Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- you will use the copy only for the purposes of research or private study
- you will recognise the author's right to be identified as the author of the thesis and due acknowledgement will be made to the author where appropriate
- you will obtain the author's permission before publishing any material from the thesis.
COST-EFFECTIVE CONTROL OF 1080

BAIT-SHY POSSUMS (*Trichosurus vulpecula*)

A thesis

submitted in partial fulfilment

of the requirements for the Degree of

Doctor of Philosophy

at

Lincoln University

by

J.G. Ross

Lincoln University

1999
Abstract of a thesis submitted in partial fulfilment of the requirements for the Degree of Ph.D.

COST-EFFECTIVE CONTROL OF 1080 BAIT-SHY POSSUMS (Trichosurus vulpecula)

by J.G. Ross

The brushtail possum (Trichosurus vulpecula) has been identified as a significant New Zealand conservation pest and a major wildlife reservoir of bovine tuberculosis (Tb; Mycobacterium bovis). To combat its continuing impact, central and local government agencies currently spend more than $50 million per annum on possum management activities. The current objective of this effort is to maintain possum population densities in selected areas below predetermined environmental and disease thresholds. Six toxicants are currently registered for possum control, with sodium monofluoroacetate (1080) being the most extensively used. 1080 can be incorporated into various baits types and has been shown to be an extremely cost-effective method of initially removing <90% of a possum population. Unfortunately, ‘bait shyness’ induced among the surviving possums means that the efficacy of this acute-acting toxicant can decrease markedly when used repeatedly for maintenance control, which sometimes can be required at annual or biennial intervals. Given that there are currently few feasible alternative control options, 1080 bait shyness poses a threat to the sustainability of possum control in New Zealand.

Three pen trial studies were conducted to investigate the best methods of preventing and mitigating 1080 cereal bait shyness. In each trial, 1080 cereal bait shyness was induced with an approximate LD_{50} 1080 dose (0.8 mg.kg^{-1} bodyweight). The first trial investigated the effectiveness of switching to alternative, slower-acting toxicants in cereal bait for maintenance control of 1080 cereal bait-shy possums. The three alternative toxicants tested in this trial (gliftor, cholecalciferol, marketed as Campaign® and brodifacoum, marketed as Talon®) had been identified in previous trials as being promising alternatives to 1080. The second trial investigated whether 1080 cereal bait-shy possums could be controlled using
these alternative toxicants in an unfamiliar bait matrix (Pestoff® fruit paste). The third pen trial investigated the use of non-toxic cereal ‘prefeed’ and ‘postfeed’ as potential ways of inhibiting and overcoming 1080 cereal bait shyness. The postfeed result was also compared with changing to another unfamiliar bait matrix (Kiwicare fruit gel) containing 0.13% 1080.

A bioeconomic possum model was then constructed to identify the most cost-effective control strategies to achieve a sustained 60% or 80% population reduction over a 10 year period, given that bait shyness can develop and that new alternative, slower-acting toxicants have become available for maintenance control.

All of the alternative toxicants were relatively successful in the pens, killing 50-83% of the cereal 1080 bait-shy possums when in a familiar cereal bait. After the first night, consumption of the acute and subacute-acting toxicants decreased dramatically, whereas consumption of the chronic-acting brodifacoum toxicant increased progressively over subsequent nights. Some 1080 cereal bait-shy possums (40%) were killed when exposed to 0.8% 1080 in the unfamiliar paste bait. The effectiveness of the two alternative, slower-acting toxicants (cholecalciferol; a subacute-acting toxicant and brodifacoum; a chronic-acting toxicant) was enhanced using the unfamiliar paste bait, with both achieving a 100% kill. Gliftor was not investigated further because of similarities between it and the existing acute-acting toxicant 1080. Prefeeding non-toxic cereal bait significantly reduced the number of possums that become 1080 cereal bait shy, with only 22% of the pre-fed possums developing an aversion to 1080 cereal bait compared to 97% of the non pre-fed groups. Postfeeding with non-toxic cereal bait, after the LD₂₀ 1080 dose, was relatively ineffective in reducing the number of 1080 bait-shy possum, with mortality of these possums being 30% compared with 0% of non post-fed possums. In contrast, the 0.13% 1080 gel bait killed 64% of the 1080 cereal bait-shy possums.

The modelling simulation results suggest that it is possible to achieve a sustained 60% or 80% reduction in possum numbers using predominantly 1080-based control strategies, provided reasonably large (>100 ha) areas are controlled and 90% of the susceptible (i.e., non bait-shy) possums are killed in each operation. The 60% sustained population
reduction can be achieved solely using 1080 control, however, the 80% population reduction will require the occasional use of an alternative, slower acting toxicant such as brodifacoum. Sensitivity analysis indicated that the most important variable influencing the overall success of these control strategies was the maximum rate of migration following control, which is influenced by control area size. With the high rates of migration that are sometimes observed into small (<100 ha) forest reserves, expensive permanent bait stations, containing brodifacoum bait, may be required in these to minimise the effects of immigration.

The results of this study suggest that most 1080 cereal bait-shy possums will consume a lethal dose of a chronic brodifacoum toxicant provided their exposure to it is prolonged. However, subacute cholecalciferol poisoning symptoms do not appear to be delayed for long enough to be effective in the field when used in a familiar bait matrix. The effectiveness of 1080 and the alternative, slower-acting toxicants is enhanced when presented in the unfamiliar bait matrixes and these bait types should be field trialed in maintenance control operations. The low number of pre-fed possums (22%) that become 1080 bait shy following multiple doses of 1080 bait suggests that field managers should consider making greater use of non-toxic prefeed prior to bait station control operations.

In conclusion, the modelling simulations suggest that sustained population reductions of 60-80% can be achieved using current control techniques. Further studies are required to determine the effectiveness of these strategies in the field. Possum researchers also need to investigate the factors determining population recovery in different sized control areas. The actual timing of control may vary between different control sites, and can only be established by direct measures of animal recovery and abundance.

**Keywords:** brushtail possum, *Trichosurus vulpecula*, bait shyness, bait aversion, behavioural resistance, prefeeding, postfeeding, bioeconomic modelling, cost-effectiveness analysis, numerical simulation, 1080, sodium monofluoroacetate, cholecalciferol, brodifacoum, gliflor, Campaign®, Talon®, Pestoff®.
ACKNOWLEDGEMENTS

Well here it is - the thesis is finished - can it be true?

It is difficult to know whom to thank first, so I will start at the top. First, I would like to thank my supervisor Dr. Graham Hickling, who is no longer BAD! Graham, you have always been helpful, thought provoking and a whole lot better than me at proof reading. For all the times you have read through those long drafts (especially Chapter 6) - thanks mate. Second, I would like to thank my associate supervisor Dr. Katie Bicknell. Katie, your excellent mathematical guidance was sorely needed and we have finally managed to turn what always sounded like a good research idea into a working model. Thank you for your understanding and there will always be a place for you in my triathlon team. Third, I would like to acknowledge all the people at Landcare Research (N.Z.) Ltd. Thank you Dr. Charlie Eason (my external supervisor), Dave, Malcolm, Cheryl and Ray for your expertise and occasional proof reading. I also thank all the staff at the captive-animal facility, especially Lynne and Andrea (who always put my possums back in their cages).

Next, I would like to thank all the funky people in the Animal Ecology and Entomology Department. The Department seems like my second home and I will miss the great debates (and sometimes arguments) that frequently echo down the 5th floor corridor. I have many warm memories of my time wandering about checking out what happened at Bob’s after I headed off home. Special thanks to Dr. Adrian Paterson, who can be an arrogant, thieving Leo but is a top bloke (does a lot of work for charity) when he isn’t talking about Dungeons and Dragons (remember the dice never lies). Thanks for all the proof reading and for being a sounding board for all those flaky Gemini ideas. Special thanks also to Cor Vink who always reminded me that life is great when you have a pudder-wudder cat. Thanks for all the interesting chats that we have had and if you BE NICE there could be some free liquorice and a car ride in it for you. To Mandy and Nic, YES I have finally finished!!!! Thank you both for putting up with me (and my Star Wars calendar mmmm Princess Leia) in the 7th floor write-up room over the last few months. Other special people of note are Helen (who also watches great TV programmes like Changing Rooms), Milky (who enables me to talk about cars - lovvve it), Frances (who can occasionally wind me
up), Jim (who will help me drink my Bourbon), Alison (who is always good for a chat),
Chris (who is a fellow TV addict and helped me to scale the slopes of Mt. Statistics) and
my German friends, Katrin and Sonke (who were always fun and never mentioned the
war). For those of you I didn’t mention, thank you for your friendship.

Finally, I would like to thank a very special person - my partner Jessica. You have always
been there for me and I hope you know how much I love you for this. Life with me can be
like a box of chocolates - you never quite know what you are going to get. Over the last
dfew months all you have been getting is the pathetic little hard chocolates that everybody
leaves behind - I’m sorry. I promise it will only be hazelnut praline and caramel cremes
from now on (P.S. I bags all the turkish delights). Special thanks also to Tigger who was
always there (especially around dinner time).

In conclusion, I present you with my thesis. Not exactly a ‘roller-coaster of a thesis in
seven sizzling chapters’, but there may be a few hot gypsies thrown into Chapter 4.
CONTENTS

Abstract ii

Acknowledgements v

Contents vii

List of Tables x

List of Figures xiii

Chapter 1 GENERAL INTRODUCTION 1

1.1 Objectives 5

1.2 Structure of thesis 5

1.3 Acknowledgements 6

1.4 References 6

Chapter 2 LITERATURE REVIEW: ECOLOGY, HISTORY OF COLONISATION AND CONTROL OF THE COMMON BRUSHTAIL POSSUM IN NEW ZEALAND 10

2.1 Ecology 10

2.2 History of colonisation 13

2.3 History of possum control 19

2.4 Concluding comments 44

2.5 References 46

Chapter 3 CONTROL 1080 BAIT-SHY POSSUMS USING ACUTE, SUBACUTE, AND CHRONIC-ACTING TOXICANTS IN A FAMILIAR BAIT MATRIX 64

3.1 Abstract 64

3.2 Introduction 65

3.3 Objectives 66
3.4 Methods  
3.5 Results  
3.6 Conclusions  
3.7 Recommendations for future research  
3.8 Acknowledgements  
3.9 References  
3.10 Appendixes  

Chapter 4  
THE EFFECTIVENESS OF ACUTE, SUBACUTE AND CHRONIC-ACTING TOXICANTS, IN BOTH FAMILIAR AND UNFAMILIAR BAIT MATRIXES, FOR THE CONTROL OF 1080 BAIT-SHY POSSUMS  
4.1 Abstract  
4.2 Introduction  
4.3 Objective  
4.4 Methods  
4.5 Results  
4.6 Conclusions  
4.7 Recommendations for future research  
4.8 Acknowledgements  
4.9 References  

Chapter 5  
THE ROLE OF NON-TOXIC PREFEED AND POSTFEED IN THE DEVELOPMENT AND MAINTENANCE OF POSSUM 1080 BAIT SHYNESS  
5.1 Abstract  
5.2 Introduction  
5.3 Objective  
5.4 Methods
## LIST OF TABLES
(Titles abbreviated)

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Experimental design for a 1996 possum pen trial investigating induced 1080 bait shyness.</td>
</tr>
<tr>
<td>2.2</td>
<td>Experimental design for a 1996 possum pen trial investigating induced 1080 bait shyness.</td>
</tr>
<tr>
<td>2.3</td>
<td>Experimental design for a 1995 possum pen trial investigating induced 1080 bait shyness.</td>
</tr>
<tr>
<td>2.4</td>
<td>Experimental design for a 1997 possum pen trial investigating induced 1080 bait shyness.</td>
</tr>
<tr>
<td>2.5</td>
<td>Experimental design for a 1998 possum pen trial investigating induced 1080 bait shyness.</td>
</tr>
<tr>
<td>2.6</td>
<td>Average percentage kill of naive possum by three toxicants.</td>
</tr>
<tr>
<td>3.1</td>
<td>Experimental design for a possum pen trial investigating the efficacy of various toxicants for overcoming 1080 bait shyness.</td>
</tr>
<tr>
<td>3.2</td>
<td>Mortality of captive 1080 bait-shy possums exposed to cereal bait containing different toxicants over a 2 week period.</td>
</tr>
<tr>
<td>4.1</td>
<td>Numbers of 1080 cereal bait-shy possums killed by alternative, slower-acting toxicants in familiar and unfamiliar bait bases.</td>
</tr>
<tr>
<td>4.2</td>
<td>Mean consumption of various toxic baits by captive 1080 bait-shy possums over a 4 week period.</td>
</tr>
<tr>
<td>5.1</td>
<td>Effect of 1 week of prefeeding and postfeeding on 1080 bait consumption and possum mortality.</td>
</tr>
<tr>
<td>5.2</td>
<td>Consumption of 1080 gel by 1080 cereal bait-shy possums, and subsequent mortality.</td>
</tr>
<tr>
<td>6.1</td>
<td>Variable definitions and values used in a computer simulation of a possum population.</td>
</tr>
<tr>
<td>6.2</td>
<td>Proportion of possums eating from bait stations at various station spacings.</td>
</tr>
<tr>
<td>6.3</td>
<td>Estimated kill achieved in aerial control operations using 1080 cereal bait; sowing rate ≥ 5 kg/ha.</td>
</tr>
</tbody>
</table>
6.4 Estimated kill achieved in bait station control operations using 1080 cereal bait.

6.5 Estimated kill achieved in bait station control operations using cholecalciferol cereal bait.

6.6 Estimated kill achieved in bait station control operations using brodifacoum cereal bait.

6.7 Kill rate for bait station control operations using acute and subacute-acting toxicants for initial and maintenance control.

6.8 Kill rate for bait station control operations using acute and subacute-acting toxicants for initial control and a chronic-acting toxicant for maintenance control.

6.9 Reported costs of 1080 aerial operations using cereal bait at a sowing rate of 5 kg/ha.

6.10 Cost of theoretical and actual 1080 cereal bait station control operations.

6.11 Cost of cholecalciferol cereal bait station control operations.

6.12 Cost of brodifacoum cereal bait station control operations.

6.13 Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill using aerial 1080.

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

6.15 Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill using cholecalciferol and brodifacoum.

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

6.17 Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using cholecalciferol and brodifacoum.

6.18 Average possum density/ha of possum control strategies attempting to achieve a sustained 60% kill with and without bait shyness.

6.19 Average possum density/ha of possum control strategies attempting to achieve a sustained 80% kill with and without bait shyness.

6.20 Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill with and without bait shyness.
6.21 Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill following an unsuccessful 1080 operation.

6.22 Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill following an unsuccessful 1080 operation.

6.23 Average possum density/ha of possum control strategies attempting to achieve a sustained 60% kill with and without bait shyness degradation.

6.24 Average possum density/ha of possum control strategies attempting to achieve a sustained 80% kill with and without bait shyness degradation.

6.25 Estimated maximum rate of possum migration in various sized control areas.

6.26 Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill with high and low rates of possum migration.

6.27 Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill with high and low rates of possum migration.

6.28 Accumulated cost of possum control strategies attempting to achieve a sustained 60% kill with and without a discount rate.

6.29 Accumulated cost of possum control strategies attempting to achieve a sustained 80% kill with and without a discount rate.

6.30 Average possum density/ha for possum control strategies attempting to achieve a sustained 80% kill with and without enhanced neophobia.

6.31 Accumulated discounted cost for possum control strategies attempting to achieve a sustained 60% kill over 10 and 20 year terms.

6.32 Accumulated discounted cost for possum control strategies attempting to achieve a sustained 80% kill over 10 and 20 year terms.

6.33 Average possum density/ha for possum control strategies attempting to achieve a sustained 80% kill using either brodifacoum or 1080 paste.

6.34 Accumulated discounted cost for possum control strategies attempting to achieve a sustained 60% kill with and without non-toxic prefeed.

6.35 Accumulated discounted cost for possum control strategies attempting to achieve a sustained 80% kill with and without non-toxic prefeed.
LIST OF FIGURES
(Titles abbreviated)

FIGURE PAGE
2.1 Common brushtail possum. 11
2.2 Tb vector-risk control areas. 18
2.3 Speed of onset of poisoning symptoms. 40
3.1 Average nightly consumption of acute, subacute and chronic-acting toxicants by 1080 bait-shy possums. 71
3.2 Average nightly consumption of non-toxic bait by 1080 bait-shy possums. 72
3.3 Average nightly consumption of brodifacoum by 1080 bait-shy possums. 73
4.1 Flow diagram of the experimental design. 85
5.1 Flow diagram of the experimental design. 99
5.2 Consumption of dyed and undyed RS5 non-toxic prefeed by naive possums. 102
5.3 Cumulative percentage of possums developing shyness following re-exposure to 1 g doses of 0.08% 1080 bait. 103
5.4 Nightly consumption of non-toxic postfeed by 1080 bait-shy possums. 104
6.1 Flowchart for a possum population computer simulation model. 117
6.2 The estimated decline of possum 1080 bait shyness. 134
6.3 The annual changes in possum density/ha incorporated into the model. 141
6.4 Possum population density following aerial control with 1080. 143
6.5 Possum population density following control with cholecalciferol in bait stations. 145
6.6 Possum population density following control with 1080 and brodifacoum in bait stations. 146
6.7 Possum population density following control with cholecalciferol and brodifacoum in bait stations. 147
6.8 Possum population density following control with 1080 in bait stations following an initial unsuccessful 1080 operation. 151
6.9 Possum population density after control with 1080 and brodifacoum in bait stations following an unsuccessful 1080 operation. 152

6.10 Possum population density following control with 1080 in bait stations with high possum migration (60% kill). 156

6.11 Possum population density following control with 1080 in bait stations with high possum migration (80% kill). 157

6.12 Flowchart for a possum population computer simulation model. 160
CHAPTER 1

GENERAL INTRODUCTION

The contemporary fauna of terrestrial mammals in New Zealand is, very different, in composition and origin, to that of any other country in the world. In particular, the islands of New Zealand were free of all terrestrial mammals except bats until a mere 1000 years ago (Stevens et al. 1988).

The land mammals now present in New Zealand were introduced in two distinct groups. The first group arrived with the Polynesians who settled in New Zealand about 850-950 AD (possibly much earlier; Holdaway 1996). These pioneering settlers brought with them kiore (Polynesian rat; Rattus exulans) and kuri (Polynesian dog; Canis familiaris) (Davidson 1984). The second much larger, group started to arrive from 1769 with the Europeans, who liberated domestic species such as goats (Capra hircus), pigs (Sus scrofa) and sheep (Ovis aries) to establish feral populations (Stevens et al. 1988).

Following the annexation of New Zealand by Britain in 1840, the number of European settlers, and the other mammals they bought with them, increased dramatically (King 1990). Many of these introduced mammals found the lack of predators and the palatability of the indigenous vegetation to their liking and quickly became established. Over time some of these species began to have a detrimental effect on agricultural and/or conservation land. Species of most nuisance were the European rabbit (Oryctolagus cuniculus), red deer (Cervus elaphus scoticus), Bennett’s wallaby (Macropus rufogriseus), feral goat (Capra hircus) and the Australian brushtail possum (Trichosurus vulpecula) widely considered New Zealand’s most serious mammal pest species (King 1990).

Possums were first brought to New Zealand in 1837 and the first successful introduction was made in 1858 (Pracy 1974). An active policy of legal liberations (at least 464 between 1858-1922), with Government approval and protection, ensured that they became abundant and widespread. The first reports of possum damage (to fruit orchards) came as early as the 1890s. The general view was that this damage was localised and insignificant when
compared with the benefits of the developing fur industry (King 1990). However, in the 1920s and 30s there was increasing scientific evidence that possums were also damaging commercial exotic (Lever 1985) and indigenous forests (Wodzicki 1950) and the view of the possum as a pest species gained ascendancy in 1946, after which all protection was removed (Parkes et al. 1996).

The first large-scale attempt at possum control was via a bounty scheme that ran from 1951-1961. Over eight million bounties were paid out, but the scheme was eventually abandoned in favour of more focused control in priority areas (Pracy 1980). Large scale control of possums on conservation land, using aerially delivered 1080 (sodium monofluoroacetate) bait began in the 1960s (King 1990). These operations were conducted in piecemeal fashion, as funding was available (Pracy 1980). The status of the possum as a pest on the conservation estate received a boost in 1967 when possums were found to be carrying bovine tuberculosis (Tb; Mycobacterium bovis) (Lever 1985). Accordingly, in the 1970s, additional possum control began on farmland and along forest borders in areas of the country where cattle Tb was endemic (Atkinson et al. 1995).

Recognition of the continuing impact of possums on the environment, and their potential to dramatically influence our future trade, resulted in the allocation of increasingly large possum control budgets beginning in 1990 (Parkes et al. 1996). By 1994, total funding for possum control and research had increased to $58 million (NZD) for the financial year (Livingstone 1994). Around this time, the government agencies responsible for possum control (Animal Health Board and the Department of Conservation; AHB and DOC) developed national control strategies which are coordinated by the National Possum Coordinating Committee (PCE 1994).

A proportion of this possum budget is specifically for research. This has correspondingly increased from $2.7 million in 1990/91 to $14.5 million in the 1996/97 financial year (NSSC 1997). This research is coordinated by the National Science Strategy Committee on Possum and Bovine Tuberculosis Control (NSSC), which has thus far organised four possum research workshops since its conception in 1991. One term of reference for this
committee is the identification of research priorities and important gaps in the possum research agenda. Two of the NSSC's current short-term research priorities are:

1. ‘research on toxins, ...bait and poison shyness’; and

2. ‘research to develop models to assist in the management of bovine Tb’.

The contribution of this Ph.D. thesis is the continuation of research in these two key areas, which are briefly reviewed below.

1080 bait shyness

In the 1990s, the government control agencies began to focus on sustained control to reduce possum densities below predetermined environmental and disease thresholds. The disease threshold is derived from epidemiological modelling simulations that suggested Tb could be eradicated from a possum population over a period of 6-8 years (PCE 1994). To achieve this the possum population was severely reduced (at least 75% kill) in an initial control operation and then maintenance control is frequent enough to maintain the population below the threshold for the disease transmission (estimated at 40% of the habitat’s carrying capacity; (Barlow 1991b). The environmental threshold typically involves an initial knockdown of at least 80% of the population, followed by future work to slow or prevent population recovery (Spurr 1981; Efford 1992). The regularity of maintenance control is dependent on the rate of possum population recovery and the vulnerability of vegetation to possum browse (DOC 1994). The achievement of both target thresholds sometimes requires maintenance control at annual or biennial intervals.

Large-scale aerial 1080 baiting techniques were first developed in the late 1950s and this technique can be an extremely cost-effective method of removing 85-95% of a possum population (Warburton et al. 1992; Eason et al. 1994). Unfortunately, the efficacy of this acute-acting toxicant decreases markedly when regularly used for maintenance control. A striking example of this comes from Mapara Forest in the central North Island, where 1080
possum kills declined from 79% to 32%, and then to 0%, during a series of three annual aerial operations (Warburton and Cullen 1993).

Given that there are only a few alternative feasible control options, 1080 'bait shyness' poses an immediate threat to the sustainability of possum control in New Zealand (O'Connor and Matthews 1996). Accordingly, there was a need to investigate methods of preventing and mitigating 1080 bait shyness. First, I reviewed relevant literature on rodent, rabbit and possum control (Chapter 2). Based on this review, I investigated several strategies for mitigating 1080 bait shyness. The strategies I investigated were the effectiveness of changing to an alternative, slower-acting toxicant (cholecalciferol, marketed as Campaign® and brodifacoum, marketed as Talon®) for maintenance control (Chapter 3); changing 1080 bait components such as the base and the lure to mitigate cereal 1080 bait shyness (Chapter 4); and using non-toxic cereal prefeed to prevent the development of 1080 bait shyness and cereal postfeed to mitigate 1080 bait shyness amongst survivors of previous 1080 control operations by acclimatisation (Chapter 5).

**Possum population modelling**

Previous possum-control simulation studies suggested that regular aerial 1080 control is the most cost-effective possum control strategy (Barlow 1991). However, these simulations generally overlook the problem of 1080 bait shyness and do not incorporate the new slower-acting possum toxicants (Chapter 2). The decision of when to use these alternative toxicants is difficult, because these control methods are more expensive than those based on the use of 1080 (Henderson et al. 1994). Accordingly, there was a need to develop a new possum bioeconomic model, which incorporated both bait shyness and alternative possum toxicants. This model was used to determine the most cost-effective combination of toxicants for sustained control over 10 and 20 year time frames (Chapter 6).
1.1 Objectives

This thesis addressed the following objectives:

- To investigate nightly consumption of acute, subacute and chronic-acting toxicants by 1080 bait-shy possums, during prolonged exposure to those toxicants.

- To determine the role of alternative toxicants in combating 1080 bait-shy behaviours in possums, with a view to recommending alternative bait formulations that shy possums will accept.

- To determine the role of acute, subacute and chronic-acting toxicants in both familiar and unfamiliar bait matrixes, to combat 1080 bait-shy behaviours in possums, with a view to recommending alternative bait formulations that those possums will accept.

- To determine the influence of non-toxic cereal prefeed and postfeed in the development and maintenance of 1080 cereal bait-shyness.

- To model the most cost-effective way of reducing the possum population to a predetermined target density, given that alternative formulations of 1080 bait, and alternative toxicants, may be required to sustain the efficacy of such control.

1.2 Structure of thesis

This thesis represents work that commenced in March 1995 under the supervision of Drs. Graham Hickling and Katie Bicknell. The thesis is structured as a series of complementary, yet self-contained chapters. Chapters 3-6 have been prepared for submission to various journals. However, the format and layout of these three chapters has been adjusted to ensure the overall presentation of this thesis is consistent.
Chapter 2 reviews the colonisation and impacts of possums in New Zealand. The history of possum control and research is also given. Chapter 3 describes a preliminary pen trial that investigated the effectiveness of alternative, slower-acting toxicants, in cereal baits, for the control of 1080 bait-shy possums. Guidelines for future pen possum trials are provided. Chapter 4 compares the effectiveness of changing the toxicant (from Chapter 3) versus changing the bait type and lure. Chapter 5 investigates the role of cereal prefeed and postfeed in the development of 1080 bait shyness. Implications of results for management and areas of future research are discussed. Chapter 6 presents a possum bioeconomic model, which is used to determine cost-effective control strategies. Implications of these results for possum control management are discussed. Chapter 7 identifies key findings of the previous chapters and makes recommendations for possum researchers and field managers.

1.3 Acknowledgements

Three of the chapters were written under contract to Landcare Research (N.Z.) Ltd (funded by the Foundation for Research, Science and Technology; FORST). The author was supported by a Lincoln Doctoral Scholarship. Additional funding was received from the Entomology and Animal Ecology Group (Lincoln University), the Kathleen Anne Stevens Scholarship, the Syd Bodmin Scholarship, the Gordon Williams Postgraduate Fellowship, MacMillan Brown Agricultural Research Scholarship, Masterton Trust Lands Trustee Scholarship and the Lincoln University Fund for Excellence.

1.4 References


CHAPTER 2

LITERATURE REVIEW: ECOLOGY, HISTORY OF COLONISATION, AND CONTROL OF THE COMMON BRUShTAIL POSSUM IN NEW ZEALAND

In this Chapter I provide background on the ecology of the common brushtail possum *Trichosurus vulpecula* (Kerr 1792) (henceforth referred to as ‘possum’). I also provide a historical overview of New Zealand possum colonisation and the response of the various control agencies to the pest problems that subsequently arose. I then review previous research investigating mammalian behavioural resistance to poisoning; this section highlights the current gaps in knowledge of this problem and is the basis for the three pen trial studies detailed in Chapters 3, 4 and 5. Finally, I discuss past research investigating cost-effective control of possums; this section emphasises the need to develop a new bioeconomic possum model and is the basis for the Chapter 6 simulation study.

2.1 Ecology

The possum is an arboreal, nocturnal marsupial (Cowan 1992; Figure 2.1) belonging to the family Phalangeridae (‘fingered’). The species’ natural distribution is principally eastern and northern Australia and Tasmania, however, the species is also found in southwestern Australia and northern Queensland (Lever 1985). Three sub-species are recognised, two of which were successfully introduced to New Zealand. These sub-species came from eastern Australia (*T. v. vulpecula*) and Tasmania (*T. v. fuliginosus*), with the Tasmanian species being slightly larger and more robust (Strahan 1983).
In New Zealand possum populations, there is little difference in size or weight between the sexes, when corrected for age (Clout 1977). Typical adult measurements are as follows: total length 650-930 mm, head length 80-115 mm and tail length 250-405 mm (Triggs 1982). Average adult weight is also dependent on habitat and climate; for example, farmland possums are generally lighter than possums living in exotic or indigenous forest (Cowan 1990). Adult body weight is closely correlated to mean annual temperature; with North Island populations typically lighter ($n = 13$ trials; $2.45 \text{ kg} \pm 0.04 \text{ S.D.}$) than South Island ones ($n = 17$ trials; $3.04 \text{ kg} \pm 0.08 \text{ S.D.}$) (Green and Coleman 1986).

There are two main colour forms, grey and black, but with such variation that the New Zealand fur trade recognises eight different colours (Cowan 1990). Black forms predominate in wet areas and indigenous forest, whereas greys predominate on farmland and dry, open country (Wodzicki 1950).
Reproduction and development

New Zealand possum populations differ in their reproductive parameters, mortality rates and productivity (Spurr 1981). Males generally become reproductive at 1-2 years old, which is slightly older than females (Gilmore 1966). The main birth season is in autumn with a second, smaller and more variable season in spring (Batcheler and Cowan 1988). Seasonal changes in body condition suggest that the timing and amount of reproduction is primarily regulated by food supply (Humphreys et al. 1984). Annual mortality is highest amongst pouch young, with the rate varying from 10% in low density populations (Clout 1977) to 42% in high density populations (Bell 1981). Rates of adult mortality vary from 10% at low-medium densities (Barlow 1987) to 20% for an established population at carrying capacity (Spurr 1981). Average life expectancy of possums, which survive to independence, is 8-9 years with some animals living to 14 years (Brockie et al. 1981).

Diet

Possums are opportunistic, destructive herbivores, feeding mainly on leaves (Cowan 1990). However, possums will also feed on berries, seeds, invertebrates (Cowan and Moeed 1987), small animals, birds and eggs (Brown et al. 1993). While they will feed on more than 70 species of indigenous trees, possums show a pronounced preference for some plants relative to their abundance (Green and Coleman 1984). In six separate study areas, the six most commonly eaten plants (largely determined by local availability) comprised 65-90% of the total food intake (Green and Coleman 1984).

Habitat

Cover and a suitable food supply are possums' main habitat requirements. Hence, they are found in most habitats excepting only the high rainfall, mountainous terrain of southwest Fiordland. Possums are found in all types of indigenous forest from sea level to the treeline (2400 m), where rainfall ranges from 350 mm to >8 000 mm. Average density in indigenous (podocarp-broadleaf) forest is 10-12 possums/ha (range 7-24 possums/ha) (Coleman et al. 1980; Brockie 1982). They are also found in exotic and indigenous
grasslands, exotic forests, shelter belts, orchards, sand dunes, swamps, urban and city areas (Cowan 1990). Population densities in these habitats are generally much lower than indigenous forest, although densities of 5-10 possums/ha can still be reached in streamside willows and scrub-filled swamp habitat (Brockie et al. 1991).

Comparison of Australian and New Zealand possum populations

In Australia, possums often feed on *Eucalyptus* leaves if little else is available (Cowan 1990). The nutritional value of these leaves is generally low and toxic secondary compounds in them can limit populations if alternative food is scarce (Freeland and Winter 1975). Australian possums are preyed on by dingos (*Canis familiaris dingo*), feral dogs (*C. f. familiaris*) and cats (*Felis catus*), foxes (*Vulpes vulpes*), wedge-tailed eagles (*Aquila audax*), lace monitors (*Varanus varius*) and carpet pythons (*Morelia spilota*) (Jones and Coleman 1981).

Australian possums compete for food and den sites with several other species of possums and gliders (Smith et al. 1994). In New Zealand, there are far fewer predators and parasites and few arboreal folivores. The consequence of these differences is a two to twentyfold increase in the density of possum populations in New Zealand, relative to populations in Australian *Eucalyptus* forests (Cowan 1990).

2.2 History of colonisation

Possums were liberated in New Zealand to establish a fur trade similar to one that had flourished in Australia since the early 1800s (Parkes et al. 1996). The first animals arrived in the country in 1837 and were liberated at Riverton by Captain J. Howell (Pracy 1974). These animals failed to establish and the first successful liberation was not until 1858, at the same site; by 1889, the population had increased enormously (Lever 1985). Between 1858 and 1922, at least 464 additional ‘sanctioned’ liberations were made; most used New Zealand born progeny. In total, only 200-300 possums were imported from the Australian mainland (southeastern) and Tasmania (Cowan 1990).
Only about half of the total number of New Zealand possum liberations were legal, having been made by the Acclimatisation Societies and private individuals with official government approval (Wodzicki 1950). The number of legal liberations declined after 1922 as a growing conflict of interest developed between the Acclimatisation Societies and farmers, orchardists and conservationists. After 1920, illegal liberations became common (Pracy 1974) and these continued as late as the 1980s (Julian 1984). Throughout the 1920-40s there was increasing evidence that possums were causing significant damage to commercial plantations and indigenous forest (Cowan 1990). Nevertheless, as this debate continued, the possum continued to have various forms of government protection.

Eventually, the tide of opinion swung against the protection of possums and in 1946 all protection was removed. Early attempts at nation-wide control (e.g., the bounty scheme) were ineffective (Kean and Pracy 1953) and established populations continued to increase and expand (assisted by further illegal liberations) (Cowan 1991). Currently, possums are established on more than 91% of New Zealand with an estimated population of 60-70 million; two thirds of which are on the North Island. Possums are continuing to colonise the few remaining unoccupied, remote areas of South Westland, south-east Fiordland, Coromandel and Northland (PCE 1994).

**Impacts of colonisation**

In most parts of their Australian range, possums cause only minor damage to exotic and indigenous forests (Clout 1977). In contrast, New Zealand possums are considered a major pest due to their much higher population density, the susceptibility of New Zealand’s indigenous vegetation to browsing, due to the reduced number of secondary compounds in the vegetation, and their role in the transmission of bovine tuberculous (Tb; *Mycobacterium bovis*).

**Impact of possum on indigenous flora**

At the current population size, it is estimated that possums consume approximately 21 000 tonnes of vegetation per night (Nugent 1994). The New Zealand flora has evolved in
isolation from land mammals and consequently has little innate resistance to their browsing (Lever 1985); two thirds of the North Island forest canopy, and one quarter of South Island forest canopy is particularly vulnerable (Cowan 1991).

There have been three broad impacts of this browsing on the indigenous flora. Firstly, catastrophic dieback may occur in forest types dominated by just few possum-preferred species such as the rata (*Metrosideros* spp.) and kamahi (*Weinmannia racemosa*) dominated forests of Westland (Batcheler and Cowan 1988). In these forests there has been widespread and progressive canopy mortality over the last 40 years (Cowan 1990) and it is estimated that less than 10% of Westland forest remains in an unmodified state (Cowan 1991). The relationship between major canopy dieback and the timing of possum invasion is debatable. Large-scale canopy dieback is a natural event in some forest types, related to past catastrophic events, and Veblen and Stewart (1982) argued that the effect of possums may sometimes be secondary to inevitable natural dieback and erosion. However, other researchers maintain that possums are largely responsible for rata-kamahi forest dieback, especially in areas where the diet of the possum is dominated by these two species (e.g., Allen and Rose 1983). In these areas, dieback affects trees of mixed ages and the rata-kamahi dominated forest canopy has been replaced by other less palatable species (Batcheler 1983).

Secondly, in diverse forest communities with a mix of palatable and unpalatable species, the main impact of possum browsing has been gradual, possibly episodic, depletion of plant species (Nugent 1994). In areas like the Orongorongo Valley (lower North Island), palatable species such as fuchsia (*Fuchsia excorticata*), titoki (*Alectryon excelsus*), tutu (*Coriaria arborea*), toro (*Myrsine salicina*) and five finger (*Pseudopanax arboreus*) have disappeared (Campbell 1990). The greatest impact on forest composition occurs in mixed broadleaf forests where possum-preferred species are most abundant. However, even in the least susceptible forests, with lower possum densities, some minor plant species have disappeared (e.g., mistletoes, *Lythranthe* spp., in beech forest; Nugent 1994).

Thirdly, possums have the potential to inhibit regeneration, although damage to the sub-canopy has not been extensively studied because it is difficult to separate possum browse
from that of ungulates such as red deer (*Cervus elaphus*), feral goat (*Capra hircus*) and
chamois (*Rupicapra rupicapra*) (Nugent 1994). However, possums have been reported
browsing and killing seedlings of some species on Kapiti Island where ungulates are absent
(Atkinson 1992). Researchers have also noted that sustained possum browsing prevents the
flowering and fruiting of tree species such as kohekohe (*Dysoxylum spectabile*) (Cowan
1990).

*Impact of possum on indigenous fauna*

There have been two main impacts of possums on the indigenous fauna. First, possums
have killed eggs, chicks and adults of North Island kokako (*Callaeas cinera wilsoni*),
brown kiwi (*Apteryx australis mantelli*), kahu (*Circus approximans*), fantail (*Rhipidura
fuliginosa*), North Island saddleback (*Philesturnus carunculatus*) and kereru (*Hemiphaga
novaeseelandiae*) (Brown *et al.* 1993). As this is a recently discovered phenomenon it is
difficult to ascertain the significance of possum predation. However, time-lapse video
monitoring has revealed that possums caused the failure of four out of 19 kokako nests in
Mapara Forest, Central North Island, in one breeding season. It has since been speculated
that possums were likely to have been responsible for 10 out of 33 recorded kokako
predations (30%) over a period of four years (Innes 1994).

Possums also prey on invertebrate species with half of the possum-faeces examined at an
Orongorongo Valley study site containing invertebrate remains (mainly larger stick insects,
wetas, cicadas and beetles; Cowan and Moeed 1987). These researchers concluded that the
consumption of invertebrates was opportunistic and large-bodied nocturnal species such as
indigenous snails (*Powelliphanta* spp.) were most at risk.

Secondary effects of possum browsing on indigenous fauna may also occur. The reduction
of plant biomass by possums probably deprives indigenous animals of food and thereby
reduces their numbers (Nugent 1994). For example, there is considerable overlap in diet
between possums and the North Island kokako (Fitzgerald 1984). This may partly explain
the decline of this bird (Leathwick *et al.* 1983) and other nectivorous/frugivorous birds
Williams 1976). Possums may also compete for nest sites with hole-nesting birds such as kiwi (Apteryx spp.), parakeet (Cyanoramphus spp.) and saddleback (Philesturnus spp.).

Invertebrates are especially likely to be affected because many are dependent on one or a few plant species (Dugdale 1975). Accordingly, some invertebrate species are very vulnerable to extinction, being restricted to a single habitat (Ramsay et al. 1988). For example, possums heavily browse pohutukawa (Metrosideros excelsa), which has five host-specific scale insects.

**Impact of possums on exotic flora**

Possums can also damage exotic trees, pasture and horticultural produce. New Zealand’s exotic forest plantations exceed 1 million ha in area; about 90% of which are planted in *Pinus radiata* (Cowan and Moeed 1987). Approximately 50% of the trees are less than 10 years old and are particularly susceptible to possum browse (Cowan 1991).

Possums cause three types of damage to pine trees: i) browsing of terminal shoots; barkstripping; ii) breakage of leader/top whorl; and iii) cone loss from seed stands (Jacometti 1997). Possums inflict similar damage to exotic poplar (Populus spp.) and willow poles (Salix spp.) used for erosion protection on susceptible hill country and along river stop banks. They can also cause localised damage to almost all types of agricultural and horticultural plantings located near areas of indigenous/exotic forest or scrub (Livingstone 1994).

**Possum as a disease vector**

In 1967, possums in Westland were infected with Tb (Ekdahl et al. 1970). By 1971, it was recognised that the possum was acting as a significant vector in the transmission of Tb to cattle; and later to farmed deer (Livingstone 1994). In countries with an efficient nationally coordinated veterinary service, Tb has not usually been a difficult disease to control and eradicate from livestock populations. However, in New Zealand, as in other countries where there have been wildlife vectors of the disease, there have been ongoing problems
with controlling or eradicating the disease (Ryan et al. 1996). It has been estimated that possums are currently the source of more than 90% of tuberculous cattle and 75% of tuberculous deer infections in New Zealand (Livingstone 1994).

New Zealand’s approach to the management of the Tb problem has been to divide the country into Tb vector-risk (VRA), vector-free (VFA) and fringe areas based on the incidence of livestock Tb vectors and the discovery of Tb in local wildlife (AHB 1995). Currently, VRAs make up 23% of New Zealand’s land area (Figure 2.2), with new VRAs continuing to be identified, some of which apparently originated from the movement of Tb feral/wild animals through large tracts of conservation estate. Epidemiological studies indicate that the rate of spread of the disease through possum to possum contact is, in the absence of control, 3-4 km/year (Batcheler and Cowan 1988). Unless controlled, the VRAs will continue to expand outward through the migration of infected juvenile possums and other feral/wild animals such as red deer, pig (Sus scrofa) and possibly ferret (Mustela furo) (Livingstone 1991; Caley and Morley 1998).

Figure 2.2: Tb vector-risk control areas (VRAs; AHB 1995)
In conclusion, the cost to New Zealand attributable to possums is enormous, both in ecological and monetary terms. The current level of Tb infection in New Zealand cattle and deer herds could in the medium term restrict our $5 billion per annum (NZD) export market for venison, beef and dairy products (Livingstone and Nelson 1994). Australia has already reacted to New Zealand's high incidence of Tb by banning the importation of live cattle (AHB 1995). It has been estimated that further trade restrictions for meat and dairy products could cost New Zealand up to $500 million annually (Eason et al. 1996). Possums are also thought to consume $12 million worth of pasture annually; to inflict annual damage of $7-8 million on pine plantations; to inflict about $1 million damage on crops and horticulture and between $300 000 and $800 000 damage on poplars and willows planted to limit soil erosion (Cowan 1991). No monetary value has yet been placed on possum damage to conservation resources, but there is strong public support for limiting their impact on indigenous vegetation and wildlife (Livingstone and Nelson 1994).

2.3 History of possum control

Possum damage to economic crops was noticed as early as 1910, but it was not until the late 1940s that the Department of Internal Affairs began control operations (PCE 1994). Before this there had been limited private trapping, with the possum skin export trade starting in 1919 (56 million skins have since exported; Parkes et al. 1996). The first large scale attempt at possum control was via a bounty scheme, that ran from 1951 until 1961, with over eight million bounties paid (Pracy 1980). This system was eventually discontinued when it became clear that it was ineffective at controlling expanding possum populations (Parkes et al. 1996).

In 1956, the control of possums on conservation land was transferred to the New Zealand Forest Service (NZFS). Initially, control efforts aimed to protect the susceptible forest canopy by achieving a high initial kill using aerially delivered sodium monofluoroacetate (1080) bait. Such operations were repeated after a decade or more, when funding was available. Funding for possum control on conservation land was not guaranteed and control operations generally began and stopped in a piecemeal fashion (Parkes et al. 1996). With the cessation of the bounty system, control of possums on agricultural and neighbouring
conservation land was conducted by Rabbit Boards (which, in 1967, became the Animal Pest Destruction Boards; APDBs) (Coleman 1981). These Boards aimed to protect commercial plantings (where the possum was declared a pest of local importance) using ground control techniques such as 1080, cyanide and phosphorus poisoning, trapping and shooting.

The status of the possum as a pest received a boost in 1967 when possums were identified as carriers of Tb (Ekdahl et al. 1970). To combat the spread of this disease, the then Department of Agriculture (1972) contracted the APDBs and the NZFS to conduct more extensive possum control work. During the years 1978 to 1981, the number of cattle reactors decreased significantly and possum control funding from central government was consequently reduced (PCE 1994). Indicators of Tb infection in herds began steadily increasing from 1982, but possum control funding did not return to previous levels until 1988 (PCE 1994).

In the late 1980s and early 1990s, there was considerable restructuring of the possum control agencies. In 1987, the forest protection role of the NZFS was transferred to the Department of Conservation (DOC); in 1989, the pest control function of the APDBs was transferred to the seven Regional Councils (PCE 1994); and in 1990, the Animal Health Board (AHB) was established to administer the Tb control programme. At this time recognition of the continuing impact of the possum on the environment and its potential to dramatically influence our future trade, resulted in the allocation of progressively larger annual control budgets (Parkes et al. 1996). By 1994, total funding for possum control and research had reached $58 million per annum (Livingstone 1994). The government agencies responsible (AHB and DOC) also began developing national control strategies that were coordinated by the National Possum Co-ordinating Committee (PCE 1994).
The present situation

DOC Possum Control Plan 1993-2002

DOC's overall goal is to protect and conserve indigenous vegetation, animals and ecosystems on Crown land (DOC's legal responsibilities in this area derive from the Wild Animal Control Act 1977). However, the annual control budget of the Department (as at 1995/96) was only sufficient to effectively control possum impacts on about 17% of the conservation estate (i.e., 13 000 of 78 000 km²). It is estimated that approximately 18 000 km² are dominated by canopy species at major risk from possums (Parkes et al. 1996). A primary purpose of DOC's National Possum Control Plan 1993-2002 was to allocate this control budget amongst competing 'at-risk' conservation areas. To achieve this, a ranking system was developed that identified the most at-risk biota, vegetation types and biological communities (DOC 1994).

Once an area has been selected for control, DOC’s preferred strategy is eradication. However, to achieve the eradication of any vertebrate pest, various conditions have to be met (Bomford and O'Brien 1995) and for possums these are achieved only on small offshore islands. Possums have recently been eradicated from several such islands (e.g., Tommy, Native, Codfish and Kapiti Islands; DOC 1994).

For most mainland-possum populations, the usual strategy is selective sustained control. This typically involves an initial knockdown of at least 80% of the population, followed by future work to slow or prevent population recovery. The regularity of maintenance control is dependent on the rate of possum population recovery and the vulnerability of vegetation to possum browse (DOC 1994). These rates obviously differ and cannot be accurately assessed unless there is monitoring of plant species recovery. Some species of plant and animals respond slowly to reduced browsing/predation pressure (Nugent 1994) so, in the interim, it has been assumed that a sustained 80-90% reduction of an initial possum population should provide significant protection for indigenous flora and fauna (Hickling 1994).
Animal Health Board Strategic Plan 1993-1998

The AHB is responsible for the control of possums on both Crown and private land in Tb VRAs (PCE 1994). The long-term goal of the AHB is to eradicate Tb from New Zealand’s domestic livestock (AHB 1995). However, total eradication is not a realistic possibility given the current control technology (AHB 1995) so the current short-term objectives of the AHB are to:

1. reduce the number of infected herds in Tb VFAs from 0.7% to 0.2% of the total herds in those areas;

2. prevent the establishment of new Tb VRAs and/or the expansion of existing Tb vector areas into farmland free of Tb vectors;

3. decrease the number of infected herds in Tb VRAs from 17% to 11% of the total number of herds in those areas; and

4. encourage individuals to take action against Tb on their properties and in their herds (AHB 1995).

These objectives were based on an AHB assessment of what was required to reassure New Zealand’s trading partners that effective measures were being undertaken to control Tb and to reduce the level of risk to livestock (PCE 1994). The AHB strategy for achieving these objectives involves Tb status testing, movement control for livestock and targeted control of Tb vectors. Essentially there are four types of vector control (AHB 1995):

1. preventive control carried out in areas where there is a perceived risk of Tb becoming established;

2. control to establish buffer zones to contain vectors within the current Tb VRAs;
3. control to reduce the risk to livestock by reducing the number of Tb vectors in risk areas; and

4. control used in an attempt to eradicate Tb from those areas where it is considered technically possible.

Vector control principally involves the reduction of possum populations. However, other species (wild pig, deer and ferret) may also be controlled where it is likely that they are acting as vectors.

In these VRAs a strategy of sustained possum-population control is adopted. This strategy is derived from epidemiological modelling simulations that suggested Tb could be eradicated from a possum population over a period of 6-8 years (PCE 1994), provided the possum population was severely reduced (at least 75% kill) in an initial control operation and maintenance control was then frequent enough to maintain the population below the threshold for the disease transmission (estimated at 40% of the habitat’s carrying capacity; (Barlow 1991b). This control strategy has been successful in eradicating Tb from possum populations in Te Puna in the Bay of Plenty and at Fortification in Southland (AHB 1995), and has been widely adopted, with AHB-funded possum control operations now encompassing a land area of c. 40 000 km² (V. Anderson, pers. comm. 1998).

Nationally co-ordinated control strategies

Possum control in New Zealand has changed considerably from the earlier sporadic control operations of the 1960s (Parkes et al. 1996); the main change being the development of two co-ordinated national control strategies for possums on Crown and private land. National strategies are viewed as crucial for the management of vertebrate pests for a number of reasons (Braysher 1993). First, possum-control managers now have clear interim and long term control objectives. Earlier attempts at control (e.g., the bounty system) had no clear objective other than to kill possums. Effective pest control also requires managers to concentrate on reducing the impacts of pest species (Hone 1994). Accordingly, possum control in New Zealand now focuses on reducing possum
populations to pre-determined control thresholds. Threshold densities enable managers to anticipate the frequency of control that will keep the pest population at or near that density. Too often in the past vertebrate pest control has been sporadic and has allowed pest numbers to return quickly to pre-control levels (Braysher 1993).

Another important benefit of the national control strategies is that there is now a co-ordinated research effort, which helps the government and other funding bodies to facilitate future research (Braysher 1993). In New Zealand, the recognition of the importance of possum research was demonstrated by the establishment of the National Science Strategy Committee on Possums and Bovine Tuberculosis Control (NSSC) (PCE 1994). The goal of the NSSC is 'to identify, co-ordinate, promote and disseminate research that will provide the information and techniques required to: i) create a bovine Tb-free status for New Zealand; ii) protect national conservation and environmental values; and iii) protect the economic value of crops threatened by possums'.

The NSSC recognises that both Tb control and conservation protection requires regular, sustained possum control. Currently, there are only a few control options that can lower possum populations below Tb or conservation impact thresholds, on a medium-large scale. Of these control options, 1080 is currently considered the most cost-effective, particularly in areas of difficult terrain and poor access (PCE 1994). Potential new control methods such as Tb vaccines and sterilisation of possums hold much promise, but remain as yet unrealised. For example, despite good progress, the development of a successful possum immunocontraceptive is still thought to be 5-10 years away (Cowan and Bayliss 1998). In recognition of this, the NSSC recommends that institutions invest, in part, in short term research that seeks to improve existing possum control methods. In particular, the NSSC supports research investigating methods of overcoming 1080 bait shyness (NSSC 1997).

**Possum 1080 bait shyness**

Large-scale aerial 1080 baiting techniques for possums were developed in the late 1950s and used extensively thereafter (Morgan *et al.* 1986). Aerial control was implemented because cheap control was needed in very large, rugged areas of scrub and forest
The aim of this control was to provide each possum in the poisoning zone with at least one palatable bait containing a lethal dose. Due to the long intervals between operations, there has typically been little concern about induction of bait shyness among the survivors of these aerial operations (Hickling 1995).

In the 1990s, possum control was intensified because of the continuing spread of Tb (Livingstone 1994). Field managers increasingly began to use ground-based techniques such as bait stations, often at annual or biennial intervals, for maintenance control. There was little work at the time published on the efficacy of these 'maintenance control' campaigns, but preliminary pen and field trials began to raise concerns that increasing numbers of 1080 bait-shy possums could lead to poor kills in ongoing control programmes. For example, early pen trial studies found that 60\% of possums sub-lethally dosed with 1080 rejected the same 1080 bait on re-exposure (Morgan 1990).

The extent of this problem was later highlighted in a series of field studies investigating the efficacy of 1080 bait stations for annual control. For example, bait-shy possums were observed 'dumping' dyed 1080 bait at the base of feeders as they searched for undyed, non-toxic prefeed, which they continued to consume (Hickling et al. 1991). Thomas (1994) estimated that 5-25\% of naive possums (i.e., ones that had not been previously controlled) that encountered a bait station either avoided the toxic bait or consumed a sub-lethal dose. In two other 1080 bait station trials, the estimated kill was only 39\% and 60\%, which was substantially lower than that achieved by a one-off aerial application of 1080 bait (Thomas and Hickling 1995). These trials suggested that the average yearly kill rate, using solely 1080 in bait stations, would not be high enough to maintain a significant population reduction.

Another striking example of this problem came from Mapara Forest (central North Island), where 1080 possum kills declined from 79\% to 32\%, and then to 0\%, during a series of three annual aerial operations (Warburton and Cullen 1993). It was speculated that such reduction in the efficacy of repeat 1080 operations was due to the residual population developing 'bait shyness'. This hypothesis was supported when 60\% of adult possums
trapped from Mapara Forest avoided 1080 baits 15 months, in a series of bait acceptance pen trials, after the last aerial operation (O'Connor and Matthews 1996).

**Animal resistance to poisoning**

When 1080 bait-shy possums were first identified, there had been relatively little research conducted on the feeding behaviour of marsupials (Matthews and Pearson 1990). However, there had been considerable research on the chemical control of other mammalian pests such as rabbit (*Oryctolagus cuniculus*), mice (*Apodemus* spp.) and rats (*Rattus* spp.) (Brunton et al. 1993). Many of these studies discussed aspects of bait shyness, which is a generic term used in this thesis to indicate the avoidance of a poison or bait.

These studies have demonstrated that there are two general mechanisms of bait shyness (physiological and behavioural) through which an animal can avoid succumbing to a lethal dose of poison. The following two sub-sections introduces these mechanisms and defines some specific behavioural responses.

**Physiological resistance**

Physiological resistance refers to poisoning-induced metabolic strategies that enable animals to tolerate or detoxify a toxicant that they have consumed (Kandel and Chenoweth 1952). Short-term tolerance of a toxicant may be acquired through repeated ingestion of it in sub-lethal quantities. For example, the short-term tolerance of rats and mice to 1080 increases after repeated sub-lethal doses (Kandel and Chenoweth 1952).

The ability to tolerate or detoxify a toxicant may also increase over generations in populations that are repeatedly poisoned, as individuals carrying resistant genes are selected (Buckle 1994). Such resistance and its selection is well documented in populations of rats, mice, and invertebrates, many of which have been poisoned for decades (e.g., Pelz *et al.* 1995). This also occurs naturally in Australian native animals exposed to 1080-bearing plants (Twigg and King 1991).
Behavioural resistance

There are four main types of behavioural mechanisms that can reduce an animal's tendency to consume a lethal dose of a poison. These mechanisms can be both genetically determined (neophobia towards novel food or bait and innate rejection of poison) and learned (conditioned food aversion and enhanced neophobia).

Neophobia

Neophobia (*sensu* Cowan 1977) is an innate wariness of unfamiliar objects or foods in a familiar environment and may be associated with a 'cautious feeding' strategy (Hickling 1994). Neophobic animals may be highly cautious when they encounter a novel food, only consuming small (sub-lethal) amounts during initial encounters (Brunton and MacDonald 1996). Neophobia can be pronounced in populations of commensal rodents that are frequently exposed to manufactured traps and toxic baits (Cowan 1977).

Innate rejection of poison

Innate poison avoidance may result from selection pressure over many generations of exposure. A possible example of this is the level of innate cyanide avoidance by some possum populations in New Zealand. Warburton and Drew (1994) observed that more than 60% of a possum population, with no previous exposure, avoided cyanide. In Australia, possums have co-evolved with some species of *Eucalyptus* that produce hydrogen cyanide gas (Pass *et al.* 1993), so may have evolved the ability to detect and reject cyanide. The lack of previous exposure to cyanide, among the possums Warburton and Drew (1994) studied, suggests that the avoidance was not a learned behavioural response generated by previous sub-lethal exposure. Another possible example of this also comes from Australia, where higher than expected numbers of *Sminthopsis crassicaudata* (a small carnivorous marsupial mouse) avoided meat baited with 1080 (Sinclair and Bird 1984). In this experiment 25% of the animals (previously starved) did not touch poisoned meat, while continuing to eat unpoisoned meat after the treatment. In this case, it seemed that the animals had a strong innate olfactory aversion to the bait treated with 1080.
Conditioned food aversion

Conditioned food aversions (CFAs) arise where a particular food (e.g., a bait) is rejected on subsequent exposure, if the animal has associated illness from its first encounter with that food. However, this is dependent on lag phase associated with the ingestion and subsequent effects of the toxin. For example, with rats CFAs can develop with a lag phase of up to 16 hours (Andrews and Braveman 1975). Once an animal has developed a CFA, it will completely avoid or drastically reduce its consumption of food that it perceives to be the same or possessing similar characteristics (Gustavson 1977).

Enhanced neophobia

In addition to developing a CFA, a sub-lethally poisoned animal may become increasingly cautious of other novel food. For example, rats (R. rattus) poisoned with one novel food subsequently show increased avoidance of that food and also of other novel foods (Brunton et al. 1993).

Of these different mechanisms, the strongest effect is seen with the learned aversions; this is a problem frequently encountered in vertebrate pest control (Robbins 1981). Most bait shyness observed in possum populations is likely a learned behaviour (CFA) caused by prior sub-lethal exposure. This hypothesis is supported by pen trials demonstrating that the majority (>60%) of possums exposed to a sub-lethal dose of 1080 or cyanide will develop a CFA to a familiar bait (O'Connor and Matthews 1995). Though the significance of physiological and non-learned avoidance mechanisms should not be overlooked (O'Connor and Matthews 1996), the speed at which CFAs form suggests that they are the most immediate threat to the sustainability of possum control in New Zealand (Hickling 1994). The following two sections detail some of the research on CFAs in possums and other species.
Research investigating rodent bait shyness

The history of field and house mouse control using plant-based (organic) toxins dates back to the Roman Empire. The spread of the black rat (*R. rattus*) across Europe in the Middle Ages did little to change this approach, with organic toxins being relied on for rodent control until the late 19th century (Buckle 1994). The first inorganic compounds such as phosphorus, red squill and barium carbonate then came into use (Chitty 1954). Compound 1080 was first synthesised in 1896 and was used for the control of London sewer rats at the turn of the century (Meehan 1983).

In the 20th century, development of new inorganic acute-acting toxicants continued until the 1940s (an acute-acting toxicant is one with rapid onset of toxicosis after an effective dose is ingested). With these compounds, symptoms of toxicosis generally appear in less than 24 hours and, with some compounds, in only minutes (Buckle 1994). Around this time, bait-shy rats began to become a problem in areas that were being poisoned frequently with these acute-acting toxicants (Chitty 1954). These rats had developed a conditioned taste aversion and altered their feeding behaviour (Brunton *et al.* 1993). A conditioned food aversion (CFA) was first demonstrated in the laboratory in 1955 with rats (*R. norvegicus*) that received a dose of radiation and a novel food, subsequently avoided such food (Smith *et al.* 1994). Since then, numerous studies have examined the phenomenon and over 150 compounds (including 1080) are now listed as capable of inducing a CFA (Riley and Tuck 1985).

Acute-acting toxicants are prone to causing CFAs because the rapid onset of toxicosis enables the animal to associate cause and effect (Buckle 1994). Strong aversions in rats (*R. rattus*) can form with delays over 16 hours between ingestion and illness (Andrews and Braverman 1975). The first generation anticoagulants of the 1950s were consequently a major advance in rodent control. Anticoagulants disrupt the clotting mechanism in the blood so that a fatal haemorrhage occurs after 4-10 days (Buckle 1994). This delay prevents rodents associating the symptoms of toxicosis with the anticoagulant and thus does not induce a CFA. The advantages of these chronic-acting toxicants over the acute-
acting toxicant were soon evident and within a few years anticoagulants (particularly \textit{warafin}) were in widespread use (Lazarus 1989).

Throughout the 1950s these first generation anticoagulants remained particularly successful and there was almost universal reliance on them for rodent control (Buckle 1994). It, therefore, came as a surprise when the physiological resistance of \textit{R. norvegicus} to \textit{warafin} was first detected in 1958 (Lazarus 1989). Attempts were made to control these resistant rats with acute-acting toxicants. However, these attempts were largely unsuccessful due to bait shyness and in the 1960-70s researchers began more in depth study of CFAs and developed more potent second-generation anticoagulants (Quy \textit{et al.} 1995).

Nachman and Hartley (1975) assessed the strength of a CFA caused by sub-lethal doses of various toxicants. They demonstrated that there was no strong relationship between the effectiveness of a toxicant (i.e., how sick the animal became) and its tendency to produce a CFA. Barnett \textit{et al.} (1975) concluded that the level of aversion may be mediated by how the physiological system responds to the toxicant. For example, strychnine and sodium cyanide both produce profound symptoms of illness, but are ineffective at inducing CFAs in rats (\textit{R. rattus}). More recent studies suggest that the conditioning agent must affect the emetic system of the brain stem (Garcia 1989). Consequently, the failure of cyanide and strychnine to induce strong CFAs in rats has been attributed to their mode of action on the nervous system and metabolism, rather than the emetic system.

Kalat and Roxin (1973) demonstrated that an animal is less likely to develop a CFA if it has had previous experience of a food or flavour and not become ill (termed ‘learned-safety’). This hypothesis was supported by Kalat (1974) and Fenwick \textit{et al.} (1975) whose studies demonstrated that one of the most significant factors influencing the development of a CFA was the novelty of the food. Klein \textit{et al.} (1976) later showed that the period of pre-exposure to non-toxic bait influenced the length of time it took for an animal to develop a CFA. For example, Elkins (1973) showed that the strength of saccharin-based aversion in rats (\textit{R. rattus}) was inversely proportional to the duration of their pre-treatment exposure to non-toxic saccharin. Bhardwaj and Prakash (1982) demonstrated that three
days of prefeeding non-toxic bait increased the amount of zinc phosphide bait (an acute-acting toxicant) consumed by rats (*R. rattus*) on first encounter. Prefeeding is now viewed as an important pre-control technique that should be used to increase the likelihood of rodents consuming a lethal dose, particularly when using an acute-acting toxicant (Prakash 1988). For example, prefeeding non-toxic bait significantly improved the efficacy of aerially distributed zinc phosphide bait targeting Polynesian rats (*R. exulans*) in Hawaiian sugarcane fields (Sugihara *et al.* 1995).

In the 1980s and 1990s, research increasingly focused on the role of individual bait components and methods of mitigating a CFA. Several studies indicated that the stronger the taste of a bait, then the greater the aversion formed to it (Prakash 1988). This hypothesis was supported by Naheed and Khan (1989) who found that baits containing flavour additives, to make the toxicant more palatable, resulted in higher levels of aversion. Mason *et al.* (1991) showed that rats (*R. norvegicus*) are also able to associate certain rodenticides with flavour characteristics. For example, a sub-lethal dose of warafin (a first generation anticoagulant) made the rats bait-shy of bitter or sweet flavours, which consequently made the rats averse to other rodenticides with those flavours. Barnett *et al.* (1975) suggested that taste was a more influential factor than was smell, with rats (*R. rattus*) still developing a CFA when anosmatic (i.e., rendered incapable of smelling).

Sridhara (1983) suggested that rats (*R. rattus*) associate the unpleasant effect of the poison through the medium of the bait base. For example, bait-shy rats did not avoid husked lentil (*Lens esculenta* Moench) and green gram (*Cicer arienatum* L.) after being poisoned with zinc phosphide in whole lentil and green gram (Bhardwaj and Khan 1979). These researchers also demonstrated that the level of a CFA could be reduced, if during successive baiting groundnut oil was added to the original bait material (Bhardwaj *et al.* 1984). Singh and Saxena (1991) demonstrated that the magnitude of a CFA could be increased (by up to 45%) by extending the number of days (from 1-7) the rats (*R. rattus*) were initially exposed to the toxicant. It is now considered important to minimise the period of exposure for initial rodent control when using an acute-acting toxicant (Buckle 1994). It is also recommended that the bait base be changed in subsequent control efforts, in an attempt to mitigate any bait aversion. However, the effectiveness of these control
strategies differs between species and toxicants (Prakash 1988). For example, a CFA persisted for bandicoot (*Bandicota bengalensis*), that had been sub-lethally dosed with zinc phosphide, even after the bait base and the poison had both been changed (Sridhara 1983).

Social interactions can play a part in maintaining bait-shy populations. Galef (1990) demonstrated that young rats (*R. norvegicus*) avoided poison bait, without ever tasting it, so long as they remained with older rats. He suggested that the older rats could influence the young rats in four ways: i) the presence of adult rats encouraged feeding (this was also observed by Heyes and Durlach 1990); ii) novel food soiled by others was more readily consumed than unsoiled food; iii) there are flavour cues in the mothers’ milk; and iv) there are olfactory cues on the adult rats’ breath and fur. However, Heyes and Durlach (1990) demonstrated that the presence of food on an older rat (*R. norvegicus*) was not enough in itself to influence young rats’ feeding behaviour and the above four factors most likely work in unison to influence the younger rats (Galef 1990).

Rat control today involves the extensive use of second generation rodenticides (Eason 1991). First generation compounds are still effective for control purposes in some areas, but increasing levels of physiological resistance have occurred in some frequently poisoned populations (Pelz *et al.* 1995). Second generation anticoagulants developed in the 1970s were considered the answer to the problem of physiological resistance. The euphoria associated with the release of the second-generation anticoagulants partly abated after the discovery of cross-resistance to some of these new compounds (Lazarus 1989). However, the more potent of these new poisons (e.g., brodifacoum) are capable of killing both susceptible and warafin-resistant animals (Quy *et al.* 1995). The problem with these new anticoagulant compounds is that they are relatively expensive when compared with some of the acute-acting toxicants. They also pose a threat to non-target species due to their higher toxicity and persistence in the environment (Lazarus 1989). This has resulted in restrictions being placed on their use, with some of the more toxic compounds (e.g., brodifacoum) being confined to indoor use in the United Kingdom. These environmental concerns have also meant that some of the more potent second-generation anticoagulants are not widely registered for application in open-field agriculture (Buckle 1994).
Current rodent-control research has increasingly focused on improving the efficacy of current control methods and improving the management of genetic resistance. The prevention of genetic resistance involves the development of co-ordinated control programmes, which use multiple control techniques (non-anticoagulants toxicants and non-chemical control) to target physiologically resistant populations (Buckle 1994). For example, the non-anticoagulant rodenticide calciferol (a subacute-acting toxicant) was used to substantially reduce a population of anticoagulant resistant rats (*R. norvegicus*) in Berkshire, United Kingdom (Quy *et al.* 1995).

**Research investigating rabbit bait shyness**

Poole (1963) was one of the first researchers to note that some populations of Australian rabbits were becoming increasingly wary of 1080 baits. He termed this behaviour ‘1080 shyness’ and believed that it could be overcome with extended periods of prefeeding. By the 1970s, it was evident that the efficacy of ongoing Australian rabbit 1080 poison campaigns was declining (Oliver *et al.* 1982). These researchers suggested that ultra-cautious rabbits were a possible cause of the low kills. They concluded that the rabbit response was similar to that of commensal rodents (c.f. Cowan 1977) and the increasing number of bait-shy rabbits was a direct result of selection for neophobic behaviour in regularly poisoned areas.

Bell (1975) demonstrated that New Zealand rabbits surviving 1080 control were initially wary of both non-toxic and 1080 bait. Fraser (1985) also observed this bait-shy behaviour in his observational study of rabbits during a control operation. These data supported the hypothesis that rabbits survived poison campaigns because they were neophobic. However, more recently, this interpretation has been questioned. Ross *et al.* (1991) observed that in Twizel, an area previously poisoned with insufficient amounts of 1080 bait for the rabbit population density, a large 1080 bait-shy population had developed. However, most of these rabbits readily consumed non-toxic carrot with prolonged exposure. Rabbits could apparently distinguish between toxic and non-toxic bait, implying that the rabbits in this area were not neophobic, but rather were exhibiting a specific aversion to the acute-acting 1080 toxicant (c.f., Sinclair and Bird 1984).
This hypothesis was supported by subsequent trials demonstrating that 1080 bait-shy rabbits could be poisoned using anticoagulant pindone baits (Nelson and Hickling 1994). Bait avoidance in this case seems to be a learned mechanism (CFA or enhanced neophobia) and not a non-learned neophobic response. Control of New Zealand rabbits, before the illegal release of the rabbit calcivirus disease (RCD; Martin and Donaldson 1998) was, therefore, shifting to the use of a variety of control methods such as 1080, pindone and shooting to mitigate the problem of bait shyness in regularly controlled rabbit populations (D. Robson, pers. comm. 1998).

Social interactions can also play a part in maintaining bait-shy populations. Walters and Bloomfield (1991) observed that young, ‘timid’ rabbits were able to make an association between the ailing dominant rabbits and the toxic bait. This is similar to the behaviour seen in rodent populations and so may also play a part in maintaining bait-shy rabbit populations.

During the 1990s, New Zealand and Australian rabbit control research has focused on assessing the effectiveness of current biological control agents (myxomatosis and RCD), the development of immunocontraceptive control methods (Hinds et al. 1998) and improving conventional control tactics (Allen et al. 1998). In New Zealand, RCD has reduced populations, but the percentage kill has been variable (mean 50%; range 20-90%; Martin and Donaldson 1998). Immunocontraceptive control shows some promise, as researchers have recently been able to render laboratory mice infertile for 5-9 months (Hinds et al. 1998) and the first rabbit immunocontraceptive field trials will commence soon.

**Research investigating possum bait shyness**

A striking aspect of research investigating mammalian bait shyness is the consistency and similarities in behaviour observed across a variety of species (Gustavson 1977). Possum researchers have recognised this and many of the possum control theories and terminology used today are consequently derived from studies on other vertebrate pest species. Based
on these studies, possum researchers (under NSSC guidance) have recently focused on the following major research topics:

1. the role of individual bait components in inducing 1080 bait shyness;

2. the influence of prefeed as a means of limiting the formation of 1080 bait shyness;

3. the efficacy of alternative (slower-acting) toxicants for control of 1080 bait-shy possums; and

4. cost-effective control of 1080 bait-shy possums.

The following four sub-sections briefly review possum research in these areas. A notable feature of this research has been the variation between studies in the procedures and definitions used, so all details have been included in the following summary to help ensure comparisons can be made.

**Role of individual bait components in inducing 1080 bait shyness in possums**

Using captive possums, Morgan et al. (1996a) investigated the duration of 1080 bait shyness and the effect of changing the bait material and lure (Table 2.1).

**Table 2.1:** Experimental design for a 1996 possum pen trial investigating induced 1080 bait shyness; shyness defined as less than 1 g of bait consumed (Morgan et al. 1996a).

<table>
<thead>
<tr>
<th>Pre-treatment 1080 dose(^1) (n=131)</th>
<th>Interval(^2)</th>
<th>Treatment dose(^3,4)</th>
<th>(n^5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal 1080 (0.4 mg.kg(^{-1}) or 1.0 mg.kg(^{-1})) (cin. and dye)</td>
<td>3 months</td>
<td>Cereal 1080 (cin. and dye)</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>3 months</td>
<td>Cereal 1080 (Jaffa and dye)</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>3 months</td>
<td>Carrot 1080 (Jaffa and dye)</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>3 months</td>
<td>Cereal brodifacoum (cin. and dye)</td>
<td>7</td>
</tr>
</tbody>
</table>

\(^1\) Where used: Cinnamon (cin.) lure (0.1% conc.); Bayer V200A green dye (0.1% conc.); and Jaffa orange lure (0.1% conc.); 1080 (0.13% conc)
\(^2\) Between pre-treatment and treatment
\(^3\) Excluding those possums not confirmed bait-shy
\(^4\) Possums exposed to treatment dose for 5 days only
After three months, the majority of survivors from the pre-treatment 1080 dose (23/35; 66%) were still bait-shy when re-exposed to cereal 1080 or to cereal brodifacoum bait. However, most of these cereal bait-shy possums (10/13; 77%) consumed a lethal dose of 1080 when the bait was changed to carrot with an orange lure.

O’Connor and Matthews (unpubl. data) investigated the effect of changing all four bait components (Table 2.2).

**Table 2.2**: Experimental design for a 1996 possum pen trial investigating induced 1080 bait shyness; shyness defined as less than 0.2 g of bait consumed (O’Connor and Matthews, unpubl. data).

<table>
<thead>
<tr>
<th>Pre-treatment 1080 dose(^1 (n=107))</th>
<th>Interval(^2)</th>
<th>Treatment dose(^3,4)</th>
<th>(n)(^5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal 1080 (0.4 mg.kg(^{-1})) (cin. and dye) Shyness confirmed after 1 week</td>
<td>1 week</td>
<td>Carrot 1080/Cereal 1080</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>1 week</td>
<td>Carrot 1080 (Jaffa)</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>1 week</td>
<td>Cereal 1080 (cin. and dye)</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>1 week</td>
<td>Cereal (dye and cin.)</td>
<td>17</td>
</tr>
</tbody>
</table>

\(^1\) Where used: Bayer V200A green dye (0.1% conc.); Cin. lure (0.1% conc.) for cereal baits; and Jaffa orange lure (0.1% conc.) for the carrot bait; 1080 (0.08% conc.)

\(^2\) Between pre-treatment and treatment

\(^3\) Excluding those possums not confirmed bait-shy

\(^4\) Possums exposed to treatment dose for 2 days only

In this trial, 71% (12/17) of cereal bait-shy possums consumed a lethal dose of orange-lured, 1080 carrot bait, compared with only 18% (3/17) of possums re-exposed to cinnamon-lured, 1080 cereal bait. The results of this trial support the Morgan et al. (1996a) study in demonstrating that the bait material and lure are the most important cues for initial bait avoidance. The presence/absence of 1080 or dye did not significantly affect the level of cereal bait rejection on subsequent re-exposure.

Shyness to 1080 bait has also been investigated in populations of free-ranging possums. In one of these trials, Ogilvie et al. (1995) investigated the consumption of non-toxic cereal and carrot bait in paired bait stations, preceding and following a simulated 1080 aerial control operation using low-strength 1080 bait (0.04% conc. compared to the standard concentration of 0.08%; Table 2.3).
Table 2.3: Experimental design for a 1995 field trial investigating 1080 bait shyness (Ogilvie et al. 1995).

<table>
<thead>
<tr>
<th>Prefeed</th>
<th>Pre-treatment 1080 dose</th>
<th>Interval</th>
<th>Treatment dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal (cin.) and carrot</td>
<td>Cereal 1080 (0.04% conc.) (cin. and dye) Shyness not confirmed</td>
<td>11 weeks</td>
<td>Carrot</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11 weeks</td>
<td>Cereal (cin. and dye)</td>
</tr>
</tbody>
</table>

1 Where used: Cin. lure (0.1% conc.); and Bayer V200A green dye (0.1% conc.); 1080 (0.04% conc.)
2 Between pre-treatment and treatment

Following the low-strength cereal 1080 control, the surviving free-ranging possums rejected non-toxic cereal bait in favour of the non-toxic carrot. Before ground control, 64% of the non-toxic bait consumed was cereal. After 1080 poisoning, non-toxic cereal bait consumption reduced to 4% of the non-toxic carrot consumption.

In a similar field trial, Thomas (1997) investigated the feeding behaviour of possums following exposure to low-strength 1080 carrot bait (0.02% conc. compared to the standard concentration of 0.08%) 1080 carrot bait, aerially distributed for rabbit control (Table 2.4).

Table 2.4: Experimental design for a 1997 field trial investigating 1080 bait shyness (Thomas 1997).

<table>
<thead>
<tr>
<th>Prefeed</th>
<th>Pre-treatment dose</th>
<th>Interval</th>
<th>Treatment dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot</td>
<td>1080 carrot (0.02% conc) (dye) Shyness not confirmed</td>
<td>6 months</td>
<td>Maize</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 months</td>
<td>Carrot</td>
</tr>
</tbody>
</table>

1 Where used: Cin. lure (0.1% conc.); and Bayer V200A green dye (0.1% conc.); 1080 (0.02% conc.)
2 Between pre-treatment and treatment

After the operation consumption of carrot in the non-control area was 98.9% that of maize, which was significantly higher than in the rabbit control area where carrot consumption was only 40.1% that of maize. The results support the Ogilvie et al. (1995) study in demonstrating that possums exposed to sub-lethal doses of 1080 bait avoid both toxic and non-toxic versions of the same bait.
The influence of prefeed as a means of limiting the formation of 1080 bait shyness

The effect of non-toxic prefeed on the development of 1080 bait shyness among captive possums was investigated by Moss (1997) (Table 2.5).

Table 2.5: Experimental design for a 1998 pen trial investigating induced 1080 bait shyness; shyness defined as less than 0.5g of bait consumed (Moss 1997).

<table>
<thead>
<tr>
<th>Prefeed</th>
<th>Pre-treatment 1080 dose</th>
<th>Interval</th>
<th>Treatment dose</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>No prefeed</td>
<td>Cereal 1080 (0.4% conc.) (cin. and dye) Shyness confirmed after 7 days</td>
<td>7 days</td>
<td>Cereal 1080 (cin. and dye)</td>
<td>24</td>
</tr>
<tr>
<td>Cereal (cin.)</td>
<td></td>
<td>7 days</td>
<td>Cereal 1080 (cin. and dye)</td>
<td>27</td>
</tr>
<tr>
<td>Cereal (cin. and dye)</td>
<td></td>
<td>7 days</td>
<td>Cereal 1080 (cin. and dye)</td>
<td>13</td>
</tr>
</tbody>
</table>

1 Where used: Cin. lure (0.1% conc.); and Bayer V200A green dye (0.1% conc); 1080 (0.04% conc.)
2 Between pre-treatment and treatment
3 Excluding those possums not confirmed bait-shy
4 Possums exposed to treatment dose for 1 day only

This trial demonstrated that possums are less likely to become 1080 bait shy if they have been prefed with similar non-toxic bait. Most non pre-fed possums (23/24; 96%) were shy of green-dyed, cinnamon-lured 1080 cereal bait following the sub-lethal dose. In contrast, only 8% (1/13) of the possums prefed with green-dyed, cinnamon-lured non-toxic cereal bait became shy.

The efficacy of alternative toxicants for control of 1080 bait-shy possums

Large-scale possum control in New Zealand is very dependent on 1080. Control using aerially sown 1080 baits can be extremely successful, removing >90% of the possums over areas of up to 20 000 ha (Eason et al. 1993). However, over-reliance on a single toxicant is unwise for a number of reasons. First, with the increasing emphasis on maintenance control, alternative toxicants are required to rotate with 1080 to mitigate the problem of 1080 bait shyness. Secondly, 1080 was introduced in 1954 and some of the toxicology and metabolism data are out-of-date when compared with the extensive data now required for the registration of a new pesticide (Eason et al. 1994). Given this and the continuing environmental concerns voiced regarding the short and long term risks associated with 1080 use (PCE 1994), there are concerns regarding its future availability. Thirdly, 1080 can be used only by licensed operators, who must be employed by a government agency,
local authority or private organisation approved by the Pesticides Board (Livingstone 1994). Ideally, a toxicant for possum control should be usable by farmers for ground control (Eason et al. 1993).

By the early 1990s, only five toxicants were legally available for possum control in New Zealand. Three are acute-acting toxicants (1080, cyanide and phosphorus), with 1080 the only one regularly used in control operations. Cyanide is often not used because of poor field efficacy, possibly due to innate poison rejection (Warburton and Drew 1994). Phosphorus is widely considered to be inhumane and the deregistration of this toxicant is pending (Eason et al. 1993). The other two toxicants are the chronic-acting anticoagulants pindone and brodifacoum (trade names Pindone® and Talon®). Both these toxicants are more expensive than 1080, in part because possums take 2-5 weeks to die and continue eating bait during that period (Henderson et al. 1994). There are also concerns regarding the persistence of anticoagulants in animal tissue, increasing the risk of secondary poisoning of birds of prey and humans if they eat animals that have consumed brodifacoum bait (Eason and Spurr 1995). Accordingly, both anticoagulants are not considered appropriate for aerial distribution and are registered for use only in bait stations.

In a search for new alternatives to 1080 in the early 1990s, Landcare Research (N.Z.) Ltd screened 16 unregistered acute, subacute and chronic-acting toxicants; brodifacoum and pindone were also re-screened to confirm the susceptibility of possums to these anticoagulants (Eason et al. 1994). Of the unregistered toxicants, eight were effective at killing orally dosed captive possums. The two most promising was cholecalciferol and glifitor and it was subsequently confirmed that both remain effective when loaded into cinnamon-lured cereal bait. Of all the anticoagulants tested, only brodifacoum was effective at killing orally dosed captive possums. Possums were found to be relatively tolerant to pindone at the concentration (0.05%) used in commercial bait (Eason et al. 1994).

Cholecalciferol, glifitor and brodifacoum were then tested in a series of field trials using bait stations. These studies demonstrated that good kill rates are achievable using all three toxicants on naive possum populations (Table 2.6). Following the success of these and other field trials, cholecalciferol (trade name Campaign®) was registered for bait station control of possums in 1995. Glifitor has not been registered due to the similarities between
it and the existing acute-acting toxicant 1080 (M. Thomas, pers. comm. 1998) and because it has been relatively toxic to birds in subsequent pen trial studies (Eason et al. 1994). In contrast, cholecalciferol has low avian toxicity (Eason et al. 1993), however, this toxicant has been de-registered (Quintox®) in Australia due to non-target effects on domestic dogs (L. Twigg pers. comm. 1999).

Table 2.6: Average percentage kill of naive possums by three toxicants, used in cereal bait, placed in bait stations; \( n \) indicates the number of separate field operations monitored.

<table>
<thead>
<tr>
<th>Toxicant</th>
<th>Nominal conc. (% wt./wt.)</th>
<th>Mortality (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brodifacoum</td>
<td>0.002%</td>
<td>83 (( n=6 ))</td>
</tr>
<tr>
<td>Cholecalciferol</td>
<td>0.8%</td>
<td>84 (( n=12 ))</td>
</tr>
<tr>
<td>Gliftor</td>
<td>0.4%</td>
<td>76 (( n=4 ))</td>
</tr>
</tbody>
</table>

Cholecalciferol is classified as a subacute-acting toxicant (Buckle 1994) with the onset of poisoning symptoms falling between that of the acute and anticoagulant possum toxicants (Figure 2.3).

\[ \text{Cholecalciferol} \]

<table>
<thead>
<tr>
<th>Cyanide</th>
<th>1080</th>
<th>Phosphorous</th>
<th>Cholecalciferol</th>
<th>Pindone</th>
<th>Brodifacoum</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 min</td>
<td>1-2 hr</td>
<td>5-10 hr</td>
<td>24-36 hr</td>
<td>1-3 weeks</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.3: Speed of onset signs of poisoning for six toxicants used for possum control.**

With cholecalciferol, poisoning symptoms are delayed for 24-36 after consuming a lethal dose (Eason et al. 1993). The animal may then loses its appetite (cf., Twigg and Kay 1992), which helps prevent it from eating excessive amounts of bait. This contrasts with
anticoagulant baits where possums take 2-5 weeks to die, during which time they continue
to feed readily on bait (Eason et al. 1994). The delayed onset of poisoning symptoms,
compared with the acute-acting toxicants, would also seem less likely to induce CFAs
amongst any survivors.

Cost-effective control of 1080 bait-shy possums

Central and local government spends millions of dollars every year on possum control. However, as noted above the present level of funding is insufficient to control possums in all DOC and AHB priority areas (PCE 1994). Accordingly, difficult decisions must be made regarding the location of control operations. DOC currently controls possums on conservation land of high ecological importance. Essentially, it ranks areas based on the flora and fauna at risk, and their vulnerability to possum damage (DOC 1994). This is a biological scoring system and there has been economic research identifying ways to improve the efficiency of this ranking system (Kerr and Cullen 1995). The AHB’s main control priority is to prevent Tb from spreading and establishing in adjacent Tb-free areas. Accordingly, ‘at risk’ Tb clear areas and buffer zones around existing VRAs have high funding priority. Any remaining funding is used to reduce the numbers of Tb possums in the VRAs with the eventual goal of disease eradication. Regardless of the methods used to determine where possum control takes place, choices must also be made regarding the control technique. As there is only a limited amount of money available for pest control it is important that the most cost-effective techniques are used (Warburton et al. 1992).

Most previous research on possum control has focused on comparing the operational costs of the different control techniques. Control techniques investigated in these studies have generally been aerial 1080 control and other ground control options such as trapping and cyanide poisoning. Generally, these studies have demonstrated that aerial 1080 control is the most cost-effective large-area control technique (Warburton and Cullen 1993). In smaller, accessible areas (<5 000 ha) capable hunters can achieve effective control at costs comparable to current aerial operations (Montague 1997). However, this may not always be the case in small (<100 ha) forest remnants. For example, Thomas et al. (1993) demonstrated that the mean cost of contract hunters (in five forest reserves), where the
hunters were set a post-operational residual trap catch of less than 10%, was significantly higher than brodifacoum bait station control.

Other studies have investigated ways to reduce the cost of existing control techniques. For example, new aerial sowing buckets can reliably deliver bait at rates as low as 0.5 kg/ha (Morgan *et al.* 1996b). Until quite recently, bait sowing rates of 20 kg/ha were used to ensure complete bait coverage. The advent of global positioning navigation systems (GPS) ensures total bait coverage, at sowing rates as low as 2 kg/ha. Analysis of aerial control costs has demonstrated that the sowing rate is one of the main factors influencing cost. Hence, substantial cost savings have been made though these reductions in sowing rate (D. Morgan, pers. comm. 1998).

While the above-mentioned research has helped field managers reduce the operational cost of possum control, it has provided little guidance regarding the most cost-effective combination of current control techniques for sustained control, given the problem of 1080 bait shyness. Over much of the country, the goal of possum control is to maintain possum populations below pre-determined target densities (PCE 1994). A preliminary modelling exercise suggested that the one of most cost-effective control strategies for maintaining a possum population below a target density is widespread poisoning with 1080 every six years (Barlow 1991a). However, the AHB is sometimes forced to control more frequently than this (sometimes annually; K. Stewart, pers. comm. 1998), due to rapid population recovery. As noted above, possums in regularly controlled populations can develop behavioural mechanisms to avoid familiar toxic bait, which was a factor, that Barlow's (1991a) model did not consider. Since shyness can be long-lived (O'Connor and Matthews 1996), a control strategy that simply relies on frequent 1080 operations is unlikely to be sustainable (Hickling 1995). Field managers need to incorporate other techniques into their ground control operations to minimise the impact of 1080 bait shyness. Alternatives include bait station control with the new alternative possum toxicants. The choice of which control technique to use is complicated because these alternatives are generally more expensive than 1080 (Eason *et al.* 1994), and this problem is the focus of the later sections of this thesis.
**Other possum bait research**

Based on earlier studies investigating mammalian bait shyness, researchers have recently begun investigating physiological resistance, non-learned behavioural resistance (neophobia) and the implications of social learning in possums.

*Possum physiological resistance to 1080*

The ability to tolerate or detoxify a toxicant may increase in populations of animals that are repeatedly poisoned, since animals carrying resistant genes are genetically favoured. Such tolerance is well documented in populations of rats and mice that have been exposed to anticoagulants for decades (Pelz *et al.* 1995).

Increased tolerance of a plant-produced toxin can also occur though the process of natural evolution (Twigg and King 1991). For example, there are 41 legumes of the genera *Gastrolobium* and *Oxylobium*, which produce fluoroacetate bearing vegetation in Western Australia (Twigg 1994). Over time animals evolving a tolerance to this compound are genetically advantaged as these legumes are highly nutritious (King *et al.* 1978). Consequently, possums from Western Australian have one of the highest recorded mammalian tolerances of fluoroacetate and the synthesised version of this compound - sodium monofluoroacetate (1080; Mead *et al.* 1979).

Fortunately, the possums introduced into New Zealand were principally from southeastern Australia and Tasmania (Cowan 1990) and consequently have a relatively low tolerance to 1080 (McIlroy 1983). There is also no evidence of an increase in 1080 tolerance in repeatedly poisoned New Zealand possum populations, although as yet no studies have specifically aimed to detect such changes (G. Hickling, pers. comm. 1998). However, Australian rabbit populations that had been regularly poisoned with 1080 for more than 20 years show no significant decrease in their sensitivity to bait containing 1080 (Wheeler and Hart 1979).
Neophobia

It seems that regular use of 1080 for rabbit control has generated populations of neophobic rabbits in both New Zealand and Australia (Oliver et al. 1982; Fraser 1985). O'Connor and Matthews (1996) observed some neophobic behaviour among captive possums with 16-20% avoiding non-toxic bait on first encounter. However, to date, there has been little evidence of possum neophobia in the field (Morgan et al. 1986; Hickling 1994), where only a small proportion (<5%) of possums, in various studies, failed to consume non-toxic bait on first encounter.

The influence of social learning

Rodent and rabbit research has suggested that the feeding behaviour of juveniles is influenced by older animals (Galef 1990; Walters and Bloomfield 1991). Again, there is little evidence of this occurring in possum populations. Morgan and Milne (1997) observed captive juveniles whose mothers were bait shy; four of five juveniles consumed a lethal dose of 1080 bait when first exposed to it.

2.4 Conclusions

When I commenced this study in 1995, 1080 bait shyness had only recently been identified as a potential major control problem (Morgan 1990; Hickling et al. 1991; Hickling 1993; Hickling 1994). The toxicant cholecalciferol had just been registered and new bait types were under development. After reviewing the rodent, rabbit and possum control literature at that time, I identified four main areas where additional research was required.

First, the rodent and rabbit literature demonstrated that one of the best methods of avoiding CFAs is to use chronic-acting toxicants (e.g., anticoagulants) (Fraser 1985; Buckle 1994). It is thought that these slower toxicants work because the onset of poisoning symptoms is delayed and the animal is unable to associate cause and effect. Bait-shy possums will return to feeding stations and consume small amounts of 1080 bait, which are usually not lethal and probably reinforce their shyness (Hickling 1994). When a chronic or subacute-
acting toxicant is used, it is feasible that 1080 bait-shy possums will eat progressively more bait until eventually a lethal dose is consumed (Henderson et al. 1994). Further research was required to confirm the efficacy of chronic and subacute-acting toxicants on 1080 bait-shy possums. Research was also needed to ascertain whether the type of toxicant included in the bait is instrumental in determining the amount eaten by a bait-shy possum and whether consumption increases or decreases with prolonged exposure to each toxic bait.

Secondly, the rodent research suggested that field managers should regularly change the bait type when acute-acting toxicants are being used regularly. This strategy is believed to work because the animals fail to associate the new unfamiliar bait with previous poisoning symptoms (Prakash 1988). Preliminary possum research had already supported this hypothesis by indicating that the majority (>70%) of 1080 cereal bait-shy possums would consume a lethal dose of 1080 in a new (unfamiliar) bait matrix (O'Connor and Matthews 1996; Morgan and Milne 1997). However, these trials only assessed the effectiveness of 1080 in an unfamiliar bait matrix. As previously mentioned, there were other subacute and chronic-acting possum toxicants available. Also, there had been some variation in the methodology adopted in the early possum pen trials (i.e., the pre-treatment 1080 dose and length of exposure to treatments; see tables 2.1-2.5). This variation was of concern and further pen trials were, therefore, required to: i) validate the results of the previous possum trials; and ii) to compare the efficacy of 1080 in an unfamiliar bait matrix to alternative toxicants in unfamiliar and familiar bait matrixes.

Thirdly, the rodent research demonstrated that exposure to a flavour (or bait) before poisoning inhibits the formation of a CFA (Sugihara et al. 1995). Preliminary possum research supports this hypothesis, with a recent pen trial study demonstrating that pre-fed possums are significantly less likely to become 1080 bait shy (Moss 1997). In another possum pen trial, O'Connor and Matthews (1995) demonstrated that the strength of an aversion to a bait type (previously containing a sub-lethal dose of cyanide) significantly reduces after five re-exposures. Further trials were, therefore, required to confirm the results of Moss (1997) and to investigate the effect of postfeeding non-toxic bait after sub-lethal poisoning.
Finally, field managers must make difficult decisions regarding the frequency and magnitude of control operations. The availability of alternative toxicants makes these decisions increasingly complicated. These new toxicants are more expensive than 1080, but they are less likely to induce shyness amongst the survivors. Studies suggested that 1080 is the most cost-effective control method of ‘knocking down’ a possum population (Warburton and Cullen 1993). However, post operational monitoring indicated that the efficacy of 1080 reduces with frequent use (Bradfield and Flux 1996). There was, therefore, a need to develop a new possum bioeconomic model for possums that incorporates both 1080 bait shyness and alternative possum toxicants (cf. Barlow 1991a). This model should then be used to investigate the most cost-effective combinations of these toxicants for sustained control.

The remainder of this thesis looks at advancing scientific knowledge in these four areas by investigating the efficacy of promising alternative (slower-acting) possum toxicants in familiar bait (Chapter 3) and in unfamiliar bait (Chapter 4). Chapter 5 investigates the influence of non-toxic prefeed and postfeed on the level of 1080 bait shyness. Finally, Chapter 6 investigates the most cost-effective combination of control option for sustained possum control.

2.5 References


CHAPTER 3

CONTROL OF CAPTIVE 1080 BAIT-SHY POSSUMS USING ACUTE, SUBACUTE AND CHRONIC-ACTING TOXICANTS IN A FAMILIAR BAIT MATRIX

3.1 Abstract

Sodium monofluoroacetate (1080) is an acute-acting toxicant; its rapid onset of poisoning allows possums (*Trichosurus vulpecula*) to associate cause and effect, leading to persistent aversion to 1080 cereal bait among the survivors of control operations. In contrast, the symptoms of poisoning with a chronic or subacute-acting toxicant are delayed and consequently may be less likely to be associated with the ingestion of toxic bait. This trial, using five treatments groups of possums made 1080 'bait shy' in captivity, investigated the effectiveness of switching to an alternative toxicant for maintenance control of pest populations. The three toxicants tested were gliftor (an acute-acting toxicant similar to 1080), cholecalciferol (a subacute-acting toxicant; marketed as Campaign®) and brodifacoum (a chronic-acting toxicant; marketed as Talon®). All of these toxicants were relatively successful, killing 50-83% of the 1080 bait-shy possums. After the first night, consumption of the acute and subacute-acting toxicants decreased dramatically, whereas the average nightly consumption of chronic-acting brodifacoum toxicant increased progressively over the duration of the experiment. These results suggest that most 1080 bait-shy possums will eventually consume a lethal dose of a slow acting alternative toxicant with prolonged exposure. However, subsequent field trial studies suggested that cholecalciferol poisoning symptoms are not sufficiently delayed for this toxicant to be effective on 1080 bait-shy possums in the field. Therefore, when an acute or subacute-acting toxicant is used in the field the first night of baiting is crucial, as possums are unlikely to consume lethal amounts of bait after experiencing poisoning symptoms. Research investigating the use of alternative, slower acting toxicants in an unfamiliar bait matrix, which should enhance their effectiveness against 1080 cereal bait-shy possums, is currently underway.
3.2 Introduction

Aversions caused by sub-lethal doses of sodium monofluoroacetate (1080) can persist in captive possums (*Trichosurus vulpecula*) for at least 24 months (O'Connor and Matthews 1996). During this time such possums remain averse to eating familiar bait when re-exposed to it for short (<5-day) periods, regardless of whether it contained a chronic or an acute-acting toxicant (Morgan *et al.* 1996). These trials, therefore, suggested that when possums become shy to cereal 1080 bait they cannot be successfully controlled by reapplying such baits, regardless of the toxicant used. Instead, these trials resulted in the recommendation that the best method of overcoming 1080 'bait shyness' is to change the bait type (e.g., by replacing the 1080 cereal bait with 1080 carrot bait).

In the field, 1080 bait-shy possums have been observed returning to bait stations and sampling small amounts of 1080 bait. Generally, these animals consume sub-lethal amounts and this discourages further consumption, presumably by reinforcing shyness (Hickling 1994). In contrast, unpublished field trial studies investigating weekly bait station consumption of the chronic-acting toxicant brodifacoum by naive possums reported that total consumption by naive possums increased during the first 5 weeks of control (Henderson *et al.* 1994). The most likely explanation for this increase is that individual possums are increasing their consumption over time, in the absence of any further acute poisoning symptoms. While the increasing intake of brodifacoum bait could be attributed to new possums locating the bait stations, a 1080 bait station trial has demonstrated that 87% of possums locate bait stations in the first 2 weeks (Thomas and Fitzgerald 1994). These data suggest that when presented with a chronic-acting toxicant 1080 bait-shy possums may eat progressively more bait at each night’s exposure, until eventually the cumulative dose becomes lethal. Whilst 1080 can be detoxified within 24 hours, brodifacoum can accumulate and persist in possum tissue for over 14 weeks (Eason and Spurr 1995).

These pen and field trial studies thus offer different conclusions about how best to combat 1080 bait shyness, so further research was required to clarify this issue. I, therefore, undertook the following captive trial to ascertain:
i) how the type of toxicant influences the amount of bait that 1080 bait-shy possums eat when they next encounter a cereal bait; and

ii) whether their nightly *per capita* consumption increases or decreases during prolonged exposure to such baits.

The toxicants investigated were 1080, gliftor, cholecalciferol and brodifacoum. Gliftor and 1080 are both acute-acting toxicants, with 1080 producing signs of poisoning in 30 to 165 minutes and death in 10 to 40 hours (Morgan 1990). Gliftor has a similar mode of action to 1080 and kills most possums within 48 hours (Eason *et al.* 1993). Cholecalciferol (marketed as Campaign®) is a subacute-acting toxicant with symptoms that cause cessation of feeding in 24-60 hours and death after several days (Eason *et al.* 1994). Brodifacoum (marketed as Talon®) is a chronic-acting anticoagulant toxicant that produces relatively few overt symptoms until death after 2-5 weeks (Eason *et al.* 1996). Field trial studies have already demonstrated that cholecalciferol, brodifacoum, and gliftor are all effective at killing naive possums (i.e., those that have not been previously poisoned) in the field (Eason *et al.* 1994).

### 3.3 Objectives

- To investigate nightly consumption of acute, subacute and chronic-acting toxicants by 1080 bait-shy possums, during prolonged exposure to those toxicants.

- To determine the role of alternative toxicants in combating 1080 bait-shy behaviours in possums, with a view to recommending alternative bait formulations that shy possums will accept.
3.4 Methods

Animal husbandry

The trial was undertaken using 62 wild-caught possums from North Canterbury. Possums were acclimatised to captivity in outdoor pens (2 m x 1.5 m x 1.5 m) for 30 nights before the start of the trial. Possums shared pens (two or three per pen) during acclimatisation, but were relocated to individual pens before the trial began.

The trial aimed to mimic a non pre-fed aerial possum control exercise (i.e., the first bait that each possum encountered was a toxic 1080 cereal pellet; Morgan et al. 1986). Therefore, possums in the pens were fed on a range of fruit and vegetables provided *ad libitum*. No cereal-based food was provided during the acclimatisation period to avoid influencing their responses to the treatments.

Checking body weight during the acclimatisation period monitored health of individual possums. All possums were weighed three times at 7-day intervals immediately prior to the induction of 1080 bait shyness. Any significant weight loss over this period was considered indicative of stress and any possum losing more than 2 standard deviations from their mean weight was withdrawn from the trial (Buddle et al. 1992). Typically, weight loss was negligible (mean weight loss 0.028 kg; 1% of mean capture body weight); only one possum was withdrawn from the trial for this reason.

This study was conducted with the approval of the Landcare Research (N.Z.) Ltd Animal Ethics Committee.

Induction of 1080 bait shyness

After acclimatisation, each possum was weighed and fed 1 g of 0.08% 1080 cereal bait per kg liveweight (bait specifications are given below) over one night. At this concentration the bait represented an approximate LD$_{20}$ for possums (R. Henderson, unpubl. data).
1080 bait shyness was not confirmed after the sub-lethal dose as the trial aimed to mimic a non-prefed aerial application of 1080 cereal baits (cf. Morgan et al. 1986).

**Experimental procedure**

Possums surviving the pre-treatment 1080 dose were allocated to one of five equal-weight treatment groups (Table 3.1):

**Table 3.1**: Experimental design for possum pen trial investigating the efficacy of various toxicant for overcoming 1080 bait shyness

<table>
<thead>
<tr>
<th>Group</th>
<th>Treatment</th>
<th>Nominal conc. (%)</th>
<th>Bait type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Non-toxic</td>
<td>0%</td>
<td>RS5</td>
</tr>
<tr>
<td>2</td>
<td>1080</td>
<td>0.08%</td>
<td>RS5</td>
</tr>
<tr>
<td>3</td>
<td>Glifto</td>
<td>0.4%</td>
<td>RS5</td>
</tr>
<tr>
<td>4</td>
<td>Cholecalciferol</td>
<td>0.8%</td>
<td>RS5</td>
</tr>
<tr>
<td>5</td>
<td>Brodifacoum</td>
<td>0.002%</td>
<td>Agtech</td>
</tr>
</tbody>
</table>

The minimum number of acclimatised possums for each group was six. It is considered that at least five animals per group is satisfactory for preliminary laboratory tests (EPPO 1982; Buckle 1994).

Each treatment was provided *ad libitum* for 2 weeks, together with *ad libitum* vegetables, and fruit and water. Consumption of the treatment bait (nearest 1 g) was measured daily for each possum over the 2 week period. Possum survival was also monitored daily during the 2 week treatment period and then for another 30 days post-treatment, during which time they were maintained on their normal diet.

Additional baits placed in nearby empty pens provided a correction for changes in moisture content of the baits (which were negligible).
Bait preparation

The non-toxic, 1080 and glifto baits were manufactured by Landcare Research staff using RS5 cereal mix supplied by Animal Control Products (ACP), Waimate. The 1080 and glifto toxicants were supplied by ACP and Robert Bryce Ltd, Christchurch respectively; these baits also contained 0.1% cinnamon lure supplied by Bush, Boake and Allen Ltd, Auckland and 0.1% green Bayer V200A dye supplied by Bayer Ltd, Wellington. The cholecalciferol bait was manufactured by Hoechst Schering AgrEvo Pty Ltd, N.S.W., Australia (marketed as Campaign® possum bait); these baits are also manufactured using the RS5 cereal mix and contain 0.5% cinnamon lure and 0.1% green Bayer V200A dye. The brodifacoum bait was manufactured by ICI Crop Care Ltd, Nelson (marketed as Talon® possum pellets); these baits are manufactured using Agtech cereal mix supplied by ACP and also contain 0.1% cinnamon lure and 0.1% green pigment dye supplied by Bayer Ltd, Wellington. The concentration of toxicant in the cereal 1080 baits was verified by Landcare Research using a gas-liquid chromatography method (Okuno et al. 1982).

Data analysis

A $\chi^2$ test was used to compare the mortality rate amongst the treatment groups. Consumption data was not normally distributed (see below), so comparisons among the groups were made using a Kruskal Wallis test; with Mann-Whitney U tests (appropriate for the sample size) used to identify significant differences between pairs of independent groups. A repeated measures ANOVA was used to test for significant changes, in bait take, between nights within the treatment groups (these changes were relatively normally distributed). Linear trends in these changes were tested using orthogonal, polynomial contrasts (C. Frampton, pers. comm. 1998).

Data normality was visually assessed from a series of frequency histograms for each treatment. These indicated that bait consumption was typically multi-modal and not normally distributed.
3.5 Results

Induction of shyness

Only one of the 61 possums failed to eat the entire pre-treatment 1080 dose on the night it was provided. This possum was classified as neophobic rather than 1080 bait shy and was excluded from the remainder of the trial. Mortality of the remainder was slightly higher than expected, with 18 of the possums (30%) being killed by the intended LD$_{50}$ 1080 dose.

Mortality rates

All possums exposed to non-toxic bait survived the trial. The majority of possums exposed to toxic bait were killed (Table 3.2).

<table>
<thead>
<tr>
<th>Toxicant</th>
<th>Toxic loading (% wt./wt.)</th>
<th>No. of possums</th>
<th>Mean weight (kg)</th>
<th>Mortality (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>-</td>
<td>8</td>
<td>2.40 ± 0.15</td>
<td>0%</td>
</tr>
<tr>
<td>1080</td>
<td>0.08%</td>
<td>6</td>
<td>2.44 ± 0.25</td>
<td>66%</td>
</tr>
<tr>
<td>Gliflor</td>
<td>0.4%</td>
<td>6</td>
<td>2.75 ± 0.17</td>
<td>50%</td>
</tr>
<tr>
<td>Cholecalciferol</td>
<td>0.8%</td>
<td>6</td>
<td>2.42 ± 0.15</td>
<td>83%</td>
</tr>
<tr>
<td>Brodifacoum</td>
<td>0.002%</td>
<td>16</td>
<td>2.71 ± 0.11</td>
<td>75%</td>
</tr>
</tbody>
</table>

*1 Verified by laboratory assay

The mortality rate did not differ significantly between the groups exposed to toxic baits ($\chi^2 = 1.89$, d.f. = 3, $P = 0.6$).

Initial consumption of bait

One of eight possums (13%) avoided the non-toxic bait on the first night. This animal remained bait shy thereafter, consuming only small amounts of non-toxic bait over the next 13 nights. The other seven possums accepted the non-toxic bait readily and consumed an average of 68.1 g ($\pm$ 18.5 S.E.) on the first night of exposure.
Five of 18 possums (28%) avoided the 1080, glifto or cholecalciferol bait on the first night (Appendix 3.1). The bulk of the bait consumption by the remaining 13 possums occurred on the first night (Figure 3.1) and shyness was rapidly reinforced amongst those that survived, so that negligible bait was consumed over the next 13 nights. Average nightly consumption of cholecalciferol was slightly higher than for 1080 or glifto, with some possums continuing to consume small amounts of cholecalciferol bait over the next 4-7 nights.

Eight of 16 possums (50%) avoided the brodifacoum bait on the first night (Appendix 3.1). Four of these animals remained bait shy consuming only small (sub-lethal) amounts of bait over the next 13 nights. In contrast to the other toxic bait groups, average nightly consumption did not decrease after the first night (Figure 3.1).

![Average nightly consumption of acute, subacute and chronic-acting toxicants by 1080 bait-shy possums. Bait consumption was monitored for 7 days or until death; means are presented ± S.E.](image)

**Figure 3.1:** Average nightly consumption of acute, subacute and chronic-acting toxicants by 1080 bait-shy possums. Bait consumption was monitored for 7 days or until death; means are presented ± S.E.

On the first night, possums consuming non-toxic bait ate significantly more than any of the other groups \((U = 40-112.5, \text{d.f.} = 1, \text{all } P < 0.01)\) (Appendix 3.1). There was no significant difference in the amount of toxic bait consumed on the first night amongst the other four treatment groups \((H = 2.92, \text{d.f.} = 3, P = 0.4)\).
Average nightly bait consumption

Average nightly consumption of non-toxic bait was relatively consistent (mean 48.3 g ± 3.4 S.E; Figure 3.2) and did not significantly increase with continuous exposure (F₁,₇ = 0.6, P = 0.46).

![Average nightly consumption of non-toxic cereal bait by 1080 bait-shy possums. Means presented ± S.E.](image)

**Figure 3.2:** Average nightly consumption of non-toxic cereal bait by 1080 bait-shy possums. Means presented ± S.E.

After the first night average nightly consumption of the acute-acting toxicants (1080 and gliflor) declined dramatically so that there was minimal bait take over the next 13 nights. Significant consumption of the subacute-acting cholecalciferol toxicant continued for 2 nights; thereafter consumption of this bait also reduced dramatically (Figure 3.1).

Average nightly consumption of the chronic-acting brodifacoum toxicant increased significantly from 5.5 g (± 2.5 S.E.) on the first night to 32.2 g (± 7.6 S.E.) on the last night (F₁,₁₅ = 10.8, P = 0.01) (Figure 3.3).
Figure 3.3: Average nightly consumption of brodifacoum by 1080 bait-shy possums \((n = 16)\). Means presented ± S.E.; trend line fitted by linear regression \((\hat{Y} = 3.8404(X) + 1.8164, r^2 = 0.8787, P < 0.01)\).

3.6 Conclusions

Seven of eight possums (88%) readily consumed non-toxic cereal bait, with daily consumption remaining relatively stable throughout the trial. This was contrary to my expectation that 1080 bait-shy possums would show some initial shyness to the bait matrix, which would subsequently fade as possums sampled small amounts of bait and had no further adverse symptoms. This pattern of behaviour was not evident; moreover the only possum that showed any initial bait shyness did not increase consumption with prolonged exposure.

One possible explanation for the lack of initial shyness to the non-toxic bait is that possums have the ability to detect 1080. This seems unlikely as other pen trials have demonstrated that the majority of 1080 bait-shy possums will consume a lethal dose of 1080 in a new bait type (Morgan et al. 1996; O'Connor and Matthews 1996). Another explanation could be the time interval between the distribution and weighing of the baits. Field trials have observed that possums usually feed in two to three sessions, separated by 2-3 hours (MacLennan 1984; this behaviour has also been observed with other marsupials see Sinclair & Bird 1984; Twigg & King 1991). With 1080, poisoning symptoms can occur within 30 minutes (but usually 1-2 hours), and this rapid onset of toxicosis may then
discourage the possum from consuming additional bait after the first feeding session. An absence of poisoning symptoms probably encourages additional bait consumption in the next feeding session, with average nightly consumption increasing over time. This hypothesis could be explored in future trials using a video camera to monitor the number of feeding sessions.

Seven of 12 supposedly bait-shy possums (56%) consumed a lethal dose of the acute-acting 1080 and gliflor toxicants on the first night. After the first night there was only minimal bait take by the remaining possums over the next 13 nights. This result supports earlier field trials where it has been observed that the survivors of pre-treatment 1080 dose become cautious, and subsequently consume little or no additional bait (Hickling 1994). Clearly, the first night of baiting is crucial when acute-acting toxicants are used for maintenance control. If the possum does not consume a lethal dose on that night it is very unlikely that it will eat a lethal dose of bait thereafter.

Five of six possums (83%) consumed a lethal dose of the subacute-acting cholecalciferol toxicant. As with the 1080 and gliflor treatments, the bulk of the bait was consumed on the first night. However, it took 4-36 nights for these five possums to die and during this time they all consumed some additional toxic bait (Appendix 3.1). Cholecalciferol poisoning symptoms are delayed for at least 24 hours, which means the first night of baiting is not quite as important as there is a 2-day ‘window of opportunity’ during which 1080 bait-shy possums are likely to consume a lethal cholecalciferol dose. In contrast, when 1080 bait-shy possums are exposed to a familiar bait type with an acute-acting toxicant this window may be ‘open’ for a mere 30 minutes (cf. Morgan 1990).

The high consumption non-toxic bait, and the efficacy of the acute and subacute-acting toxicant treatments, were surprising as the LD_{20} dose was expected to induce bait shyness amongst the majority of survivors (Morgan et al. 1996). It is, therefore, not clear whether the success of the gliflor and cholecalciferol treatments was due to the slower onset of poisoning symptoms or because the pre-treatment 1080 dose generated variable levels of bait shyness. This result also contrasts with other field trial studies, which have demonstrated that the survivors of initial control using an acute or subacute-acting toxicant
cannot be killed in subsequent control operations using similar acting toxicants (e.g., Henderson et al. 1997). A possible explanation is that captive possums may be less cautious than free-ranging animals. This hypothesis is supported by recent field trials which have demonstrated that free-ranging possums consume approximately 30% less non-toxic bait than their captive counterparts (R. Henderson, pers. comm. 1998). Similar behaviour has been observed in captive and free-ranging rodent populations. For example, free-ranging brown rats (*Rattus norvegicus*) are significantly more cautious of novel containers and food than are captive rats (Brunton and MacDonald 1996). To counteract this, future trials should confirm 1080 bait shyness before possums progress to the next treatment. This could be achieved by continuing additional pre-treatment 1080 dosing until bait is rejected (e.g., consumption less than 1 g).

Twelve of 16 possums (75%) consumed a lethal dose of chronic-acting brodifacoum toxicant. As in previous possum pen trials, most possums ate little bait on the first few nights (cf. Morgan et al. 1996). However, average nightly consumption increased with prolonged exposure. This result supports the hypothesis that individual brodifacoum consumption will increase over time in the absence of additional acute poisoning symptoms. The four possums surviving this treatment ate some bait and it is conceivable that these animals would have consumed a lethal dose with sufficiently prolonged exposure. This trial ran for only 14 nights and brodifacoum field trials have demonstrated that brodifacoum bait needs to be available for 20 weeks to achieve a high kill (Henderson et al. 1997). Note: The ecological impacts of any non-target effects due to long-term exposure to brodifacoum are discussed in the General Conclusions chapter.

Rodent control researchers have demonstrated that rats (*Rattus norvegicus*) can become mildly bait shy following a sub-lethal dose of an anticoagulant rodenticide (difenacoum; dose 0.5 ml per 100 g liveweight), which produced a significant change in food preference 1-4 days after sub-lethal dosing (Smith et al. 1994). However, previous possum researchers have been unable to induce brodifacoum bait shyness with varying sub-lethal doses (0.05 and 0.1 mg.kg$^{-1}$ body weight; O'Connor et al. 1998). A pen trial investigating the effects of brodifacoum in possums indicates that it takes approximately 7 days for significant physiological symptoms to occur following a sub-lethal dose (0.1 mg.kg$^{-1}$ body weight;
Eason et al. 1996). In the current trial, there is also no evidence of possum brodifacoum bait shyness, given that average nightly consumption increased steadily over the 14-day trial period (Figure 3.3).

As mentioned, four possums survived the brodifacoum treatment. It is possible that these animals would have eventually begun to eat bait, however, there are other behavioural mechanisms that these animals might be using to avoid brodifacoum bait. One of these is enhanced neophobia, where an animal surviving previous sub-lethal poisoning not only avoids a specific food, but is also wary of anything new (O'Connor and Matthews 1996). Enhanced neophobia has been suggested as a possible cause for higher than expected numbers of rats surviving anticoagulant control in Hampshire, England (Quy et al. 1992). Further trials should run for longer periods of time to assess whether all possums will eventually consume a lethal dose of anticoagulant, given longer exposure to such bait.

In conclusion, this trial has demonstrated that the majority (24 of 34; 70%) of captive 1080 bait-shy possums can be killed using an alternative toxicant in the same bait base. Most (29 of 42; 70%) possums consumed some bait on the first night. However, average nightly consumption dramatically decreases when an acute or subacute-acting toxicant is used. Previous studies have demonstrated that 1080 bait-shy possums can be also be killed using 1080 in a new bait base, so future trials should compare the efficacy of these alternative toxicants to 1080 in a new bait such as a fruit paste or gel.

3.7 Recommendations for future research

A future pen trial is needed to determine the number of feeding sessions 1080 bait-shy possums have each night. The results of this current trial suggest that it is the onset of acute poisoning symptoms, which discourages additional bait consumption. Feeding patterns could be monitored using time-lapse video, with the amount of bait consumed in each feeding session assessed using electronic scales attached to a data logger.

Given the variable results recorded here it is also recommended that future trials confirm bait shyness to the initial dose by re-exposing possums to 1080; only those possums
rejecting 1080 should be included in the subsequent treatment groups. The induction of 1080 bait shyness was not expected to be a problem as previous possum trials had suggested that the majority (>60%) of possums would become 1080 bait-shy following the LD$_{20}$ dose (Hickling 1994; Morgan et al. 1995).

It would be advisable to replicate this trial using 1080 and the alternative toxicants in a different bait type (i.e., carrot, paste or gel). Pen trials have already indicated that changing the bait type also has potential for controlling 1080 cereal bait-shy possums. This trial should be run for longer than 14 nights to assess whether brodifacoum efficacy is enhanced with extended exposure.

### 3.8 Acknowledgements

I thank the Foundation for Research, Science and Technology, Lincoln University (Entomology and Animal Ecology Group) and Landcare Research (Summer Scholarship) for funding this experiment, Drs. Graham Hickling and Adrian Paterson for helpful comments on the draft paper and Lynne Milne and other staff at the Landcare Research animal facility for their assistance with the trial.

I was responsible for conceptual development, planning, practical work and data analysis of the above experiment. Dr. Graham Hickling provided guidance during all phases of the above experiment. Lynne Milne and other Landcare Research staff were responsible for the animal husbandry.

### 3.9 References


### 3.10 Appendices

**Appendix 3.1:** Consumption of toxic and non-toxic cereal bait over 2 weeks following a pre-treatment LD<sub>20</sub> 1080 dose (0.8 mg.kg<sup>-1</sup> body weight); * indicates that the possum ate no more bait after the first night.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Estimated LD&lt;sub&gt;95&lt;/sub&gt; (bait g)</th>
<th>Dose as of Night 1</th>
<th>proportion of LD&lt;sub&gt;95&lt;/sub&gt;</th>
<th>Feeding nights&lt;sup&gt;6&lt;/sup&gt;</th>
<th>Total consumption (g)</th>
<th>Nights until death&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-toxic</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>14</td>
<td>1080</td>
<td>Survived</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>13</td>
<td>431</td>
<td>Survived</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>13</td>
<td>557</td>
<td>Survived</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>14</td>
<td>722</td>
<td>Survived</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>14</td>
<td>540</td>
<td>Survived</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>28</td>
<td>Survived</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>828</td>
<td>Survived</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>14</td>
<td>1188</td>
<td>Survived</td>
</tr>
<tr>
<td>1080&lt;sup&gt;2&lt;/sup&gt;</td>
<td>1</td>
<td>11.5</td>
<td>1.3</td>
<td>*</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>11.1</td>
<td>3.1</td>
<td>*</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>9.0</td>
<td>2.2</td>
<td>*</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.8</td>
<td>0.5</td>
<td>*</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>13.0</td>
<td>0.2</td>
<td>0.3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>9.9</td>
<td>0.1</td>
<td>*</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Gliptor&lt;sup&gt;3&lt;/sup&gt;</td>
<td>1</td>
<td>19.0</td>
<td>0.3</td>
<td>*</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>16.1</td>
<td>1.2</td>
<td>*</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>14.5</td>
<td>1.4</td>
<td>*</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>14.0</td>
<td>0.4</td>
<td>*</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>15.9</td>
<td>0.2</td>
<td>0.3</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>20.1</td>
<td>0.0</td>
<td>0.1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Cholecalciferol&lt;sup&gt;4&lt;/sup&gt;</td>
<td>1</td>
<td>11.5</td>
<td>1.8</td>
<td>4.7</td>
<td>2</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8.6</td>
<td>0.0</td>
<td>0.9</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>10.2</td>
<td>4.7</td>
<td>4.9</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>8.0</td>
<td>0.0</td>
<td>4.1</td>
<td>1</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>10.7</td>
<td>0.0</td>
<td>0.2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>11.7</td>
<td>1.3</td>
<td>1.4</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Brodifacoum&lt;sup&gt;5&lt;/sup&gt;</td>
<td>1</td>
<td>138.0</td>
<td>0.1</td>
<td>2.4</td>
<td>14</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>114.0</td>
<td>0.0</td>
<td>3.5</td>
<td>13</td>
<td>395</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>107.2</td>
<td>0.1</td>
<td>2.4</td>
<td>13</td>
<td>253</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100.0</td>
<td>0.1</td>
<td>4.5</td>
<td>14</td>
<td>452</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>83.6</td>
<td>0.1</td>
<td>6.1</td>
<td>14</td>
<td>511</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>135.6</td>
<td>0.1</td>
<td>1.2</td>
<td>12</td>
<td>164</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>132.8</td>
<td>0.0</td>
<td>0.2</td>
<td>7</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>125.2</td>
<td>0.1</td>
<td>4.2</td>
<td>14</td>
<td>529</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>116.4</td>
<td>0.0</td>
<td>1.0</td>
<td>9</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>110.8</td>
<td>0.0</td>
<td>2.5</td>
<td>9</td>
<td>273</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>107.6</td>
<td>0.0</td>
<td>3.5</td>
<td>11</td>
<td>375</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>100.8</td>
<td>0.1</td>
<td>1.4</td>
<td>13</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>96.0</td>
<td>0.0</td>
<td>0.0</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>93.6</td>
<td>0.0</td>
<td>0.0</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>94.8</td>
<td>0.4</td>
<td>3.2</td>
<td>13</td>
<td>304</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>78.4</td>
<td>0.0</td>
<td>0.4</td>
<td>9</td>
<td>32</td>
</tr>
</tbody>
</table>

<sup>1</sup> Survival was monitored for 30 days post treatment
<sup>2</sup> 1080 LD<sub>20</sub> 3.3 mg.kg<sup>-1</sup> (R. Henderson, pers. comm. 1996)
<sup>3</sup> Gliptor LD<sub>95</sub> 24.1 mg.kg<sup>-1</sup> (Henderson et al. 1994)
<sup>4</sup> Cholecalciferol LD<sub>95</sub> 33.4 mg.kg<sup>-1</sup> (Henderson et al. 1994)
<sup>5</sup> Brodifacoum LD<sub>95</sub> 0.8 mg.kg<sup>-1</sup> (R. Henderson, pers. comm. 1996)
<sup>6</sup> Number of nights which possums fed from the 14 available
CHAPTER 4

THE EFFECTIVENESS OF ACUTE, SUBACUTE AND CHRONIC-ACTING TOXICANTS, IN FAMILIAR AND UNFAMILIAR BAIT MATRIXES, FOR THE CONTROL OF CAPTIVE 1080 BAIT-SHY POSSUMS

4.1 Abstract

Aversions to sodium monofluoroacetate (1080) in cereal bait can persist in sub-lethally poisoned possum (Trichosurus vulpecula) populations. I investigated whether captive sodium monofluoroacetate (1080) ‘bait-shy’ possums could be controlled with an alternative, slower-acting toxicant (cholecalciferol, marketed as Campaign®; or brodifacoum, marketed as Talon®) and/or an alternative bait material (apple paste, marketed as Pestoff®). Some 1080 cereal bait-shy possums (40%) were killed when exposed to 1080 in apple paste, whereas the alternative, slower-acting toxicants killed 70% when in cereal bait and 100% when in paste. These results demonstrate that 1080 cereal bait-shy possums can be controlled using alternative, slower-acting toxicants, provided the onset of poisoning symptoms is subacute or chronic. Presenting these toxicants in a bait matrix that is unfamiliar can further enhance effectiveness.

4.2 Introduction

Aversions caused by sub-lethal doses of the sodium monofluoroacetate (1080) can persist in captive possums (Trichosurus vulpecula) for at least 2 years, during which time such possums remain averse (or ‘shy’) to 1080 bait (Morgan and Milne 1997). O’Connor and Matthews (1996) suggested that when shyness has been induced with cereal 1080, captive possums cannot be successfully controlled by reapplying cereal bait, regardless of the toxicant used. Similarly, Morgan et al. (1996) suggested that changing the bait matrix is a promising way of overcoming shyness to 1080 baits. Nevertheless, cereal baits containing chronic-acting toxicants such as brodifacoum appear to be successful in controlling bait-
shy possums in the field, where it seems that possums eat progressively more bait at each night’s exposure until eventually the cumulative dose becomes lethal (Henderson et al. 1997).

These past assessments of possum behaviour with captive animals in pens and free-ranging animals thus suggest different, but perhaps complementary, approaches for how best to combat 1080 bait shyness. The objective of this study was to determine the role of two alternative, slower-acting toxicants (cholecalciferol, marketed Campaign® and brodifacoum, marketed as Talon®) in combating 1080 bait-shy behaviours in possums, with a view to recommending alternative bait formulations that bait-shy populations would accept.

4.3 Objective

- To determine the role of acute, subacute and chronic-acting toxicants in both familiar and unfamiliar bait matrixes, for combating 1080 bait-shy behaviours in possums, with a view to recommending alternative bait formulations that those possums will accept.

4.4 Methods

Animal husbandry

The trial was undertaken using 122 wild-caught possums from North Canterbury. Possums were housed in individual wire cages (1 m x 0.4 m x 0.4 m) with mesh floors and a removable nest box (0.35 m x 0.2 m x 0.2 m) and acclimatised to captivity over a 6 week period (Duckworth and Meikle 1995). Possums were fed a range of fruit and vegetables provided ad libitum. No cereal-based food was provided during the acclimatisation period to avoid influencing their responses to these treatments.

Health of individual possums was monitored by checking body weight during the acclimatisation period. All possums were weighed three times at 7-day intervals.
immediately prior to the induction of 1080 bait shyness. Significant weight loss over this period was considered indicative of stress and any possum losing more than 2 standard deviations from the group mean weight would have been withdrawn from the trial (Buddle et al. 1992). Typically, weight loss was negligible and no possums were withdrawn due to excessive weight loss during acclimatisation.

At the completion of the acclimatisation period, the possums were inadvertently exposed to an unidentified viral disease that killed 26 of the animals (21%). All surviving possums were monitored (as above) for an additional 2 weeks to ensure that only healthy possums were used in the bait consumption trial. As a further safeguard, all possums dying during the treatment phase were postmortem ed to confirm cause of death. An additional six possums were withdrawn from the trial because no physiological signs of poisoning were evident at postmortem. Weight loss for remaining healthy possums was negligible (mean weight loss prior to the induction of 1080 bait shyness was 0.26 kg; 9.4% of mean capture body weight).

This study was conducted with the approval of the Landcare Research (N.Z.) Ltd Animal Ethics Committee.

**Induction of 1080 bait shyness**

After the extended acclimatisation period each possum was weighed and fed 1 g of 0.08% 1080 cereal bait per kg liveweight (bait specifications are given below). This dose level was used because it was expected to cause low mortality (an approximate LD_{20} dose; R. Henderson, unpubl. data) and was likely to induce high levels of bait shyness amongst the survivors.

After 1 week, re-exposing each possum to a further 1 g of 0.08% 1080 bait assessed shyness. If the possum ate the entire bait, it was presented with two additional baits over the next 2 days. If the possum continued to eat toxic bait on its third re-exposure (i.e., the 3rd day) the possum was removed from the trial. Possums taking more than one re-exposure
to develop bait shyness were randomly distributed equally amongst the subsequent treatment groups.

Confirmation of 1080 bait shyness was the major methodological difference from the Chapter 3 pen trial. 1080 bait shyness was confirmed in this, and subsequent, pen trials to ensure uniform levels of bait shyness amongst subsequent treatment groups.

**Experimental procedure**

Once the possums were confirmed as 1080 bait shy, they remained on the vegetable diet for 1 week. They were then re-weighed and randomly allocated to six treatment groups balanced for weight and sex (Figure 4.1):

![Flow diagram of the experimental design for the pen trial investigating the efficacy of various toxicants for the control of 1080 bait-shy possums (shading denotes the use of green dye).]
The minimum number of acclimatised animals for each group was nine (with a maximum of 11). It is considered that five animals per group is satisfactory for preliminary laboratory tests (EPPO 1982; Buckle 1994).

Treatment 3 was provided *ad libitum* for 4 weeks, together with *ad libitum* vegetables, fruit and water. Consumption of the treatment bait (nearest 1 g) was measured daily for each possum over the 4 week period. Possum survival was also monitored daily during the 4 week treatment period and for another 30 days post-treatment, during which time they were maintained on their normal diet.

Additional baits placed in nearby empty pens provided a correction for changes in moisture content of the baits (which were <10% for the paste bait and negligible for the cereal bait).

**Bait preparation**

The 1080 and brodifacoum toxicants were loaded into cereal baits by Landcare Research staff and were supplied by Animal Control Products Ltd, Waimate (ACP) and ICI Crop Care Ltd, Nelson respectively. These bait pellets were manufactured using RS5 cereal mix obtained from ACP; also containing 0.1% cinnamon lure supplied by Bush, Boake and Allen Ltd, Auckland (BBA) and 0.1% green Levanyl dye supplied by Bayer Ltd, Wellington. The cholecalciferol cereal bait was supplied by Hoechst Schering AgrEvo Pty Ltd, N.S.W., Australia (HSAP). These pellets were also manufactured using the RS5 cereal mix and contained 0.5% cinnamon lure and 0.1% green Lavanyl dye. All three toxicants were loaded into the undyed BB13 apple paste bait (marketed as Pestoff®) by Landcare Research staff and was supplied by ACP, Wanganui. The cholecalciferol toxicant was supplied by HSAP and all paste bait contained 0.4% jaffa lure supplied by BBA.

The concentration of toxicant in each bait was verified in the laboratory using a gas-liquid chromatography method for the determination for 1080 (Okuno *et al.* 1982), or liquid chromatography methods for cholecalciferol (Gehrig and Stringham 1987) and brodifacoum (Felice and Murphy 1989). The cholecalciferol bait was intended to have a toxicant loading of 0.8%, however, the cereal bait was only 0.6% when assayed, therefore,
the paste was diluted to the same concentration to enable comparison; this may have reduced the effectiveness of this toxicant. Pre-trial 'two-choice' palatability tests (Grote and Brown 1971) demonstrated that both bait types were equally palatable to naive possums (J. Ross, unpubl. data).

Data analysis

A $\chi^2$ test was used to compare the mortality rate amongst the treatment groups.

4.5 Results

Induction of 1080 bait shyness

All 96 possums ate the entire 1080 dose on the night it was provided. Mortality was slightly higher than expected, with 30 of the possums (31%) being killed by the intended LD$_{20}$ 1080 dose.

All survivors were confirmed 1080 bait shy after 1, 2 or 3 re-exposures to 1 g of 0.08% 1080 bait (52%, 67% and 100% of the 66 possums, respectively).

Mortality

All 1080 bait-shy possums re-exposed to 1080 in a familiar cereal bait matrix failed to eat a lethal dose. In contrast, the cholecalciferol and brodifacoum toxicants in a familiar matrix were relatively successful, killing 64% and 73% of bait-shy possums respectively (Table 4.1). The difference in kill between these two toxicants and 1080 was highly significant ($\chi^2 = 13.02$, d.f. = 2, $P < 0.01$).

In the unfamiliar apple paste, 1080 killed 40% of possums previously made bait shy with 1080 in cereal bait (Table 4.1). Brodifacoum and cholecalciferol in apple paste both killed 100% of the 1080 bait-shy possums; these two toxicants killed significantly more possums in the new bait matrix ($\chi^2 = 6.35$, d.f. = 1, $P = 0.01$).
Table 4.1: Numbers of 1080 cereal bait-shy possums killed by alternative, slower-acting toxicants in familiar and unfamiliar bait bases.

<table>
<thead>
<tr>
<th>Toxicant</th>
<th>Bait matrix</th>
<th>Measured conc. (% wt./wt.)</th>
<th>No. of possums</th>
<th>Numbers dying</th>
<th>Mortality (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1080</td>
<td>Cereal pellet</td>
<td>0.09%</td>
<td>10</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Cholecalciferol</td>
<td>Cereal pellet</td>
<td>0.6%</td>
<td>11</td>
<td>7</td>
<td>64%</td>
</tr>
<tr>
<td>Brodifacoum</td>
<td>Cereal pellet</td>
<td>0.002%</td>
<td>11</td>
<td>8</td>
<td>73%</td>
</tr>
<tr>
<td>1080</td>
<td>Apple paste</td>
<td>0.07%</td>
<td>10</td>
<td>4</td>
<td>40%</td>
</tr>
<tr>
<td>Cholecalciferol</td>
<td>Apple paste</td>
<td>0.6%</td>
<td>9</td>
<td>9</td>
<td>100%</td>
</tr>
<tr>
<td>Brodifacoum</td>
<td>Apple paste</td>
<td>0.002%</td>
<td>9</td>
<td>9</td>
<td>100%</td>
</tr>
</tbody>
</table>

Bait consumption

Possums confirmed as bait shy, retained this shyness when re-exposed to 1080 cereal bait in the subsequent trial. The mean amount of bait eaten on the first night was negligible (0.63 g ± 0.43 S.E.) with the subsequent nightly consumption reducing further (Table 4.2). These 1080 bait-shy possums also exhibited shyness to the cholecalciferol cereal bait, with little consumption on the first night (0.92 g ± 0.78 S.E.) and a decline in consumption thereafter. In contrast, the mean consumption of brodifacoum in cereal on the first night (6.6 g ± 3.49 S.E.) was considerably higher than for the other two toxicants and consumption increased on subsequent nights.

As with 1080 cereal bait, the bulk of the 1080-paste consumption occurred on the first night. However, the mean amount of 1080 paste consumed on that night (10.5 g) was higher than for any of the cereal baits. Mean nightly consumption then reduced over the next 13 nights (Table 4.2). The 1080 cereal bait-shy possums exhibited a low level of shyness to the cholecalciferol paste, consuming a mean of 26.2 g (± 6.6 S.E.) on the first night. Mean nightly consumption reduced markedly thereafter. The 1080 cereal bait-shy possums also showed no initial aversion to the brodifacoum paste, with consumption remaining relatively high throughout the trial.
Table 4.2: Mean consumption of various toxic baits by captive possums over a 4 week period. All possums had previously survived a sub-lethal dose of 1080 of 0.8 mg.kg\(^{-1}\) body weight in cereal bait. Means are presented ± SE; sample size in brackets.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Bait eaten per night(^1) (g)</th>
<th>Total eaten per possum (g)</th>
<th>Days to death</th>
<th>No. surviving</th>
</tr>
</thead>
<tbody>
<tr>
<td>1080 in cereal</td>
<td>0.63 ± 0.43</td>
<td>0.17 ± 0.04</td>
<td>2.9</td>
<td>10 (10)</td>
</tr>
<tr>
<td>Cholecalciferol in cereal</td>
<td>0.92 ± 0.78</td>
<td>0.31 ± 0.11</td>
<td>18</td>
<td>3 (11)</td>
</tr>
<tr>
<td>Brodifacoum in cereal</td>
<td>6.62 ± 3.49</td>
<td>12.5 ± 1.12</td>
<td>281</td>
<td>3 (11)</td>
</tr>
<tr>
<td>1080 in paste</td>
<td>10.5 ± 4.7</td>
<td>3.64 ± 0.56</td>
<td>43</td>
<td>1</td>
</tr>
<tr>
<td>Cholecalciferol in paste</td>
<td>26.2 ± 6.6</td>
<td>3.06 ± 0.68</td>
<td>42</td>
<td>6 (10)</td>
</tr>
<tr>
<td>Brodifacoum in paste</td>
<td>28.3 ± 8.7</td>
<td>12.3 ± 1.86</td>
<td>320</td>
<td>0 (9)</td>
</tr>
</tbody>
</table>

\(^1\)Until death

4.6 Conclusions

Cholecalciferol and brodifacoum were chosen for this trial because they had been previously identified as the most promising of 18 toxicants trialed by Eason et al. (1994). An important difference between these two toxicants and 1080 is the speed of onset of poisoning symptoms. The acute onset of 1080 poisoning symptoms can enable the animal to associate cause and effect (Ottoboni 1983) so those survivors are likely to develop bait shyness. With the anticoagulant brodifacoum, the symptoms are chronic and far less noticeable, hence the possum is unlikely to associate them with the bait (Buckle 1994). The disadvantage of anticoagulants is that the possum needs to eat a large amount of bait in multiple doses to be poisoned, whereas a single dose of 1080 can be lethal. Therefore, anticoagulant bait has to be made available for extended periods. This is not a problem for rodent control as anticoagulant baits are at higher concentrations and a lethal dose can generally be ingested after 1-2 feeds (Buckle 1994). Cholecalciferol is intermediate between acute and chronic in its speed of action and is, therefore, classified as a subacute-acting toxicant (Pascoe 1983); victims may eat a lethal dose in one sitting, but the onset of symptoms is delayed for more than 24 hours. Consequently, cholecalciferol is less likely than 1080 to induce bait shyness (D. Morgan, unpubl. data).

This trial suggests that it is possible to kill the majority of 1080 bait-shy possums using a subacute (cholecalciferol) or chronic-acting toxicant (brodifacoum) in a familiar cereal bait matrix, provided baits are available for an extended period (Table 4.1). This contrasts with
studies by O'Connor and Matthews (1996; Table 2.2) and Morgan et al. (1996; Table 2.1), which suggested that the greatest success in overcoming 1080 cereal bait shyness would be obtained by changing the bait matrix.

There seems little difference in the effectiveness of cholecalciferol and brodifacoum as a means of overcoming 1080 bait shyness. It also needs to be considered that the cereal and paste cholecalciferol had a toxicant concentration of only 0.6%. Previous field trial studies have demonstrated that the efficacy of 0.6% cholecalciferol bait (64% kill; \( n=6 \) trials) is significantly lower than for the standard 0.8% concentration cholecalciferol bait (87% kill; \( n=3 \) trials) (Henderson and Morris 1996). In my study, changing the bait matrix enhanced the effectiveness of the cholecalciferol and brodifacoum toxicants, so that both achieved a 100% kill (Table 4.1). In contrast, several possums survived the cholecalciferol and brodifacoum cereal treatments, apparently by avoiding the bait matrix throughout the trial (Table 4.2). This shyness to the cereal bait could not be overcome by changing the toxicant.

In earlier pen trials, O’Connor and Matthews (1996) and Morgan et al. (1996) reported minimal consumption of non-toxic and brodifacoum cereal baits by 1080 cereal bait-shy possums. Their hypothesis was that the 1080 bait-shy possums remained cautious of the familiar cereal bait type and changing/removing the toxicant had little effect on mitigating these bait shy behaviours. However, the 1080 bait shy possums in these trials were exposed to bait for only 2-5 days. In the trial reported here, it took in excess of 2 weeks for some bait-shy possums to consume a lethal dose of brodifacoum cereal or paste bait (Table 4.2).

These results highlight the advantage of switching to a subacute or chronic-acting toxicant when trying to poison 1080 bait-shy possums. The slower acting nature of these toxicants, compared with 1080, means that possums are able to consume sub-lethal doses without associating the bait with the onset of poisoning symptoms. This and the trial conducted by Morgan et al. (1996) both suggested that at least some possums are unable to detect the 1080 toxicant once the bait matrix has been changed. Nevertheless, re-exposing 1080 bait-shy possums to 1080 again in a new matrix does not appear to be as effective as using a subacute or chronic-acting toxicant in either the same, or in a new, bait matrix. This result
suggests either that some 1080 bait-shy possums can detect the 1080, or that they have developed a cautious feeding strategy (Hickling 1994) that results in insufficient bait being consumed on the first night of exposure to be killed by any acute-acting toxicant.

4.7 Recommendations for future research

Favourable results were achieved with all the toxicants when the bait matrix was changed. Researchers need to evaluate the field effectiveness of 1080 in an unfamiliar bait matrix (i.e., change the bait type, dye and lure) for maintenance control. Field trial studies investigating the efficacy of ground laid 1080 paste or gel baits have demonstrated that these bait types are suitable for use in the field (Wickstrom et al. 1997) and are significantly cheaper than brodifacoum cereal bait (Thomas and Meenken 1995). Finally, researchers should also trial the alternative, slower-acting toxicants in the new bait matrix. In this pen trial, the new bait matrix enhanced the effectiveness of these toxicants (even with the low strength cholecalciferol paste bait) as possums were significantly less cautious of the jaffa-lured paste bait. It is possible that changing the bait matrix will improve the field efficacy of cholecalciferol and brodifacoum in maintenance or even initial control operations.

This trial also demonstrated that 1080 bait shyness should be confirmed in any pen trial using captive possums. As with the chapter 3 pen trial only 50-60% of the possums were bait shy following their initial LD$_{20}$ 1080 dose. While a single sub-lethal 1080 dose may more accurately mimic the field situation, bait shyness should always be confirmed. This will ensure that the results are not confounded by differences in the level of bait shyness amongst the subsequent treatment groups.

4.8 Acknowledgements

I thank the Foundation for Research, Science and Technology and Lincoln University (Entomology and Animal Ecology Group) for funding this experiment, Dave Morgan, Dr. Graham Hickling, Dr. Charlie Eason and two anonymous referees for helpful comments on
the draft paper and Lynne Milne and other staff at the Landcare Research animal facility for their assistance with the trial.

I was responsible for conceptual development, planning, practical work, data analysis and some animal husbandry duties for the above experiment. Dr. Graham Hickling provided guidance during all phases of the above experiment. Lynne Milne and other Landcare Research staff were responsible for the remaining animal husbandry duties.

4.9 References


5.1 Abstract

Shyness to sodium monofluoroacetate (1080) in cereal bait can persist in sub-lethally poisoned possum (Trichosurus vulpecula) populations for at least 2 years. I investigated the use of non-toxic cereal ‘prefeed’ and ‘postfeed’ as ways of inhibiting and overcoming such shyness. The postfeed result was also compared with changing to non-cereal (gel) 1080 bait. Prefeeding significantly influenced the number of possums that became ‘bait shy’ following an approximate LD$_{20}$ 1080 dose, with 97% of non pre-fed possums developing an aversion to 1080 cereal bait compared with only 22% of pre-fed possums. Postfeeding with cereal was relatively ineffective in reducing the number of 1080 bait-shy possums, with mortality of these possums being 30% compared with 0% of non post-fed possums. In contrast, the gel 1080 bait killed 64% of 1080 cereal bait-shy possums. These results suggest that 1080 bait shyness can be markedly reduced by prefeeding non-toxic bait to possums before each control operation. However, this may not be the most cost-effective control option, given the efficacy of the 1080-gel bait treatment. This result requires further investigation in the field.

5.2 Introduction

The Australian brushtail possum (Trichosaurus vulpecula) is a major vertebrate pest in New Zealand causing damage to forests (Cowan 1991) and preying on indigenous invertebrates and the eggs of endangered birds (Brown et al. 1993). Possums have also been identified as a major vector of bovine tuberculosis (Tb; Mycobacterium bovis), that they transmit to farmed deer and cattle (Livingstone 1991). Due in part to the continuing spread of Tb, possum control efforts intensified in the 1990s and have made increasing use of ground-
based techniques such as bait stations, often at annual or biennial intervals. Subsequent poor kills in control programmes have raised concerns that such programmes result in increasing numbers of possums exhibiting bait aversions (Hickling 1994). Trials with possums have shown that long-lasting aversions to sodium monofluoroacetate (1080) cereal bait can be induced in this species (Hickling 1994; Morgan et al. 1996; O'Connor and Matthews 1996), which makes survivors extremely difficult to control with an acute-acting toxicant such as 1080 (Ross et al. 1997).

Mammalian toxic bait aversions (hereafter termed ‘bait shyness’) have mainly been in rodent species. These rodent studies demonstrated that bait shyness is influenced by specific bait characteristics such as taste (Naheed and Khan 1989) and texture (Prakash 1988). If rodents are exposed to a flavour (or bait) before poisoning, this familiarisation can inhibit the formation of bait shyness (Bhardwaj and Prakash 1982), particularly with bait containing acute-acting toxicants (Sugihara et al. 1995). New Zealand possum researchers have recently conducted similar trials, which have likewise demonstrated that possums can become shy to specific bait components such as the flavour of the lure and the type of cereal bait base (O'Connor and Matthews 1996). For example, shyness to 1080 cereal baits can be largely overcome by switching to a non-cereal bait type with a different lure (Morgan et al. 1996; Ross et al. 1997).

Other possum studies have investigated the influence of bait familiarisation on the development of bait shyness. For example, Moss (1997) demonstrated that the number of possums becoming 1080 bait shy can be reduced by ‘prefeeding’ with non-toxic bait before sub-lethal poisoning. Further research demonstrated that cyanide bait shyness would weaken if sub-lethal poisoning is followed by at least five exposures to similar non-toxic bait (O'Connor and Matthews 1996). This suggests that the number of 1080 bait-shy possums can be reduced by prefeeding and possibly minimised by also ‘postfeeding’ after sub-lethal poisoning. I, therefore, undertook the following trial to determine the influence of non-toxic cereal prefeed and postfeed in the development and maintenance of 1080 cereal bait-shyness. This research had four aims:
1. To confirm the results of Moss (1997). This was the first time that the influence of non-toxic prefeed on the formation of 1080 bait shyness had been investigated and a repeat trial was needed;

2. To clarify the influence of dyed/non-dyed prefeed on shyness behaviour. In the field, possums are prefeed undyed, non-toxic bait before exposure to dyed, 1080 bait. It is important to ensure the presence or absence of dye does not confound the results of such trials;

3. To investigate the influence of postfeeding following sub-lethal poisoning. Pen and field trials have demonstrated that 1080 bait-shy possums will return to feed on non-toxic bait, if exposed to them for several days (Ross et al. 1987; Hickling 1994). These results, together with those from O'Connor and Matthews (1996) cyanide trial, suggest that several nights of postfeeding may encourage 1080 bait-shy possums to consume a lethal dose of toxic bait on subsequent re-exposure;

4. To compare the postfeeding result with the alternative strategy of changing the cereal bait base. Changing the bait base is currently the only chemical control technique that can kill 1080 bait-shy possums without requiring a switch to an expensive chronic-acting toxicant (Ross et al. 1997). This aspect of the research has particular relevance for managers because prefeeding with non-toxic bait is a common strategy when possums are being controlled using bait stations (Thomas et al. 1996) and postfeeding could be a logical extension of this strategy.

5.3 Objective

- To determine the influence of non-toxic cereal prefeed and postfeed in the development and maintenance of 1080 cereal bait-shyness.
5.4 Methods

Animal husbandry

The trial was undertaken using 83 wild-caught possums from North Canterbury. Possums were housed in individual wire cages (1 m x 0.4 m x 0.4 m) with mesh floors and a removable nest box (0.35 m x 0.2 m x 0.2 m) and acclimatised to captivity over a 6 week period (Duckworth and Meikle 1995). Possums were fed a range of fruit, vegetables and cereal food provided ad libitum. Except for the experimental treatments, they received no food in pellet form to avoid influencing their responses to the treatments.

Checking body weight at 7-day intervals monitored health of individual possums during acclimatisation. Any significant weight loss over this period was considered indicative of stress and any possum losing more than 2 standard deviations from the group mean weight loss was withdrawn from the trial (Buddle et al. 1992). Typically, weight loss was negligible (group mean weight loss 0.23 kg; 8% of mean capture body weight) and no possums were withdrawn from the trial during acclimatisation.

During the treatment phase some possums were exposed to multiple doses of 1080 cereal bait to determine the level of 1080 bait shyness (experimental design detailed below). Possum weight was monitored at 7-day intervals during the treatment phase and at post-mortem. Again, weight loss was negligible and only two possums were withdrawn from the trial due to excessive weight loss.

This study was conducted with the approval of the Landcare Research (N.Z.) Ltd Animal Ethics Committee.

Experimental procedure

After acclimatization, remaining healthy possums were then randomly divided into four groups balanced for weight and sex (Figure 5.1):
The minimum number of acclimatised possums for each group was seven. It is considered that at least five animals per group is satisfactory for preliminary laboratory tests (EPPO 1982; Buckle 1994).

Groups 1-3 were given 100 g/night of non-toxic prefeed for 1 week (Pre-treatment 1). In week 2, possums in all four groups received 1 g of 0.08% 1080 bait per kg liveweight (Pre-treatment 2). This dose level was used because it was expected to cause low mortality (an approximate LD$_{30}$ dose; R. Henderson, unpubl. data) and induce high levels of bait shyness amongst the survivors. In week 3, re-exposing each possum to 1 g of the same 1080 cereal bait (Pre-treatment 3) assessed the level of shyness. Each possum that rejected the 1 g bait was categorised as bait-shy and moved to the next phase of the trial. Possums that consumed bait were presented further toxic baits over the next two nights, in a further attempt to induce shyness. In week 4, 10 bait-shy animals were postfed 100 g/night of non-toxic prefeed for 1 week (groups 1 and 3) with the other 10 receiving no postfeed (group 2). Group 4 bait-shy possums received no postfeed during this week (Pre-treatment 4). In week 5, the level of shyness was re-assessed by exposing the bait-shy possums from all
four treatment groups to a potential lethal dose of 1080 cereal bait (20 g of 0.08% conc; approximately twice the LD_{95} dose) over two nights (Treatment 1).

In week 6, all surviving possums were exposed to a potential lethal dose of 1080 gel bait (50 g of 0.08 or 13% conc; at least four times the LD_{95}) to assess the effectiveness of alternative bait (Follow-up treatment) as a means of overcoming cereal bait shyness. Possums in groups 1-3 were presented with 0.13% 1080 gel bait and possums in group 4 received 0.08% 1080 gel bait. Previous pen trial studies have demonstrated that both concentrations are equally effective at killing 1080 cereal bait-shy possums (Morgan et al. 1996; O'Connor and Matthews 1996). However, the 0.08% conc. bait used in the chapter 4 study only killed 40% of the 1080 bait-shy possums. Accordingly, I also used the higher 0.13% conc. to assess whether the higher 1080 toxic loading is more effective.

Consumption of the treatment bait was measured daily (nearest 1 g) for each possum over the 6 week period. Possum survival was also monitored daily during the treatment phase and then for another 30 days post-treatment, during which time they were maintained on their normal diet.

Additional baits placed in nearby empty pens provided a correction for changes in moisture content of the baits (which were negligible for both the cereal and gel baits).

**Bait preparation**

The 1080 toxicant was loaded into the cereal and gel baits by Landcare Research staff and was supplied by Animal Control Products Ltd, Waimate (ACP). The cereal bait pellets were manufactured using RS5 cereal mix obtained from ACP, with gel bait supplied by Kiwicare Corporation Ltd, Christchurch. Both bait types also contained 0.1% cinnamon lure supplied by Bush, Boake and Allen Ltd, Auckland and 0.1% green Levanyl dye supplied by Bayer Ltd, Wellington.

The concentration of toxicant in each bait type was verified in the laboratory using a gas-liquid chromatography method for the determination for 1080 (Okuno et al. 1982).
Data analysis

The number of bait-shy possums and rates of mortality were compared using \( \chi^2 \) tests. Bait consumption data were not normally distributed (see below) and so were analysed using non-parametric statistical tests. A Mann-Whitney (U) test was used (appropriate for the sample size) to compare bait consumption between pairs of independent groups (e.g., possums eating dyed prefeed vs. possum eating undyed prefeed). Wilcoxon signed-rank tests were used to compare changes in bait consumption by individuals (e.g., prefeed consumption vs. postfeed consumption). Kruskal Wallis (H) tests were used to compare bait consumption between three or more independent groups (e.g., consumption of 1080 by post-fed possums vs. non pre-fed possums vs. pre-fed possums). Finally, Spearman’s rank correlation coefficients (\( r_s \)) were used to measure the strength of the association between pairs of variables (e.g., consumption of postfeed with time from initial exposure).

Data normality was visually assessed from a series of frequency histograms for each treatment. These indicated that bait consumption was typically multi-modal and not normally distributed.

5.5 Results

Consumption of prefeed by naive possums

All 48 pre-fed possums consumed prefeed readily during the 1st week of the trial. On average each individual ate 36.1 g (± 2.5 S.E.) per night (Figure 5.2) with no significant difference in the consumption of dyed and undyed prefeed (\( U = 264 \), d.f. = 1, \( P = 0.26 \)).
Consumption of the LD_{20} 1080 dose

All 81 possums ate their approximate LD_{20} 1080 dose on the night it was provided, so there was 0% initial shyness of the 1080 bait for each treatment group. This dose (intended to be an LD_{20}) killed 15 of the 81 possums (18.5%).

Bait shyness following the LD_{20} 1080 dose

Group 4, which had not been prefed, had significantly more bait-shy possums on every night than did the other three groups (Figure 5.3; χ² tests; d.f. = 3, P < 0.001 for all nights). Possums that ate the same colour prefeed as their approximate LD_{20} 1080 dose (groups 1 and 3; refer Figure 5.1) had the fewest bait-shy individuals following each re-exposure. Although, the proportion bait-shy (14%) was not statistically different from those possums that ate different coloured prefeed (group 2; 23%, χ² tests; d.f. = 1, P > 0.16 for all nights).
Consumption of postfeed by 1080 bait-shy possums

All bait-shy possums survivors from groups 1 and 3 (n = 10 for each group) ate some postfeed bait during the week of pre-treatment 4 (normal food was provided ad libitum). However, mean nightly consumption during that week was only 12.9 g/night (± 5.2 S.E.), which was significantly lower than the 34.5 g/night (± 2.3 S.E.) of prefeed eaten by the same possums immediately before the LD$_{20}$ 1080 dose (T = 2.4, d.f. = 1, P = 0.01). Mean nightly postfeed consumption rose from a mean of 7.5 g (± 4.7 S.E.) on the first night to 16.9 g (± 6.5 S.E.) on the last night (Figure 5.4), however, this increase was not statistically significant over time (r$^2$ = 0.57, d.f. = 5, P = 0.18).
Effectiveness of postfeeding as a means of overcoming 1080 bait shyness

Possums that had eaten neither prefeed nor postfeed (group 4) ate the least 1080 bait on subsequent re-exposure (Table 5.1). Possums that had been both prefed and postfed (groups 1 and 3) consumed the most 1080 bait and consequently had the highest mortality rate. However, in neither case were the differences between the groups significant (H = 2.99, d.f. = 2, P = 0.22 for consumption; \( \chi^2 = 4.73, \) d.f. = 2, \( P = 0.09 \) for mortality).

<table>
<thead>
<tr>
<th>Groups</th>
<th>Prefed before</th>
<th>Postfed after</th>
<th>1080 bait</th>
<th>Mortality</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 3</td>
<td>Yes</td>
<td>Yes</td>
<td>3.97 ± 1.84</td>
<td>30%</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>No</td>
<td>2.09 ± 1.02</td>
<td>20%</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>No</td>
<td>0.63 ± 0.43</td>
<td>0%</td>
<td>10</td>
</tr>
</tbody>
</table>

\( ^1 \text{Assayed 1080 bait concentration 0.083%} \)
Effectiveness of 1080 gel as a means of overcoming 1080 bait shyness

All remaining 1080 cereal bait-shy possums (n=25) were then exposed to 0.13% and 0.08% 1080 gel for one night. This treatment was relatively effective, killing 16 of 25 (64%) of these possums (Table 5.2). Consumption of 1080 gel (mean; 13.8 g ± 3.1 S.E.), by the survivors from treatment 1, was significantly higher than their consumption of 1080 cereal bait (mean; 2.3 g ± 0.7 S.E.; T = 3.98, d.f. = 1, P < 0.01). No significant difference in gel consumption or mortality was evident between the pre-fed and non pre-fed possums from the previous treatment (H = 0.09, d.f. = 2, P = 0.96 for consumption; χ² = 4.81, d.f. = 2, P = 0.09 for mortality).

Table 5.2: Consumption of 1080 gel by 1080 cereal bait-shy possums, and subsequent mortality (possums were exposed to the Follow-up Treatment 1080 gel bait for one night only; Figure 5.1). Means presented + SE.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Mean 1080 gel Consumption (g)</th>
<th>Measured conc. (% wt./wt.)</th>
<th>Mortality (%)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 3</td>
<td>11.9 ± 3.6</td>
<td>0.13%</td>
<td>71%</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>12.8 ± 5.7</td>
<td>0.13%</td>
<td>88%</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>15.9 ± 5.9</td>
<td>0.085%</td>
<td>40%</td>
<td>10</td>
</tr>
</tbody>
</table>

5.6 Conclusions

The benefits of prefeeding non-toxic cereal bait appear to be twofold. First, it attracts additional possums to feeding stations and improves the percentage kill (Thomas et al. 1996). This occurs even though trials with captive animals have shown that pre-fed possums on their first exposure individually eat about 40% less 1080 bait than do non pre-fed possums (Ross et al. 1987; Thomas et al. 1996). Second, survivors are less likely to become 1080 bait shy if they were prefed than if they were not; this confirms the results of Moss (1997). Accordingly, the use of non-toxic prefeed appears to be a useful management tool that can help minimise the number of bait-shy survivors following control operations.

All 1080 bait-shy possums consumed some non-toxic bait during the week of postfeeding. This result supports the findings of previous field and pen trials which indicated that 1080
bait-shy possums will consume non-toxic prefeed bait on re-exposure (e.g., Ross et al. 1987; Hickling 1994; Ross et al. 1997). Postfeeding had little influence on consumption when the possums where re-exposed to 1080 cereal bait later in the trial. This result supports an earlier pen trial that indicated that once shyness to a cereal bait base has been induced, it is difficult to kill these animals using the same bait base, particularly if it contains an acute-acting toxicant such as 1080 (Ross et al. 1997).

In contrast, 1080 gel was highly effective at killing 1080 cereal bait-shy possums. The high mean 1080 gel consumption (13.8 g ± 3.1 S.E. compared with mean 1080 cereal bait consumption of only 2.3 g ± 0.7 S.E.) suggests that bait base recognition is more important than toxicant detection in triggering shyness behaviour. The 1080-gel result also compares favourably with an earlier pen trial in which 64-73% of 1080 cereal bait-shy possums were killed using a subacute and chronic-acting toxicant (cholecalciferol and brodifacoum) in cereal bait (Ross et al. 1997). The 1080 gel percentage kill could also have been higher had toxicant concentration been uniform. While not significant, the 0.085% 1080 gel bait was less effective than the 0.13% gel bait. However, the 0.13% 1080 gel bait is still not as effective as using alternative, slower-acting toxicants in a non-cereal bait (apple paste), which killed 100% of the 1080 cereal bait-shy possums in the Chapter 4 pen trial (Ross et al. 1997).

An alternative explanation for the success of 1080 gel bait in killing 1080 cereal bait-shy possums is that the lethality of a toxicant can be influenced by stomach contents (e.g., fasted versus unfasted possums; Bogan et al. 1984) and the formulation of the bait matrix (Talanov and Leshchev 1972; Medinsky and Klaassen 1996). Both factors can affect the speed of onset of toxicosis, which may in turn influence-feeding behaviour. Bait-shy possums are cautious feeders and unlikely to consume a lethal doses if the onset of poisoning is too rapid. The 1080-gel bait may be more effective because the bait formulation, and other stomach contents, can delay poisoning symptoms and thus encourage possums to consume more bait. Preliminary investigation of 1080 bait lethality supports this hypothesis by indicating that 1080 paste is less toxic than 1080 cereal bait (with the same toxin loading; R. Henderson, unpubl. data).
In conclusion, the results of this trial support Moss's (1997) earlier pen trial, which demonstrated that prefeeding significantly reduces the number of 1080 bait-shy survivors. Furthermore, the presence/absence of dye was insignificant in terms of the amount of prefeed consumed by 1080 bait-shy possums, which suggests that field managers can use undyed prefeed without losing any positive effects. The lack of significant difference between the dyed and undyed treatments may have been due to the small sample sizes ($n=24$). For example, only 14% of the possums eating dyed prefeed developed bait shyness compared with 23% of possum eating undyed prefeed. However, this could be an important result that requires further investigation with larger samples to confirm validity.

Postfeeding did not significantly reduce the level of the 1080 bait-shyness, and achieved only a 30% kill compared with a 20% kill for non-postfeed possums. Again, the lack of significant difference may have been due to the small sample sizes ($n=10$). This could also be an important result, which has direct implications for possum control managers. In comparison, 1080 gel bait was much more effective, achieving an average 64% kill (this percentage includes possums that had not been prefed and/or postfed; Table 5.2). Currently, field managers' target 1080 bait-shy possums using either leg-hold traps or a chronic-acting toxicant such as brodifacoum. The 1080-gel result suggests that this could be another viable control technique, which could be incorporated into maintenance control programmes. However, this result was achieved with captive possums and so requires field validation.

Finally, the success of 1080 gel bait raises questions regarding the most cost-effective method of controlling 1080 cereal bait-shy possums. Non-toxic prefeed can cost up to $12.80/ha (NZD) when used before a 1080 bait station control operation (Thomas et al. 1996). A more cost-effective strategy may be to avoid prefeeding and then, if required, immediately follow up cereal 1080 control with 1080-gel bait. If 1080 gel can be shown to be effective in the field (particularly over rugged terrain), researchers should then investigate the cost-effectiveness of using non-toxic prefeed versus a 1080 gel bait follow-up operation.
5.7 Recommendations for future research

Field trial studies have demonstrated that prefeeding increases both toxic bait consumption and the percentage kill achieved (Thomas 1998). For this reason alone, field managers should always consider using non-toxic prefeed before control with an acute or subacute-acting toxicant. The Chapter 5 pen trial result suggests that prefeeding will also reduce the number of 1080 bait-shy survivors, but this requires field validation.

Postfeeding does not appear to be good technique for overcoming 1080 bait shyness, as only 30% of these possums subsequently consumed a lethal dose when re-exposed to 1080 cereal bait. As detailed above, free ranging possums are likely to be more cautious than their captive counterparts (with a greater range of foods), so postfeeding would probably be even less effective in the field. In terms of mitigating 1080 bait shyness researchers should investigate the field efficacy of possum toxicants in unfamiliar bait when undertaking maintenance control.

5.8 Acknowledgements

I thank the Foundation for Research, Science and Technology and Lincoln University (Entomology and Animal Ecology Group) for funding this experiment, Dr. Graham Hickling, Dr. Charles Eason, Dave Morgan, two anonymous referees for helpful comments on the draft paper and Lynne Milne and other staff at the Landcare Research animal facility for their assistance with the trial.

I was responsible for conceptual development, planning, practical work, data analysis and some animal husbandry duties for the above experiment. Dr. Graham Hickling provided guidance during all phases of the above experiment. Lynne Milne and other Landcare Research staff were responsible for the remaining animal husbandry duties.
5.9 References


CHAPTER 6

COST-EFFECTIVE CONTROL OF 1080 BAIT-SHY POSSUMS

6.1 Abstract

Previous possum control simulation studies have suggested that regular aerial control with bait containing sodium monofluoroacetate (1080) is the most cost-effective possum control strategy. However, there is a growing awareness that the survivors of 1080 operations can develop 'bait shyness'. This factor can markedly alter the efficacy of future 1080 control operations, but has not been considered in previous simulation studies. I, therefore, constructed a possum control simulation model that incorporated fast-acting toxicants (e.g., 1080) and the development of bait shyness. The objective of this simulation study was to identify the most cost-effective control strategy that would achieve sustained population reductions of 60% and 80%, given bait-shy behaviour and population recovery due to immigration.

The simulation results suggest that it is possible to achieve sustained 60% or 80% reductions in possum numbers using a 1080-based control strategy, provided reasonably large (>100 ha) areas are controlled and 90% of susceptible possums are killed. The chronic-acting toxicant brodifacoum (Talon®) kills the majority of any non-susceptible (i.e., 1080 bait-shy) survivors and its occasional use for follow-up control provided the most cost-effective way of maintaining a possum population at low density. Sensitivity analysis indicated that the most important variable influencing the overall success of these control strategies was the maximum rate of immigration following control. With the high rates of immigration that are sometimes observed in small forest reserves (i.e., up to 4 possums/ha/yr), it was not possible to maintain a sustained 80% reduction in numbers using any combination of toxicants. Expensive, continued application of brodifacoum, using permanent bait stations, may be required to minimise the effects of immigration into these small reserves.
6.2 Introduction

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

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

Regardless of the criteria used to determine which areas receive possum control, field managers must then make decisions concerning the most appropriate control technique. As there is only a limited amount of money available for pest control, it is important that the most cost-effective techniques are used (Warburton et al. 1992). Previous research investigating cost-effective control of possums has favoured the use of aerially delivered sodium monofluoroacetate (1080) bait (Barlow 1991a). This technique can significantly reduce high density possum populations over areas as large as 20 000 ha (Eason et al. 1994).
An over-reliance on one toxicant, however, is considered unwise for a number of reasons (Eason et al. 1994). One of the main reasons is that regularly controlled populations can develop behavioural mechanisms to avoid toxic bait (Hickling, 1994; O'Connor and Matthews 1996). Field and pen trials have demonstrated that the majority of survivors from 1080 control operations are likely to develop 'bait shyness' following sub-lethal poisoning (Ross et al. 1997). This bait shyness is long lasting (Morgan and Milne 1997) and can render 'follow up' maintenance control with 1080 baits ineffective (Hickling 1994). Accordingly, possum control strategies need to incorporate other control techniques such as bait station ground control with alternative, slower-acting possum toxicants (four other possum toxicants are currently registered). This chapter extends previous possum modelling work (e.g. Barlow 1991a; Hickling 1995) by developing a new possum bioeconomic model that incorporates 1080 bait shyness and the two most promising alternative possum toxicants (cholecalciferol, marketed as Campaign® and brodifacoum, marketed as Talon®).

6.3 Background

The purpose of this study was to estimate the control efficacy and cost-effectiveness of various alternative possum control strategies. The analysis focused primarily on the costs, because managers typically have pre-determined target population densities imposed on them by current central government policies (PCE 1994). Therefore, a Cost-Effectiveness Analysis (CEA) of different control strategies (including alternative, slower-acting toxicants) should be of use to managers who want to determine the least-cost solution of reducing possums to a pre-determined target population density. For example, DOC now sets a post-operational trap catch rate of 5% as the target population density for control operations on their land (DOC 1997). In other areas, epidemiological models have suggested that keeping the population below 40% of the initial pre-knockdown population size may be sufficient to eradicate Tb from a possum population in 6-8 years (Barlow 1991b).
Most previous pest management simulation models have focused on the control of invertebrate pests. Early research in this field used simple static models to determine economic damage thresholds above which the application of insecticides became economically justifiable (e.g., Mumford and Norton 1984; Pedigo et al. 1986). More recent studies have explored the optimal use of pesticides in light of the dramatic increases in pesticide resistance (Knight and Norton 1989). The dynamic nature of resistance has also encouraged the development of Integrated Pest Management (IPM) strategies, where pest numbers are controlled using a multitude of different strategies (chemical and non-chemical). To cope with the problem of pesticide resistance these models have become increasingly complex and dynamic (Kennedy 1988). Recent optimal pest control research has used stochastic dynamic programming and numerical simulation models (Barlow 1991a; Huffaker et al. 1992; Harper et al. 1993; Yu et al. 1993).

After reviewing the previous (invertebrate and vertebrate) pest-management research the decision was made to advance Barlow’s (1991a) CEA for possums. The contribution of my research was that the new bioeconomic model incorporated 1080 bait shyness and the option of using two new alternative, slower-acting toxicants. A numerical simulation model was used as it was perceived that quantifying all the relationships into a set of functions suitable for dynamic programming would unduly sacrifice realism.

### 6.4 Objective

- To model the most cost-effective way of reducing the possum population to a predetermined target density, given that alternative formulations of 1080 bait, and alternative toxicants, may be required to sustain the efficacy of such control.

### 6.5 Methods

This section is divided into three sub-sections, with the first detailing the mathematical equations used in the model. The second defines the model parameter values and the third sub-section provides empirical justification for these parameter values. The third also
details previous possum pen and field trial studies that have investigated: possum population growth, possum movement, the efficacy of possum control campaigns using acute, subacute and chronic-acting toxicants, the development of possum bait shyness and the economics of possum control.

**Equations**

The basic model (Figure 6.1) was written in the Microsoft Excel for Windows 95® (Version 7.0) and is provided on a 1.44-Mb computer disk in IBM format attached to back cover of the thesis. The model uses the following equations for changes in density of the total population (T), susceptible sub-population (S) and the shy of acute/subacute-acting toxicant bait sub-population (A):

**Susceptible sub-population:**

\[
\frac{dS}{dt} = (S + I + (Tr(1 - (T/K)^0) + L) \times (1 - C_1C_2 - C_2\alpha_2))
\]  

**Shy of acute/subacute-acting toxicant bait sub-population:**

\[
\frac{dA}{dt} = A(1 - \mu - \phi) + C_1(1 - \alpha_i) \times (S + I + (Tr(1 - (T/K)^0) + L) - C_2\alpha_2A(1 - \mu - \phi)
\]  

**Total population:**

\[
T = (S + A)
\]

(Note: all abbreviations are detailed in Table 6.1)
Figure 6.1: Flowchart for a computer simulation of possum population responses to a toxic baiting strategy employing acute, subacute and chronic-acting toxicants. The total population (T) is made up of two sub-populations; one susceptible to poisoning (S) and one shy of acute/subacute-acting toxicant bait (A). See Table 6.1 for an explanation of the variables (Sub-population B is detailed in Figure 6.12).

Model variable definitions and values

The modelling simulation was set up to estimate the total possum population (T) at 12-month intervals. The values in the table below are, therefore, per annum estimates that have been derived from various pen and field trial studies. Assessing the numbers of possums at 12 month intervals is similar to the way that the possum density is estimated in the field, where population index assessments (using techniques such as residual trap catch; Warburton 1996) are generally made following each control operation.
Table 6.1: Variable definitions and values used in a computer simulation of possum population responses to a toxic baiting strategy employing acute, subacute and chronic-acting toxicants (explanation of these variables is provided below).

<table>
<thead>
<tr>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Density of possums susceptible to poisoning</td>
</tr>
<tr>
<td>A</td>
<td>Sub-population of possums shy of acute/subacute-acting toxicant bait</td>
</tr>
<tr>
<td>B</td>
<td>Sub-population of possums shy of all bait</td>
</tr>
<tr>
<td>I</td>
<td>Number of immigrants from neighbouring population</td>
</tr>
<tr>
<td>T</td>
<td>Total possum population in controlled habitat</td>
</tr>
<tr>
<td>L</td>
<td>Number of possums losing acute/subacute bait shyness</td>
</tr>
<tr>
<td>C₁</td>
<td>Acute toxicant control activity</td>
</tr>
<tr>
<td>C₂</td>
<td>Chronic toxicant control activity</td>
</tr>
<tr>
<td>M</td>
<td>Maximum rate of immigration (possums/ha/yr)</td>
</tr>
<tr>
<td>r</td>
<td>Intrinsic rate of increase for controlled possums/year</td>
</tr>
<tr>
<td>K</td>
<td>Carrying capacity for controlled possums</td>
</tr>
<tr>
<td>μ</td>
<td>Natural mortality rate/year</td>
</tr>
<tr>
<td>θ</td>
<td>Shape parameter for possum population growth curve</td>
</tr>
<tr>
<td>δ₁</td>
<td>Percentage of population exposed to acute/subacute-acting toxicant bait</td>
</tr>
<tr>
<td>δ₂</td>
<td>Percentage of population exposed to chronic-acting toxicant bait</td>
</tr>
<tr>
<td>α₁</td>
<td>Percentage of population killed by acute/subacute-acting toxicant bait</td>
</tr>
<tr>
<td>α₂</td>
<td>Percentage of population killed by chronic-acting toxicant bait</td>
</tr>
<tr>
<td>φ</td>
<td>The rate of acute and sub-acting toxicant bait shyness degradation/year</td>
</tr>
<tr>
<td>ϵ</td>
<td>Proportion of acute/subacute bait-shy possums avoiding chronic-acting toxicant bait</td>
</tr>
<tr>
<td>C</td>
<td>Cost of control operation</td>
</tr>
<tr>
<td>t</td>
<td>Number of years since start of simulation</td>
</tr>
<tr>
<td>f</td>
<td>Discount rate</td>
</tr>
</tbody>
</table>

Biological growth

Possum population growth was modelled using a $\theta$-logistic equation (Gilpin et al. 1976). Ecological studies investigating population dynamics suggest that New Zealand brushtail possum populations are regulated by density-dependent mortality, intensifying near carrying capacity (Barlow 1991c). This implies that the possum population growth curves are asymmetrically, rightward peaked (Barlow and Clout 1983). The $\theta$-logistic is an asymmetric growth equation (rightward peaked when $\theta>1$) and has been used in previous ecological studies modelling the dynamics of brushtail possums (Clout and Barlow 1982; Barlow 1991c). $\theta$-logistic equations have also been used by researchers to model the population dynamics of similar mammalian pest species such as foxes (Urocyon cinereoargenteus) in Europe (Murray and Seward 1992), feral pigs (Sus scrofa) in
Australia (Pech and McIlroy 1990) and feral donkeys (*Equus asinus*) in Northern Australia (Choquenot 1990).

Age-structured deterministic/stochastic equations (Efford 1991; Pfieffer 1994; Roberts 1996) have also been used model population growth and the transmission of Tb between possum populations. The advantage of these age-structured models is that the number of animals in each age class can vary according to appropriate age specific birth and death rates. Previous research suggests that rates of mammalian breeding and survival can vary with age and this can affect the overall growth rate of a population (Efford 1991). Nevertheless, Barlow and Clout (1983) constructed an age-structured possum model and found that age specificity in density-dependent mortality did not greatly alter the shape of a possum population growth curve, when compared with the curve generated by non age-structured $\theta$-logistic models. Accordingly, they recommended the use of $\theta$-logistic models for possum population modelling because of their simplicity and tractability. This recommendation is also supported by Efford (1991) who constructed an age-structured possum model using empirical data obtained from the Orongorongo Valley (North Island) possum population. He concluded that age structure confers little advantage when the overall focus of the model is population growth and the much simpler logistic model produces broadly similar results. Both papers, therefore, suggest that the $\theta$-logistic model is a good 'general' model of population growth and is appropriate for a study such as this, where the age composition of the population is not a focus of the research.

All the models detailed above, assume that possum population growth is regulated by intra-specific competition for resources (referred to as the *density-dependent paradigm*; Krebs 1995). While there are numerous examples of animal population models based on this paradigm (Hone 1994), there are other researchers who advocate that population size is density independent and limited by environment mechanisms, such as the availability of food or the number of parasites predators and the effects of disease (referred to as the *mechanistic paradigm*; Hone 1994; Krebs, 1995). In New Zealand, the current evidence suggests that possum numbers are more likely limited more by food than other environmental factors (Cowan 1990). Accordingly, the best choice of model (based on the mechanistic paradigm) would be a plant-herbivore model, where the total number of
possums is limited by the availability of palatable vegetation (Caughley 1976). While there is growing academic support for these type of models (Krebs, 1995), they do require a detailed investigation to determine several key parameter values (e.g., the intrinsic rate of increase for the plants etc.). Currently, vegetation damage thresholds and subsequent rates of recovery are unknown for the majority of New Zealand plant species (Hickling 1994; Nugent 1994). Accordingly, the 0-logistic model, based on the density-dependent paradigm, was considered to be the best current option for the following possum population simulations.

Maximum rate of intrinsic growth/year

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

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

The natural mortality ($\mu$) parameter is required for possums that have survived a baiting programme and became part of population A or B (refer Figure 6.12), following control with 1080 (Figure 6.1). Previous modelling estimates for this value range from 10% (Barlow 1987) to 20% (Spurr 1981). The value of 20% was derived from an empirical study conducted on a well-established population near carrying capacity. Other population studies suggested that this value is more likely to be 10% when the population is at low-moderate densities (Spurr 1981). This value has also been adopted in other possum population models investigating the impact of control programmes on the dynamics of possum populations (Barlow 1987; Barlow and Clout 1983; Clout and Barlow 1982).

**Carrying capacity**

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

**Theta**

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

**Possum movement**

The movement of small mammals between adjacent parcels of habitat has been widely investigated by population ecologists. It is hypothesised that dispersal of some species is governed by within-group competition for resources, such as den space, and between-group exchange of individuals through immigration (Hestbeck 1982). This is referred to as a 'social-fence', which opens and closes depending on the population densities in the parcels of habitat. When the density of the neighbouring parcel is low, within-group pressure will be greater than between-group pressure and animals will disperse into the neighbouring habitat. During periods of high population densities, there is a high degree of between-group aggression, which makes immigration into neighbouring parcels much less likely. Essentially the social-fence closes when relative population densities are high. Accordingly, when the neighbouring population is controlled, there will be immigration into the low-density habitat through the open social-fence.

Hestbeck (1988) and Stenseth (1988) formulated mathematical models of the social-fence hypothesis. This model has been adapted and applied to bioeconomic models investigating optimal control of beavers (Huffaker et al. 1992) and the spread of bovine Tb by the brushtail possum (Barlow 1993):

\[
\frac{dI}{dt} = M \left(1 - \frac{T}{K}\right)
\]

(4)

This equation assumes that when the density in the controlled area is low possums will migrate from the relatively densely populated non-control (neighbouring) area up to the maximum rate of net immigration (M). The equation also assumes that dispersing possums are of breeding age and equal sex ratio. Both assumptions are consistent with the field data, which has demonstrated that control areas are rapidly recolonised by a high proportion of adult possums of both sexes (Clout and Efford 1984; Keber 1985; Green and Coleman
123

1984). It is speculated that possums dispersing into a control area are made up of adult female possums settling in areas of low density relative to carrying capacity (Efford 1996), and young adult male possums who seem to disperse, with no specifically preferred direction, regardless of the population density at the natal site (Cowan et al. 1997).

This equation also assumes that density of the neighbouring population will remain at carrying capacity, whilst possums migrate into the control area. A long term study investigating possum population dynamics indicated that, in the absence of control, established possum populations maintain relatively stable densities with some seasonal fluctuations (Efford and Hearfield 1992). Any immigration loss from a high density population appears to be compensated for by recruitment and immigration of foreign possums (Efford 1998).

In conclusion, these data suggest that a fully accurate model of possum immigration would need to be quite complex. These mechanisms are only approximated in the modelling simulations. However, Equation 4 seems appropriate for my control simulations as I was primarily concerned with the overall numbers, rather than the age-sex composition, of possums re-colonising the control area.

*Maximum rate of net immigration (per ha)*

An estimate for M was derived from a number of empirical studies. In a total removal experiment, possums began re-colonising a 24 ha pine plantation (Kinleith Forest, North Island) within 1 month of the control operation. After 1 year, the density was 1.6 possums/ha, which was 55% of the original population (Clout and Efford 1984). In another total removal experiment, a 12 ha area in the Orongorongo Valley (1200 ha) was re-colonised by 12 possums after 1 year (Barlow 1993; using data derived from P. Cowan, pers. comm. 1993). In an experiment in the South Island, possums were removed from a block (125 ha) of indigenous forest in Westland. The pre-control density was 10.7 possums/ha and 3 years later this population was back to 26% of the pre-control density (i.e., 3 possums/ha; Green and Coleman 1984). In a more recent study, 255 possums (90% kill) were removed from swamp and willow habitat (23 ha) in Hawkes Bay (North Island).
Five years later the population had recovered to 136, which is 5.9 possums/ha (Cowan et al. 1997). These studies suggest that the maximum rate of net possum immigration (termed immigration from now on), under a variety of conditions is approximately 1.2 possums/ha/yr, and this value was used in my model.

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

Current possum toxicants

There are currently five toxicants registered for the control of possums in New Zealand, which can be categorised by the speed of onset of poisoning symptoms. Acute-acting toxicants (1080, cyanide and phosphorous) have rapid onset of toxicosis with symptoms generally appearing in less than 24 hours, but in the case of cyanide, within seconds (Lazarus 1989). For possums, 1080 poisoning symptoms appear in 1-2 hours (Morgan 1990), with death usually within 24 hours (Ross et al. 1997). Chronic-acting toxicants (such as brodifacoum and pindone, which are anticoagulants) have delayed onset of poisoning symptoms. For possums, the physiological symptoms of brodifacoum poisoning begin to appear within approximately 7 days (Eason et al. 1996b), with death occurring 2-5 weeks after consumption of a lethal dose (Eason et al. 1994). Subacute-acting toxicants (e.g., cholecalciferol) fall somewhere in between acute and chronic-acting toxicants (Buckle 1994). With possums, cholecalciferol-poisoning symptoms are delayed for 24-36 hours, with death usually occurring within 4-6 days.

The main advantage of acute-acting toxicants is that they are fast acting and a lethal dose is usually consumed in a single feed (Buckle 1994). Consequently, these toxicants have the potential to quickly knock down a high-density pest population using small amounts of toxic bait. The fast onset of toxicosis, however, means that any animals consuming sub-lethal doses are likely to associate cause and effect. Affected animals will usually refuse to consume poisoned food on subsequent occasions and are referred to as being bait shy (Buckle 1994).
The advantage of chronic and subacute-acting toxicants is that the delayed onset of symptoms helps to prevent the animal from associating symptoms with the bait so that it is less likely to become bait shy. The disadvantage is that animals generally require multiple feeds of these toxicants to ingest a lethal dose. These compounds are, therefore, usually more expensive in terms of quantities of bait consumed (particularly when the population density is high) and labour costs. Chronic-acting toxicants can also pose a higher risk to non-target species due to the persistence of these compounds in the food chain. For example, brodifacoum is only slowly eliminated from the liver and accumulates in non-target vertebrates that eat toxic bait or prey on/scavenge the target pest species (Eason and Spurr 1995). Due to the bait costs and secondary poisoning risks, subacute and chronic-acting toxicants are not usually used in aerial control operations on the mainland. For example, cholecalciferol is registered for use only in bait stations (Thomas et al. 1996).

Percentage of population encountering and consuming bait

Aerial operations

Bait coverage is the most important factor influencing the number of possums encountering baits spread by aircraft (Morgan 1982). In the 1980s, bait coverage could vary from 52%-100%, with extent of coverage strongly correlated with the subsequent kill (Morgan 1994a). This problem has been largely overcome with the advent of aerial navigation guidance systems such as the Global Positioning System (GPS). GPS enables comprehensive bait coverage, even with sowing rates of less than 5 kg/ha (Morgan et al. 1995). With comprehensive bait coverage, up to 100% of possums should encounter a bait (Morgan 1982).

Bait station operations

Bait station spacing is the most important factor influencing the number of possums encountering bait (Table 6.2).
Table 6.2: Proportion of possums eating from bait stations at various station spacings.

<table>
<thead>
<tr>
<th>Bait station spacing (m)</th>
<th>Possums eating bait (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>100%</td>
<td>Hickling et al. (1990)</td>
</tr>
<tr>
<td>100</td>
<td>93%</td>
<td>Thomas (1994)</td>
</tr>
<tr>
<td>101-150</td>
<td>95%</td>
<td>Thomas et al. (1996)</td>
</tr>
<tr>
<td>200-300</td>
<td>79%</td>
<td>Thomas and Fitzgerald (1994)</td>
</tr>
<tr>
<td>301-600</td>
<td>50%</td>
<td>Thomas and Fitzgerald (1994)</td>
</tr>
</tbody>
</table>

These field trials (which were undertaken using bait impregnated with Rhodamine-B dye) suggest that with bait station spacing of 50-150 m approximately 95-100% of possums should encounter bait. This reduces to around 80% with 200-300 m spacing and to 50% with 301-600 m spacing.

Because bait stations may aggregate possums in a localised area, social behaviour of possums can also have an influence over the success of control operations using bait stations. This contrasts to aerial control, where each possum is likely to locate toxic bait during its nightly movement. For example, an aerial operation with a sowing rate of 5 kg/ha delivers 900 lethal baits/ha (Morgan et al. 1997). In a bait station operation, there are only 80 (500 g) lethal baits/ha (Thomas et al. 1997) and these are all concentrated at one feeding station/hectare. Accordingly, aggressive interactions are common at bait stations and this increases the chance of a possum being excluded from an individual station (Henderson and Hickling 1997). When the bait station spacing is low (<150 m), there are relatively few possums feeding at each station and each is more likely to encounter at least one station within its home range.

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

**Percentage kill**

**Acute-acting toxicant - 1080**

When bait is correctly delivered to a naïve possum population survival is typically <10% (Morgan 1990) (Table 6.3).
Table 6.3: Estimated kills achieved in aerial control operations using 1080 cereal bait; sowing rate ≥ 5 kg/ha; n indicates the number of separate field operations monitored.

<table>
<thead>
<tr>
<th>1080 Concentration (% wt./wt.)</th>
<th>Aerial Navigation</th>
<th>Kill (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15%</td>
<td>Yes</td>
<td>90% (n=8) Morgan et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>0.08-0.15%</td>
<td>Yes</td>
<td>92% (n=16) Morgan et al. (1996b)</td>
<td></td>
</tr>
<tr>
<td>0.06-0.15%</td>
<td>No</td>
<td>86% (n=27) Brown and Arulchelvam (1995)</td>
<td></td>
</tr>
</tbody>
</table>

These data suggest that a 90% kill of susceptible possums is an appropriate value for aerial 1080 simulations using aerial guidance systems and 0.08-0.15% concentration 1080 bait (the preferred 1080 bait concentration is currently 0.08%). In most of these aerial operations, the possum population was well established and at a moderate-high population density. Field trials investigating the effectiveness of aerial 1080 operations indicate that a 90% kill value is still appropriate when the population density is low-moderate density (Warburton 1997).

The two main factors influencing 1080 bait station operational success are the toxicant concentration and the availability of non-toxic prefeed (Table 6.4).

Table 6.4: Estimated kills achieved in control operations using 1080 cereal bait in bait stations; n indicates the number of separate field operations monitored.

<table>
<thead>
<tr>
<th>1080 concentration (% wt./wt.)</th>
<th>Prefed</th>
<th>Spacing (m)</th>
<th>Kill (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08%</td>
<td>No</td>
<td>50-100</td>
<td>45% (n=1) Thomas et al. (1996)</td>
<td></td>
</tr>
<tr>
<td>0.08%</td>
<td>Yes</td>
<td>100</td>
<td>58% (n=2) Thomas and Hickling (1995)</td>
<td></td>
</tr>
<tr>
<td>0.08%</td>
<td>No</td>
<td>100</td>
<td>56% (n=6) Henderson and Morriss (1996)</td>
<td></td>
</tr>
<tr>
<td>0.15%</td>
<td>Yes</td>
<td>100</td>
<td>98% (n=1) Thomas (1994)</td>
<td></td>
</tr>
<tr>
<td>0.15%</td>
<td>No</td>
<td>100</td>
<td>100% (n=1) Thomas et al. (1996)</td>
<td></td>
</tr>
<tr>
<td>0.15%</td>
<td>No</td>
<td>100</td>
<td>87% (n=3) Henderson and Morriss (1996)</td>
<td></td>
</tr>
<tr>
<td>0.15%</td>
<td>No</td>
<td>100</td>
<td>75% (n=1) Henderson et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>0.15%</td>
<td>No</td>
<td>150</td>
<td>75% (n=2) Thomas et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>0.15%</td>
<td>Yes</td>
<td>100</td>
<td>98% (n=1) Thomas and Meenken (1995)</td>
<td></td>
</tr>
<tr>
<td>0.15%</td>
<td>Yes</td>
<td>150</td>
<td>99% (n=2) Thomas et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>0.5%</td>
<td>No</td>
<td>100</td>
<td>93% (n=1) Thomas (1992)</td>
<td></td>
</tr>
</tbody>
</table>

These figures suggest that a 90% kill of susceptible possums should also be used for bait station control simulations using 0.15% 1080 bait with non-toxic prefeed. Without prefeed a mean value of 80% is appropriate, especially when using a bait station spacing of greater than 100 m, as some possums seem unable to locate stations without a prolonged period of prefeeding (Thomas et al. 1996).
Subacute-acting toxicant - Cholecalciferol (marketed as Campaign®)

The two main factors influencing cholecalciferol control success is the toxicant concentration and the amount of CaCO₃ (calcium carbonate; this compound assists in elevating plasma calcium, eventually causing heart failure; Eason et al. 1994) added to the cereal bait (Table 6.5) (cholecalciferol is registered for use only in bait stations; Jolly et al. 1995).

Table 6.5: Estimated kills achieved in bait station control operations using cholecalciferol cereal bait with no prefeed and a bait station spacing of 100 m; n indicates the number of separate field operations monitored.

<table>
<thead>
<tr>
<th>Cholecalciferol concentration (%wt./wt.)</th>
<th>CaCO₃ (%)</th>
<th>Kill (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6%</td>
<td>10%</td>
<td>64% (n=3)</td>
<td>Henderson and Morriss (1996)</td>
</tr>
<tr>
<td>0.8%</td>
<td>0%</td>
<td>58% (n=3)</td>
<td>Eason et al. (1994)</td>
</tr>
<tr>
<td>0.8%</td>
<td>10%</td>
<td>82% (n=3)</td>
<td>Eason et al. (1994)</td>
</tr>
<tr>
<td>0.8%</td>
<td>10%</td>
<td>87% (n=3)</td>
<td>Henderson and Morriss (1996)</td>
</tr>
<tr>
<td>0.8%</td>
<td>10%</td>
<td>86% (n=1)</td>
<td>Henderson et al. (1994)</td>
</tr>
<tr>
<td>0.8%</td>
<td>10%</td>
<td>82% (n=5)</td>
<td>Henderson et al. (1997)</td>
</tr>
<tr>
<td>0.8%</td>
<td>20%</td>
<td>46% (n=1)</td>
<td>Eason et al. (1994)</td>
</tr>
</tbody>
</table>

These figures suggest that a mean 80% kill value should be used for control simulations using 0.8% concentration cholecalciferol bait with 10% CaCO₃.

Chronic-acting toxicant - Brodifacoum (marketed as Talon®)

The main factor influencing brodifacoum operational success is the baiting regime (Table 6.6). In a pulse baiting regime toxic bait is available for only several days every 2-3 weeks whereas, with a saturation baiting regime, the bait stations are kept topped up every eight weeks (brodifacoum is registered for use only in bait stations; Thomas et al. 1996).
Table 6.6: Estimated kills achieved during control operations using brodifacoum cereal bait and no prefeed in bait stations; \( n \) indicates the number of separate field operations monitored.

<table>
<thead>
<tr>
<th>Brodifacoum concentration (% wt./wt.)</th>
<th>Baiting regime</th>
<th>Spacing (m)</th>
<th>Kill (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002% Pulsed</td>
<td>N/A</td>
<td>100</td>
<td>52% ((n=1))</td>
<td>Thomas et al. (1996)</td>
</tr>
<tr>
<td>0.002% Pulsed</td>
<td>100</td>
<td>56% ((n=1))</td>
<td>Eason et al. (1994)</td>
<td></td>
</tr>
<tr>
<td>0.002% Saturation</td>
<td>100</td>
<td>59% ((n=1))</td>
<td>Henderson et al. (1994)</td>
<td></td>
</tr>
<tr>
<td>0.002% Saturation</td>
<td>100</td>
<td>85% ((n=2))</td>
<td>Henderson et al. (1997)</td>
<td></td>
</tr>
<tr>
<td>0.002% Saturation</td>
<td>N/A</td>
<td>78% ((n=1))</td>
<td>Thomas et al. (1996)</td>
<td></td>
</tr>
<tr>
<td>0.002% Saturation</td>
<td>100</td>
<td>78% ((n=1))</td>
<td>Henderson et al. (1994)</td>
<td></td>
</tr>
</tbody>
</table>

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

**Bait palatability and toxicant concentration**

Bait quality is an important factor influencing the success of all control operations. Palatability is affected by dampness as cereal baits are hygroscopic and will readily absorb moisture when stored in a damp place, used in areas with high humidity, or directly exposed to the rain. Once damp, bait will remain palatable for about 1 day, but then degrade relatively quickly (Henderson and Morris 1996). Recent trials have shown that dampness halves the acceptance of 0.8% concentration cholecalciferol in only 2 weeks, when compared with the consumption of dry bait (Wickstrom et al. 1997). Bait consumption is correlated with the kill rate, with dry 0.8% concentration cholecalciferol bait killing 87% of possums \((n=3\) trials), compared with only 48% \((n=2\) trials) with degraded bait (Henderson and Morris 1996).

Other trials have investigated the efficacy of baits with differing toxicant concentrations. These results demonstrated that a small difference in toxicant concentration can have a significant influence on the overall percentage kill. For example, 0.8% concentration cholecalciferol bait killed 87% \((n=3\) trials) of possums, compared with only 64% \((n=3\) trials) for 0.6% concentration bait (Henderson and Morris 1996). This is also the case for 1080 in bait stations with 0.15% concentration 1080 bait killing significantly more
possums than 0.08% concentration bait (Table 6.4). In this simulation it was assumed that all bait was dry and of uniform toxicant concentration.

**Development of bait shyness**

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

**Acute and subacute-acting toxicant bait shyness**

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

Recent field trials investigated the efficacy of various possum toxicants for maintenance control, following initial control with an acute or subacute-acting toxicant (Henderson et al. 1997). In these field trials sub-standard bait was deliberately used in the initial control operation to generate a high number of bait-shy survivors (Table 6.7).
Table 6.7: Kill rates for operations using acute and subacute-acting toxicants for initial and maintenance control using cereal bait in bait stations (Henderson et al. 1997).

<table>
<thead>
<tr>
<th>Initial control</th>
<th>Kill (%)</th>
<th>Maintenance control1</th>
<th>Kill (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8% Cholecalciferol</td>
<td>63%</td>
<td>0.08% 1080</td>
<td>0%</td>
</tr>
<tr>
<td>0.8% Cholecalciferol</td>
<td>46%</td>
<td>0.4% Glifor1</td>
<td>0%</td>
</tr>
<tr>
<td>0.08 % 1080</td>
<td>56%</td>
<td>0.8% Cholecalciferol</td>
<td>0%</td>
</tr>
<tr>
<td>0.08 % 1080</td>
<td>75%</td>
<td>0.4% Glifor1</td>
<td>0%</td>
</tr>
<tr>
<td>Cyanide Paste</td>
<td>75%</td>
<td>0.8% Cholecalciferol</td>
<td>0%</td>
</tr>
</tbody>
</table>

1 An unregistered acute-acting toxicant being trialed by Landcare Research (N.Z.) Ltd
2 Undertaken 1-3 months later

These field trials suggest that the survivors of initial control, using either an acute or subacute-acting toxicant, are all bait shy and cannot be killed in subsequent (within 1-3 months) maintenance control operations using similar acting toxicants. The failure of the subacute-acting cholecalciferol toxicant contrasts with the results of the pen trial detailed in Chapter 4. In this trial, 64% of 1080 bait-shy possums were killed using cholecalciferol bait. It has since been speculated that cautious feeding (caused by a sub-lethal dose of 1080) combined with social activity around bait stations increases the chance of sub-lethal cholecalciferol dosing (R. Henderson, pers. comm. 1998). As detailed previously, cholecalciferol-poisoning symptoms are delayed for 2-3 days. In the Chapter 4 pen trial, possums had unrestricted access to cholecalciferol bait and the majority consumed a lethal dose in the crucial first 48 hour period.

The rate of acute and subacute-acting toxicant bait shyness degradation/year

An estimate of the rate of degradation of the acute/subacute bait-shyness (ϕ) was derived from field trials and from two long-term pen trials conducted by Landcare Research (N.Z.) Ltd at Lincoln (South Island) and the Animal Behaviour and Welfare Centre (ABWC) at Ruakura (North Island). Both pen trials ran for 24 months and produced similar results. In the Landcare Research trial, 71% of sub-lethally dosed (1080) possums remained shy of the 1080 bait after three months, 63% after 12 months and 57% after 24 months (Morgan and Milne 1997). In the ABWC pen trial, 80% of sub-lethally dosed (cyanide) possums were bait shy 1 month later and 60% after 24 months (C. O'Connor, pers. comm. 1998). These data suggest that the number of bait-shy possums will decrease by approximately 40% over 2 years with most of the reduction occurring in the first 12 months.
Other pen trial studies have demonstrated that the number of possums becoming bait shy is influenced by the amount bait consumed on first exposure (Morgan et al. 1986; Clapperton et al. 1996; O'Connor and Matthews 1996). In pen trials, possums are fed similar amounts of toxic bait to induce bait shyness whereas, in the field survivors of control operations can consume varying amounts of toxic bait. Accordingly, some survivors of 1080 control operations may have eaten very little 1080 and their bait shyness could be short lived. Interestingly, field trials investigating the number of bait-shy possums amongst the survivors of 1080 control operations have generated similar results to the pen trials. In one population (Mapara Forest) 63% of adult possums avoided 1080 bait 15 months after the last control operation. In another population (Pureora Forest, North Island) 71% of trapped adult possums avoided 1080 bait 30 months after the last control operation (O'Connor and Matthews 1996).

In conclusion, these data suggest that the rate of bait-shyness degradation is not linear. The data in Table 6.7 indicate that immediately following control with an acute or subacute toxicant, all survivors are bait shy and cannot be controlled using similar acting toxicants in the same bait material. The long-term pen trials indicate that the number of bait-shy possums will decrease over time with the greatest reduction in the first 12 months. This relationship is best modelled using an exponential decay equation (Equation 5). Using this equation, the maximum rate of bait shyness degradation occurs in the 1st year (17%) and then slows over the remaining 9 years (Figure 6.2). This type of equation has been used by other researchers to model the rate of degradation of pesticide residue in soil (Feder and Regev 1975).

\[
\frac{dL}{dt} = (A\varphi)
\]
Field trials have investigated the effectiveness of the chronic-acting brodifacoum toxicant for maintenance control for possums (within 1-3 months), following initial control operation with an acute or subacute-acting toxicant (Henderson et al. 1997). Again, substandard bait was deliberately used in the initial control operation to generate a high number of bait-shy survivors (Table 6.8).

Table 6.8: Kill rates for bait station control operations using acute and subacute-acting toxicants for initial control and a chronic-acting toxicant for maintenance control using cereal bait in bait stations (Henderson et al. 1997).

<table>
<thead>
<tr>
<th>Initial control with acute toxicant</th>
<th>Kill (%)</th>
<th>Maintenance control</th>
<th>Kill (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6% Cholecalciferol</td>
<td>55%</td>
<td>0.002% Brodifacoum</td>
<td>74%</td>
</tr>
<tr>
<td>0.6% Cholecalciferol</td>
<td>55%</td>
<td>0.002% Brodifacoum</td>
<td>79%</td>
</tr>
<tr>
<td>0.08 % 1080</td>
<td>51%</td>
<td>0.002% Brodifacoum</td>
<td>88%</td>
</tr>
<tr>
<td>0.15 % 1080</td>
<td>75%</td>
<td>0.002% Brodifacoum</td>
<td>60%</td>
</tr>
</tbody>
</table>

These field trials indicate that the majority of survivors following initial control can be killed using brodifacoum. This hypothesis is also supported by a recent possum pen trial where researchers were unable to detect any brodifacoum bait shyness following sub-lethal
doses of 0.05 and 0.1 mg/kg body weight (O'Connor et al. 1998). Brodifacoum bait shyness was also investigated in Chapter 3. In this trial, 12 of 16 1080 bait-shy possums consumed a lethal dose of brodifacoum within 14 nights with no evidence of any bait shyness developing to brodifacoum.

Field trials using brodifacoum for maintenance control, however, could achieve a mean kill of only 75% (Henderson et al. 1997). This is lower than the mean kill of 80% achieved in populations that have not been previously poisoned (Table 6.6). This suggests that possums can be more difficult to kill following initial 1080 control and a lower kill value of 75% should be used for brodifacoum maintenance control simulations. There are also other behavioural mechanisms that possums might be using to survive brodifacoum control. One of these mechanisms is enhanced neophobia where an animal becomes wary of anything new following sub-lethal poisoning (O'Connor and Matthews 1996). Enhanced neophobia has been suggested as a possible cause for higher than expected numbers of rats (R. norvegicus) surviving anticoagulant control in Hampshire, England (Quy et al. 1992). Possums that survive brodifacoum control due to enhanced neophobia should be moved into a ‘shy of all bait’ sub-population (B) where they cannot be killed. While there is currently no evidence of enhanced neophobia in possums, additional simulations were run to ascertain the implications of this behaviour on the model’s results (these are discussed in the sensitivity analysis section).

**Economics of control**

*1080-aerial baiting*

The cost of aerial control operations for 1080 was estimated using empirical data from aerial 1080 operations applying cereal bait at a sowing rate of 5 kg/ha (Table 6.3). These data suggest that a mean cost of $20.00/ha (NZD) should be used for control areas over 1 000 ha (Table 6.9). Morgan (1994a) calculated a cost of $23.50/ha for an aerial 1080 operation using a sowing rate of 5 kg/ha, which broadly supports this estimate.
Table 6.9: Reported costs of 1080 aerial operations using cereal bait at a sowing rate of 5 kg/ha; \( n \) indicates the number of separate field operations monitored.

<table>
<thead>
<tr>
<th>Area (ha)</th>
<th>Cost/ha</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 000-5 400</td>
<td>$13 (n=15)</td>
<td>DOC (unpublished data)</td>
</tr>
<tr>
<td>5 600-8 000</td>
<td>$19 (n=2)</td>
<td>DOC (unpublished data)</td>
</tr>
<tr>
<td>1 329-17 000</td>
<td>$21 (n=5)</td>
<td>DOC (unpublished data)</td>
</tr>
<tr>
<td>3 426-18 000</td>
<td>$17 (n=2)</td>
<td>Warburton and Cullen (1993)</td>
</tr>
<tr>
<td>101-500</td>
<td>$29 (n=3)</td>
<td>Warburton and Cullen (1993)</td>
</tr>
</tbody>
</table>

1080-bait stations

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

Costs for 1080 bait stations were calculated using a bait station spacing of 150 m (Table 6.4) and a 3-week prefeed regime (Hickling et al. 1991). Without prefeed, the smaller 100 m spacing bait station grid is recommended (Thomas et al. 1997). The number of visits to maintain the bait stations was assumed to be six (with one visit to install the feeder, three visits to fill it with 2 kg of prefeed and then keep it topped up, one visit to deliver 0.5 kg of 1080 bait and one final visit to take away the station and uneaten toxic bait).

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

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

This value is realistic when compared with other bait station cost simulations. However, it is low compared with the average cost of nine 1080 bait station operations conducted by DOC (Table 6.10). An important consideration is that this simulation was set up for easy terrain. Changing the terrain to ‘moderate’ (one person can service 15 stations per day) or ‘hard’ (one person can service 10 stations per day) increases the cost to $31.22/ha and $44.02/ha respectively. These estimates seem realistic compared with an average cost of $42.00/ha for nine DOC bait station operations conducted on varying terrain on the West Coast, South Island.

Table 6.10: Cost of theoretical and actual 1080 cereal bait station control operations; n indicates the number of separate field operations monitored.

<table>
<thead>
<tr>
<th>Station spacing (m)</th>
<th>Prefeed</th>
<th>Area (ha)</th>
<th>Cost/ha</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Yes</td>
<td>70</td>
<td>$31 (n=1)</td>
<td>Thomas (1992)</td>
</tr>
<tr>
<td>100</td>
<td>No</td>
<td>144</td>
<td>$13* (n=1)</td>
<td>Thomas et al. (1996)</td>
</tr>
<tr>
<td>150</td>
<td>Yes</td>
<td>144</td>
<td>$22 (n=1)</td>
<td>Thomas et al. (1996)</td>
</tr>
<tr>
<td>150</td>
<td>Yes</td>
<td>2 800</td>
<td>$41 (n=1)</td>
<td>DOC (unpublished data)</td>
</tr>
<tr>
<td>N/A</td>
<td>Yes</td>
<td>800-2 252</td>
<td>$42 (n=9)</td>
<td>DOC (unpublished data)</td>
</tr>
</tbody>
</table>

*Theoretical estimate

Cholecalciferol-bait stations

Cholecalciferol bait station costs were calculated using a bait station spacing of 100 m with no prefeeding (Table 6.5). Prefeeding would increase the overall bait take, but is not currently recommended for cholecalciferol bait station control due to its additional cost (M. Thomas, pers. comm. 1998). Analysis of cholecalciferol bait consumption indicates that possum feeding activity at bait stations peaks after 1 week and then quickly tails off, becoming negligible after 5-6 weeks (Henderson et al. 1997). Based on this, the number of visits required to service the bait stations was assumed to be three (one visit to install the feeder, one visit to deliver the cholecalciferol bait and one final visit to take away the station and uneaten toxic bait).
With easy terrain one field worker can service 20 bait stations per day. As each station is visited three times this means it would take this field worker 3 days to service 20 bait stations for the entire control operation; or 1 day to service 6.7 bait stations. With 100 m spacing each bait station theoretically controls an area of 1 ha. Therefore 6.7 ha can be controlled at the cost of 1 workday. Using the same flat wage rate, total labour costs are $21.60/ha.

Field trials investigating toxic bait consumption indicate that populations at low-moderate densities (1-5 possums/ha) consume a total of $3.50 of bait/ha (70 g) and at moderate-high population densities (5-10 possums/ha) $7.00 of bait/ha (150 g) (Henderson et al. 1997). Bait station costs increased to $2.30/ha with the smaller bait station spacing of 100 m (Thomas et al. 1996). With a 100 m grid there is one station per ha, compared with one station every 2.25 ha with a 150 m grid. Using these figures total cholecalciferol bait station control costs came to $27.40/ha when the population density was low-moderate and $30.90/ha when the density was moderate-high. Cost estimates from cholecalciferol field trials indicated that my values fell within the acceptable range of field trial cost estimates (Table 6.11).

\[
\begin{array}{|c|c|c|}
\hline
\text{Area (ha)} & \text{Cost/ha} & \text{Source} \\
\hline
25 & $26 (n=1) & \text{Morriss and Henderson (1997)} \\
18 & $35 (n=1) & \text{Morriss and Henderson (1997)} \\
\text{unknown} & $31 (n=10) & \text{Landcare Research (unpublished data)} \\
\hline
\end{array}
\]

\textbf{Table 6.11:} Cost of cholecalciferol cereal bait station control operations with a station spacing of 100 m; \( n \) indicates the number of separate field operations monitored.

\textbf{Brodifacoum-bait stations}

Cost for brodifacoum bait station control was calculated with a bait station spacing of 100 m with no prefeeding (Table 6.6). Prefeeding is currently not recommended for brodifacoum baiting (Thomas et al. 1997). Brodifacoum is a chronic-acting toxicant with delayed poisoning symptoms such that the toxic bait acts like non-toxic prefeed with most possums consuming a lethal dose before the onset of toxicosis. Analysis of brodifacoum bait consumption indicates that possum activity at bait stations peaks after 5 weeks, but bait needs to be available for a further 15 weeks to achieve a high kill (Henderson et al.)
Based on this it was assumed that the bait stations need to be replenished with 2 kg of brodifacoum bait every 6 weeks. Accordingly, the number of visits to the bait stations was assumed to be five (with one visit to install the feeder, one visit to fill bait station with 2 kg of brodifacoum, two visits to top up stations and one final visit to take away the station and uneaten toxic bait).

With easy terrain one field worker can service 20 bait stations per day. As each station is visited five times this means it would take this field worker 5 days to service 20 bait stations for the entire control operation; or 1 day to service four bait stations. With 100 m spacing one bait station controls an area of 1 ha. Therefore 4 ha can be controlled at the cost of 1 workday. Using the same flat wage rate total control labour costs were $36.00/ha.

As brodifacoum is a chronic-acting toxicant most possums may take several weeks to die after consuming a lethal dose (Eason et al. 1993). During this time, possums will continue to eat additional bait and individuals can consume more than 1 kg of bait before death (Henderson et al. 1994). Field trials investigating the cost of brodifacoum bait eaten/ha indicated that with a moderate-high population density possums will consume a total of $27.00 of bait/ha (6 kg, or around 600 g per possum). At low-moderate densities they consume a total of $9.00 of bait/ha (2 kg or around 400 g per possum) (Henderson et al. 1997). Using these figures and a bait station cost of $2.30/ha, total brodifacoum bait station control costs came to $47.30/ha when the possum population density was low-moderate and $65.30/ha when the density was moderate-high.

These values are low compared with the cost of two brodifacoum control operations conducted by DOC (Table 6.12). In these trials, however, DOC used permanent brodifacoum bait stations that were serviced all year. These cost estimates were significantly lower than the cost of two brodifacoum field trials conducted by Landcare Research. In this trial, Landcare Research used bait stations with a 1 kg capacity that were serviced every 2 weeks. Currently, Landcare Research recommends larger 2 kg bait stations that only need servicing every 6-8 weeks (Thomas et al. 1997). In consideration of these factors, it was assumed my cost estimations were realistic, especially compared with an average cost of $57.00/ha for five DOC brodifacoum bait station operations.
Table 6.12: Cost of brodifacoum cereal bait station control operations with a station spacing of 100 m; \( n \) indicates the number of separate field operations monitored.

<table>
<thead>
<tr>
<th>Area (ha)</th>
<th>Cost/ha</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1630</td>
<td>$87 (n=1)</td>
<td>DOC (unpublished data)</td>
</tr>
<tr>
<td>700</td>
<td>$93.3 (n=1)</td>
<td>DOC (unpublished data)</td>
</tr>
<tr>
<td>30</td>
<td>$80 (n=1)</td>
<td>Morriss and Henderson (1997)</td>
</tr>
<tr>
<td>18</td>
<td>$82 (n=1)</td>
<td>Morriss and Henderson (1997)</td>
</tr>
<tr>
<td>unknown</td>
<td>$57 (n=5)</td>
<td>Landcare Research (unpublished data)</td>
</tr>
</tbody>
</table>

**Indirect and variable costs**

The above control cost estimates have focused on some key direct operational costs such as bait and labour. Control operations also involve many indirect costs such as planning, supervision and monitoring. Warburton and Cullen (1993) research paper indicated that these additional indirect costs can vary markedly, but are generally consistent on a per ha basis. Another consideration is any variable cost related to the use of the different toxicants such as special handling and storage. Unlicensed operators can use both cholecalciferol and brodifacoum and they have no special safety, storage or disposal requirements compared with 1080 (M. Thomas, pers. comm. 1998). There are no additional variable costs for aerial 1080 operations provided the same bait type is used as for 1080 ground control. This may not have been the case if I had used carrot bait in the aerial 1080 operations. For example, 1080 carrot bait is usually made on site with special bait cutters and the small fragments must be screened out (Morgan 1994a). This suggests that both indirect and variable costs are unlikely to vary substantially among control operations and consequently was not incorporated in the model.

**Discount rate**

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

Previous possum models have run over a simulated time frame of 5 (Barlow 1993; Roberts 1996), 8 (Barlow 1991a), 12 (Hickling 1995) and 28 years (Pfieffer 1994). Hickling (1995), who was the first to investigate the implications of behavioural resistance on the efficacy of 1080 control operations, argued that a 10 year period is the minimum required to gauge the effectiveness of multiple-poisoning campaigns on a possum population. In my simulation, a 10 year period was used. However, additional simulations were run over 20 years to ascertain the implications of extending the time frame on the model results (refer sensitivity analysis section).

Simulation objectives

The objective of each control simulation was to reduce the possum population below the target population density (T) in year 1 and then to maintain the average population below this density for the remaining 9 years. The average population density was calculated using the following equation:

\[
\sum_{i=0}^{T} \frac{C}{(1+i)^i}
\]  

(Definitions are detailed in Table 6.1)

\[
(\Sigma \text{of the annual total (T) populations)} / (\text{No. of control years})
\]  

(7)

However, assessing the total population at 12 month intervals underestimated the density of possums in the control years, as it did not consider new births, immigration and mortality for possums in sub-population A (see Figure 6.1). Field trial studies have demonstrated that both these factors are seasonal, so it was assumed that the population increased from \(T_i\) to \(U_i\) (Figure 6.3) during the summer/autumn seasons (Cowan 1990;
Efford (1998), before any control operation that would typically be scheduled for the winter (Warburton 1997).

![Diagram showing the annual changes in possums/ha density](image)

**Figure 6.3:** The annual changes in possums/ha density incorporated into the model, which assumes that all breeding and immigration occur in autumn and that control work is done in winter.

In the modelling simulations the value $U_1$ is incorporated into the average population density estimate to more accurately reflect the possum density over the entire 12 month period. A value for $U_1$ was calculated using the following equation:

$$U_1 = (S + I + (Tr\mu(1 - (T/K)^k)) + L) + A(1 - \mu - \phi)$$  \hspace{1cm} (8)

The adjusted average population density was, therefore, calculated using the following equation:

$$\frac{(\Sigma \text{of the annual total (T) populations}) + (\Sigma \text{of the annual U values})}{(\text{No. of control years} \times 2)}$$  \hspace{1cm} (9)

At equilibrium density, the annual total population (T) was the same as the $U_1$ value and had no effect on the average population density. However, if the population were increasing after control work in earlier years the $U_1$ equation calculates what the population...
would have increased to, before the winter control operation, and incorporates this value in the overall average population estimate.

Two target population densities were used in the simulations: either 40% of pre-control carrying capacity (for elimination of Tb); or 20% of pre-control carrying capacity (for protection of conservation values). The 40% target population density was derived from epidemiological modelling which suggests that Tb could be eradicated from a possum population over a period of 6-8 years if such a reduction could be maintained (PCE 1994). To achieve this the possum population must be severely reduced (at least 75% kill) in the initial control operation. Maintenance control must then be frequent enough to maintain the population below the predicted threshold for disease transmission (40% of carrying capacity for possums; Barlow 1991b). The 20% target population density is somewhat arbitrary, as ecological damage thresholds have not been adequately defined for possums in New Zealand forests (Hickling 1994). It is however, generally accepted that a sustained 80-90% reduction of a possum population should provide significant protection for the indigenous flora and fauna (Hickling 1994). Consequently, DOC aims to reduce possums to a post operational trap catch of 5% in many of their upcoming possum control operations (DOC 1997). DOC considers that most conservation values are protected from possum damage at around this level of trap catch. In my simulation, a 5% residual trap catch equates to a population of 1-2 possums/ha, which is a kill rate of 80-90%. The residual trap catch was converted using a simple formula devised by Landcare Research (NZ) Ltd. Their population monitoring research has indicated that a residual catch rate of less than 20% can be divided by 5 to crudely estimate the number of possums/ha (R. Henderson, pers. comm. 1998).

6.6 Results

The most successful control strategy maintained the total average population (over the 10 years) below the desired target density at the least discounted cost. The first series of simulations were run using combinations of 1080, cholecalciferol and brodifacoum. However, as 1080 is available only to licensed operators, subsequent simulations were run
using only cholecalciferol and/or brodifacoum. Both of these toxicants may be used by unlicensed operators (e.g., farmers) for ground control of possums.

**Sustained 60% kill using aerial 1080 baits**

The most cost-effective control strategy achieving a sustained 60% kill was 4 yearly aerial control with 1080 cereal bait. This strategy had an accumulated discounted cost of $43/ha (Table 6.13) and maintained an average population density of 3.96 possums/ha (Figure 6.4).

**Table 6.13:** Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill using aerially broadcast 1080 baits; here and in all tables that follow, the most cost-effective strategy is in bold and the accumulated discounted cost/ha has been rounded to the nearest dollar.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated Discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% 1080 kill every 3 years</td>
<td>3.28</td>
<td>$55</td>
</tr>
<tr>
<td>90% 1080 kill every 4 years</td>
<td>3.96</td>
<td>$43</td>
</tr>
<tr>
<td>90% 1080 kill every 5 years</td>
<td>4.92</td>
<td>$32</td>
</tr>
</tbody>
</table>

**Figure 6.4:** Possum population density following aerial control with 1080 (▲). Starting population density was 10.0 possums/ha (- line denotes target population density).
Sustained 60% kill using 1080 in bait stations

If aerial control is not a desirable control option, a similar result can be achieved using 0.15% concentration 1080 cereal bait in bait stations. Again the most cost-effective strategy was 4 yearly control (Table 6.14). However, this was slightly more expensive at an accumulated discounted cost of $53/ha due to the higher per ha cost of servicing the bait stations.

Table 6.14: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill using 1080 in bait stations.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated Discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% 1080 kill every 3 years</td>
<td>3.28</td>
<td>$68</td>
</tr>
<tr>
<td>90% 1080 kill every 4 years</td>
<td>3.96</td>
<td>$53</td>
</tr>
<tr>
<td>90% 1080 kill every 5 years</td>
<td>4.92</td>
<td>$50</td>
</tr>
</tbody>
</table>

As cholecalciferol and brodifacoum are registered only for use in bait stations, in all of the following comparisons, the control strategies that have been assessed assume that 1080 is being used in bait stations.

Sustained 60% kill using cholecalciferol

A sustained 60% kill could be achieved using cholecalciferol, however, due to the lower efficacy of cholecalciferol compared with 1080, more intensive control was required.

The most cost-effective strategy was 3 yearly cholecalciferol control with an additional one-off operation in year 6 (Figure 6.5). The accumulated discounted cost of this strategy was $100/ha and maintained an average population density of 3.97 possums/ha (Table 6.15).
Table 6.15: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill using cholecalciferol and brodifacoum in bait stations.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 yearly cholecalciferol - 80% kill plus 1 year brodifacoum - 75% kill</td>
<td>3.54</td>
<td>$112</td>
</tr>
<tr>
<td>3 yearly cholecalciferol - 80% kill plus Year 6 additional cholecalciferol - 80% kill</td>
<td>3.97</td>
<td>$100</td>
</tr>
<tr>
<td>2 yearly cholecalciferol - 80% kill</td>
<td>4.2</td>
<td>$101</td>
</tr>
</tbody>
</table>

Figure 6.5: Possum population density following control with cholecalciferol (▲) in bait stations. Starting population density was 10.0 possums/ha (- line denotes target population density).

Sustained 80% kill using 1080

The most cost-effective strategy was 2 yearly 1080 control with a one-off brodifacoum operation in year 2 (Figure 6.6). As detailed in Table 6.7, 1080 bait-shy possums will avoid the subacute-acting cholecalciferol bait. Accordingly, cholecalciferol was not used for maintenance operations following initial 1080 control.

Following the brodifacoum operation, regular 1080 control held the population in check by killing most of the immigrants and new recruits (provided there is no evidence of genetic
resistance). The accumulated discounted cost of this strategy was $131/ha and maintained an average population density of 2.03 possums/ha (Table 6.16). This was considerably more expensive than the sustained 60% kill using 1080 ($53/ha; a 147% cost increase) as maintenance control was regularly required to limit population recovery.

Table 6.16: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using 1080 and brodifacoum in bait stations.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 years 1080 - 90% kill</td>
<td>1.98</td>
<td>$135</td>
</tr>
<tr>
<td>2 yearly 1080 - 90% kill plus 1 year brodifacoum - 75% kill</td>
<td>2.03</td>
<td>$131</td>
</tr>
<tr>
<td>3 yearly 1080 - 90% kill plus 2 years brodifacoum - 75% kill</td>
<td>2.24</td>
<td>$140</td>
</tr>
</tbody>
</table>

![Figure 6.6: Possum population density following control with 1080 (▲) and brodifacoum (▲) in bait stations. Starting population density was 10.0 possums/ha (— line denotes target population density).](image)

**Sustained 80% kill using cholecalciferol**

The lower efficacy of cholecalciferol meant that brodifacoum was required on a regular basis to kill the increasing numbers of cholecalciferol bait-shy survivors. The most cost-effective strategy was 2 yearly cholecalciferol control with 3 years of brodifacoum (Figure...
This strategy had an accumulated discounted cost of $197/ha and maintained an average population density of 1.98 possums/ha (Table 6.17). This was considerably more expensive than the sustained 60% kill using cholecalciferol ($100/ha; a 97% cost increase) as control was required nearly every year and brodifacoum bait is more expensive than cholecalciferol.

Table 6.17: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using cholecalciferol and brodifacoum in bait stations.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 years cholecalciferol - 80% kill plus 2 years brodifacoum - 75%</td>
<td>1.99</td>
<td>$205</td>
</tr>
<tr>
<td>2 yearly cholecalciferol - 80% kill plus 3 years brodifacoum - 75% kill</td>
<td>1.98</td>
<td>$197</td>
</tr>
<tr>
<td>3 yearly cholecalciferol - 80% kill plus 4 years brodifacoum - 75% kill</td>
<td>2.01</td>
<td>$214</td>
</tr>
</tbody>
</table>

Possum population density following control with cholecalciferol (▲) and brodifacoum (▲) in bait stations. Starting population density was 10.0 possums/ha (- line denotes target population density).
6.7 Sensitivity Analysis

Impact of bait shyness

The main novel feature of this bioeconomic model was that the survivors of 1080 or cholecalciferol control became bait shy. As detailed in Chapter 2, most previous control simulations have overlooked this issue (but see Hickling 1995) and thus, have recommended control strategies that predominately use 1080. Pen trial studies have ascertained that the majority of possums will become bait shy following a sub-lethal dose of 1080, cyanide or cholecalciferol (O'Connor and Matthews 1996; Morgan and Milne 1997; O'Connor et al. 1998) and this bait shyness may be long-lived (2-5 years; Henderson et al. 1998). In the field, this long-lived bait shyness has the potential to significantly reduce the efficacy of subsequent maintenance control operations, particularly when the control frequency is annual-or biennial (Hickling et al. 1991; Bradfield and Flux 1996). For this simulation I calculated the most cost-effective strategies for sustained control (60% and 80% kill) without bait shyness, using predominately 1080 or cholecalciferol (see above). Accordingly, the strategies in Tables 6.19-6.19 are different to those detailed in Tables 6.14-6.17 because, the base run simulations had to use brodifacoum to kill any bait-shy survivors of previous control. I then re-ran these simulations with bait shyness activated to ascertain its influence on the average population density and the accumulated cost of control.

Sustained 60% kill

Bait shyness had negligible effect on the strategies that aimed to achieve a sustained 60% kill, particularly for the control strategy using 1080 (Table 6.18). The reason for this is that both 1080 and cholecalciferol have high control efficacy (80-90%) and there were not sufficient numbers of bait-shy survivors to significantly decrease the efficacy of 4 yearly control. This result is similar to Hickling’s (1995) conclusion, which suggested that learned bait shyness has minimal effect on 1080 control operations if they are run at greater than 3-4 year intervals over a 10 year simulation.
Table 6.18: Average possum density/ha of possum control strategies attempting to achieve a sustained 60% kill using either cholecalciferol or 1080 in bait stations, with and without bait shyness.

<table>
<thead>
<tr>
<th>Target kill</th>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Percentage increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustained 60%</td>
<td>4 years cholecalciferol - 80%</td>
<td>3.83</td>
<td>4.12</td>
</tr>
<tr>
<td>Sustained 60%</td>
<td>1080 - 90% kill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Using Cholecalciferol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sustained 60%</td>
<td>4 yearly 1080 - 90% kill</td>
<td>3.94</td>
<td>3.96</td>
</tr>
<tr>
<td>Using 1080</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Sustained 80% kill*

In contrast, bait shyness did have a significant effect on the strategies that aimed to achieve the sustained 80% kill, particularly for the control strategy using cholecalciferol (Table 6.19). The reason for this is that cholecalciferol has lower control efficacy (80%) and generates higher numbers of bait-shy survivors after each control operation. To achieve the target density of 20% with bait shyness, field managers would need to schedule brodifacoum control operations to target the bait-shy survivors (see Tables 6.16 and 6.17).

Table 6.19: Average possum density/ha of possum control strategies attempting to achieve a sustained 80% kill using cholecalciferol and 1080 in bait stations, with and without bait shyness.

<table>
<thead>
<tr>
<th>Target kill</th>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Percentage increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustained 80%</td>
<td>8 years cholecalciferol - 80%</td>
<td>1.99</td>
<td>2.96</td>
</tr>
<tr>
<td>Using Cholecalciferol</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sustained 80%</td>
<td>2 yearly 1080 - 90% kill</td>
<td>1.97</td>
<td>2.31</td>
</tr>
<tr>
<td>Using 1080</td>
<td>Year 8 additional 1080 - 90%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The major difference between the control strategies calculated with shyness (Tables 6.14-6.17) and those without shyness is that the expensive brodifacoum toxicant is not used due to the absence of 1080 bait-shy survivors. The cost of scheduling these brodifacoum operations to target these animals significantly increases the accumulated cost of control (Table 6.20), which demonstrates the need to include bait shyness in the modelling simulations. It also highlights how important it is for field managers to consider bait
shyness when formulating possum control strategies, particularly for those attempting to achieve a >80% sustained population reduction.

**Table 6.20:** Accumulated discounted cost of possum control strategies achieving a sustained 80% kill using cholecalciferol, 1080 and brodifacoum in bait stations, with and without bait shyness.

<table>
<thead>
<tr>
<th>Target kill</th>
<th>Accumulated discounted cost/ha</th>
<th>Percentage increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without bait shyness</td>
<td>With bait shyness</td>
</tr>
<tr>
<td>Sustained 80% kill using cholecalciferol</td>
<td>$153</td>
<td>$197(^1)</td>
</tr>
<tr>
<td>Sustained 80% kill using 1080</td>
<td>$101</td>
<td>$131(^1)</td>
</tr>
</tbody>
</table>

\(^1\) These control strategies are detailed in Tables 6.16 and 6.17

**Impact of an unsuccessful initial 1080 operation**

When toxic bait is correctly prepared and delivered, possum populations can be reduced by up to 95% (Morgan 1990). However, control efficacy can vary and an unsuccessful operation with an acute or subacute-acting toxicant will generate a large number of bait shy survivors (Table 6.7). For this simulation, the initial 1080 operation kill was reduced to 60%. This meant that 40% of the starting susceptible population survived initial control and were 1080 bait shy (refer Table 6.7).

**Sustained 60% kill**

The unsuccessful initial 1080 operation had a notable effect on the success of future 1080 control operations due to the large remaining population of 1080 bait-shy survivors. The most cost-effective strategy was to revert to 2 yearly 1080 control (Table 6.21). This strategy had an accumulated discounted cost of $88/ha and maintained an average population density of 3.90 possums/ha (Figure 6.8). This is notably more expensive than the sustained 60% kill ($53/ha; a 66% cost increase) when all 1080 operations were successful.
Table 6.21: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 60% kill using 1080 and brodifacoum in bait stations, following an initial unsuccessful 1080 operation.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial 1080 - 60% kill 4 yearly 1080 - 90% kill plus 1 year brodifacoum - 75% kill</td>
<td>3.99</td>
<td>$115</td>
</tr>
<tr>
<td>Initial 1080 - 60% kill plus 2 yearly 1080 - 90% kill</td>
<td>3.90</td>
<td>$88</td>
</tr>
<tr>
<td>Initial 1080 - 60% kill plus 4 yearly 1080 - 90% kill</td>
<td>5.64</td>
<td>$53</td>
</tr>
</tbody>
</table>

Figure 6.8: Possum population density following control with 1080 (▲) in bait stations, following an initial unsuccessful 1080 operation. Starting population density was 10.0 possums/ha ( - line denotes target population density).

Sustained 80% kill

In contrast to the 60% sustained kill model, the influence of an initial unsuccessful 1080 operation meant it was not possible to achieve a sustained 80% kill using only 1080. The most cost-effective strategy was immediate one-off brodifacoum control to target the 1080 bait survivors (Figure 6.9). This was followed by annual 1080 control and an additional brodifacoum operation in year 6. This strategy kept the population in check by killing most of the immigrants and new recruits at an accumulated discounted cost of $219/ha (Table
6.22). This option is notably more expensive than the sustained 80% kill ($131/ha; a 67% cost increase) when all 1080 operations were successful.

**Table 6.22:** Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using 1080 and brodifacoum in bait stations, following an initial unsuccessful 1080 operation.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial 1080 - 60% kill 5 years brodifacoum - 75% kill plus 4 years 1080 - 90% kill</td>
<td>1.95</td>
<td>$236</td>
</tr>
<tr>
<td>Initial 1080 - 60% kill 2 years brodifacoum - 75% kill plus 7 years 1080 - 90% kill</td>
<td>1.98</td>
<td>$219</td>
</tr>
<tr>
<td>Initial 1080 - 60% kill 1 year brodifacoum - 75% kill plus 8 years 1080 - 90% kill</td>
<td>2.09</td>
<td>$205</td>
</tr>
</tbody>
</table>

![Figure 6.9: Possum population density following control with 1080 (▲) and brodifacoum (▲) in bait stations, following an initial unsuccessful 1080 operation. Starting population density was 10.0 possums/ha (- line denotes target population density).](image-url)
Impact of a changed rate of acute-acting toxicant bait shyness period decay

Pen and field trials suggest that the number of bait-shy possums will decrease over time (O'Connor and Matthews 1996; Morgan and Milne 1997). However, the rate of bait shyness decay is still a 'best guess' and requires more long term research. Hickling's (1995) possum modelling paper suggested there is a strong relationship between the length of time possums remain 1080 bait shy and the impact this has on the efficacy of future control. For my simulation, the rate of bait shyness decay was reduced to 0%. Effectively this meant that possums in sub-population (A) did not filter back to population (S) over time (Figure 6.1) and only decreases due to natural mortality.

*Sustained 60% kill*

Reducing the rate of bait shyness degradation to 0% had little effect on the average possum-population density following control with 1080. On a percentage basis, this impacted most on strategies with frequent 1080 control (Table 6.23). When the rate of degradation is set at 0% the 1080 bait-shy sub-population (A) decreased only at 10% per annum due to natural mortality. Provided each 1080 control operation has a 90% kill, the number of bait-shy possums does not increase enough to render 3 yearly control with 1080 ineffective. This is similar to Hickling's (1995) model result, which suggested that learned bait shyness has limited effect on 1080 control efficacy at 3-4 year intervals.

**Table 6.23**: Average possum density/ha of possum control strategies attempting to achieve a sustained 60% kill using 1080 in bait stations, with and without acute toxicant bait shyness degradation.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Percentage increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With bait shyness</td>
<td>Without bait shyness</td>
</tr>
<tr>
<td></td>
<td>Degradation</td>
<td>degradation</td>
</tr>
<tr>
<td>90% 1080 kill every 3 years</td>
<td>3.28</td>
<td>3.57</td>
</tr>
<tr>
<td>90% 1080 kill every 4 years</td>
<td>3.96</td>
<td>4.17</td>
</tr>
<tr>
<td>90% 1080 kill every 5 years</td>
<td>4.92</td>
<td>4.75</td>
</tr>
</tbody>
</table>
**Sustained 80% kill**

Strategies with more frequent 1080 control are not significantly affected by the development of 1080 bait shyness so long as brodifacoum is also used (Table 6.24). Control with brodifacoum kills 75% of the 1080 bait-shy possums (Table 6.8). Following the brodifacoum operation 2 yearly 1080 control does not filter sufficient number of possums to sub-population (A), so as to render the previous most cost-effective control strategies ineffective. Also, the number of shy possums will decrease over time due to natural mortality (10% pa) and young, susceptible animals eventually replace these possums.

**Table 6.24:** Average possum density/ha of possum control strategies attempting to achieve a sustained 80% kill using 1080 and brodifacoum in bait stations, with and without acute toxicant bait shyness degradation.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Percentage increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With bait shyness degradation</td>
<td>Without bait shyness degradation</td>
</tr>
<tr>
<td>8 years 1080 - 90% kill</td>
<td>1.98</td>
<td>2.38</td>
</tr>
<tr>
<td>2 yearly 1080 - 90% kill plus 1 year brodifacoum - 75% kill</td>
<td>2.03</td>
<td>2.16</td>
</tr>
<tr>
<td>3 yearly 1080 - 90% kill plus 2 years brodifacoum - 75% kill</td>
<td>2.24</td>
<td>2.28</td>
</tr>
</tbody>
</table>

**Effect of population recovery due to increased and decreased rates of immigration**

The estimate for the maximum rate of immigration was an average derived from four empirical studies investigating the rate of possum re-colonisation following control operations. However, other field trials and anecdotal evidence has suggested that the actual rate of immigration varies in different-sized control sites. For example, in five small forest reserves (14-135 ha), possum populations increased by approximately 4 possums/ha/yr following brodifacoum and leg-hold trapping control operations (Thomas et al. 1995). In contrast, Hickling and Pekelharing (1989) considered that immigration did not significantly contribute to the population recovery that they recorded in a >10 000 ha control area.
If the absolute rate of possum immigration is assumed proportional to the length of the boundary of the control block, then the immigration rate per unit area (M) will be related to the area of the control block as follows:

\[ M \propto \frac{1}{\sqrt{\text{control area} \times a}} \quad (10) \]

where:

\[ a = 37.947 \]

This formula describes the relationship between the circumference and the total area of a square-shaped control block (i.e., control sites with larger boundaries have less immigration per/unit area; G. Hickling pers comm 1998). In previous simulations, I assumed that the hypothetical control block (approximately 1 000 ha in size) had a \( M = 1.2 \) possums/ha/yr. Using this formula I was able to derive estimates for the maximum rate of possum immigration into smaller (100 ha) and larger (10 000 ha) control areas (Table 6.25).

**Table 6.25: Estimated maximum rate of possum immigration in various sized control areas (rates of immigration are rounded to 1 decimal place).**

<table>
<thead>
<tr>
<th>Control area size (ha)</th>
<th>Estimated maximum rate of immigration (possums/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>4.0</td>
</tr>
<tr>
<td>1 000</td>
<td>1.2</td>
</tr>
<tr>
<td>10 000</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Using these values I then varied the maximum rate of immigration in the simulation model to assess the impact of low and high immigration on the most cost-effective control strategies detailed in the results section.

**Sustained 60% kill**

Changing the maximum rate of immigration had a significant affect on the number of control operations required to achieve a sustained 60% kill (Table 6.26). With high immigration (4 possums/hectare/yr), control was almost required every year to limit the
rapid population recovery (Figure 6.10). This strategy had an accumulated cost of $135/ha, which was significantly more expensive than the simulation using a immigration rate of 1.2 possums/ha/yr ($53/ha; a 155% cost increase). With low immigration, 1080 control was only required every 7 years and this was significantly cheaper than the simulation using a rate of 1.2 possums/ha/yr ($53/ha; a cost decrease of 28%).

Table 6.26: Accumulated discounted cost of possum control strategies achieving a sustained 60% kill using 1080 in bait stations, with high (4/possums/ha/yr) and low (0.4 possums/ha/yr) rates of possum immigration.

<table>
<thead>
<tr>
<th>Target kill</th>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustained 60% kill with high immigration</td>
<td>8 years 1080 - 90% kill</td>
<td>3.98</td>
<td>$135</td>
</tr>
<tr>
<td>Sustained 60% kill with low immigration</td>
<td>7 yearly 1080 - 90% kill</td>
<td>3.88</td>
<td>$38</td>
</tr>
</tbody>
</table>

Figure 6.10: Possum population density following control with 1080 (▲) in bait stations, with a high rate of possum immigration (4 possums/ha/yr). Starting population density was 10.0 possums/ha (- line denotes target population density).
**Sustained 80% kill**

With high immigration (4 possums/ha/yr), it was not possible to achieve a sustained 80% kill using any combination of toxicants (Table 6.27; Figure 6.11). With low immigration (0.4 possums/ha/yr) 1080 control was only required every 3 years to achieve a sustained 80% kill, and this was significantly cheaper than the simulation using a immigration rate of 1.2 possums/ha/yr ($131/ha; a cost decrease of 48%).

**Table 6.27:** Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using 1080 in bait stations, with high (4 possums/ha/yr) and low (0.4 possums/ha/yr) rates of possum immigration.

<table>
<thead>
<tr>
<th>Target kill</th>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustained 80% kill with high immigration</td>
<td>Annual 1080 - 90% kill</td>
<td>3.44</td>
<td>$168</td>
</tr>
<tr>
<td>Sustained 80% kill with low immigration</td>
<td>3 yearly 1080 - 90% kill</td>
<td>1.99</td>
<td>$68</td>
</tr>
</tbody>
</table>

**Figure 6.11:** Possum population density following control with 1080 (▲) in bait stations, with a high (4 possums/ha/yr) rate of possum immigration. Starting population density was 10.0 possums/ha (- line denotes target population density).
Influence of the discount rate

As mentioned in the methods section, there is debate over how best to determine the most appropriate social discount rate. There is also an argument that suggests there is no requirement to discount for control campaigns, which are funded by the public sector taxation (Cullis and Jones 1992). Discounting effectively favours strategies that accumulate most costs in the future. Thus removing the discount rate will favour strategies that have most of their control costs in the early years. For this simulation I used a 0% discount rate which increased the estimated per ha cost as expenditure was not discounted over time.

Sustained 60% kill

Reducing the discount rate to 0% had no significant effect on the simulation results (Table 6.28). It was not possible to delay control operations until the end of the simulation and still maintain the average possum density below the target population density of 4 possums/ha. Therefore, reducing the discount rate had little overall effect, as there were no successful strategies that placed the bulk of the control expenditure in the later years of the simulation.

Table 6.28: Accumulated cost of possum control strategies attempting to achieve a sustained 60% kill using 1080 in bait stations, with and without a discount rate.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
<th>Accumulated cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% 1080 kill every 3 years</td>
<td>3.28</td>
<td>$68</td>
<td>$99</td>
</tr>
<tr>
<td>90% 1080 kill every 4 years</td>
<td>3.96</td>
<td>$53</td>
<td>$74</td>
</tr>
<tr>
<td>90% 1080 kill every 5 years</td>
<td>4.92</td>
<td>$50</td>
<td>$40</td>
</tr>
</tbody>
</table>

Sustained 80% kill

This was also the case with strategies using the more expensive brodifacoum toxicant, as the brodifacoum control operation occurs generally early in the simulation, before the influence of the discount rate has much effect (Table 6.29).
Table 6.29: Accumulated cost of possum control strategies attempting to achieve a sustained 80% kill using 1080 in bait stations, with and without a discount rate.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
<th>Accumulated cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 years 1080 - 90% kill</td>
<td>1.98</td>
<td>$135</td>
<td>$199</td>
</tr>
<tr>
<td>2 yearly 1080 - 90% kill</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 year brodifacoum - 75% kill</td>
<td>2.03</td>
<td>$131</td>
<td>$171</td>
</tr>
<tr>
<td>3 yearly 1080 - 90% kill</td>
<td>2.24</td>
<td>$140</td>
<td>$194</td>
</tr>
<tr>
<td>2 years brodifacoum - 75% kill</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Enhanced neophobia

Enhanced neophobia could develop following a sub-lethal dose of an acute or subacute-acting toxicant. The data in Table 6.8 suggests that any enhanced neophobia can be largely overcome by allowing for prolonged exposure to a chronic-acting toxicant such as brodifacoum. Field trials using brodifacoum for maintenance control, however, could only achieve an average kill of 75%. Furthermore, a recent possum pen trial has demonstrated that some 1080 bait-shy possums (25%) will only eat small amounts of brodifacoum even after 4 weeks of exposure (Ross et al. 1997). These data suggest that approximately 25% (ε) of 1080 bait-shy possums may not be controlled using brodifacoum and should be moved into the shy of all bait sub-population (B) following brodifacoum control (Figure 6.12). Once in this sub-population these animals cannot be controlled using any toxicant. For this simulation I used the following equations:

Susceptible sub-population:

\[
\frac{dS}{dt} = (S + I + (Tr_m(1-(T/K_i)^\theta)) + L)*(1-C_1\delta_i - C_2\alpha_i) \tag{11}
\]

Shy of acute/subacute-acting toxicant bait sub-population:

\[
\frac{dA}{dt} = A(1- \mu - \varphi) + C_i(1-\alpha_i)*(S + I + (Tr_m(1-(T/K_i)^\theta)) + L) - C_2\alpha_2 A(1 -\mu - \varphi) - C_2\varepsilon A(1 -\mu - \varphi) \tag{12}
\]
Shy of all bait sub-population:

\[
\frac{dB}{dt} = B(1-\mu) + C_sA(1-\mu - \phi)
\]  

(13)

Total population:

\[T = (S + A + B)\]  

(14)

**Figure 6.12:** Flowchart for a computer simulation of possum population responses to a toxic baiting strategy employing acute, subacute and chronic-acting toxicants. The total population (T) is made up of three sub-populations; one susceptible to poisoning (S); one shy of acute/subacute-acting toxicant bait (A); and one shy of all bait (B). See Table 6.1 for an explanation of the variables.

*Sustained 60% kill*

Enhanced neophobia does not affect 1080 control as the survivors of 1080 control are already bait shy and the brodifacoum toxicant was not used.
Sustained 80% kill

Incorporating enhanced neophobia did not have a significant effect on the average population density following control. This was due to the fact that a good initial 1080 operation kills 90% of the possum population. Of the surviving bait shy possums (sub-population A) only 25% of these possums move to sub-population (B) every time the brodifacoum toxicant was used. Over the 10 years sub-population (B) never increased higher than 0.18 possums/ha and this was not sufficient to render the previous most cost-effective possum strategies ineffective (Table 6.30). However, this is dependent on 90% of the susceptible possums being killed in the initial 1080 control operation.

Table 6.30: Average possum density/ha of possum control strategies attempting to achieve a sustained 80% kill using 1080 and brodifacoum in bait stations, with and without enhanced neophobia.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha without enhanced neophobia</th>
<th>Average density/ha with enhanced neophobia</th>
<th>Percentage increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 years 1080 – 90% kill</td>
<td>1.98</td>
<td>1.98</td>
<td>0%</td>
</tr>
<tr>
<td>2 yearly 1080 - 90% kill plus</td>
<td>2.03</td>
<td>2.08</td>
<td>2.6%</td>
</tr>
<tr>
<td>1 year brodifacoum - 75% kill</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 yearly 1080 - 90% kill plus</td>
<td>2.24</td>
<td>2.31</td>
<td>3%</td>
</tr>
<tr>
<td>2 years brodifacoum - 80% kill</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Effect of extending the time frame

In the results section I determined the cost-effective control strategies over a 10 year time frame. It is likely that chemical possum control will continue for much longer than this (O'Connor et al. 1998). The most likely new control method is a biological agent delivered by viral vector (Gregory et al. 1996). While it is likely that much progress will be made over the next 10 years, it is unlikely that this new control method will be available in the near future (Morgan 1994b). Therefore, if chemicals are to remain the main form of control it is important that the most cost-effective strategies for 10 years are also viable over a longer term. For this simulation I extended the time frame to 20 years.


**Sustained 60% kill**

Increasing the length of control to 20 years had little effect on the effectiveness of strategies using 1080 to achieve a sustained 60% population reduction (Table 6.31).

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha over 10 years</th>
<th>Accumulated discounted cost/ha</th>
<th>Average density/ha over 20 years</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% 1080 kill every 3 years</td>
<td>3.28</td>
<td>$68</td>
<td>3.07</td>
<td>$86</td>
</tr>
<tr>
<td>90% 1080 kill every 4 years</td>
<td>3.96</td>
<td>$53</td>
<td>4.04</td>
<td>$67</td>
</tr>
<tr>
<td>90% 1080 kill every 5 years</td>
<td>4.92</td>
<td>$51</td>
<td>4.78</td>
<td>$60</td>
</tr>
</tbody>
</table>

**Sustained 80% kill**

The most successful control strategies over 10 years were actually more effective over the 20 year term (Table 6.32). Over 10 years the average population density is slightly inflated due to the high starting population of 10.0 possums/ha. Over a 20 year term this high starting value has less effect on the population average.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha over 10 years</th>
<th>Accumulated discounted cost/ha</th>
<th>Average density/ha over 20 years</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 years 1080 - 90% kill</td>
<td>1.98</td>
<td>$135</td>
<td>1.73</td>
<td>$187</td>
</tr>
<tr>
<td>2 yearly 1080 - 90% kill plus 1 year brodifacoum - 75% kill</td>
<td>2.03</td>
<td>$131</td>
<td>1.82</td>
<td>$181</td>
</tr>
<tr>
<td>3 yearly 1080 - 90% kill plus 2 years brodifacoum - 75% kill</td>
<td>2.24</td>
<td>$140</td>
<td>2.02</td>
<td>$189</td>
</tr>
</tbody>
</table>
Recommendations from the Chapters 4 and 5 pen trials

The following two sub-sections detail control simulations derived from the research recommendations in Chapters 4 and 5. The purpose of these simulations was to calculate the potential control cost savings ($/ha) and thus support the need to field trial both recommendations.

1080 in an unfamiliar bait matrix for maintenance control

One of the main results from the Chapters 4 and 5 pen trials was the success of the 0.15% 1080 gel and paste baits (marketed as Pestoff®) at killing 1080 cereal bait-shy possums (80% kill). These baits need to be field tested, as cereal brodifacoum is currently the only bait that has been shown to kill 1080 bait-shy possums in the field (Henderson et al. 1997).

As detailed in the economics of control sub-section, brodifacoum bait station control is expensive in terms of labour and the quantity of bait consumed. Field trial studies investigating the efficacy of ground-laid 1080 paste baits, for initial control in naive possum populations, state that this control technique is very cost-effective with an average cost of only $10.73/ha (± $3.8 S.E. n=5 trials; Henderson et al. 1998). This type of control is cheaper than the other alternatives because it can be ground-laid without bait stations and the paste bait is less bulky than pellets which results in fewer visits to the control area (Wickstrom et al. 1997).

For this simulation, I substituted cereal brodifacoum bait station control with ground-laid 0.15% 1080 paste and compared the costs/ha with the most cost-effective control strategies in the results section that used brodifacoum cereal bait (Tables 6.16 and 6.17).

Sustained 80% kill

Using 1080 paste significantly reduced (by 25-38%) the accumulated cost of the two control strategies, whilst still achieving the sustained 80% kill (Table 6.33). This result supports the Chapter 4 recommendation to field trial these alternative 1080 bait matrixes (paste and gel) for follow-up maintenance control operations. Significant control cost
savings may be possible if either of the two non-cereal bait types are found to be as effective as cereal brodifacoum bait for maintenance control in the field.

Table 6.33: Average possum density/ha of possum control strategies attempting to achieve a sustained 80% kill using 1080 and cholecalciferol cereal bait for initial control and either brodifacoum cereal bait or 1080 paste bait for maintenance control.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 yearly 1080 - 90% kill</td>
<td>2.03</td>
<td>$131</td>
</tr>
<tr>
<td>1 year brodifacoum - 75% kill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 yearly cereal 1080 - 90% kill</td>
<td>2.00</td>
<td>$98</td>
</tr>
<tr>
<td>1 year 1080 paste - 80% kill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 yearly cholecalciferol - 80% kill</td>
<td>1.98</td>
<td>$197</td>
</tr>
<tr>
<td>3 years brodifacoum - 75% kill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 yearly cholecalciferol</td>
<td>1.91</td>
<td>$122</td>
</tr>
<tr>
<td>3 years brodifacoum - 75% kill</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The effect of non-toxic prefeed on cholecalciferol bait station control

In the previous modelling simulations, a mean 80% kill value was used for cholecalciferol control operations. However, recent field studies have demonstrated that prefeeding non-toxic bait improves cholecalciferol bait-station efficacy of susceptible possum from 80% to 90% (with a bait station grid of 100 m; Wickstrom et al. 1997). Whilst non-toxic cereal prefeed can be expensive, control costs/ha need not increase if a wider bait station grid of 150 m is used. Field trial studies investigating 1080 bait-station spacings have demonstrated that 1080-control efficacy does not decrease with the wider grid and Landcare Research currently recommends the use of non-toxic prefeed before 1080 bait-station control with a 150 m grid spacing (Thomas 1998).

For this simulation I have calculated the cost of cholecalciferol bait station control (refer economics of control sub-section) with a 150 m grid spacing and 3 weeks of prefeeding. Using these parameters the cost of cholecalciferol control came to $27.30/ha when the population density was low-moderate (1-5 possums/ha) and $28.90/ha when the population density was moderate-high (6-10 possums/ha).
Sustained 60% kill

Increasing the efficacy of cholecalciferol control to 90%, by prefeeding non-toxic bait, significantly reduced the number of control operations required to achieve a sustained 60% kill (Table 6.34), resulting in a 38% cost saving.

Table 6.34: Accumulated discounted cost of possum control strategies achieving a sustained 60% kill using cholecalciferol in bait stations, with and without non-toxic prefeed.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 yearly cholecalciferol - 80% kill</td>
<td>3.97</td>
<td>$100</td>
</tr>
<tr>
<td>Year 6 additional cholecalciferol - 80% kill (without non-toxic prefeed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 yearly cholecalciferol - 90% kill</td>
<td>3.96</td>
<td>$62</td>
</tr>
<tr>
<td>(with non-toxic prefeed)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sustained 80% kill

Increasing the efficacy of cholecalciferol control to 90% also significantly reduced the number of control operations required to achieve a 80% sustained kill resulting in a 28% cost saving (Table 6.35). These results suggest that significant cost savings could be achieved in cholecalciferol control operations, if control efficacy is increased by 10%. However, these simulations used a bait station grid spacing of 150 m. Cholecalciferol control costs with a 100 m spacing and 3 weeks of prefeeding are significantly more expensive ($62.10/ha) and this is not a cost-effective option. Accordingly, future field studies are required to ensure that cholecalciferol efficacy remains consistent with the wider 150 m bait station spacing.
### Table 6.35: Accumulated discounted cost of possum control strategies attempting to achieve a sustained 80% kill using cholecalciferol in bait stations, with and without non-toxic prefeed.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Average density/ha</th>
<th>Accumulated Discounted cost/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 yearly cholecalciferol - 80% kill</td>
<td>1.98</td>
<td>$197</td>
</tr>
<tr>
<td>3 years brodifacoum - 75% kill (without non-toxic prefeed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 yearly cholecalciferol - 90% kill</td>
<td>2.03</td>
<td>$141</td>
</tr>
<tr>
<td>1 year brodifacoum - 75% kill (with non-toxic prefeed)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 6.8 Conclusions

Barlow’s (1991a) possum modelling paper suggested that one of the most cost-effective strategies for eliminating Tb possums was widespread aerial poisoning with 1080 every 6 years. In that model, the target population density for disease elimination was about half of the uncontrolled population density. The results from my model (which is an adaptation of Barlow’s earlier possum model) indicate that, in the presence of density-dependent possum immigration and 1080 bait shyness, more intensive control (e.g., every 4 years) is required to achieve a similar (60%) sustained population reduction. The control technique used in the most cost-effective strategy was aerially distributed 1080 bait. Analysis of current operational costs suggests that this is still the cheapest control technique, compared with the costs of bait station control. However, this cost difference was minimal (a 19% cost saving). Table 6.10 suggests that, for areas <1 000 ha, the costs of bait station control may be comparable to aerial operations.

A sustained 80% kill could be achieved using only 1080 (in bait stations), but the most cost-effective strategy also included brodifacoum as this toxicant has the ability to remove the 1080 bait-shy survivors over a 10 year simulation. The model indicated that it was necessary to use brodifacoum only once, immediately after the initial 1080 operation. This strategy reduced the combined susceptible (S) and shy (A) sub-populations to below the target population density. Regular control with 1080 then maintained the average population below this density by killing the majority of new recruits and immigrants.
This was an interesting result as field trials, investigating the use of 1080 for maintenance control, have demonstrated that annual 1080 control programmes quickly become ineffective (Thomas and Hickling 1995). In the Mapara Forest example discussed earlier (Chapter 2) the percentage kill dropped from 79% to 0% in three consecutive aerial 1080 operations (Warburton and Cullen 1993). The low kill at Mapara Forest was attributed to the development of 1080 bait shy ness and the field managers then switched to brodifacoum bait for the next 2 years (Bradfield and Flux 1996). An important consideration is that the initial 1080 aerial operation achieved only a 79% kill. This means that the majority of the remaining 21% were probably 1080 bait shy. The persistence of these survivors may explain why the 1080 percentage kill decreased so dramatically for the next two operations (barring any major undetected operational faux pas).

Based on the failure of the next two 1080 operations to further reduce the possum population at Mapara, annual 1080 maintenance control was then considered an ineffective control strategy. Even though the percentage kill dropped to 0%, 1080 control did maintain the population at a 3-5% residual trap catch rate (approximately 1-2 possums/ha) for 3 years. This is a sustained 80% kill from the pre-control population density (30% trap catch rate; Bradfield and Flux 1996). The model suggests that if the initial 1080 aerial control had been followed up with a brodifacoum operation the population would have been reduced below the 3-5% residual trap catch rate. This additional kill would have been due to the ability of brodifacoum to kill the bulk of the 1080 bait-shy possums, which survived the initial control operation. The model, therefore, suggests that further brodifacoum control would not be required as regular 1080 control would have maintained the population at this lower density, with numbers of bait-shy possums reducing due to natural mortality and loss of 1080 bait shyness over time.

The model also suggested that it was possible to achieve a sustained 60% or 80% kill using bait stations containing cholecalciferol and brodifacoum. However, more intensive control was required due to the lower efficacy of cholecalciferol, which left more bait-shy survivors following each cholecalciferol control operation. Accordingly, additional brodifacoum operations were required to kill the cholecalciferol bait-shy possums accumulating in sub-population (A). Given: i) the increased frequency of cholecalciferol
control; ii) the increased use of brodifacoum; and iii) the higher per ha cost of cholecalciferol bait, these control strategies were substantially more expensive than those using 1080. Substantial cost savings could be made if cholecalciferol control efficacy is increased. For example, the sensitivity section suggested that increasing control efficacy from 80-90% would save an accumulated discounted cost of $38/ha (a 38% cost reduction) while maintaining the possum population at 40% of the pre-control density.

The sensitivity analysis also identified two parameters that significantly influenced the ability of a previously successful control strategy to achieve a sustained kill. The first was the kill rate of the initial 1080 control operation; the model indicated that it was still possible to achieve target population densities provided additional control operations were scheduled. The inclusion of these additional operations, however, had a notable effect on total cost of control over the 10 year simulation. For example, an unsuccessful 1080 operation increased the cost of a sustained 60% kill by $35/ha (a 66% cost increase). As detailed in the methods section there are many reasons why a control operation can fail. These results stress how important it is for field managers to ensure all bait is probably prepared, particularly for the initial control operation when the population density is high. As demonstrated by the model, a high population density of bait-shy possums would be expensive to control using brodifacoum bait.

The second parameter that had a significant influence over the success of a control strategy was the maximum rate of immigration. The model indicated that with a high immigration rate (4 possums/ha/yr) it was no longer possible to achieve a sustained 80% kill using any combination of toxicants. The maximum rate of immigration used in the base model (1.2 possums/ha/yr) was derived from four empirical studies investigating population recovery in a variety of habitats. Some of these study sites were small (12-24 ha) and some (e.g., the Orongorongo Valley site) were surrounded by very favourable possum habitat. These data suggest that the higher rate of immigration (4 possums/ha/yr) is exceptional and a rate of 1.2 possums/ha/yr is more typical, particularly in the moderate-large forest stands (cf. Hickling and Pekelharing 1989). Therefore, it seems important that field managers gauge the rate of population recovery, using pre-control population monitoring, before scheduling ongoing maintenance control operations. Without this information, managers may make
incorrect decisions regarding the frequency of control work required to achieve target population densities. If population recovery rates are high, due to rapid re-colonisation, field managers may need to reassess the benefits of possum control work in that area. Field trial studies in small forest reserves, with rapid population re-colonisation, has demonstrated that a >80% sustained kill is achievable, but requires expensive ($80/ha) permanent bait stations, that are filled up every month with 1 kg of brodifacoum bait (Thomas et al. 1995).

Various pen trial studies have demonstrated that 1080 bait shyness persists for at least 2-5 years in captive possums (O'Connor and Matthews 1996; Morgan and Milne 1997; O'Connor et al. 1998). To counteract this researchers currently recommend leaving at least 3-4 years between 1080 control operations (Henderson et al. 1998), whilst integrating alternative control methods such as trapping, shooting and bait stations containing brodifacoum bait (Morgan et al. 1996a). Previous possum modelling simulations suggest that more frequent 1080 control will not be effective in the medium-long term due to increasing numbers of bait-shy survivors, particularly when bait shyness persists for longer than 1 year (Hickling 1995). The sensitivity analysis in my model suggests that learned behaviours such as bait shyness and enhanced neophobia do not pose a major control problem provided 1080 control efficacy is at least 90% (particularly in the initial control operation). With high 1080 control efficacy and a one-off brodifacoum control (required to achieve a sustained 80% kill) the number of bait-shy possums does not increase sufficiently to render frequent 1080 control ineffective. This is still the case when the rate of bait shyness degradation is reduced to 0% or the possums become shy of all bait through enhanced neophobia.

In my model I used bait stations containing 1080, brodifacoum and cholecalciferol bait as the ground control options. There is other possum ground control options that could be utilised. For example, private hunters using leg-hold traps can also kill 1080 bait-shy possums in maintenance control operations (Morgan et al. 1995). It is, therefore, up to field managers to decide which ground control technique is most acceptable. Only a 10% reduction in control efficacy can have a significant influence on the frequency of control operations required to achieve the target population density. Therefore, non-chemical ground control must achieve at least an 80% kill at comparable cost to be as effective as
brodifacoum bait. Field trial studies have demonstrated that contract ground hunters can be as cost-effective as aerial 1080 operations in accessible, <5 000 ha control blocks (both achieving an 80% kill; Montague 1997). However, other field trials evaluating the use of brodifacoum concluded that bait station control can be cheaper than annual leg-hold trapping control when the goal of control is to reduce the possum population to very low densities (<90% kill) (Thomas et al. 1995).

In conclusion, there are six key outcomes from the modelling simulations. First, bait shyness had a significant effect on the frequency of control required to achieve a sustained population reduction. Future possum control-modelling simulations should include bait shyness, particularly when modelling intensive control (e.g., >80% sustained kill). Second, it was possible to achieve both target population densities (i.e., sustained 60% and 80% kills) using currently available possum toxicants. This is an important result as biological control techniques may not be available in the near future (Gregory et al. 1996). Third, it was also possible to achieve these target population densities using toxic bait delivered in bait stations. This result is reassuring as public opposition to widespread aerial 1080 control could render this technique unavailable in the near future (Eason et al. 1994). Possum control campaigns using bait stations are viewed more favourably as they uses significantly less toxic bait and all uneaten bait can be collected after the operation (Thomas et al. 1996). Fourth, none of the control strategies were heavily reliant on brodifacoum. From an ecotoxicological perspective, minimising the use of brodifacoum, in favour of 1080, is desirable as brodifacoum is best avoided if there are concerns regarding the primary and secondary poisoning of non-target species (Eason and Spurr 1995). Fifth, the control simulations indicate that learned behaviours such as bait shyness and enhanced neophobia should not be a major problem, provided 1080 bait control efficacy is at least 90% (particularly in the initial 1080 control operation) and alternative, slower-acting toxicants such as brodifacoum bait are used occasionally (only required for the sustained 80% kill). To consistently achieve a 90% 1080 kill field managers need to: i) use bait of high palatability (R. Henderson, unpubl. data); ii) ensure bait has the correct toxicant concentration (Henderson and Morris 1996); iii) ensure bait is of adequate size (Frampton et al. in press); iv) use GPS navigation equipment to ensure total bait coverage in aerial operations (Morgan et al. 1996b); and v) use non-toxic prefeed in bait station ground
control operations (Thomas 1998). This strategy should ensure that few, if any, possums are sub-lethally poisoned (Henderson et al. 1998). Finally, the model suggested that it is also possible to achieve the target population densities using cholecalciferol and brodifacoum. This result is also reassuring as the majority of possum control strategies in New Zealand are currently dependent on 1080. It is recognised that an over-reliance on a single toxicant is unwise (Eason et al. 1994).

6.9 Recommendations for future research

Future field trials

Researchers need to investigate whether the most cost-effective strategies identified by the model, work in the field. The control strategy achieving the sustained 80% kill could be assessed in a 3 year field trial (e.g., 1080yr1→brodifacoumyr2→1080yr3). This trial would enable researchers to gauge how effective 1080 control is at maintaining the possum population below the 20% target density. This is important as annual 1080 control is currently viewed as an ineffective strategy (Thomas and Hickling 1995). Substantial cost savings are possible as control strategies using predominately brodifacoum are substantially more expensive than those reliant on 1080.

The model indicated that significant cost savings could be made by improving the efficacy of all toxicants. As detailed in Table 6.5 cholecalciferol only achieves an average kill of 80%. Field researchers need to investigate methods of improving the efficacy of this toxicant. The Chapter 4 pen trial has demonstrated that cholecalciferol is very effective at killing possums in a paste bait. As detailed in the methods section, cereal baits are hygroscopic and palatability of these baits can decline very quickly. Paste baits may be more effective in the field, particularly in damp conditions.

Another way of improving cholecalciferol efficacy may be to use non-toxic prefeed. Recent field trials have demonstrated that prefeeding increases the percentage kill in cholecalciferol bait station operations from 80% to 90% (n=2 trials; Wickstrom et al. 1997). The problem is that the use of prefeed increases the simulated cost of cholecalciferol
bait station control by $9.60/ha with a 100 m station spacing. 1080 bait station trials suggest that a wider 150 m grid can be used without compromising control efficacy (Table 6.4). The simulated cost of a cholecalciferol control operation, using bait stations with a 150 m grid and non-toxic prefeed, is actually cheaper than control with a 100 m grid and no prefeeding ($28.90/ha when possum population density is moderate-high; a 7% cost decrease). Research needs to investigate the efficacy of cholecalciferol control using prefeed and a 150 m grid. As detailed in the sensitivity analysis section, increasing control efficacy by only 10% will result in significant cost savings.

Another area of potential cost savings is the use of 1080 in a new unfamiliar bait matrix for maintenance control operations. As detailed in Chapter 5, 1080 cereal bait shyness can be mitigated by ‘bait-switching’ (e.g., 1080 in orange-lured gel, paste or carrot; Morgan et al. 1996a; O'Connor and Matthews 1996; Ross et al. 1997). Ground-laid 1080 paste control is substantially cheaper than the current alternatives. However, the effectiveness of these alternative 1080 baits need to be evaluated in the field.

**Future possum model development**

Given the current level of knowledge, my model appears to accurately simulate population recovery when compared to the empirical data available. However, this model does not incorporate density independent juvenile male dispersal (Barlow 1993). Research investigating juvenile dispersal indicates that these possums can move up to 12 km from their natal site and these long distance movements could be a key factor in initial rates of recovery after control (Cowan et al. 1997). Future modelling needs to replicate this possum model over a larger control area, containing blocks of alternative habitat and populations densities (i.e., includes spatial dynamics). The would allow modellers to determine the influence of juvenile dispersal on the currently recommended control strategies. Another issue is the susceptibility of either sex to the various control techniques. For example, pen-trial studies have indicated that all possums generally consume similar amounts of toxic bait, but that the females and juveniles ingest a higher toxic dose (in mg/kg) because they tend to have smaller body weights (R. Henderson, unpubl. data). Therefore, adult males may be more likely to survive 1080 poisoning than juveniles or adult female possums.
Other field trial studies have demonstrated that female mountain brushtail possums (*T. caninus*) are more likely to be caught in leg-hold traps than are males (Lindenmayer *et al.* 1998). These sex differences need to be considered in future modelling simulations as they may influence the rate of population recovery following control. Finally, there is the issue of upgrading this model into a dynamic programming framework. Most of the ecological relationships are relatively comprehensible and appear suitable for dynamic programming.

A final consideration is the (1 year) timesteps used in these simulations. When setting up the model it seemed that a 12 month timestep was the best option, as possum breeding and control are generally annual events. However, monthly or daily timesteps, as used by other modellers (Pfieffer 1993 Hickling 1995), may be a superior option. For example, I have detailed in the methods section that estimating the total population at 12 monthly intervals underestimates the density of possum during years with control operations. While adjustments were made to account for winter/spring births/immigration a model with a 1 month timestep would more accurately estimate the average possum population over the 12 month period. Accordingly, I would recommend that future possum modelling simulations use smaller timesteps.

### 6.10 Acknowledgements

I thank Lincoln University (Entomology and Animal Ecology Group) for funding this research, and Drs. K. Bicknell and G. Hickling for helpful comments on this chapter.

I was responsible for the conceptual development, model construction and data analysis. Dr. K. Bicknell provided mathematical guidance and assistance during all phases of this research.

### 6.11 References


CHAPTER 7

GENERAL CONCLUSIONS

7.1 Introduction

Mammalian pest species cause problems worldwide and programmes for the development of improved control techniques are of international importance. Rodent-control researchers have had some success in overcoming problems of genetic (although resistance to 1st and 2nd generation anticoagulants is well developed in some European countries) and behavioural resistance by using potent second generation anticoagulants, but these toxicants have not been considered sufficiently cost-effective, technically feasible nor environmentally safe for use on widespread environmental pest species such as the brushtail possum (*Trichosurus vulpecula*). The problem with using cheaper acute-acting toxicants such as 1080 (sodium monofluoroacetate) is that mammalian pests can develop learned behavioural mechanisms such as a conditioned food aversion to such baits. This 'bait shyness' can be long lasting and thus can threaten the sustainability of control strategies that are dependent on acute-acting toxicants. The objective of this Ph.D. was, therefore, to identify methods of preventing and mitigating the problem of 1080 bait shyness for the New Zealand brushtail possum. The following section summarises the main research findings and discusses the implications of these for possum field managers and researchers.

Control of 1080 bait-shy possums using acute, subacute and chronic toxicants in a familiar bait matrix

Pen trials (Chapters 3 and 4) demonstrated that 64-83% of captive 1080 bait-shy possums can be killed using a subacute or chronic-acting toxicant (cholecalciferol, marketed as Campaign® and brodifacoum, marketed as Talon®) in a familiar cereal bait. There was no significant difference in the efficacy of either toxicant. While there was some uncertainty regarding the efficacy of the pre-treatment 1080 dose in inducing bait shyness, all possums
in the pen trial were confirmed as being shy to 1080 bait. None of these confirmed 1080 bait-shy possums were killed when re-exposed to 1080 in the familiar cereal bait.

Some 1080 bait-shy possums avoided cereal bait on the first night of re-exposure to them, however, most did sample some bait over the 14 nights of the trial. This cautious behaviour is similar to that observed in earlier field trial studies where 1080 bait-shy possums would return to bait stations and sample small (sub-lethal) amounts of 1080 cereal bait (Hickling 1994). 1080 bait-shy possums exposed to the subacute and chronic-acting toxicants continued to consume bait after the first night, whereas shy possums surviving exposure to the acute-acting toxicants (1080 and gliftor) avoided the bait thereafter. Possums eating cholecalciferol continued to sample bait for 2-7 nights, however, average nightly consumption did not increase with prolonged exposure. In contrast, the average nightly consumption of brodifacoum significantly increased over time, with all possums consuming at least 30 g of bait by the end of the trial (this can also lead to excessive toxic loadings in target species/individuals). These results suggest that 1080 bait-shy possums are particularly cautious of a familiar bait, but will sample small amounts of bait with prolonged exposure. When this bait contains an acute-acting toxicant (i.e., 1080 or gliftor) it is likely the possum will experience poisoning symptoms and the bait shyness is reinforced. In captivity the poisoning symptoms of both cholecalciferol and brodifacoum are sufficiently delayed so that the majority of the 1080 bait-shy possums will eventually consume a lethal dose of these toxicants even in a familiar bait matrix.

Recent field studies (Henderson et al. 1997) have since investigated the efficacy of cereal cholecalciferol and brodifacoum baits for maintenance control of possums in an area that had been subject to initial, unsuccessful 1080-control operation. Henderson et al. (1997) concluded that the survivors of previous 1080 control operations could not be successfully controlled using the cholecalciferol toxicant in the same bait matrix (0% kill; n=3 trials). The most likely explanation for this failure of cholecalciferol cereal bait is that free-ranging possums are more cautious than their captive counterparts and thus are less likely to consume a lethal dose before experiencing poisoning symptoms. This hypothesis is supported by studies that have demonstrated that possums can become cholecalciferol bait shy (O'Connor et al. 1998) and that free-ranging possums consume approximately 30%
less non-toxic bait than their captive counterparts (R. Henderson, unpubl. data). Similar differences in behaviour have been observed in comparisons of captive and free-ranging rodent populations. For example, free-ranging brown rats (R. norvegicus) are significantly more cautious of novel containers and food than are captive rats (Brunton and MacDonald 1996). Wild rats (R. norvegicus) are also superior to their captive counterparts at redirecting their food-seeking behaviour to a safe source following sub-lethal poisoning with zinc phosphide (Shepherd and Inglis 1993).

The brodifacoum control field trials killed similar numbers of 1080 bait-shy possums as the trials detailed in Chapters 3 and 4 (Henderson et al. 1997; 75% kill; n=8). The most likely explanation for the success of brodifacoum cereal bait is that the possums do not become brodifacoum bait shy. This hypothesis is supported by a recent pen trial study where the researchers were unable to detect any shyness to brodifacoum cereal bait following various sub-lethal 1080 doses in the same bait matrix (O'Connor et al. 1998). These results suggest that all 1080 bait-shy possums are initially cautious of the familiar cereal bait, but with prolonged exposure and no further associated poisoning symptoms, most animals will eventually consume a lethal dose of brodifacoum bait.

While brodifacoum appears to work well in the pen and field trials, some possums (25-36%) did not consume a lethal dose of brodifacoum even after 14-120 nights of exposure (Chapters 3 and 4; Henderson et al. 1997). Other pen trials have indicated that possums are mildly neophobic to novel (non-toxic) palatable foods, however, this weak initial neophobia decreases with prolonged exposure (O'Connor and Matthews 1996). Neophobia can be enhanced after an animal has been made ill by a novel food; the animal will then not only avoid a specific food, but also becomes wary of anything new (Brunton et al. 1993). Possums may thus be surviving control with brodifacoum cereal bait due to the development of enhanced neophobia, bought on by previous exposure to a cereal bait containing an acute or subacute toxicant.

The pen trials described in Chapter 3 and 4 support earlier field and pen trial studies (Hickling 1994; O'Connor and Matthews 1996) that suggested that learned behavioural mechanisms such as bait shyness and enhanced neophobia have the potential to markedly
reduce the efficacy of maintenance control operations using 1080. However, the number of possums surviving prolonged exposure to brodifacoum could also be cause for concern. For example, in some frequently poisoned rodent populations, higher than expected numbers of rats (*R. norvegicus*) are surviving anticoagulant control due to low bait take (Brunton and MacDonald 1996). Rodent-control researchers speculate that regular poisoning could exert intense selection for more neophobic rats over time (Quy *et al.* 1992). While innate neophobia is currently not considered to be a major problem (see Chapter 2), genetic and learned behavioural mechanisms could interact and eventually lead to possums that are very resistant to consuming new poisons and baits (O'Connor and Matthews 1996).

As mentioned, the poisoning symptoms of cereal-based cholecalciferol baits are most likely not sufficiently delayed for this toxicant to be effective for maintenance control. Accordingly, further research should investigate techniques for delaying poisoning symptoms. For example, rodent-control researchers have recently delayed the onset of subacute-acting rodenticide poisoning symptoms by using microencapsulation techniques (Cowan *et al.* 1994). If it is cost-effective to microencapsulate possum toxicants in cereal bait, this technique should be field trialed for maintenance control following 1080-based control operations.

**The effectiveness of acute, subacute and chronic toxicants, in both familiar and unfamiliar bait matrixes, for the control of 1080 bait-shy possums**

Pen trials (Chapters 4 and 5) demonstrated that 1080 bait-shy possums are significantly less cautious of an unfamiliar bait (gel or paste) than a familiar one (cereal), with the majority (57%) consuming a lethal dose of 1080 paste (marketed as Pestoff®) or gel on the first night of exposure. Survivors that sampled the paste or gel 1080 bait dramatically reduced their consumption thereafter (as was seen in the cereal bait trial). This result supports the enhanced neophobia hypothesis, as both the 1080 paste and gel baits have achieved >90% kills when used for initial control in populations of relatively naive free-ranging possums (Thomas and Meenken 1995; Wickstrom *et al.* 1997). Although the
difference was not statistically significant, the higher concentration 0.13% 1080 bait killed more 1080 bait-shy possums (80%) than did the 0.08% conc bait (40%).

Free-ranging possums have been observed returning to bait stations and dumping dyed 1080 cereal bait at the base of the station whilst consuming undyed non-toxic baits (Hickling et al. 1991), which led to the hypothesis that some possums can detect 1080 toxin. The results of this pen trial do not support this hypothesis; it seems more likely that the possums were using dye-related cues to reject the dyed toxic bait in favour of the undyed non-toxic bait. This hypothesis is supported by other pen trial studies which have demonstrated that 1080 bait-shy possums are more likely to reject dyed non-toxic than they are undyed bait (Morgan et al. 1996)

The reduced level of initial shyness to paste bait enhanced the effectiveness of the two alternative, slower-acting toxicants (cholecalciferol and brodifacoum), with both achieving a 100% kill when in a paste formulation. Possums surviving exposure to the cereal baits containing these toxicants did so by remaining cautious of the familiar bait throughout the trial. These results suggest bait recognition is an important factor in the development of bait shyness for some possums. For example, consumption of paste bait containing brodifacoum did not significantly increase over time (contrary to the results with cereal-based brodifacoum bait in Chapter 3) mainly because there was little initial shyness to the paste bait on the first few nights of the trial.

As mentioned, previous trials have only investigated the field efficacy of 1080 gel and paste baits in naive possum populations. Pen trials (Chapters 4 and 5) have demonstrated that bait-shy possums are significantly less cautious of an unfamiliar bait matrix than a familiar cereal bait, with the majority consuming a lethal dose of 1080 (particularly the 0.15% bait) on the first night of exposure. This is a very positive result and warrants further field investigation.
The role of non-toxic prefeed and postfeed in the development and maintenance of possum 1080 bait shyness

In the Chapter 5 pen trial, pre-fed possums were significantly less likely than non pre-fed possums to become 1080 bait shy following an initial sub-lethal 1080 dose. Non pre-fed possums quickly associated the cereal bait with previous acute poisoning symptoms and were very cautious of such bait on subsequent re-exposure. The presence or absence of green dye did not have a significant effect on this result, although the groups of possums that ate the same coloured ‘prefeed’ as their sub-lethal dose did have the fewest 1080 bait-shy individuals.

With prolonged exposure, all 1080 bait-shy possums consumed some non-toxic ‘postfeed’. Initial bait consumption was low, but the level of bait shyness decreased progressively so that average nightly consumption had doubled after seven nights (this is similar to the cereal brodifacoum consumption in Chapter 3, which also increased over time). This result is also similar to O'Connor and Matthews (1997) pen trial study, which demonstrated that consumption of a familiar non-toxic bait by cyanide bait-shy possums increases with repeated exposure.

Postfeeding did not have a significant effect on the overall level of bait shyness, with only 30% of these possums consuming a lethal dose of cereal 1080 bait later in the trial. However, postfeeding did increase the mean nightly 1080 bait consumption and the lack of a statistically significant difference may have been due to the small numbers of survivors from the previous 1080 bait treatments (n=10). The most likely explanation is that the possums were still cautious of the familiar cereal bait and so consumed only small amounts of postfeed in multiple feeding sessions. Field trial studies have observed that possums generally feed in short bouts interspersed with long periods of other activity (Henderson and Hickling 1997). Intermittent feeding combined with bait shyness means that most possums are likely to experience some poisoning symptoms (particularly when an acute or subacute-acting toxicant is used) before a lethal dose is consumed.
Field trial studies have demonstrated that prefeeding increases both toxic bait consumption and the percentage kill achieved (Thomas 1998). For this reason alone field managers should consider using non-toxic prefeed before bait station control with an acute or subacute-acting toxicant. The Chapter 5 pen trial result suggests that prefeeding will also reduce the number of 1080 bait shy control survivors. It is possible that these results are interrelated, such that pre-fed possums consume more toxic bait because it takes them longer to become bait shy; however, this requires field validation.

Postfeeding does not appear to be a good technique for overcoming 1080 bait shyness, as it achieved a poor (30%) kill. As detailed above, free ranging possums are likely to be more cautious than their captive counterparts, so postfeeding would probably be even less effective in the field. In terms of mitigating 1080 cereal bait shyness researchers should investigate the field efficacy of possum toxicants in unfamiliar bait for maintenance control.

Cost-effective control of 1080 bait-shy possums

The modelling simulations in Chapter 6 suggest that sustained 60% and 80% kills can both be achieved with a control strategy using predominantly 1080 cereal bait. This is an interesting result as previous field trial studies have cautioned that annual possum using 1080-based bait is unlikely to be sustainable (Warburton and Cullen 1993; Thomas and Hickling 1995). The control simulations suggest that problems with sustainability are most likely to arise as a consequence of a low kill in the initial 1080 operation that leaves a relatively large number of 1080 bait shy survivors. In contrast, when the initial kill is high (80-90%) regular control with 1080 bait at intervals of several years can effectively maintain the population at low density by killing the majority of immigrants, new recruits and remaining resident non-bait-shy possums. Increasing the interval between control operations in this way will markedly reduce the impact of bait shyness on control efficacy (see Hickling 1995 and Chapter 6).

Brodifacoum bait should not be used for the initial knockdown control operation, but is valuable for follow up after initial, or unsuccessful, 1080 control operations. This chronic-
acting toxicant will kill the majority of any 1080 bait-shy survivors and thus is capable of reducing the total possum population to a very low density following an initial (successful) 1080-control operation. However, repeated use of brodifacoum is unlikely to be cost-effective. Minimising the use of brodifacoum is also desirable from an ecotoxicological perspective as there are major concerns regarding the potential for primary and secondary poisoning of non-target species with this toxicant (Eason and Spurr 1995; Eason et al. 1996).

Sustained population reductions of 60% or 80% can both be achieved using cholecalciferol instead of 1080. However, the lower toxicant efficacy and higher cost of the cholecalciferol bait significantly influenced the overall cost of this control strategy. This result is reassuring, as the majority of current possum control strategies remain dependent on 1080. Another reassuring aspect of the cholecalciferol simulations was that satisfactory control operations were achieved by using the toxicant in bait stations. From an ecotoxicological perspective bait station control is more favourable than aerial control because significantly less toxic bait is used and any surplus bait can be retrieved (Thomas et al. 1996).

The most important variable influencing the ability of a control strategy to achieve a high-sustained kill was the maximum rate of possum immigration. With a high rate (4 possums/ha/yr) of immigration (as is sometimes observed in small forest reserves; Thomas et al. 1995) it was not possible to achieve a sustained 80% kill using any combination of toxicants. Sustained control in small reserves may, therefore, require expensive, permanent bait stations containing brodifacoum bait. While these high rates of immigration would be exceptional for moderate-large sized control areas, field managers need to keep in mind that rates of immigration may indeed be high for small areas. Other field trial studies investigating population recovery in tuberculosis (Tb; Mycobacterium bovis) buffer zones have indicated that these buffers are re-colonised fastest along the edges. Accordingly, rates of local immigration may also be high along the edges of large control areas and control may need to focus on these immigration ‘hotspots’ (e.g., Fraser et al. 1998).

Previous possum-control modelling simulations have typically overlooked the issue of 1080 bait shyness and/or have not incorporated operational costs in their outcomes (e.g.,
Barlow 1991; Henderson et al. 1998). The sensitivity analysis presented in Chapter 6 supports Hickling (1995) in suggesting that 1080 bait shyness is an important consideration that can significantly influence the efficacy of future 1080 maintenance control operations. All future possum control simulations should, therefore, incorporate bait shyness, particularly when modelling situations which require large reductions in possum numbers (e.g., >80% sustained kill). The modelling simulations also suggest that minimising the use of brodifacoum and improving cholecalciferol efficacy could make significant cost savings. The control strategies highlighted in Chapter 6 now need to be field-tested.

7.2 Recommendations for field managers

To kill possums in endemic Tb areas the AHB funds aerial broadcasts of 1080 bait at relatively frequent intervals (e.g., every 3-4 years; K. Stewart, pers. comm. 1998). At this control frequency 1080 bait shyness should not be a major problem (refer to Chapter 6) and there should be no need to switch to an alternative, slower-acting toxicant. However, the results from the Chapter 4 and 5 pen trials suggest that field mangers should use 0.15% 1080 bait in all maintenance control operations. When 0.15% 1080 bait is used 95% of the population will be lethally dosed after consuming a single 5 g bait (Frampton et al. in press). With 0.08% 1080 bait possums generally need to consume more than one bait and this increases the chances of sub-lethal dosing, particularly if there are cautious bait-shy survivors from previous 1080 control.

Field managers should use non-toxic cereal prefeed prior to any bait station control operation using an acute or subacute toxicant for two reasons. First, a series of paired bait station field trials has demonstrated that prefeeding significantly improves cholecalciferol and 1080 control efficacy (Thomas et al. 1997; Wickstrom et al. 1997). As detailed in my sensitivity analysis even a 10% difference in toxicant efficacy will have a significant effect on the frequency of control operations required to achieve a sustained kill. Secondly, the survivors are less likely to become 1080 bait shy, as pre-fed possums find it significantly more difficult to associate the cereal bait with previous 1080 poisoning symptoms. Prefeeding, prior to control with 1080 using bait stations is not significantly more expensive, provided the wider 150 m bait station grid spacing is used, and this does not
reduce control efficacy (Thomas et al. 1996). Field trials are required to confirm this prediction for cholecalciferol bait.

Prefeeding is currently not recommended for aerial control as it is not known whether this would improve aerial 1080 control efficacy enough to justify the substantial additional cost (Fraser and Knightsbridge 1995). Landcare Research (N.Z.) Ltd (under contract to the Animal Health Board) is currently undertaking field trials to investigate this further (G. Hickling, pers. comm.).

7.3 Recommendations for future research

In hindsight, measuring the penned-possums' bait consumption every 24 hours did not allow me to clearly identify possums' consumption patterns. For example, 1080 bait-shy possums exposed to the non-toxic (Chapter 3) and brodifacoum (Chapter 4) treatments consumed more bait on the first night than did possums in the other treatment groups. The most likely explanation for this is that, after sub-lethal poisoning, possums only sample small amounts of bait in subsequent feeding bouts. When an acute-acting toxicant is used possums most likely experience poisoning symptoms after the first feeding bout and avoid bait thereafter. This multiple-feeding-bout hypothesis may also explain why cholecalciferol cereal bait seems to be ineffective for maintenance control in the field. For example, a 1080 bait-shy possum may consume a sub-lethal dose of cholecalciferol at a bait station early in the evening. If this individual were then to be displaced by a more dominant possum when returning to the station (cf. Henderson and Hickling 1997), it may then feed elsewhere or return to its den and so will experience poisoning symptoms before the next evening's activities. This hypothesis needs to be explored in future pen trials that investigate the consumption of bait in more detail, for example by using time-lapse cameras placed above the cages.

Previous possum field (Henderson et al. 1997) and the pen trials detailed in Chapters 3 and 4 suggest that the speed of poisoning symptoms is a very important factor affecting the total amount of toxic bait consumed. For example, subacute cholecalciferol poisoning symptoms do not appear to be sufficiently delayed for 1080 bait-shy possums to be killed
in the field. Rat-control researchers suggest that rodenticide-poisoning symptoms could be delayed for a number of hours by using microencapsulation techniques (Cowan et al. 1994). They speculated that this technique would substantially reduce the potential for bait shyness to develop and might be usefully extended to acute and subacute-acting toxicants. Possum-control researchers need to investigate the feasibility and cost-effectiveness of microencapsulating the current possum toxicants in cereal bait.

While not significant, there was an indication that there may be a difference in the effectiveness of the 0.08% and 0.13% 1080 paste and gel baits. The higher kill (80%) achieved with the 0.13% gel bait is similar to another pen trial where 77% of 1080 cereal bait-shy possums were killed using a 0.13% 1080 carrot bait (Morgan et al. 1996). These data suggest that the higher-concentration 1080 bait is more effective and thus should be used in all maintenance control operations. However, the lethality of a toxicant can be influenced by the bait used for administration (Talanov and Leshchev 1972; Medinsky and Klaassen 1996). For example, a recent analysis of the lethality of 1080 bait lethality has demonstrated that 1080 paste bait is less toxic than gel or carrot bait with equivalent toxicant concentrations due to different rates of toxin absorption (R. Henderson, unpubl. data). As detailed above, some possums are cautious of all bait following a sub-lethal dose and the low paste kill (40%) may be due in part to the lower lethality of the 1080 toxin in paste bait. Further studies are needed to: i) confirm that the 0.15% 1080 bait is more effective than the 0.08% 1080 bait in the same bait type; and ii) determine which 0.15% conc. 1080 bait (paste, gel and carrot) is the most effective at killing 1080 cereal bait-shy possums.

Currently, control using brodifacoum bait in stations and leg-hold trapping are the only proven means of controlling 1080 bait-shy possums in the field (Henderson et al. 1998). However, favourable results were achieved with all the toxicants when the bait matrix was changed. Researchers need to evaluate the field effectiveness of 0.15% 1080 in an unfamiliar bait (paste or gel) for maintenance control. Field trial studies investigating the efficacy of ground laid 0.15% 1080 paste or gel baits have demonstrated that they are suitable for use in the field (Wickstrom et al. 1997) and are significantly cheaper than using brodifacoum cereal bait (Thomas and Meenken 1995). As mentioned, there are also
major concerns about the fate of brodifacoum in the environment. While 1080 can kill non-target species (Powlesland et al. 1998) it is biodegradable and less likely than brodifacoum to accumulate in the food chain (Eason 1996). Other field trials investigating the secondary poisoning of stouts have recently suggested that 1080 may also have several advantages over brodifacoum as a secondary poisoning control technique (Moller and Alterio 1998). Finally, researchers should also trial the alternative, slower-acting toxicants in the new bait matrix. In my trials, this enhanced the effectiveness of these toxicants (providing a 100% kill) as possums were significantly less cautious of the new bait matrix. It is feasible that changing the type of bait will improve the field efficacy of cholecalciferol and brodifacoum for either initial or maintenance control operations.

There is also a need to verify that the most cost-effective control strategies identified in Chapter 6 are indeed effective in the field. As detailed in the literature review, the current goal of possum control is to achieve sustained possum population reductions (e.g., 60% or 80% reductions). At present there are at least 16 different possum-control methods in use in New Zealand (Henderson et al. 1998) and difficult decisions need to be made regarding the most cost-effective combination of these methods. Landcare Research has recently produced a contract report for the Department of Conservation identifying favourable control strategies for sustained possum control (Henderson et al. 1998). However, these strategies were derived from modelling simulations that did not consider the possibility that survivors of 1080 possum control campaigns may develop bait shyness, and also did not incorporate the relative costs of control using alternative possum toxicants. One of the recommendations of the Landcare report was to use brodifacoum every 3-4 years for maintenance control in moderate-large (1500 ha) sized control areas. As detailed in Chapter 6, I argue that brodifacoum is expensive and so should only be used as follow up to initial 1080 control or an unsuccessful 1080 control operation. Further studies are needed to: i) determine the effectiveness of various control strategies highlighted in Chapter 6; and ii) investigate rates of population recovery in different sized control areas. As detailed above, the most important factor influencing the frequency of control is the rate of population recovery. Actual timing of control may vary between different control sites, and can only be established by direct measures of population recovery and abundance.
To conclude, researchers should monitor levels of non-toxic bait consumption in regularly poisoned possum populations (e.g., control within endemic Tb areas). The pen trial studies in Chapters 3-5 and previous field trials, investigating acceptance of non-toxic bait, have suggested that innate neophobic is not a significant problem (Hickling, 1994; Morgan et al. 1986). However, regular poisoning has generated extremely neophobic population of rats in Europe (Quy et al. 1992) and possibly rabbits in New Zealand (Bell 1975; Fraser 1985).

As detailed in Chapter 2, genetic and behavioural mechanisms can interact and lead to very resistant populations (O’Connor and Matthews 1996). Accordingly, researchers should use non-toxic bait covered in Rhodamine fluorescent dye (refer Morgan 1982) to monitor the percentage of possums avoiding non-toxic bait (in regularly controlled areas) over time.

7.4 References


Thomas, M.D.; Hickling, G.J. 1995. An evaluation of bait stations containing sodium monofluoroacetate (1080) for sustained control of possums on farmland.


