.1) $$\underset{C_t}{Minimise}\ V_t = \int_0^T e^{-\delta t}[C(C_t, NS_t, S_t) + D(NS_t, S_t)]d_t$$

Subject to:

(4.2) $$\frac{\partial NS}{\partial t} = g(NS, S; r, K) + f(S_t, \beta) - h(C_t, NS_t, S_t; \alpha, \beta)$$

(4.3) $$\frac{\partial S}{\partial t} = h(C_t, NS_t, S_t; \alpha, \gamma) - f(S_t, \beta) - m(S_t, \mu)$$

(4.4) $NS(0)=NS_0$

(4.5) $S(0) = S_0$

Each period's costs are separated into those due to rook inflicted damage, D_t, and those incurred through the application of rook control activities, C_t. Both cost components are discounted by the annual discount rate δ. Agricultural crops susceptible to rook inflicted damage were assumed to be confined to cereals (wheat, barley, and oats), maize, and peas. The damage function therefore reflected per hectare values of sowing weight (W), harvest yield (Y), gross margin (M_t), and the metabolised energy per food item (F) for each crop in proportion to the area within the region in which it is currently being cropped. The area of land susceptible to rook damage was calculated to be approximately 74,000 hectares. The percentages of this land relating to crop types were 84.8% for cereals, 0.2% for maize, and 15% for peas. Sowing rates and harvest yields were obtained from the Lincoln University Financial Budget Manual (1995).

Annual rook inflicted damage, D_t [$/ha], is formulated as,

(4.6) $$D_t = X_t * F * M_t * E\{\frac{1}{W}[(N_1 * FT_1) + (N_2 * FT_2)] + \frac{1}{Y}(N_3 * FT_3)\}$$

Values relating to rook feeding were taken from Purchas (1980). The average daily energy requirement for a rook was assumed to be 450 kJ. It was also assumed that the proportion of time spent feeding on crop seeds, which could vary seasonally, would contribute to the equivalent proportion of the rook's daily energy requirement. The total weight of damaged crop seeds per day per bird was calculated using the weight of crop seed per kJ metabolised energy (Purchas 1980: p.574). The susceptible period for sown seeds was assumed to be 32 days in autumn and 48 days in spring. The susceptible period for seeds on the mature plant was assumed to be 32 days in summer. The annual loss in harvest yield resulting from rook damage was expressed in kilograms per hectare and then monetised by multiplying by an average gross margin per hectare using data from the Lincoln University Financial Budget Manual (1995). Seed destruction is, however, not the only damage caused by rooks. Porter et al. (1994) state that seedlings can be pulled out of the soil and the tips eaten on emerging plants, while mature maize can be trampled. This damage has not be incorporated into the analysis because at current rook population levels it is assumed to be negligible.

Table 1
Variable Definition & Parameter Values

	Definition	Value
NS_t	Population of susceptible rooks (state variable)	#
S_t	Population of bait-shy rooks (state variable)	#
C_t	Control activity (control variable)	0 - 1
r	Intrinsic growth rate of rook population	20%
μ	Natural mortality rate	5%
K	Carrying capacity for rooks (per hectare)	0.5
X_t	Total rook population ($NS_t + S_t$)	#
F	Seed weight per kJ of metabolic energy (grams/kJ)	0.118
E	Average daily energy required per bird (kJ/day)	450
FT_1	Percentage of feeding time spent on seeds (Autumn)	2%
FT_2	Percentage of feeding time spent on seeds (Spring)	2%
FT_3	Percentage of feeding time spent on seeds (Summer)	6%
N_1	Number of feeding days (Autumn)	32
N_2	Number of feeding days (Spring)	48
N_3	Number of feeding days (Summer)	32
W	Crop sowing weight (grams/ ha)	179,221
Y	Crop harvest yield (grams/ ha)	5,718,400
M_t	Crop gross margin ($/ha)	873
γ	Control effectiveness	95%
α	Bait-shyness	10%
z	Control cost parameter	0.02066
δ	Annual discount rate	6.5%
β	Bait-shyness period decay	1%

Data limitations make the estimation of the cost of control difficult. Only one data point is known which relates to the 1995/96 period. For this period cost of control was $64,000 and 1543 birds were killed out of an initial population of 1641. In a previous study by Huffaker et al. (1992), which had similar data problems, a single data point was used to calculate a control cost parameter. The control cost parameter was incorporated in a functional form that reflected increasing cost of control as the population density decreased. This approach is adopted and results in the following functional form:

$$(4.7)\quad C(C_t, NS_t, S_t) = \frac{zC_t}{NS_t + S_t}$$

To achieve the desired relationship between population density and control costs the total population density for a given period appears in the denominator of equation 4.8. Although control is only effective against the susceptible population the cost of control function reflects the assumption that the total rook density impacts on control costs. The formulation of the cost function implies that the cost of control will tend towards infinity as population density approaches zero, making eradication prohibitively expensive. Empirical observation suggests that eradication will, in fact, be difficult due to the high mobility of rooks, difficulty in accurately estimating numbers, and the possibility of encroachment into controlled regions from an uncontrolled region further south.

4.2 Equations of Motion

The annual change in rook population numbers is the difference between the biological growth of the rook population during the year and the number of birds killed. Following both Taylor and Headly (1975) and Gorddard et al. (1995) the development of shyness is modelled using a state variable for susceptible, and a state variable for non-susceptible birds. In a period when control takes place the population is separable into the following groups; birds killed through control activities (H_t), birds not killed due to technical inefficiencies of control, but are susceptible to control in the next period (NS_t), and birds that are bait-shy (S_t). Two distinct sub-populations may therefore exist in any period; birds that are not bait-shy, and those that are. A logistic growth function is used to describe the dynamics of both rook populations where r = intrinsic growth rate, and K= habitat carrying capacity. Prior work by Coleman (1971, 1972) suggests that r = 0.2. The parametric value of K was based on a study by Bull and Porter (1975) which revealed that the highest rook population density recorded in New Zealand was 20,000 breeding birds over 6,000 km^2 of farm land in Hawkes Bay during 1969, or 0.33 birds per hectare. Additionally, Bull and Porter (1975) observed that the actual numbers of rooks maybe 50% larger than estimates using extrapolations from nest counts. To allow for population underestimates rook carrying capacity was increased by 50%. This resulted in an adjusted value for the rook carrying capacity of 0.5 birds per hectare. The initial population levels are given by $NS_0 = 100$ and $S_0 = 0$.

The period change in population numbers for each sub-population (eqs. 4.9 & 4.10) depends on the biological growth of the total rook population, the effectiveness of control technology (γ), the propensity for birds to become bait-shy through exposure to control (α), the period reduction in bait-shyness (β), and the decision to control (C_t). There is an additional parameter representing natural mortality for the shy population (μ). The effectiveness of control technology is assumed to be constant. Bait-shyness is assumed not to be genetically transferred and therefore decreases over time if birds are not exposed to further control activities. Birds that are exposed to a control activity and survive will become shy in the next period. When control is absent the susceptible population increases according to the total population biological growth rate plus the number of birds that have lost their bait-shyness. The shy population declines through natural mortality and birds loosing their shyness. Alternatively, when control is administered the change in the susceptible population is a function of the effectiveness of control applied to new recruits of both populations and the previous period's susceptible population. The change in the shy population under these circumstances depends on the loss of bait-shyness and natural mortality together with the propensity for birds in the susceptible population which are exposed to control to become bait-shy.

(4.8) $$NS_{t+1} = (1-\gamma C_t)[NS_t + r(NS_t + S_t)(1 - \frac{NS_t + S_t}{K})] + \beta S_t$$

(4.9) $$S_{t+1} = \alpha\gamma C_t[r(NS_t + S_t)(1 - \frac{NS_t + S_t}{K}) + NS_t] + (1 - \beta - \mu)S_t$$

To solve the model numerically the control problem was specified in a non-linear programming format by defining the state and control variables in each time period as activities. The equations of motion were then specified as non-linear constraints linking one time period to the next. The system was solved using GAMS/MINOS (Brooke, Kendrick and Meeraus, 1988) for non-linear optimisation on a mainframe computer. GAMS/MINOS uses a reduced gradient algorithm, combined with a quasi-Newton optimisation method and sequentially linearises the non-linear constraints.

5. Results

Results of the empirical optimisation model using "base level" parameter values are displayed in Table 2. The base run resulted in two complete control operations and one incomplete operation. As a consequence of control, average rook numbers for the susceptible and shy populations were 3,777 and 1,249 birds, respectively. Note that the average figure for shy birds was taken from period 30, after the first control operation introduces shyness into the population. As illustrated in Figure 1, control activities change the composition of the total population by introducing shy individuals. Loss of shyness and natural mortality combine to reduce the shy population over time in the absence of further control. A comparison between the net present values of total control costs and total damage clearly identifies the containment of control costs to relatively low levels through infrequent control activities.

Table 2
Results of the Base Run

Number of Control Events	2 Complete 1 Partial
Control Periods	Complete: 29, 44 Partial: 38
NPV Total Damage	$13,344
NPV Total Control Costs	$2,088
Average Susceptible Population	3,777
Average Shy Population	1,249
Implicit Values:	
Susceptible Population	$13.56
Shy Population	$12.48

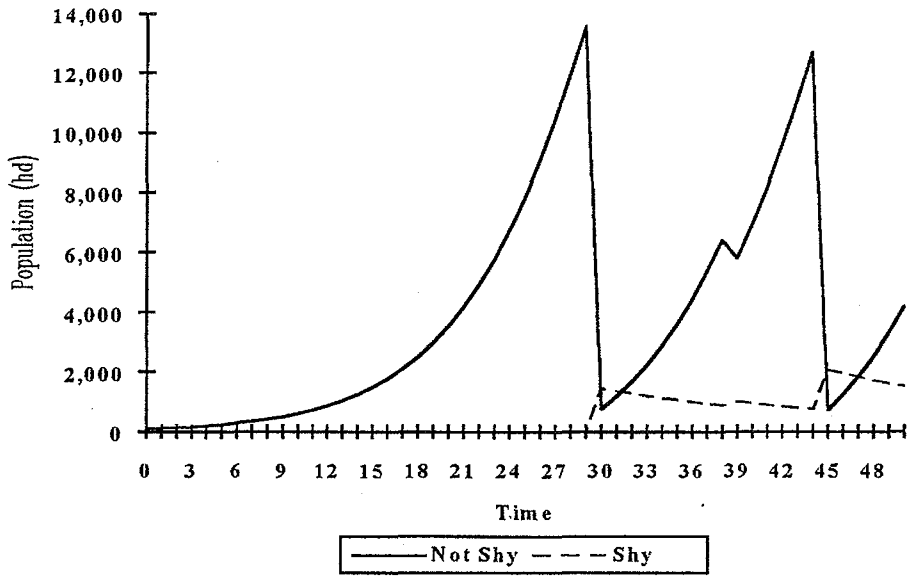

Figure 1
Rook Population Dynamics

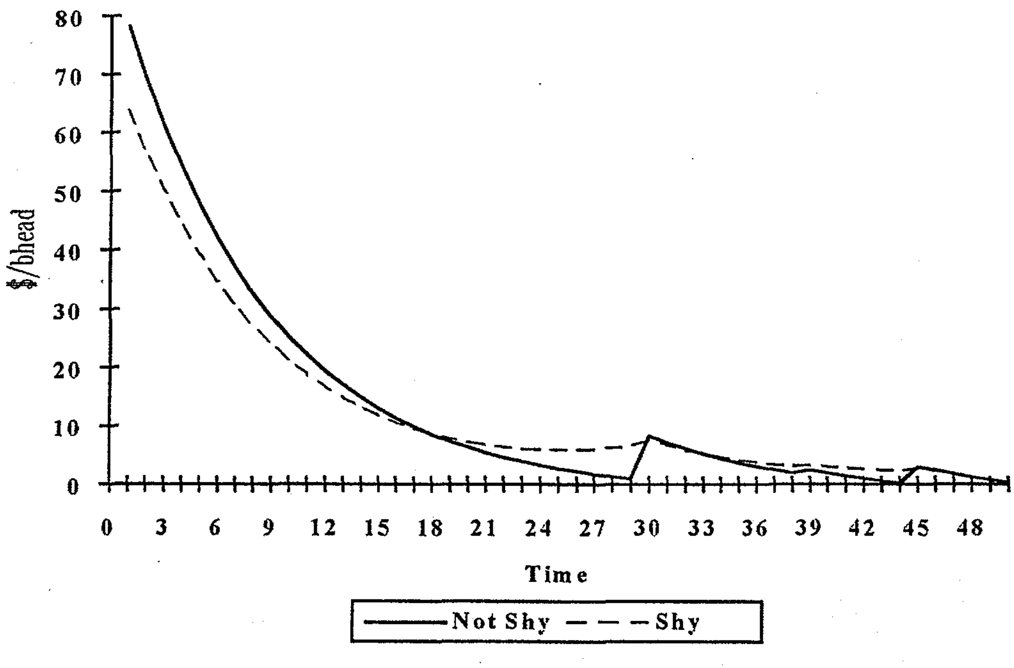

Figure 2
Implicit Cost of Rooks

With respect to the average implicit values, which are the marginal values associated with the equations of motion for each population, the susceptible population imposes a greater cost on average than the shy population. Shy birds become relatively more costly to the system as control operations draw near, however, reflecting the fact that control operations are not effective against these individuals after exposure. The dynamics of the implicit values for the two sub-populations are illustrated in Figure 2.

6. Sensitivity Analysis

Sensitivity analysis was undertaken with respect to the time spent feeding on agricultural crops, which involves a group of parameters that were considered *a priori* to have potential to significantly influence results. This analysis was performed by changing the value of the parameter in question and holding all other parameters at their base run values. The results are displayed in Table 3.

The effect of an increased feeding time on crops is obtained by adjusting the percentage of feeding time spent on crops up to 5% for autumn and spring and 10% for summer. Not surprisingly, the net present values of total damage increases in response to greater time spent foraging on crops. In addition, control costs increase as a result of a slightly higher degree of control, which was shifted forward in the time horizon. The change in timing of control results in a significant reduction in the average numbers of both populations. The fact that lower average population numbers have not translated into a reduction in damage reflects the importance of feeding time in the damage function.

7. Maintaining 'Sub-optimal' Population Levels

The final component of this analysis was to identify the impact of maintaining a maximum population which is below the economically optimal level. A control threshold of 200 birds was imposed by placing a constraint on the size of the total population. The imposition of the threshold resulted in a series of partial control operations which held the population very close to the threshold. Frequent control events dramatically increased control costs while reducing rook inflicted damage to extremely low levels. Increased control frequency introduces shyness much earlier in the time horizon, but reduces average sub-populations (relative to the base run) to 135 for the susceptible birds and 42 for the shy birds. The much larger implicit values reflect the increased incidence of control and its effect on shyness. Frequent control has a particularly profound effect on the marginal value of the bait-shy birds. The costs of applying a non-optimal threshold on control are made explicit when comparing the discounted damage and total control costs to those of the base run. While rook inflicted damage is far lower under the threshold policy, it does not fully compensate for the substantially higher costs associated with intensive control.

Table 3
Results of the Sensitivity Analysis

	Base Run	High FT	Threshold
Number of Control Events			
Complete	2	2	1
Partial	1 (25%)	1 (95%)	30
NPV Total Damage	$13,344	$17,827	$1,091
NPV Total Control Costs	$2,088	$10,109	$1,303,200
Average Susceptible Population	3,777	1,637	135
Average Shy Population	1,249	543	42
Implicit Values:			
Susceptible Population	$13.56	$11.07	$3,934
Shy Population	$12.48	$13.05	$6,834

8. Discussion and Conclusion

The results presented above highlight several important aspects associated with the control of a bait-shy population. The first of these is that when population densities are low, control operations may be prohibitively expensive relative to the damage inflicted on commercial crops. This problem is compounded by the development of bait-shy behaviour, which implies that a proportion of the total population will not be susceptible to control operations. The identification of control costs as a dominant influence on the results emphasises the need for both the control cost and damage functions to be correctly specified.

Another general result is that the timing of control is not only important with regard to the magnitude of control costs, but it also determines the average pest numbers and therefore the amount of damage incurred. Bringing control events forward in time lowers average population numbers of both sub-populations, but increases their implicit values by increasing total control costs and introducing shy individuals into the population earlier in the time horizon.

The above results have important implications for rook control policy in Canterbury. Rook control clearly involves an economic tradeoff between control costs and the level of rook inflicted damage. The bioeconomic model presented in this paper makes this tradeoff very explicit. The model specification also facilitates an understanding of the dynamic effects of control on both susceptible and bait-shy rook populations. In addition, the cost of non-optimal policies can be explored by constraining the model to maintain the total population at a sub-optimal level.

The bioeconomic model is only as good as the parameter values and specification used. While every attempt has been made to ensure both parameter values and model specification reflect accurately the empirical phenomenon, the lack of prior research on rook damage and control suggest future research into these areas is warranted.

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