CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

This thesis focuses generally on problems associated with the management of an exotic pest species, the European red fox (*Vulpes vulpes*), in the Australian environment. Specifically, I investigate factors affecting the efficiency of fox baiting practices on the central tablelands of New South Wales, Australia. This chapter provides a brief review of fox impact, biology, ecology and management before introducing the issues affecting baiting efficiency.

1.2 Exotic pests

The spread of exotic animal species is an increasing problem throughout the world (Van Driesche and Van Driesche 2000). The spread of exotics is a form of biological invasion, which by definition, occurs when an organism increases beyond its former range (Williamson 1996). It may be caused by natural movements of the species, although most invasions are due to the interventions of humans, whether accidental or deliberate (Williamson 1996, Mack *et al.* 2000). Irrespective of the cause, newly arrived species are seen as pests when they conflict with human interests (Olsen 1998), and successful colonisation is occurring with frightening regularity (Van Driesche and Van Driesche 2000; Lowe 2001). The epidemic of vigorous exotic species overwhelming native species has been described as a ‘globalisation of ecology’ and, at its endpoint, may result in a one world ecosystem (Lowe 2001).

Australia is home to many exotic pest species; the majority of these were introduced deliberately and were released for reasons including food and fibre production, hunting and sport, transport, pets or as a result of acclimatisation societies (Olsen 1998). Many species have successfully established wild populations in the relatively short period since European settlement (Rolls 1969) and are recognised as significant agricultural, environmental and social pests (McLeod 2004). Mice (*Mus domesticus*) eat and damage crops and stored grain, damage building infrastructure including electrical wiring, harass intensively housed stock, spread disease, and have significant social impacts, especially during plagues (Caughley *et al.* 1998). Feral pigs (*Sus scrofa*) range over 60% of the continent, damage grain, sugar cane and banana crops, degrade sensitive wetland areas, threaten native species, and carry diseases of stock and humans (Choquenot *et al.* 1996). Common mynas (*Acridotheres tristis*) damage horticultural crops, compete with native bird species for nesting sites and defecate profusely, fouling public places (Olsen 1998). Perhaps our best recognised vertebrate pest, the European rabbit (*Oryctolagus cuniculus*) continues to flourish and degrade the environment despite the relative success of myxomatosis and rabbit haemorrhagic disease (RHD) in reducing its numbers (Coman 1999; Story *et al.* 2004). However, relatively recent and increasing knowledge of the impacts of the European red fox has seen it become recognised as one of Australia's most significant vertebrate pests (McLeod 2004). Foxes have had a devastating effect on many wildlife species and have probably contributed to numerous extinctions of native fauna (Dickman 1996). A brief review of fox impacts in Australia is given below to demonstrate the deserved status of the study animal as a pest of national significance.

1.3 Fox impact

Environmental

Native mammals, birds or reptiles can constitute a large proportion of the diet of the fox (e.g. Green and Osborne 1981; Triggs *et al.* 1984) although this does not necessarily indicate whether the impact of predation is significant on these prey populations (NSW National Parks and Wildlife Service 2001). Few studies with adequate replication have been undertaken to quantify the impact of fox predation on prey populations, although there is ample evidence to suggest widespread and massive impact, all from direct predation (Dickman 1996). Predation of young-at-foot eastern grey kangaroos (*Macropus giganteus*) has been shown to reduce recruitment in south-eastern Australia (Banks *et al.* 2000). Foxes were responsible for taking 93% of tortoise (*Emydura* spp.) eggs from a Murray River site in South Australia (Thompson 1983), and significantly reduced the recruitment of juveniles (Spencer 2000 (Spencer and Thompson 2005)). Re-introduction experiments have also shown significant losses of translocated birds and mammals due to fox predation (Priddel and Wheeler 1989; Short *et al.*

1992). Evidence from removal experiments also supports these findings; studies in Western Australia have shown substantial population increases in a variety of marsupial species including rock-wallabies (*Petrogale* spp.), bettongs (*Bettongia* spp.) and numbats (*Myrmecobius fasciatus*), following the removal of foxes (Kinnear *et al.* 1988; Friend 1990; Morris 1992). Additionally, much anecdotal information suggests that vulnerable species appear to persist only in areas where foxes are absent or found in low densities, or in habitats that offer some protection from predation (e.g. the bridled nail-tailed wallaby, *Onychogalea fraenata,* in central Queensland) (Clancy 1994; Dickman 1996; Short *et al.* 2002; King and Smith 1985). NSW National Parks and Wildlife Service (2001) concluded that the impact of fox predation on the abundance of most native fauna is unknown, but the impacts appear to be greatest for medium-sized ground-dwelling and semi-arboreal mammals, ground-nesting birds and chelid tortoises, particularly those within the 'Critical Weight Range' of 35 g to 5500 g (Burbidge and MacKenzie 1989).

Foxes are thought to have played a major part in the demise and extinction of many ground-dwelling native species in the last 130 years (Short *et al.* 2002). The impact of fox predation has been recognised as a key threatening process under schedule 3 of the Commonwealth *Endangered Species Protection Act* 1992 and also under schedule 3 of the New South Wales *Threatened Species Conservation Act* 1995.

The environmental impact of foxes each year in Australia has been coarsely estimated at $190 million dollars per annum (McLeod 2004). This figure was based solely on the number of birds consumed by foxes each year (190 million) as estimated from the number of foxes presently in Australia (~7.2 million), their food intake, the average occurrence of birds in dietary studies (1%) and a 'value' of $1 per bird. This estimate relies on many assumptions but probably significantly underestimates the true cost since it does not account for other groups (reptiles, amphibians, mammals) lost to fox predation. It also fails to consider the cost of any surplus killing (see Short *et al.* 2002 for review) since it accounts only for items that are consumed. Regardless, the figure provided by McLeod (2004) is useful to provide a conservative estimate of the impact of foxes on the Australian environment.

Agricultural

Foxes are recognised agricultural pests, especially as predators of newborn lambs (*Ovis aries*) and goat kids (*Capra hircus*). Poultry are a favoured target, but losses to commercial poultry enterprises are usually insignificant since most are well protected (Moberly *et al.* 2004). The extent of lamb and kid losses from fox predation is difficult to measure (see Greentree *et al.* 2000; Moberly *et al.* 2003; Moberly *et al.* 2004); variations in flock health and management, together with seasonal factors may affect birthing percentages and juvenile mortality (e.g. Rowley 1970; Jordan and Orr 1989). These variations mean that primary fox predation is difficult to define and resulting estimates are usually based on direct observations of a small number of flocks. Regardless, studies have shown that foxes may take, or are perceived to take up to 30% of newborn lambs (Lugton 1993a; Heydon and Reynolds 2000), although estimates usually range between 0 and 10% (Dennis 1969; Rowley 1970; Mawson and Long 1992; Greentree *et al.* 2000).

Foxes are also known to cause damage, mostly nuisance, to various other enterprises through consuming various produce, such as horticultural crops (Olsen 1998) and/or chewing infrastructure such as irrigation equipment (S. Balogh, NSW Department of Primary Industries, pers. comm. 2003).

Disease

Foxes are hosts and potential vectors for exotic and endemic diseases, and parasites including ticks, tapeworms and lice (Mañas *et al.* 2005; Webster and Kapel 2005). Generally, little is known of the occurrence of pathogens and parasites within and impact on Australian fox populations (Saunders *et al.* 1995), but many could potentially be transmitted to domestic and/or human hosts.

Foxes are an important end-host of the hydatid tapeworm in some parts of the world (Hofer *et al.* 2000), but it appears that the incidence of infestation is very low in rural Australia (Saunders *et al.* 1995). However, they still may confer risks to human health, especially in urban areas (Jenkins and Craig 1992). Foxes are a significant carrier of the scabies mite, *Sarcoptes scabiei*, which causes severe itching, excoriation and skin inflammation leading to hair loss and mange. In Australia, scabies can result in extensive mortality of both foxes and wombats (*Vombatus ursinus*) (Bubela 1995; Kemp *et al.* 2002) and can afflict humans; a very high incidence (up to 50%) of scabies is found in some Aboriginal communities (Kemp *et al.* 2002).

In Europe and North America, foxes are the major host of sylvatic rabies and considerable effort is made annually to reduce persistence of this disease (Wandeler 1988; MacInnes and LeBer 2000). There are potentially a large number of domestic and wild mammalian host species for rabies in Australia, but canid species, including foxes, are likely to be the major vectors (Newsome and Catling 1992; Saunders *et al.* 1995). Foxes have an extremely high rate of rabies secretion in saliva (Steck and Wandeler 1980) and the behaviour (especially dispersal) and structure of fox populations ensures that rabies is maintained and spread rapidly. As a result, Australia relies heavily on quarantine and contingencies to avoid it becoming established (Saunders *et al.* 1995).

1.4 Biology and ecology of the fox

It is essential to have a sound understanding of an animal's biology and ecology to develop effective and efficient management strategies (Olsen 1998). Knowledge of a species morphological and physiological adaptations to the environment, its diet, behaviour, habitat use, reproduction and dispersal are all essential to understand the animal and develop approaches towards management (Caughley and Sinclair 1994). Such knowledge is especially important given recent pushes towards 'Achilles heel' methods that rely on developing highly-specific control techniques based on physiological, morphological, behavioural or biochemical differences between the pest and other species (Marks 2001). The following is a summary of fox biology and ecology, derived mostly from Australian studies.

Morphology

The red fox is a member of the Family Canidae, which includes carnivores such as wolves, jackals, and coyotes (*Canis* spp.). Foxes have long, slim bodies, tall slim legs, narrow muzzles, and bushy tails (Jarman 1986). The body of an adult fox generally ranges between

570 and 740 mm in length, with a tail length of 360-450 mm. Body weight ranges between 4.5 and 8.3 kg (Coman 1983) with an average of approximately 4.5 and 5.0 kg for females and males respectively (Saunders *et al.* 2002b). Both sexes suffer from seasonal fluctuations in body weight relating to either food and/or reproductive stresses.

Reproduction

Foxes are monestrous, reproducing once per year in spring. Females are reproductively active from July to October in south-eastern Australia (McIntosh 1963a; Ryan 1976; McIlroy *et al.* 2001). The gestation period is 51-53 days, with most cubs born during August and September (McIlroy *et al.* 2001). The mean litter size is four but ranges between one and ten (Saunders *et al.* 1995). Cubs are weaned after 4 weeks and become sexually mature after 10 months. Not all females in a population breed each year; the proportion of non-breeding vixens in the population is highly variable (Englund 1970) but generally increases with population density, probably due to the social suppression of reproduction in large groups. However, studies undertaken in New South Wales suggest very few non-breeding females (Saunders *et al.* 2002b), despite relatively high population densities (2-6 foxes per km^2).

Foxes use dens as secure sites to raise their offspring. Dens are typically a burrow with single or multiple entrances, but other structures that offer protection such as logs, rock piles, shrubs and even thick grass may be used as natal sites (Berghout 2001). Vixens usually prepare multiple dens and cubs may be moved several times during the cub-rearing period. Juveniles, particularly males, disperse from four months of age to seek their own territory.

Diet

Foxes are opportunistic predators and scavengers (Doncaster *et al.* 1991; Bubela *et al.* 1998b) and, although primarily carnivorous, will consume a large variety of both plant and animal material. Foxes are mostly solitary hunters and foragers but will occasionally coordinate these activities with other individuals, especially where food sources are localised. Items consumed are mainly mammalian (McIntosh 1963b; Coman 1973; Croft and Hone 1978). Where present, rabbits can make up a large proportion of their diet (Ryan and Croft 1974; Croft and

Hone 1978 (Saunders *et al.* 2004). Other food items commonly consumed include sheep (mostly as carrion), house mice, insects, reptiles and amphibians, birds, grains, vegetable matter, and fruit and vegetable crops such as melons, grapes, apples and blackberries (Woolley *et al.* 1985; Catling 1988; Lugton 1993b; Palmer 1995). The relative frequency of food items consumed varies with season and location (Croft and Hone 1978), reflecting abundance of prey more than prey preference (Ables 1975; Molsher *et al.* 2000).

Social structure and behaviour

Foxes are crepuscular, but are also active intermittently through the night (Berghout 2001). Foxes are normally solitary, but pairs form a close association during the breeding season. In Europe, the species is reported to form family groups consisting of an adult pair and subordinate vixens from the previous year's litter although this relationship may be flexible (e.g. Macdonald 1983; Voigt and Macdonald 1984 (Henry *et al.* 2005)). Each family group establishes a territory that is defended against foxes outside their family group. The predominant family group composition throughout Australia is probably a mated pair of adult foxes with a litter of cubs (Saunders *et al.* 1995; McIlroy *et al.* 2001) although more complex social structures, including non-breeding females, may be present (Bubela 1995; Berghout 2001).

Surplus killing of prey is a common behavioural trait; this is where foxes kill excess prey not intended for immediate consumption (Kruuk 1972). It is believed that surplus killing reflects the behaviour and response of the prey to predation, animals that behave 'abnormally' are more prone to be victims of surplus killing. However, foxes are known to store, or cache food that is not immediately consumed for use at a later date (Macdonald 1976; Sklepkovych *et al.* 1996), allowing greater opportunity to control food availability spatially and temporally (Vander Wall 1990).

Home range and movements

Foxes normally occupy well-defined home ranges with non-overlapping and stable borders. Home range size is generally proportional to the amount of resources it contains with greater productivity resulting in smaller home range (Harestad and Bunnell 1979; Macdonald 1980). However, home range size in territorial solitary foragers such as the fox may be set by the dispersion of the minimum number of food patches needed to sustain a pair of foxes. The productivity of those food patches dictates how many foxes can live with the primary pair in a group territory (Macdonald 1981, 1983; Kruuk and Macdonald 1985; Moehlman 1989).

Foxes can travel up to 10 km per day (Jarman 1986). Long distance movements are usually restricted to the dispersal phase, when juveniles disperse to find their own territory. Foxes usually disperse short distances (Coman *et al.* 1991) but quite considerable distances have been reported; Berghout (2001) recorded a straight-line distance of 285 km for one vixen on the central tablelands of New South Wales.

Distribution and abundance

The fox is a widespread species, with populations located in North America, Europe, North Africa, Asia and Australia (Long 2003). The worldwide distribution indicates that red foxes will adapt to and survive within a variety of different habitats, ranging from arctic tundra to semi-arid and arid areas (Saunders *et al.* 1995). Fox density within each environment varies greatly, with the more productive environments supporting higher densities of foxes. Studies in Australia suggest that fragmented landscapes, offering open areas for foraging and woodland areas for shelter, are highly favoured (Jarman 1986).

Fox density fluctuates considerably throughout the year, with the highest density occurring following whelping and the lowest during the mating season (Saunders and McLeod *in press*). This is because foxes breed only once per year, while mortality progressively reduces the population size until the following breeding season.

Fox populations are not static, with seasonal patterns of dispersal resulting in constant change (Trewhella 1988). The majority of dispersal occurs in juvenile males from late summer until early winter (Saunders *et al.* 1995). However adults are also known to undertake long-range movements to establish or extend territories. Such movements result in recolonisation of areas where foxes have been removed, and can occur rapidly (see Molsher 1999).

1.5 Management practices

Management strategies

There are three basic management strategies to alleviate problems caused by exotic pest species: exclusion, eradication or control (Bomford and O'Brien 1995; Courchamp *et al.* 2003). Exclusion is where the exotic species is excluded by means of a physical barrier (e.g. fence) from the area where it causes damage. This is only a local solution since its effectiveness is limited to a specific, usually small, area; it is not suitable for management of a widely distributed exotic species on a landscape scale. Regardless, exclusion may be effective and warranted, particularly to protect rare or threatened species, in situations where prey are confined to a small area, and/or for intensive enterprises where the economic benefits of exclusion exceed the costs (Long and Robley 2004).

Eradication is the complete removal of all individuals from a population, down to the last reproducing individual, or a reduction in the density to below self-replacing levels (Myers *et al.* 2000). Courchamp *et al.* (2003) suggest that eradication is the optimal response for managing the impacts of exotic species on islands. Eradication from islands is generally simplified compared to more widely distributed populations since the geographical scale is limited, and the isolation from other populations reduces the potential for reinvasion and recolonisation. As a result, there has been much successful eradication of exotic species from islands (see Courchamp *et al.* 2003 for review). For example, combinations of up to 12 mammal species (ranging from rodents to ungulates) have been removed from many New Zealand islands up to 2000 ha (Veitch and Bell 1990 in Mack *et al.* 2000). Even larger islands have been successfully eradicated; in 2000 feral pigs (*Sus scrofa*) were finally removed from Santiago Island (58,465 ha) part of the Galapagos group, after a 30-year campaign (Cruz *et al.*

2005). Critical to the success of this program was the sustained, dedicated control effort, the use of multiple control techniques (poisoning and hunting), the improved hunter access to pigs from additional trails and the intensive pig activity monitoring program (Cruz *et al.* 2005). However, even on mainland areas eradication of an exotic pest species is feasible, particularly is it is detected early and resources can be applied quickly and effectively (Simberloff 1997). One example of successful eradication from a mainland area is the removal of the coypu (*Myocastor coypus*), a large South American rodent, from marshes in south-western England after a 50 year campaign (Gosling 1989). Coypu were finally removed through undertaking an intensive, 8 year cage-trapping campaign costing £2.5 million, despite the presence of only a small population distributed over a relatively small area (Gosling 1989).

Such accomplishments demonstrate the ability to eradicate substantial populations of exotic mammals under suitable conditions. Where eradication has been successful, three key factors have contributed to the success: 1) the biology of the pest species was susceptible to the technique/s applied; 2) a sufficient level of resources was devoted for a sufficient duration; and, 3) there was widespread support from relevant agencies and the general public (Mack *et al.* 2000). For example, Cruz *et al.* (2005) reported that eradication, rather than sustained control of feral pigs on Santiago Island was favoured due to convincing biological (effective eradication techniques, potential non-target impacts), economic (limited conservation funds) and political (management pressure to reduce ecosystem degradation) arguments. If any of these criteria are not met, as is common in many circumstances faced by wildlife managers, eradication is simply not achievable (Braysher 1993; Caughley and Sinclair 1994; Bomford and O'Brien 1995). In many cases, eradication may be biologically feasible, but is limited by its high social, political and economic costs (Bomford and O'Brien 1995).

In contrast to islands, there has been no widely established population of an exotic species eradicated on any continent, despite enormous efforts (Bomford and O'Brien 1995). As a result, exotic species populations are usually controlled by means of regular population reduction rather than for the aim of eradication (Braysher 1993). Although control is usually more feasible than eradication, the gains from control are temporary. Since the reduction in density is not complete, control programs require constant or continued suppression to keep the population at low density (Courchamp *et al.* 2003). Undertaking regular population reductions of the exotic predator species rely on reducing the density of the pest species sufficiently to achieve 'acceptable' levels of impact upon the prey. Once such example is the fox baiting program developed to reduce the fox predation threat to loggerhead (*Caretta caretta*), green (*Chelonia mydas*) and hawksbill turtles (*Eretmochelys imbricata*) (Flakus 2002). The Australian coastline between Bundaberg and Town of 1770 is baited to coincide with the turtle nesting (October) and hatchling seasons (January/February) in addition to fox dispersal (April). At Wreck Rock, the level of fox activity has been monitored in conjunction with the level of nesting success. There have been significant increases in the hatching success of clutches laid with the reductions in fox activity resulting from fox baiting programs. Fox activity and predation has been significantly reduced; less than 1% of nests have been lost to foxes or dogs compared to up to 90% in the 1970's and 1980's (Limpus and Reimer 1994; Flakus 2002). Without the continued suppression of foxes through baiting, hatching success is likely to return to very low levels (Flakus 2002).

However, largely due to the paucity of information relating to the relationship between fox density and damage, control methods in Australia have traditionally focused on reducing fox abundance rather than specifically on reducing fox-related damage (Saunders *et al.* 1995). The control techniques commonly employed on both agricultural lands and conservation areas include poisoning, shooting, trapping, den fumigation and destruction, and exclusion fencing. Alternative management techniques, such as immunocontraception, taste aversion conditioning, and chemical deterrents are continually being researched, but none are currently in commercial use.

Shooting

Shooting is commonly employed to reduce fox numbers at a local level, especially on pastoral properties. Shooting at night with the aid of a spotlight is favoured since foxes have a very bright, characteristic eyeshine that allows them to be easily seen at large distances. Broad-scale reductions of foxes through shooting are labour intensive, with considerable effort required to target foxes within the area, especially as density decreases. There is also evidence to suggest that shooting selectively targets juvenile foxes, with older, more wary animals escaping (Englund 1980; Coman 1988; Parker 2002). Despite the lack of thorough evaluation, shooting is unlikely to be an independently effective and efficient technique for broad-scale reduction of fox numbers or impacts given these issues.

Trapping

Trapping is not suitable for undertaking large-scale control of foxes and generally lags behind poisoning and shooting in popularity (West and Saunders 2003). Soft-jawed, cage-style, or treadle-snare traps are the most commonly used (Fleming *et al.* 1998). Trapping is a labour-intensive and highly-skilled task (Baker *et al.* 2001). Kay *et al.* (2000) reported low trapping success in central-western New South Wales, with approximately 150 trap nights required to capture one fox. Such a labour-intensive effort, together with the need to check traps daily for welfare concerns, makes it inefficient for broad-scale fox control. However, it may be very effective for localised problems where small numbers of foxes are responsible, or in closely settled or populated areas where other techniques are unable to be used (Bubela *et al.* 1998b).

Den fumigation and destruction

Fumigation and destruction of breeding dens or earths can be very effective in reducing fox numbers. In most cases these techniques are used to target cubs, but adults may also be killed. Dens are fumigated during the whelping period, generally during August/September (Saunders *et al.* 1995). Dens are primarily used from early spring to summer; during other periods in the year they are used sporadically or are inactive.

Exclusion fencing

Fences may be designed to be totally exclusive or simply to reduce crossings by foxes. Foxes are agile and capable climbers and strong diggers, so most fence designs involve barriers to restrict these activities. Other designs, such as simple electrified fences, rely on avoidance learning rather than direct exclusion (Patterson 1977). Coman and McCutchan (1994) found that most fences provide an incomplete barrier to foxes. Constant fence maintenance, monitoring and quick action to remove any foxes that breach the barrier are essential to ensure that fences remain effective. Additionally, consideration must be given towards integrating control with exclusion (Coman and McCutchan 1994) to ensure that fences remain effective.

Exclusion fences are expensive to construct and maintain. Coman and McCutchan (1994) provided examples where fox exclusion fences have cost between $18 000 and $50 000 per kilometre to construct. As a result, exclusion fencing is usually restricted to protecting rare or threatened species, situations where prey are confined to a small area, and/or intensive enterprises where the economic benefits of fences exceed construction and maintenance costs (Long and Robley 2004).

Guard animals

Livestock guard dogs have been used for thousands of years to protect stock from predators (De la Cruz 1995; Rigg 2001). Other animals, including alpacas (*Lama pacos*), llamas (*Lama glama*) and donkeys (*Equus asinus*) are aggressive towards canids (Andelt 2004) and are becoming increasingly popular in Australia to protect stock from fox predation (Jenkins 2003).

Overseas studies have reported that livestock guard animals substantially reduce predation on sheep or goats by a range of predators, including foxes (Jenkins 2003). The level of effectiveness depends on a number of flock management and environmental factors, such as:

- prey species and response to predation
- the density of guard animals to prey
- the protective response of the guard animals
- the size, habitat and topography of the paddock where prey are located
- the number and density of the prey
- predator density

Factors that reduce the ability of a guard to observe or defend the flock will ultimately reduce its effectiveness. The physical constraints of guarding large areas and the need for a high ratio of guard to prey effectively limits the application of the technique for most situations (Andelt 2004). Despite this, there are many anecdotes about the effectiveness of guard animals. However, replicated studies need to be undertaken to assess the effectiveness of guards under Australian conditions (Jenkins 2003).

Fertility control

Limiting recruitment through fertility control may be a humane and cost-effective alternative to lethal control for reducing long-term fox impacts (McIlroy *et al.* 2001). It may be undertaken through use of a chemical abortifacient to induce miscarriage or abortion (Marks *et al.* 1996) or potentially via immunocontraception, which utilises the animals own immune system to block reproduction. Generally, modelling indicates that immunocontraception will be effective in reducing the rate of increase of fox populations (Hone 1992; Pech *et al.* 1997), but, as for chemical abortifacients, it is likely that animals would have to be re-treated again during their fertile lifetimes (G. Reubel, Pest Animal Control Cooperative Research Centre, pers. comm. 2003). This would make it less cost-efficient compared to lethal baiting programs at reducing either recruitment or fox-associated damage.

Although initial work has been undertaken to manufacture a self-disseminating virus to induce immunocontraception (Seamark 2001), the final form of the contraceptive is likely to be a bait-delivered vaccine (Bradley *et al.* 1997). Continuing research by the Pest Animal Control Cooperative Research Centre (now Australasian Invasive Animal Cooperative Research Centre) may see its development in the future.

Poisoning

The management of foxes on agricultural and conservation lands in Australia relies most heavily on poison baiting. In New South Wales, the use of 1080 for fox control has increased rapidly during the last 20 years; less than 50,000 baits were laid each year in the mid 1980’s, but this increased to over one million in the late 1990's (Thompson *et al.* 1991; Saunders *et al.* 1995; West and Saunders 2003). In the current decade usage across the state remains high but overall growth has reached an asymptote (H. McKenzie, NSW Department of Primary Industries, pers. comm. 2002). However, several areas of the state, including parts of the central tablelands, have experienced increases in overall effort for controlling foxes (West and Saunders 2003), indicating recognition of the fox problem and the need to undertake fox management. A survey of Rural Lands Protection Boards (RLPBs) in New South Wales indicated that baiting amounted to 74% of control effort for foxes in 2002 (West and Saunders 2003), further demonstrating our critical dependence on poisoning with 1080 for fox control.

Poisoning is undertaken by distributing poison bait across the landscape. Bait in New South Wales must be buried (5-10 cm depth) (Environment Protection Authority 2002) as a measure to prevent uptake by non-target species (Allen *et al.* 1989), although aerial baiting is permitted in some western areas under restricted circumstances e.g. Yathong Nature Reserve for protection of malleefowl (*Leipoa ocellata*). Current directions indicate that fox baits shoul be laid at no closer than 100 m intervals (recommended 200-500 m) (Environment Protection Authority 2002) in prominent positions close to roads, fencelines and along other distinct habitat ecotones to maximise the chance of uptake (Korn and Lugton 1990). Additional directions for use include: checking and replacing baits at regular intervals, retrieving and destroying (by deep burial or burning) any untaken baits at the end of the campaign, and destroying baits within 4 weeks of purchase (see Appendix 1).

A variety of bait types has been used to target foxes, but in New South Wales bait types are limited to fowl heads, fowl eggs, chicken wingettes, boneless red meat, offal (i.e. tongue, liver or kidney) and manufactured bait (Environment Protection Authority 2002). Choice of bait type is largely a result of personal preferences of the practitioner and availability of the substrate from the RLPB. The commercially manufactured Foxoff® bait is the most commonly used, comprising over 48% of baits distributed to landholders in 2001 (West and Saunders 2003). Chicken heads were popular, but concerns regarding leakage of 1080 solution following preparation means that their continued use is discouraged (D. Croft, NSW Department of Primary Industries, pers. comm. 2000). Chicken wingettes are becoming favoured and are perceived to be highly palatable (D. Bate, NSW Department of Primary Industries, pers. comm. 2000, and T. Abblett, Wentworth Rural Lands Protection Board, pers. comm. 2001). Their use is increasing; ten percent of RLPBs used wingettes in 2001 despite being introduced only in 1998 (West and Saunders 2003).

Sodium monofluoroacetate (1080) is the only toxin registered in New South Wales to target foxes and is favoured throughout Australia for its cost-efficiency (Saunders *et al.* 1997a), relative target selectivity (e.g. McIlroy 1986), and low environmental persistence (Twigg and Socha 2001). Canids are particularly susceptible to fluoroacetate; the LD_{50} for foxes is generally accepted as 0.013 mg kg^{-1} (McIlroy and King 1990). Despite this sensitivity, fluoroacetate poisoning is characterised by a latent period, with symptoms generally appearing between 30 minutes and 4 hours after consumption (Chenowith and Gilman 1946; Egekeze and Oehme 1979; Sheehan 1984; Staples *et al.* 1995) and mean time to death in foxes occurring after 4 hours (Marks *et al.* 2000).

A variety of techniques is utilised on both agricultural and conservation lands for fox control in Australia but, despite pushes towards development of new lethal and non-lethal control measures, we are still critically reliant upon the use of 1080 poison. Given the lack of alternatives, this dependence is likely to continue into the future, especially in areas where overall control effort appears to be increasing (e.g. central tablelands) (West and Saunders 2003). However, many issues pertinent to its use remain equivocal and/or contested. It continues to be plagued by ethical concerns about its humaneness (Rammell and Fleming 1978; Marks *et al.* 2000; RSPCA 2003) and (see Sharp and Saunders *in press* for review). There is some evidence that animal populations exposed to 1080 over long periods can develop forms of genetic resistance (Twigg 2001), potentially reducing the efficacy or effectiveness of control operations. There are also concerns with non-target species uptake and consumption, particularly where the susceptible spotted-tailed quoll (*Dasyurus maculatus*) is present (NSW National Parks and Wildlife Service 2001); and there are questions about its cost-effectiveness (Saunders and McLeod *in press*). Therefore, it is essential to look for viable alternatives to 1080. Meanwhile, improvements to the current techniques are required to ensure that it is undertaken in an efficient and effective manner.

The following section will identify and introduce some of the factors that influence baiting efficiency.

1.6 Factors influencing the efficiency of baiting campaigns

The efficiency of baiting programs will be influenced by complex interactions between behavioural and logistical factors (Saunders and McLeod *in press*). Factors affecting the susceptibility of an individual to a bait, including bait palatability and toxicity, may be affected by other issues such as attraction to bait, density, presentation, and campaign timing, as well as distribution and replacement strategies. Additionally, the efficiency of programs will be affected by economic costs associated with the above factors. A broad overview of pertinent issues is presented here, but each will be covered in more detail throughout the thesis.

Bait degradation

Bait must retain its lethal dose of 1080 for a sufficient period to allow the target animal to find and consume the bait (McIlroy *et al.* 1986), but it must also degrade so long-term hazards to non-target species and environmental persistence are reduced (Twigg *et al.* 2000).

The 1080 in bait can be lost through the contribution of one or more of the following - defluorination by bacteria, fungi and other microbes, leaching by rainfall, consumption by sarcophagous insects or conversion to inorganic fluoride compounds (Korn and Livanos 1986; McIlroy *et al.* 1986; Kramer *et al.* 1987; McIlroy and Gifford 1988; Fleming and Parker 1991; Parfitt *et al.* 1994; Saunders *et al.* 2000; Twigg *et al.* 2000; Twigg and Socha 2001; Twigg *et al.* 2001). If 1080 is leached from the bait, the presence of defluorinating micro-organisms will ensure that 1080 will not persist in the environment (Twigg *et al.* 2000). However, given that degradation is not consistent for each bait substrate (e.g. Wong *et al.* 1991; Saunders *et al.* 2000; Twigg *et al.* 2000; Twigg *et al.* 2001), the longevity of each bait type needs to be assessed with these considerations in mind. These considerations are the focus of Chapter 2.

Bait palatability and caching

Bait should be attractive and highly palatable to ensure that the target species will find and consume the bait upon discovery (Allen *et al.* 1989). However, several studies have shown that significant proportions of baits removed by foxes may not be consumed but stored, instead (Saunders *et al.* 1999; Thomson and Kok 2002); this caching may therefore entail a ‘waste’ of bait, and potentially reduce the efficacy and cost-effectiveness of baiting programs (Van Polanen Petel *et al.* 2001). Additionally, there may be concerns for the safety of non-target species where baits are cached, and hence are unable to be retrieved.

Caching is related to the palatability of the food, food availability and nutritional status of the predator (Scott 1943; Macdonald 1976; Van Polanen Petel *et al.* 2001); it is likely therefore that the intensity of caching will fluctuate seasonally with food availability and the annual reproductive cycle. It is important to assess the rate of bait caching for bait types across different seasons, and this issue is explored further in Chapter 3.

Bait aversion

All mammals can develop aversion to particular food materials (Prakash 1988). Bait aversion, or an acquired aversion to poison bait, is known to occur in many ‘pest’ mammal populations including rodents, possums (*Trichosurus vulpecula*) and coyotes (Sterner and Shumake 1978; Reidinger and Mason 1987; Prakash 1988; Hickling 1994) and usually results from the target animal ingesting a sub-lethal dose and becoming sick. This problem could potentially affect the efficiency of fox baiting programs, and is investigated in taste aversion trials in Chapter 4.

Baiting coverage

The long-term effectiveness of control programs is frequently hampered by the immigration of foxes back into areas from which they were removed (e.g. Molsher 1999). One strategy to counter this problem is to undertake control over relatively large areas, increasing the ‘area to edge’ ratio of the control area. This effectively isolates ‘core’ areas from most yearly immigrants by distance (Thomson *et al.* 2000). This strategy requires coordination between neighbouring landholders, especially where property sizes (or land management units) are relatively small. However, there have been few assessments to determine if this strategy is efficient, nor if it is being undertaken in an effective manner. I explore this issue using a case study in Chapter 5.

Pest abundance estimates

It is difficult to determine the efficacy of conventional poisoning programs since carcasses are rarely found, and typically used measures of abundance (e.g. spotlight counts) are inherently biased, or usually too variable to accurately detect changes in the abundance of the pest (Saunders and McLeod *in press*). This is especially true for the fox, where density seldom exceeds 4/km^2 and individuals are often cryptic. Better techniques are needed to allow for meaningful monitoring of abundance, and hence improved monitoring of management programs. I investigate the utility of one alternative method, counting breeding dens, in Chapter 6.

1.7 Study aims

In consideration of the factors influencing baiting efficiency of the fox, the aims of this study are specifically:

1. To determine the longevity of commonly used bait types in the central tablelands environment;
2. To confirm the presence of defluorinating micro-organisms in soil in eastern Australia;
3. To investigate the seasonal caching of commonly used bait types by foxes;
4. To investigate the potential of conditioned taste aversion (CTA) to reduce multiple bait uptake by individuals;
5. To investigate the effectiveness of current fox control strategies on a landscape scale;

6. To investigate fox density in the central tablelands to assist in developing/refining monitoring techniques; and
7. To investigate the cost-effectiveness of identified baiting strategies

1.8 Study area

The study was conducted on agricultural lands near the town of Molong ($33^0$10’37”S, $148^0$87’15”E; Figure 1.1) on the central tablelands of New South Wales. Several properties in this district were used for different aspects of this study. Each will be explained in greater detail in subsequent chapters, where relevant.

The central tablelands is representative of the agricultural lands of south-eastern Australia, being highly disturbed and modified by land use associated with human settlement and development (Allan 1999). Most suitable farming and grazing country has been cleared (50% of natural vegetation has been lost: NSW National Parks and Wildlife Service (2002), resulting in a highly fragmented landscape consisting of remnant patches of natural vegetation surrounded by agricultural lands (Goldney 1987).

The Molong district is typically temperate with cool to cold winters and warm to hot summers (Sturman and Tapper 1996). The mean daily temperatures in July range between -0.1 – 12.9^0C while in January the mean ranges between 13.3 and 31.0^0C (Figure 1.2). The annual mean rainfall is 707 mm and mean monthly rainfall is reasonably consistent and is neither summer nor winter dominant (Gentilli 1972 in Sturman and Tapper 1996; Bureau of Meteorology 2003). Monthly rainfall varied considerably during the study period (Figure 1.3), and annual rainfall ranged between a high of 777 mm in 2000 to below 420 mm in 2002. The relationship between mean monthly rainfall and observed rainfall, presented as a cumulative deficiency plot, is presented in Figure 3.1.

The majority of the district is gently undulating, but topography ranges from river flats to rolling and steep hills. Rock intrusions (mainly Ordovician, Tertiary, or Devonian associated) in the form of knolls and ridges are common (Packham 1969). Soil groups include krasnozems, red earths and red podzolic soils to the east and south of the town, grading to less fertile solodic soils to the west and north (Dwyer 1978; Murphy and Eldridge 2001).

Figure 1.1: Location of the central tablelands area (shaded black) in New South Wales (main) and Australia (inset).

Plant communities in non-cropping areas typically consist of open pasture interspersed with remnant trees such as white box (*Eucalyptus albens*), apple box (*Eucalyptus bridgesiana*), yellow box (*Eucalyptus melliodora*), blakelys red gum (*Eucalyptus blakelyi*) and mugga ironbark (*Eucalyptus sideroxylon*), although some patches of woodland remain. River red gum (*Eucalyptus camaldulensis*), river oak (*Casuarina cunninghamiana*) and weeping willow (*Salix babylonica*) are found along the banks of streams (Dwyer 1978). Further west, grey box (*Eucalyptus woollsiana*), narrow-leaved ironbark (*Eucalyptus crebra*) and cypress pine (*Callitrus glauca*) replace *E. bridgesiana* and *E. sideroxylon* (Dwyer 1978).

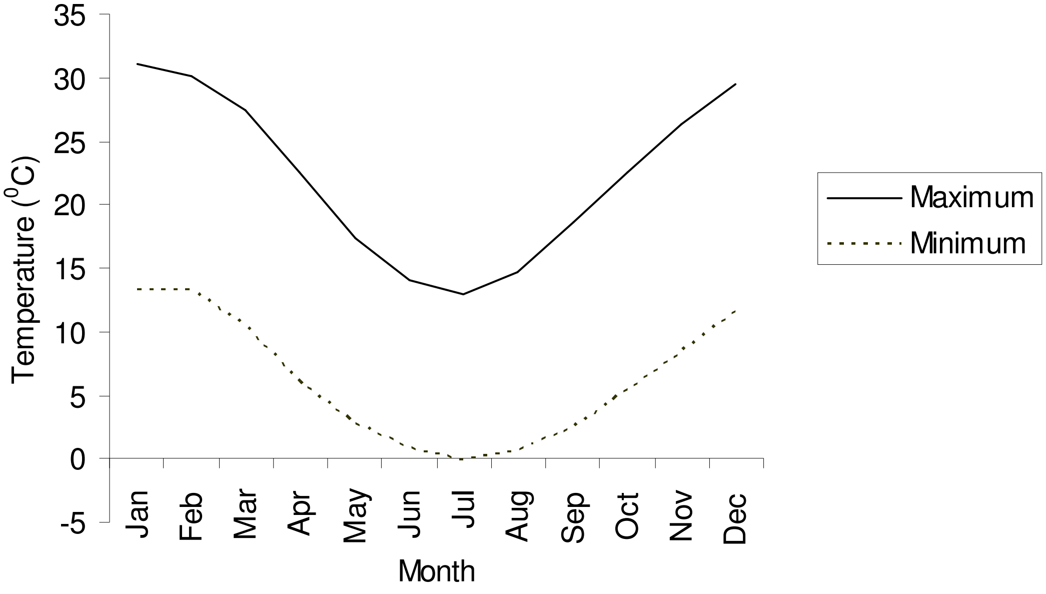

Figure 1.2: Mean daily minimum and maximum temperatures (^{0}C) for Molong from Bureau of Meteorology records (1884-2001).

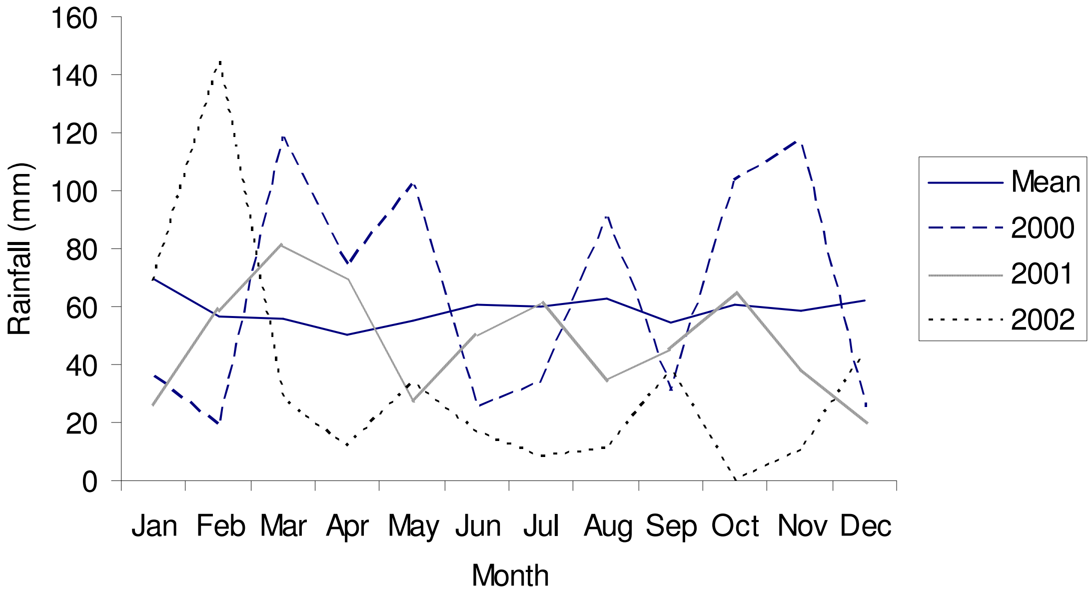

Figure 1.3: Mean monthly rainfall (mm) and the observed monthly rainfall prior to and during the study period (2000, 2001, 2002) for the town of Molong. Data sourced from the Bureau of Meteorology weather station at Molong, and monthly averages from historical records (1884-2001).

The central tablelands area produces a diverse range of agricultural commodities, with the higher altitude regions predominantly associated with horticultural enterprises with winter cereal cropping and sheep (meat and fibre) and cattle production more common on lower altitude lands. Extensive forestry (hardwood and plantation softwood) reserves also exist in patches throughout the region (Dwyer 1978; Australian Bureau of Statistics 2003).

Mammalian fauna

Settlement has brought about extensive, permanent changes to the environment and has led to the reduction and extermination of many indigenous species (Goldney 1987; NSW National Parks and Wildlife Service 2002). Regardless, many native species are reasonably common, including the eastern-grey kangaroo (*Macropus giganteus*), common wallaroo (*Macropus robustus*), swamp wallaby (*Wallabia bicolor*), common brushtail possum (*Trichosurus vulpecula*) and short-beaked echidna (*Tachyglossus aculeatus*).

Introduced free-ranging mammals that are common and widespread include foxes (*Vulpes vulpes*), hares (*Lepus capensis*) and mice (*Mus domesticus*), while rabbits (*Oryctolagus cuniculus*), feral cats (*Felis catus*), feral pigs (*Sus scrofa*) and feral goats (*Capra hircus*) are patchily distributed but may be locally abundant.

Selection of study area

The central tablelands area near Molong was chosen as the study area since it is broadly representative, in terms of land use, of a large region of New South Wales. Highly modified, fragmented landscapes like those on the central tablelands are highly suitable for foxes (Jarman 1986) and can support high density populations (e.g. Thompson and Fleming 1994). Conflict with land-use has meant that fox control is undertaken throughout the area, and is increasing at one of the highest rates throughout New South Wales (West and Saunders 2003). Additionally, much ecological research on foxes (e.g. Greentree *et al.* 2000; Molsher *et al.* 2000; Berghout 2001; McIlroy *et al.* 2001; Saunders *et al.* 2002a,b) has been undertaken in this region and are available to guide the current research.

1.9 Structure of the thesis

This thesis investigates factors affecting the efficiency of fox baiting in the central tablelands of New South Wales. It was motivated in part by acknowledgement from state government agencies (in particular the Department of Primary Industries) of problems associated with current management of foxes using poison baits, and in part by the lack of any solid theoretical or empirical underpinning of how such management should work.

The thesis consists of the present introductory chapter and 7 further chapters.

Chapter 2 compares the longevity of two commonly used bait types, Foxoff® and chicken wingettes, under field conditions on the central tablelands and western slopes of New South Wales. The presence and identification of soil micro-organisms capable of defluorinating 1080 in these areas is also investigated. The data were used to determine appropriate baiting strategies in terms of bait longevity and the potential for long-term environmental persistence and damage resulting from baiting campaigns.

Chapter 3 investigates the palatability and caching of Foxoff®, wingettes and day-old chicks under different seasons. Insights into caching behaviour are used to interpret the potential impacts of baiting campaigns and implications for baiting strategies

Chapter 4 assesses the use of conditioned taste aversion to reduce multiple bait uptake by individuals to improve the efficiency of baiting operations. Factors affecting the application of the technique in field situations are also investigated and discussed.

Chapter 5 documents the spatial and temporal coverage of baiting operations in the Molong Rural Lands Protection Board area. This case study is used to investigate baiting strategies on a landscape scale.

Chapter 6 determines fox density on one site on the central tablelands through evaluation of the density of breeding dens. The factors associated with finding and counting den locations and the implications of these for estimating fox density, are discussed.

Chapter 7 assesses the relative cost-effectiveness of using different bait types based on their longevity, palatability and cost during typical baiting strategies.

Chapter 8 is the general discussion. My findings are discussed in regard to other research, and the implications for management practices and directions for future research are considered.