Movement patterns of feral predators in an arid environment – implications for control through poison baiting

K. E. Moseby, J. Stott and H. Crisp

Abstract. Control of introduced predators is critical to both protection and successful reintroduction of threatened prey species. Efficiency of control is improved if it takes into account habitat use, home range and the activity patterns of the predator. These characteristics were studied in feral cats (Felis catus) and red foxes (Vulpes vulpes) in arid South Australia, and results are used to suggest improvements in control methods. In addition, mortality and movement patterns of cats before and after a poison-baiting event were compared. Thirteen cats and four foxes were successfully fitted with GPS data-logger radio-collars and tracked 4-hourly for several months. High intra-specific variation in cat home-range size was recorded, with 95% minimum convex polygon (MCP) home ranges varying from 0.5 km² to 132 km². Cat home-range size was not significantly different from that of foxes, nor was there a significant difference related to sex or age. Cats preferred habitat types that support thicker vegetation cover, including creeklines and sand dunes, whereas foxes preferred sand dunes. Cats used temporary focal points (areas used intensively over short time periods and then vacated) for periods of up to 2 weeks and continually moved throughout their home range. Aerial baiting at a density of 10 baits per km² was ineffective for cats because similar high mortality rates were recorded for cats in both baited and unbaited areas. Mortality was highest in young male cats. Long-range movements of up to 45 km in 2 days were recorded in male feral cats and movement into the baited zone occurred within 2 days of baiting. Movement patterns of radio-collared animals and inferred bait detection distances were used to suggest optimum baiting densities of ~30 baits per km² for feral cats and 5 per km² for foxes. Feral cats exhibited much higher intra-specific variation in activity patterns and home-range size than did foxes, rendering them a potentially difficult species to control by a single method. Control of cats and foxes in arid Australia should target habitats with thick vegetation cover and aerial baiting should ideally occur over areas of several thousand square kilometres because of large home ranges and long-range movements increasing the chance of fast reinvasion. The use of temporary focal points suggested that it may take several days or even weeks for a cat to encounter a fixed trap site within their home range, whereas foxes should encounter them more quickly as they move further each day although they have a similar home-range size. Because of high intra-specific variability in activity patterns and home-range size, control of feral cats in inland Australia may be best achieved through a combination of control techniques.

Introduction

Effective control of a pest animal species and its impacts typically relies on sound behavioural and ecological knowledge of the activity patterns, habitat use, diet and demography (Saunders et al. 1995). The feral cat (Felis catus) and red fox (Vulpes vulpes) are no exception, and control of these two species is often the most important management action required for successful re-establishment of threatened mammal species in Australia (Kinnear et al. 2002). The introduced red fox is also considered a key threat to many threatened species in North America (Lewis et al. 1999) and feral cats have been implicated in the extinction of several species in Mexico (Wood et al. 2002). The red fox has been successfully controlled in many areas with poison meat baits whereas feral cat control through poison baiting has often been less effective owing to poor bait uptake (Risbey et al. 1997; Kinnear et al. 1998; Burrows et al. 2003; Algar and Burrows 2004; Hegglin et al. 2004; Olsson et al. 2005; Algar et al. 2007). An understanding of feral cat and fox ecology can assist in optimising control methods, including the intensity, placement and timing of application of poison baits or traps (Harding et al. 2001; van Polanen Petel et al. 2001; Rountree 2004). Additionally, knowledge of feral cat and fox ecology aids in the development and correct interpretation of appropriate monitoring techniques.

Most Australian (Page et al. 1992; Meek 2003) and international studies (Panaman 1981; Mirmovitch 1995) investigating movement patterns and social behaviour in the domestic cat have focussed on urban and farm cats, with feral cats less well documented. Within Australia, feral cat home-range sizes of between 0.29 and 22.06 km² have been reported (Jones and Coman 1982; Schwarz 1995; Edwards et al. 2001; Burrows et al. 2003; Molsher et al. 2005). Although few studies
have been conducted in the arid zone, home ranges and movements of arid-zone feral cats appear to be much larger than in other environments (Edwards et al. 2001; Burrows et al. 2003), perhaps reflecting the lower productivity. Feral cat home-range size in other countries appears generally smaller, with average home-range sizes of 0.19 and 0.44 km² reported for females and males, respectively, on an island in South Africa (Apps 1986), and less than 3 km² recorded for average feral cat home ranges in Italy (Genovesi et al. 1995) and the Galapagos Islands (Konecny 1987).

Previous studies into feral cat home-range size in Australia (Jones and Conan 1982; Edwards et al. 2001; Burrows et al. 2003; Molsher et al. 2005) have been limited by small sample sizes (up to 15 individuals, although usually <6; Table 1), making reliable patterns of space use difficult to infer (Molsher et al. 2005). Few studies have linked results from ecological parameters to the design of control or monitoring programs, or have been designed to specifically test hypotheses regarding effectiveness of control. Reinvasion of feral cats into baited areas refers to the movement of cats from outside the baited zone into territories that have become vacant through the death of resident cats. Reinvasion has been poorly studied and is a critical factor in the design of successful control programs. Knowledge of feral cat movement will help determine when and how reinvasion occurs and assist in designing the optimal size of baited areas. Reinvasion pathways may also assist in identifying areas for additional control actions or opportunistic baiting.

There are a limited number of fox home-range and activity studies in Australia, with few in the arid zone. Home-range size of foxes is similar to that of feral cats and studies have reported sizes of between 0.3 and 28 km² (Coman et al. 1991; Phillips and Catling 1991; Meek and Saunders 2000; Burrows et al. 2003). Fox home-range size has been studied more extensively overseas, with home ranges of 0.45–9.28 km² reported by Trewhella et al. (1988) for Europe and North America and 8.5 km² at a desert site in Saudia Arabia (Macdonald et al. 1999). Home range of urban red foxes in North America averaged between 2.12 and 3.04 km² (Rountree 2004). Comparatively more studies have been conducted on the effect of poison baiting on foxes than on cats, with most studies indicating that baiting can be highly effective both in Australia (Kinnear et al. 1998; Thomson and Algar 2000; Olsson et al. 2005) and overseas (Hegglin et al. 2004). Thomson et al. (2000) found that reinvasion of a baited area occurred faster in autumn, possibly owing to dispersal of juveniles. For a core area to be kept free of foxes, the population in a ‘buffer’ zone around the core area must be kept as low as possible to maintain an effective ‘dispersal sink’ (sensu Thomson et al. 1992).

Arid Recovery is a conservation reserve in northern South Australia where rabbits, feral cats and foxes have been eradicated and excluded from a large fenced exclosure for the protection of threatened species. Feral cats in the region are wild and independent of any human contact, the nearest town being more than 25 km from the Reserve. Poison baits are laid outside the reserve, within several kilometres of the Reserve fence, to reduce the likelihood of foxes and feral cats breaching the fence and also to attempt to increase the area of habitat available for threatened species. Monitoring results from aerial baiting trials conducted between 2002 and 2006 at Arid Recovery have suggested that data from radio-collaring and spoor-count techniques produce conflicting results (Arid Recovery, unpubl. data). Although a large proportion of radio-collared feral cats died after 1080 baiting, there was often no detectable change in spoor counts in the baited region. In contrast, fox spoor counts were significantly lower on baited transects than on control transects after poison baiting. Several factors could be contributing to this conundrum; there may be an increase in the activity of unpoisoned resident feral cats after baiting, whereby they increase their home range to take over areas left vacant by baited animals. Christensen and Burrows (1995) found that feral cat density appeared to

---

Table 1. Comparison of the home ranges of cats and foxes between the present study (shaded) and previous studies in Australia and New Zealand

<table>
<thead>
<tr>
<th>Location</th>
<th>Landscape</th>
<th>Mean home range (km²)</th>
<th>Sample size</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Male</td>
<td>Female</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>32.32*</td>
<td>20.78*</td>
<td>7</td>
</tr>
<tr>
<td>South Australia</td>
<td>Arid rangelands</td>
<td>22.10</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>North Western Territory</td>
<td>Semi-arid woodlands</td>
<td>13.50*</td>
<td>7.00*</td>
<td>2</td>
</tr>
<tr>
<td>Western Australia</td>
<td>Arid desert</td>
<td>6.2*</td>
<td>1.7*</td>
<td>4</td>
</tr>
<tr>
<td>Victoria</td>
<td>Semi-arid mallee</td>
<td>4.23*</td>
<td>2.38*</td>
<td>11</td>
</tr>
<tr>
<td>New South Wales</td>
<td>Agricultural/open woodland</td>
<td>2.40*</td>
<td>2.39, 0.86*</td>
<td>4</td>
</tr>
<tr>
<td>Tasmania</td>
<td>Open forest</td>
<td>1.54*</td>
<td>0.29*</td>
<td>2</td>
</tr>
<tr>
<td>Red fox</td>
<td>Arid rangelands</td>
<td>28*</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>Western Australia</td>
<td>Arid desert</td>
<td>7.2*</td>
<td>5.0*</td>
<td>1</td>
</tr>
<tr>
<td>Victoria</td>
<td>Agricultural</td>
<td>1.38*</td>
<td>1.32*</td>
<td>9</td>
</tr>
<tr>
<td>South-eastern Australia</td>
<td>Coastal wilderness</td>
<td>0.7*</td>
<td>1.3*</td>
<td>2</td>
</tr>
<tr>
<td>Victoria</td>
<td>Semi-urban</td>
<td>0.23*</td>
<td>0.3*</td>
<td>4</td>
</tr>
</tbody>
</table>

* = 95% minimum convex polygon.
\* = 100% minimum convex polygon.
^-hawke’s Bay female cat home-range size includes cats from both pasture and swamp habitat respectively.
increase after aerial fox baiting at an arid zone site in Western Australia. This increase was thought to be due to a change in cat behaviour after the reduction in fox and dingo density. Alternatively, animals captured in cage traps for radio-collaring may be hungry, inefficient hunters more likely to take baits than trap-shy animals. Finally, reinvasion may occur almost immediately after baiting, leading to no detectable change in spoor counts. To facilitate effective feral cat control in the region and determine the factors influencing the inconsistencies in monitoring results, monitoring of spoor counts and radio-collared feral cats and foxes both before and after a baiting event is required.

The aims of the present study were 2-fold; firstly to collect information on temporal activity patterns, short-term movements, home ranges and habitat use of feral cats and foxes in order to recommend ways in which to improve control techniques; and secondly, to compare these parameters before and after an aerial baiting event, in order to understand spoor-count monitoring results. GPS data-logger collars were used in an attempt to provide accurate and statistically robust datasets.

Materials and methods

Study area

The study was conducted between April and August 2006 within a 50-km radius of the Arid Recovery Reserve in northern South Australia (30°29’S, 136°53’E). The climate is hot and dry, with a long-term average rainfall of 166 mm per annum. The rainfall recorded in the 12 months prior to the study was 168 mm. The minimum and maximum daily temperatures recorded during the study period averaged 5.4°C and 28.6°C respectively.

The study area supports a variety of habitats and associated vegetation, including dunes (*Acacia ligulata* and *Dodonaea viscosa*), sandplains (*A. aneura* and *Calitris glaucophylla*), chenopod swales (*Atriplex vesicaria* and *Maireana astrotricha*), swamps (*Eragrostis australasia*), claypans and creeklines. Thicker vegetation is present on dunes, whereas swales support more open, low vegetation (Finlayson and Moseby 2004). Feral cats, red foxes and European rabbits (*Oryctolagus cuniculus*) were present throughout the study area, which is primarily used for cattle (*Bos taurus*) grazing. Feral cat and fox densities in the study region fluctuate according to seasonal conditions but averaged approximately 0.8 and 0.6 per km², respectively, over a 10-year period when last measured several years prior to the study (Read and Bowen 2001). Regional targeted control is limited to irregular shooting from amateur shooters. Rabbit densities during the study period were estimated by spotlight counts, and averaged between 51 and 55 per km² (BHP Environmental Department, unpubl. data). Before the introduction of rabbit haemorrhagic disease in 1995, rabbit density averaged between 100 and 150 per km² (BHP Environmental Department, unpubl. data).

The Dog Fence, a vermin proof fence that prevents dingoes (*Canis lupus dingo*) from accessing sheep-grazing properties, bisects the study area. Dingoes are controlled to the south of the fence and 30 km to the north with poison meat baits (sodium fluoroacetate – 1080). The Olympic Dam Mine and Processing Plant are located in the centre of the study area (Fig. 1).

Aerial baiting

Aerial baiting with sodium fluoroacetate (1080; ‘Eradicat’) feral cat sausage baits (Department of Environment and Conservation, Western Australia (WA)) was conducted within a 20-km buffer of the Arid Recovery Reserve between 2003 and 2006 to control both cats and foxes. Although the Eradicat bait was developed to target feral cats, it is also highly effective against foxes (Algar and Burrows 2004). The 2006 baiting occurred on the 22nd and 23rd of May 2006. Baiting was conducted in the cooler months because previous research by Algar and Burrows (2004) suggested that bait uptake by cats in the arid zone is higher under cool, dry conditions in late autumn and winter. This is also the period when rabbit densities in the region are typically lowest (Bowen and Read 1998), and previous studies have shown that highest bait uptake is during periods of low rabbit abundance (Algar *et al.* 2007).

The 20-km radius baiting zone (1800 km²) was aerially baited with Eradicat baits containing 4.5 mg of 1080 per 30 g meat sausage (Department of Environment and Conservation, WA). A bait density of 10 baits per km² was used, and baits were individually dropped from the aircraft at intervals of one bait every 100 m, along 1-km-wide flight paths. Flight paths followed linear dunes to ensure that most baits were dropped on sand because previous trial results had indicated higher bait uptake by cats in this substrate (Arid Recovery, unpubl. data). An automated GPS recorded the location of all baits dropped during the program and ensured that no baits were dropped outside the 20-km radius boundary.

Although Algar and Burrows (2004) recommend an Eradicat bait density of at least 25 per km², bait density of 10 per km² was used in the present study because it was part of a series of aerial baiting trials that were conducted from 2002 to 2006. During these trials, various bait densities (including 10 and 25 baits per km²), bait types and baiting frequencies were trialled, and no clear relationship between bait density and decline in cat abundance emerged (Arid Recovery, unpubl. data). Studies in Western Australia have also recorded varying results, with 10 baits per km² resulting in >75% reduction in cat abundance in some years and only 25% reduction in others (Algar and Burrows 2004). Even at higher baiting densities of 50 baits per km², poor results have been recorded when prey species such as rabbits are in high abundance (Algar and Burrows 2004). The present trial was part of a quarterly baiting trial of 10 baits per km² to determine whether more frequent baiting at lower densities may assist in long-term reduction in cat abundance.

The project was conducted over a large area and as a part of a 5-year baiting trial in the region. Unfortunately, random assignment and replication of treatments were not feasible because of the requirements that the baited area be located around the Arid Recovery Reserve to protect reintroduced species, as well as funding constraints, the remote nature of the site and the large scale required for meaningful treatments. These limitations were compensated for to some degree by ensuring that control animals were obtained from both south and north of the baited area, by adopting a before, after, control,
impact (BACI) design (Stewart-Oaten et al. 1986) and, finally, by using between-animal variability to provide an estimate of variability for assessing treatment effects.

**Trapping and radio-collaring**
Feral cats were captured and fitted with radio-collars in the baited and unbaited control zones before the May 2006 baiting event, to allow before and after comparisons of movements. Seven cats were captured in the baited zone and seven in the control zone to the north and south of the baited zone to minimise differences due to rainfall, resource availability and habitat. Traps in the control zone were not set within 5 km of the baited zone edge; this distance was a compromise between minimising the number of cats and foxes with home ranges overlapping both treatments while still ensuring that the two treatments were close enough to share similarities in rainfall and habitat types.

Foxes were trapped only outside the baited zone, because previous results (Arid Recovery, unpubl. data) suggested that bait uptake was likely to be high, and few if any animals would still be

---

**Fig. 1.** Map of the study area, showing the MCP95 home range of all animals. FC = fox control, CC = cat control, CB = cat baited, AF = adult female, LM = large male, SM = small male. Hatched area designates 20-km-radius baiting zone around the Reserve. Home ranges are shaded so that areas of overlap can be observed.
alive after baiting to provide a pre- and post-baiting comparison of activity. Additionally, studying the reinvasion into the baited zone was considered a higher priority for foxes.

Feral cats and foxes were trapped with Victor Soft-Catch (No. 1.5) rubber jawed leg-hold traps (Oneida Victor Pty Ltd, Cleveland, OH). Two lures were used in association with the traps: 'pongo' (cat urine) and occasionally a felid attracting phonic, 'FAP' (Westcare Electronics, Perth). Cat urine was collected from euthanased feral cats and occasionally from live domestic cats with stainless steel litter trays. Food was not used as a lure, both to minimise capture of non-targets and because food may attract hungry, inefficient hunters that are more likely to take poison baits during the subsequent baiting session.

Traps were checked early each morning, and captured feral cats and foxes were restrained with gloves and towels, and anaesthetised with a mixture of metetomidine hydrochloride and ketamine administered intramuscularly. The anaesthetic was reversed using atipamezole hydrochloride. The cats and foxes were weighed, sexed and their snout–vent length recorded. The condition of their teeth, body and reproductive organs were also noted. Animals that died or were recaptured during the study were also examined and where possible the same details recorded.

Cats and foxes were divided into the following demographic categories on the basis of bodyweight, teeth condition and breeding condition: adult female, small male and large male. Females were classed as adult if they were pregnant or had offspring during the study period, identified by lactating or prominent teats or by palpating the abdomen for fetuses. Small male cats were less than 4 kg and had white, sharp, pointy teeth, whereas adult females and large males were heavier, with yellowing teeth that were blunt, chipped and sometimes missing.

Adult feral cats, and foxes that were 2.7 kg or heavier, were fitted with a 135-g (less than 5% of bodyweight) SIRTRACK (Havelock North, New Zealand) VHF and GPS data-logger collar. The collars were made of synthetic belting with a small buckle attached, and recorded GPS fixes every 4 h. The units were housed in epoxy resin and contained two antennas, micromouse GPS and 220-mm, 2NC-gauge whip antenna. The VHF (40/80 ppm) had a mortality sensor, triggered after more than 24 h without movement. Owing to delays in obtaining the collars, the feral cats inside the baited zone were captured first and fitted with temporary VHF collars until the GPS data-logger collars became available. Cats were recaptured with unbaited wire-mesh cage traps placed down entrances of rabbit burrows occupied by sheltering cats.

Between late April and August 2006, 13 feral cats and four foxes were radio-tracked weekly or fortnightly from a Cessna 172 aeroplane with a wing-mounted aerial to check for general location and mortality. If any collars had switched to mortality, the animal and collar were retrieved on the ground. Animals that were still alive 2 months after baiting were recaptured with wire cage traps placed down burrows, and euthanased. The only fox that remained alive after the study period was recaptured with rubber leg-hold traps set in den entrances. GPS downloads were conducted immediately after collars were retrieved, by using the SIRTRACK (Havelock North, New Zealand) download interface.

Data analysis

Data obtained from collars included the date, time, latitude and longitude, number of satellites and horizontal dilution of precision (HDOP). The HDOP ranges from 1 to 100 and is an estimation of the likely precision of the location as determined by the satellite geometry (Sirtrack GPS Receivers Manual, Sirtrack New Zealand, Havelock North, New Zealand). The HDOP can be multiplied by the receiver accuracy (in our case 6 m) to provide an estimate of accuracy. An average tracking resolution unit of 15.66 m was calculated by taking the average of all HDOP values and multiplying by receiver accuracy. Location fixes that were logged after the death of an animal were not included in the analysis.

Home range

Animals do not utilise their entire home-range area with equal intensity and tend to occupy certain areas with greater frequency than others (Dixon and Chapman 1980). The radio-collared cats and foxes followed this trend and for this reason, the following three scales of home-range activity were calculated: minimum convex polygon (MCP) using 95% of all fixes closest to the harmonic mean centre (MCP95); kernel analysis using 60% of fixes (KE60) (Worton 1989); and a more detailed analysis of temporary focal points (areas used intensively over short time periods and then vacated), such as shelter sites that were occupied within the total home range. Minimum convex polygon and kernel home-range analysis were calculated in Ranges6 (Kenward et al. 2003). Increment analysis was performed on each animal before home-range calculation for periods before and after baiting, separately, as well as combined. Only animals with home ranges that reached an asymptote were used in the analyses. Although foxes were not present in the baited area, changes in home-range size and daily distance moved were still compared before and after baiting, to assist with interpretation of feral cat results.

To identify the core home range we used an adaptive kernel analysis, with a smoothing parameter determined by least-squares cross validation (LSCV), incorporating 60% of all fixes. The adaptive kernel method was chosen because it varies the smoothing parameter in accordance with the concentration of points (Worton 1989). LSCV is considered a good smoothing parameter for higher numbers of fixes and provides a better picture of the underlying utilisation distribution (Worton 1989). KE60 was chosen by calculating kernel cores at 5% intervals and producing a utilisation distribution plot. In most animals there was a sharp or obvious discontinuity after the elimination of 40% of the outliers, indicating that a 60% core home range was most appropriate (Kenward et al. 2003). Effects of species, sex and demographics on core home ranges (KE60) and minimum convex polygons (95%) were quantified and statistically assessed by standard regression methods. To satisfy variance and distributional assumptions, both response variables were transformed by taking natural logarithms.

When all fixes were plotted using ArcView software (ESRI, Redlands, CA), clusters of radio-tracking fixes in extremely close proximity were observed. Clusters appeared to be areas used intensively over short time periods and then vacated. These clusters of fixes were called ‘temporary focal points’ and were
identified by using an adaptive kernel analysis with a smoothing parameter determined by LSCV in the Home Range Extension ver. 0.9 (HRE) for ArcView Geographic Information System (GIS) (Rodgers and Carr 1998). All areas that lay within the 0.2 contour of the kernel were deemed a focal point. However, if a temporary focal point was less than 50 m away from a neighbouring focal point, they were combined. For each focal point, the number of days it was used, time of use (day, night or crepuscular), habitat type, period of use (i.e. if they were used on consecutive days or over a non-consecutive period) and distance to the nearest focal-point neighbour were all recorded. At least three focal points for each animal were visited on the ground and the following observations were recorded: habitat type (e.g. dune, swale, sand plain or creek line), dominant vegetation species, presence of burrows and presence of spoor.

One way ANOVAs were used to determine whether the period over which temporary focal points were used and the total days visited varied among individuals of the same species. Cats and foxes were tested separately.

**Habitat use**

Location fixes with an HDOP value of $\leq 10$ (60 m) were overlaid on a satellite image of the region (Australia – Landsat ETM + Bands 742 Zone 53S 2000) in ArcMap and assigned to a habitat type. The following pooled habitat categories were used to increase sample size and facilitate $\chi^2$ analysis: dune/sandplain, creekline, canegrass swamp, swale (including swale, rockplain, breakaway), other (track, borrow pit, road, dam, fenceline, claypan). Each habitat type identified through aerial imagery was ground-truthed to ensure accurate identification. Points with more than one habitat type within the 60-m accuracy buffer were excluded.

In total, 300 random points were generated in Arcmap within a combined 2-km radius of all cat and fox captures sites. Each random fix was assigned to a habitat type and compared with the actual number of fixes in each habitat type for each cat and fox by using $\chi^2$ analysis. Because the heterogeneity $\chi^2$ analysis performed on pooled data for cats was not significant, individual cats were analysed separately. A $\chi^2$ test was also used to compare the habitat types of each fix with time of day for cats and foxes to determine whether different habitats were used at different times of day. Pooled data for all fixes within each species were used.

**Activity**

The minimum daily distance moved by cats and foxes was calculated by summing the linear distances between successive fixes during each day with a measuring tool in ArcMap. Only fixes that had an HDOP value of $<10$ and only days with four or more fixes were used. Minimum daily distances moved were compared between species, sexes and demographies. The minimum daily distance moved by cats in the baited and control areas was also compared before and after baiting to determine whether baiting affected movement of feral cats. General linear mixed model (Galwey 2006) analysis was used to model the effects species, sex, demography and interactions on the square root of minimum daily distance. The number of fixes used to calculate each minimum distance moved was included as a variable in the analysis because it assumed that the minimum distance moved would be influenced by the number of fixes recorded. This assumption was strongly supported by our data. Again animal ID was specified as a random effect to allow for possible animal-specific effects (intra-animal correlation) on minimum distance moved.

Each collar logged 4-hourly fixes at different times, rendering comparisons of diurnal movement patterns difficult. Each location fix was assigned a time category, as follows: crepuscular (0400–1130 hours, 1600–2330 hours), night (2000–0300 hours, 2400–0730 hours) and day (0800–1530 hours, 1200–1930 hours) on the basis of the time interval between successive 4-hourly fixes. The distance moved between successive fixes was measured with Hawth’s Tools (Beyer 2004) in ArcMap. For each 4-hourly interval the habitat type of the end fix was used to compare with distance moved during that period. Fixes along roads were given a separate habitat category to determine whether animals travelled further along roads than in other habitat types. A general linear mixed model analysis (Galwey 2006) was used to quantify and statistically assess the effects of species, habitat type, time of day and interactions between these factors on the logarithm of distance travelled. Animal was specified as a random effect to allow for possible animal-specific effects (intra-animal correlation) on distances travelled.

Maximum linear distance between the two furthest fixes recorded for each animal over the study period, regardless of date and time, was also calculated. If an animal followed the Arid Recovery feral-proof fence the maximum linear distance was measured around this impenetrable boundary (Moseby and Read 2006) rather than through it.

The GPS data logger collars are able to record a fix from satellites only when they have an unobstructed view of the sky. Some indication of the animal’s activity patterns can be obtained by recording the times that the collars were unable to log a fix, suggesting that the animals may be sheltering underground or under thick vegetation. The percentage of unlogged fixes recorded during each time category was determined for each animal.

**Calculating optimum baiting density**

The optimum baiting density was calculated for cats and foxes by using the minimum daily distance travelled each day and bait detection distance. Bait detection distance for cats and foxes is unknown; however, personal observations and consultation with feral cat and fox baiting experts (D. Algar, Western Australian Department for Environment and Conservation; A. Murray, Victorian Department for Sustainability and Environment) suggested that cats can detect Eradicat sausage baits within 5 m either side and foxes can detect Eradicat sausage bait and dried meat baits within 20 m. Foxes have a keen sense of smell and have been known to detect baits for up to 100 m or more; however, conservative estimates were used. Algar et al. (2007) assumed that cats passing within 3 m of a bait had been ‘in contact’ or at least detected the bait.

The following formula was used to determine the density of evenly spaced baits needed for a cat and fox to detect one bait in 3 days:

$$\text{No. of baits needed per square km to detect one bait in 3 days} = \frac{1}{[\text{dd} \times \text{dist}] \times 3}$$
where \(dd\) is the detection distance (0.01 km for cats and 0.04 km for foxes) and \(dist\) is the average minimum daily distance travelled in the present study (1.519 km for cats, 4.553 km for foxes). Three days was considered the optimum time for bait uptake, because baits are still fresh and there is a reduced risk of removal by non-targets. Non-target uptake of Eradicat baits by corvids and varanids has been reported to be as high as 22% per day in Western Australia (Algar et al. 2007) and 24% over 3 days at Arid Recovery (Arid Recovery, unpubl. data).

These calculations rely on the assumption that animals continually move through new areas of their home range and do not have fixed daily movement patterns where areas are reused. This assumption was tested by using actual daily movements of radio-collared cats and foxes. Hawth’s Analysis Tools in ArcMap 9.1 was used to reflect the bait intensity obtained from the equation for cats (22 baits per km\(^2\)) and foxes (1.8 baits per km\(^2\)) using dots placed on a grid pattern. For the purpose of the ArcMap tool, bait densities were rounded up to 25 for cats and 2 for foxes. Each radio-collared cat and fox was tested by connecting consecutive 4-hourly fixes and determining the number of days before a bait was encountered using the detection distances of 5 m either side for cats and 20 m for foxes.

**Results**

In all, 25 feral cats (1000–5350 g) and five foxes (4525–5550 kg) were captured during the study. However, owing to technical problems and size restrictions, only 13 feral cats (3 females, 10 males) and four foxes (2 females, 2 males; Tables 1, 2) were successfully radio-collared. Six cats were radio-collared in the baited zone, whereas seven cats and four foxes were radio-collared in the control zone (Table 2, Fig. 1). All female cats and foxes were reproductively active during the study.

Over a period of 172 days between April and August 2006, 3568 location fixes were obtained from the 17 radio-collared animals. High mortality was recorded among radio-collared individuals; only one died before baiting and the others died at regular intervals between 2 and 60 days after baiting. In all, 7 of the 11 control, and 3 of the 6 baited animals apparently died through either natural causes, or in the case of some cats, possible 1080 poisoning. The remaining seven animals were euthanased 2–3 months after baiting. CC5, a control cat, moved >15 km into the baited area and died the following day, possibly from 1080 poisoning. Mortality was highest amongst young male cats, with five of the six young males dying, compared with only one of the three adult females and one of the four adult males. Three of the four foxes in the control area died over the study period.

**Before- and after-baiting comparisons**

One of the aims of the study was to compare the movement patterns of feral cats before and after baiting. Two methods were used. First, comparisons were made between home-range size of individuals before and after baiting. Ideally, animals would have been captured at least 1 month before baiting to allow accurate prebaiting home-range determination; however, technical and logistical difficulties meant that only 5 of the 17 animals (two cats and three foxes) had home ranges that reached an asymptote before and after baiting. Both cats, one in the control and one in the

### Table 2. Field characteristics of radio-collared feral cats and foxes

<table>
<thead>
<tr>
<th>Animal</th>
<th>Demographic</th>
<th>Sex</th>
<th>Capture weight (g)</th>
<th>Total days tracked</th>
<th>Tracking period</th>
<th>Total no. of fixes</th>
<th>No. of days after capture</th>
<th>Death</th>
<th>No. of days after baiting</th>
<th>Total home range (km(^2))</th>
<th>Core home range (km(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cats</td>
<td>Baited</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(b)1(^a)</td>
<td>Adult female</td>
<td>F</td>
<td>4050</td>
<td>61</td>
<td>9.vi.06–8.viii.06</td>
<td>168</td>
<td>E</td>
<td>77</td>
<td>24.09</td>
<td>6.56</td>
<td></td>
</tr>
<tr>
<td>C(b)2(^a)</td>
<td>Adult female</td>
<td>F</td>
<td>3750</td>
<td>28</td>
<td>19.vi.06–16.vi.06</td>
<td>106</td>
<td>58</td>
<td>23</td>
<td>35.65</td>
<td>14.60</td>
<td></td>
</tr>
<tr>
<td>C(b)3</td>
<td>Large male</td>
<td>M</td>
<td>5350</td>
<td>8</td>
<td>25.vi.06–10.viii.06</td>
<td>23</td>
<td>E</td>
<td>79</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>C(b)4(^a)</td>
<td>Large male</td>
<td>M</td>
<td>5000</td>
<td>17</td>
<td>10.vi.06–8.viii.06</td>
<td>79</td>
<td>E</td>
<td>77</td>
<td>5.32</td>
<td>2.71</td>
<td></td>
</tr>
<tr>
<td>C(b)5(^a)</td>
<td>Small male</td>
<td>M</td>
<td>3130</td>
<td>94</td>
<td>20.vi.06–21.vii.06</td>
<td>399</td>
<td>92</td>
<td>60</td>
<td>5.52</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>C(b)6</td>
<td>Small male</td>
<td>M</td>
<td>2700</td>
<td>43</td>
<td>13.vi.06–4.vi.06</td>
<td>173</td>
<td>52</td>
<td>12</td>
<td>0.55</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(c)1(^a)</td>
<td>Adult female</td>
<td>F</td>
<td>3250</td>
<td>90</td>
<td>12.vi.06–15.viii.06</td>
<td>328</td>
<td>E</td>
<td>84</td>
<td>2.60</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>C(c)2</td>
<td>Large male</td>
<td>M</td>
<td>5250</td>
<td>106</td>
<td>29.vi.06–26.viii.06</td>
<td>550</td>
<td>E</td>
<td>95</td>
<td>20.68</td>
<td>7.20</td>
<td></td>
</tr>
<tr>
<td>C(c)3</td>
<td>Large male</td>
<td>M</td>
<td>5000</td>
<td>70</td>
<td>19.vi.06–29.vi.06</td>
<td>323</td>
<td>71</td>
<td>35</td>
<td>14.52</td>
<td>3.42</td>
<td></td>
</tr>
<tr>
<td>C(c)4</td>
<td>Small male</td>
<td>M</td>
<td>3500</td>
<td>46</td>
<td>19.vi.06–14.vii.06</td>
<td>211</td>
<td>56</td>
<td>51</td>
<td>131.98</td>
<td>34.97</td>
<td></td>
</tr>
<tr>
<td>C(c)5(^a)</td>
<td>Small male</td>
<td>M</td>
<td>3375</td>
<td>8</td>
<td>18.vi.06–26.vi.06</td>
<td>32</td>
<td>8</td>
<td>2</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>C(c)6(^a)</td>
<td>Small male</td>
<td>M</td>
<td>3000</td>
<td>73</td>
<td>7.vi.06–19.viii.06</td>
<td>200</td>
<td>E</td>
<td>88</td>
<td>47.73</td>
<td>13.04</td>
<td></td>
</tr>
<tr>
<td>C(c)7</td>
<td>Small male</td>
<td>M</td>
<td>2875</td>
<td>9</td>
<td>18.vi.06–3.vi.06</td>
<td>46</td>
<td>16</td>
<td>3 to 11</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>Foxes</td>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(c)1</td>
<td>Adult female</td>
<td>F</td>
<td>4775</td>
<td>61</td>
<td>1.vi.06–29.viii.06</td>
<td>313</td>
<td>120</td>
<td>40 to 97</td>
<td>7.44</td>
<td>3.55</td>
<td></td>
</tr>
<tr>
<td>F(c)2</td>
<td>Adult female</td>
<td>F</td>
<td>4525</td>
<td>93</td>
<td>18.vi.06–28.ix.06</td>
<td>396</td>
<td>E</td>
<td>128</td>
<td>9.14</td>
<td>2.24</td>
<td></td>
</tr>
<tr>
<td>F(c)3(^a)</td>
<td>Large male</td>
<td>M</td>
<td>4950</td>
<td>34</td>
<td>12.vi.06–22.vi.06</td>
<td>168</td>
<td>41</td>
<td>21 to 29</td>
<td>33.22</td>
<td>17.43</td>
<td></td>
</tr>
<tr>
<td>F(c)4</td>
<td>Large male</td>
<td>M</td>
<td>4900</td>
<td>15</td>
<td>22.vi.06–10.vi.06</td>
<td>53</td>
<td>18</td>
<td>14 days before baiting</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Captured north of Dog Fence.
baited area, increased their home-range size considerably after baiting (Table 3).

Second, we made before- and after-baiting comparisons of total daily distance travelled. In all, 16 of the 17 radio-collared animals were included in this analysis (fox FC4 died before baiting was conducted). The average daily distance moved for cats increased significantly from 1225 m before baiting to 1681 m after baiting (wald stat = 5.75, d.f. = 1, \( P = 0.017 \)). However, there was no significant interaction between time (before and after baiting) and treatment (baited and control areas), indicating that the daily distance moved increased in both control and baited cats. Only large males and female cats increased their daily movement after baiting, and there was no change for smaller males (demographic × time interaction wald stat = 7.19, d.f. = 2, \( P = 0.028 \)).

Although foxes were not present in the baited area, changes in home-range size and daily distance moved were still compared before and after baiting in order to assist with interpretation of feral cat results. If foxes and cats in the control area exhibit similar changes after baiting then environmental factors are more likely to be responsible. However, foxes in the control area did not show any significant change in daily distance moved after baiting. Foxes also generally had similar home ranges before and after baiting (Table 3).

**Home range**

After conducting incremental area analysis on the data for 13 cats and four foxes, only 10 cats and three foxes had sufficient fixes for home-range analysis. Home range asymptotes were reached after an average of 133 fixes (range 55–240). All home-range results quoted in this section are from combined data (before and after baiting).

Core and MCP95 home range varied considerably among individuals whereas regression analysis showed that there was no significant difference in home-range size between species, sexes or demographic groups (Fig. 2). Cats had an average total home range (MCP95) of 17.41 km² (s.e. 5.14, \( n = 10 \)) and an average core home range (KE60) of 5.6 km² (s.e. 1.67, \( n = 10 \)). A smaller male cat, Cc4, was omitted from the calculation of average MCP95 because its core range was three times larger than for other cats and therefore skewed the average. It was, however, included in all statistical comparisons. Foxes had a slightly smaller average total home range of 16.6 km² (s.e. 8.32, \( n = 3 \)) and an average core home range of 7.7 km² (s.e. 4.85, \( n = 3 \)). The male fox had a home range (33.2 km²) almost five times that of the two female foxes (7.4 km², 9.1 km²) although the sample size was too small for statistical comparison.

Home-range size was not normally distributed, with 40% of cats having home ranges less than 10 km² in size and the remaining 60% being spread evenly over the larger size categories. Males exhibited the two largest home ranges, with 132 km² being the largest range recorded. Radio-collared feral cat home ranges rarely overlapped (Fig. 1). Fox home ranges overlapped with those of radio-collared feral cats, but not with one another.

**Distance**

The maximum linear distance between the two furthest fixes averaged almost 10 km for foxes (9992 m, s.e. 3860, \( n = 4 \)) and just under 9 km for cats (8841 m, s.e. 3322, \( n = 12 \)). Again, Cc4, a smaller male cat, was excluded from this as an outlier but was included in statistical comparisons.

Of the 13 radio-collared cats, 11 moved less than 15 linear km during the study period, whereas long-range movements were recorded for four male animals. Cat Cc4 moved >45 km over 2 days, whereas another small male cat moved >26 km in 3 days, from outside the control zone and into the baited zone, where he died possibly from ingesting a poison bait. One larger, male fox moved almost 21 km in 2 days. A radio-collared 5050-g adult male cat that was not used in the study because of re-collaring difficulties was known to have travelled more than 35 linear km during an 8-month period, including >20 km in one 24-h period, to be eventually recaptured in the vicinity of his initial capture location.

The average minimum daily distance (non-linear) moved by foxes (4553 m) was significantly higher than for cats (1519 m) (wald stat = 9.56, d.f. = 1, \( P = 0.002 \)). For cats, Cc4 recorded the greatest average daily distance of 4457 m and Cc6 the smallest average daily distance of 677 m. For foxes, Fc3 travelled furthest each day, with an average daily distance of 9118 m.

Cats and foxes differed significantly in the distances they moved at different times of day (wald stat = 135.64, d.f. = 2, \( P < 0.001 \)). Foxes moved significantly further between the night and crepuscular fixes than between the day fixes whereas cats moved significantly further during crepuscular hours (Fig. 3; cat: wald stat = 13.90, d.f. = 2, \( P < 0.001 \); fox: wald stat = 150.65, d.f. = 2, \( P < 0.001 \)). Field observations showed that radio-collared cats moved almost four times that of foxes.

**Table 3.** Before versus after baiting comparisons of the total home range (MCP95) (km²) for animals with sufficient fixes for home-range analysis

<table>
<thead>
<tr>
<th>Animal id</th>
<th>Zone</th>
<th>Demographic</th>
<th>Total home range</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cats</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cc1</td>
<td>Baited</td>
<td>Adult female</td>
<td>2.0</td>
<td>24.3</td>
<td></td>
</tr>
<tr>
<td>Cc2</td>
<td>Control</td>
<td>Large male</td>
<td>9.9</td>
<td>21.6</td>
<td></td>
</tr>
<tr>
<td>Foxes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fc3</td>
<td>Control</td>
<td>Large male</td>
<td>34.0</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td>Fc1</td>
<td>Control</td>
<td>Adult female</td>
<td>6.6</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Fc2</td>
<td>Control</td>
<td>Adult female</td>
<td>6.1</td>
<td>8.9</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 2.** Minimum convex polygon (95%) home ranges for all cats and foxes. Home range is calculated in square kilometres.
cats were active during the day, night and crepuscular hours, whereas foxes were active only during the night and crepuscular hours. These observations were supported by the results of the unlogged fixes (inferred to indicate resting in vegetation or dens), with all foxes exhibiting a much lower percentage of unlogged fixes during the crepuscular and night-time periods than during daylight hours (average night = 14%, crepuscular = 19%, day = 31% of fixes unlogged). Overall, cats displayed a similar percentage of unlogged fixes in each time period (average 22% for day, 36% for night and 29% for crepuscular); however, there was a large variation in the pattern of unlogged fixes among individuals. Four cats displayed an even distribution of unlogged fixes across the three time periods, four cats had the lowest number of unlogged fixes recorded during the day and two had the lowest number of unlogged fixes at night.

When comparing the distance moved between 4-hourly fixes, both cats and foxes exhibited significant differences in the distance moved in different habitats. Cats exhibited a higher percentage of unlogged fixes in natural sandplains, creeklines and rocky swales, either as shelter sites or breeding female foxes used rabbit warrens as den sites. Foxes were active only during the night and crepuscular hours, whereas foxes were active during the day, night and crepuscular hours, and longer distances in swales, roads and other habitat types. Cats moved shorter distances through creekline than other (pastoral dams, borrow pit, fenceline, claypan) habitats and longer distances in swale and road habitats.

### Habitat use

All cats exhibited a significant preference for either dune or creekline habitat and avoided swales (all $\chi^2$ between 34 and 352, d.f. = 4, $P < 0.001$; Fig. 5). Foxes preferred dune habitats whereas swale habitat was avoided ($\chi^2 = 174$ and 207, d.f. = 4, $P < 0.001$; Fig. 6). Neither foxes nor cats showed significant differences in habitat use at different times of day. Radio-collared animals were often located in rabbit warrens and breeding female foxes used rabbit warrens as den sites.

### Activity

Temporary focal points were located in dunes, canegrass swamps, sandplains, creeklines and rocky swales, either as shelter sites or

### Fig. 3

Distances moved between fixes for cats and foxes at different time periods. Approximate 95% confidence intervals are displayed as error bars.

### Fig. 4

Distances moved between fixes for cats and foxes in different habitats. Approximate 95% confidence intervals are displayed as error bars. The upper limit of confidence interval for foxes in swale habitat is 4240 m.

### Fig. 5

Usage patterns of individual cats in each habitat using $\chi^2$ values of observed versus expected. Positive values indicate that usage is more than expected and negative values indicate that usage is less than expected. The usage patterns of temporary focal points in the different habitats are indicated (*)

### Fig. 6

Usage patterns of individual foxes in each habitat using $\chi^2$ values of observed versus expected. Positive values indicate that usage is more than expected and negative values indicate that usage is less than expected. The usage patterns of temporary focal points in the different habitats are indicated (*)
hunting grounds; however, dunes were the most frequently used focal points, compared with other habitats (Figs 5, 6). There was a significant general linear trend between the number of temporary focal points and the number of tracking days ($r^2 = 0.43, F = 8.41, d.f. = 12, P < 0.014$). $C_a^2$ (male) had the highest number of temporary focal points ($n = 23$) and he also had the longest tracking period (106 days).

Cats used temporary focal points for an average of 3.83 (s.e. = 0.05) days over a period of 15.5 (s.e. = 0.13) days and the majority (72%) of focal points were not used during consecutive days. The majority (83%) of temporary focal points for both cats and foxes were used for fewer than 6 days. This was also reflected in the behaviour of the foxes where focal points were used for an average of 3.85 days (s.e. = 0.09) over 14.62 days (s.e. = 0.46) and sequentially visited only 4% of the time.

The number of days a focal point was in use did not differ significantly among individual cats ($F = 1.93, d.f. = 8, P > 0.05$) or foxes ($F = 1.32, d.f. = 2, P > 0.05$). The period of time over which a focal point was used did not differ significantly among cats ($F = 1.99, d.f. = 8, P > 0.05$). However, there was a significant difference among individual foxes in the period of use of focal points ($F = 5.66, d.f. = 2, P < 0.001$), with some individuals using them for significantly longer periods than others.

### Optimum baiting density

In total, 11 of the 13 cats had sufficient consecutive fixes to test for optimum bait density by plotting daily movements and determining time until bait detection. At 25 evenly distributed baits per km$^2$, 10 of the 11 cats successfully ‘detected’ a bait within 3 days, and the remaining cat detected it on the fourth day. All four foxes were tested and three of the four foxes ‘detected’ a bait within 3 days at a density of two baits per km$^2$. The fourth fox died after the ninth day of consecutive fixes; however, it passed within 50 m of a bait on the fifth day.

### Discussion

In total, 50% of cats in the baited zone died during the 5-month study, compared with 57% of the control cats suggesting that the poison baiting event was ineffective and that natural mortality was high. Several factors may have contributed to the ineffectiveness of the poison-baiting event, including bait density, seasonal conditions, non-target uptake, alternative prey availability and the presence of bait-shy animals because of previous baiting in the region. A study by Edwards et al. (2001) recorded similar high mortality rates in radio-collared feral cats in the Australian arid zone, with 11 of 19 radio-collared cats dying within a few months of capture. Edwards et al. (2001) recorded low body-condition scores in cats that had died, suggesting that nutritional stress may have been responsible for mortality. The reason for high mortality in both treatment and control areas in our study is not clear: owing to the long-range movements of cats, collars could not be retrieved quickly enough for autopsies to be performed. However, deaths may have also been related to nutritional stress because most carcasses were found desiccated although intact, suggesting that predation was not the cause. Mortality occurred at various times after collars were fitted and baiting commenced, and no animals died within a week of radio-collaring, suggesting that the deaths were unrelated to trapping or collaring.

### Home range

Foxes of both sexes in south-eastern Australia occupy exclusive home ranges and have been observed to be territorial (Phillips and Catling 1991; Saunders and North America. Home ranges of foxes in a desert site in Saudia Arabia averaged a comparable 8.5 km$^2$ (Macdonald et al. 1999).

Home-range sizes reported in our study for feral cats are much higher than those in other published studies in Australia (Table 1) and overseas (Apps 1986; Konecny 1987; Genovesi et al. 1995) and surpass the previously highest average home-range size recorded for male cats by Edwards et al. (2001) of 22 km$^2$. Home-range size in cats varied considerably, ranging from 0.5 to 132 km$^2$. Despite the two largest home ranges belonging to male cats, there was no significant difference in the home-range size between the sexes, similar to the results of Molsher et al. (2005) and Langham and Porter (1991) but contrasting with the results of many other Australian studies (Table 1). Adult feral cat home ranges did not overlap in our study, whereas Molsher et al. (2005) found considerable overlap between young adults and old adults in agricultural land in New South Wales. We did not radio-collar young cats because of the extra weight of the GPS collars.

With distances travelled of between 21 and 45 km in just a few days, cats and foxes are clearly capable of long-range movements. All long-range movements were made by male animals and tended to be in a southerly direction. Edwards et al. (2001) also noted movements of up to 34 km in male feral cats in central Australia and Macdonald et al. (1999) recorded movements of 7–10 km in foxes in a desert environment in Saudia Arabia. The three animals that survived for more than a week after their long-range movements (two cats, one fox) in our study returned to their original home-range area, suggesting that movements may have been exploratory. One of the seven radio-collared cats in the control area remained in the control area after capture and then moved nearly 20 km inside the baited area, only 2 days after baiting. Long-range movements indicate that both cats and foxes are capable of quickly moving into baited areas from adjacent control areas. Although some studies have found periodic buffer-zone baiting to be effective at reducing re-invasion into central core areas (Thomson et al. 2000) others have found that when small areas are baited, re-invasion is
high and baiting frequency must be increased (Kinnear et al. 1988). Large baited areas may be required to increase the long-term effectiveness of poison baiting.

Information obtained in the present study supports previous work by Molsher et al. (2005) who found that cats in the agricultural zone did not have permanent den sites and Edwards et al. (2001) who found male cats in the arid zone continually moved within their home range. Edwards et al. (2001) suggested that this continual movement was related to male cats trying to maintain large territories, whereas we recorded similar movement patterns and home-range sizes in both males and females. Movement in our study was characterised by temporary focal points that were revisited over short periods of less than a week, before moving to a new area within their home range. Permanent dens were not recorded. Continual movement within a home range, together with the high mortality, large non-overlapping home ranges and long-range movements, suggests food availability may be strongly influencing movement patterns in arid-zone feral cats. Edwards et al. (2001) similarly attributed long-range movements of cats in their study in inland Australia to nutritional stress and other studies have found that the large home-range size and territoriality in feral cats is an indication of resource-poor environments (Corbett 1979; Jones and Coman 1982; Edwards et al. 2001). Although the abundance of rabbits, a key prey item for feral cats in the region (Read and Bowen 2001), remained relatively stable during the study period, it is known to fluctuate significantly in response to rabbit haemorrhagic disease, and seasonal and annual conditions (Bowen and Read 1998), suggesting that there are often periods of low prey availability. The high variability in home-range size and the fact that not all male cats exhibited long-range movements in our study also suggest heterogenous distribution of food resources and indicate that some cats are located in areas with high food resources and/or there is high intraspecific variability in the hunting abilities of feral cats. It appears that although cats can survive in arid Australia, the harsh conditions can lead to high mortality and necessitate longer and more frequent movements than for their more mesic counterparts.

Activity

Although home-range size did not differ significantly between cats and foxes, foxes travelled three times further each day within their home range than cats. This increased activity suggests that foxes are more likely to encounter baits within their home range than are cats, one factor that may contribute to high bait uptake by foxes.

Our results support previous work that found foxes in both mesic and arid areas are generally active only at night time (Lloyd 1980; Saunders et al. 1995; Adkins and Stott 1998; Meek and Saunders 2000; Burrows et al. 2003), although some researchers have found that foraging does occur during daylight hours during the breeding season or after long periods of wet weather (Meek and Saunders 2000).

Cats in our study moved considerably further during crepuscular hours, suggesting that they were more active during these times. However, short-distance movements are not necessarily an indication of inactivity, and field observations found cats could be active at any time of day. The ratio of logged to unlogged fixes for individual cats also suggested considerable inter-individual variation in activity patterns. Other researchers have found higher activity during crepuscular hours (Jones and Coman 1982; Page et al. 1992) although feral cats have also been observed to be active during both the day and night, particularly in less harsh environments (Langham and Porter 1991; Molsher et al. 2005). In contrast, Burrows et al. (2003) found that feral cats in the Gibson Desert of Western Australia in autumn and spring were rarely active during daylight hours, becoming active ~30 min after sunset and remaining active until just before sunrise. Activity patterns could be expected to be related to the activity patterns of the key prey species, and the key prey item in the study region for both cats and foxes is rabbits (Read and Bowen 2001). However, a study of rabbits in the same study area found higher rabbit activity between 2000 hours and 0800 hours (Moseby et al. 2005), more consistent with the movement patterns of foxes than with those of cats in our study. Cats may be able to capture some rabbits in their warrens or it is possible that movement patterns are different during the hot summer months when animals may have to seek shelter from the heat.

Habitat use

Habitat use by feral cats may reflect the influence of prey availability as well as the need for protective cover from predators and prey detection while hunting (Corbett 1979; Konecny 1987; Edwards et al. 2002). Feral cats and foxes preferred dune habitat, a habitat that both supports large numbers of rabbits, a key prey species for feral cats and foxes at Roxby Downs (Read and Bowen 2001), and has the thickest vegetation cover. Foxes (Marks and Bloomfield 2006) and feral cats (Konecny 1987; Edwards et al. 2002) in other studies have also been found to prefer areas of thick cover. Cats also preferred creeklines, another sandy habitat with dense vegetation cover. Sandy habitats also contained more rabbit warrens, structures often used as den sites in both our study and in similar studies elsewhere (Coman et al. 1991).

Baiting conundrum

One of the aims of the present study was to investigate possible reasons for conflicting monitoring results after baiting events. Previous baiting trials indicated high mortality in radio-collared cats; however, there was no change in spoor count on transects. An increase in the home range and movement of surviving radio-collared cats after baiting was suggested as one of the possible reasons for this conundrum. However, in the current study, no radio-collared cats within the baited zone died immediately after baiting and although movement and home-range size did increase after baiting, this increase was also recorded in control cats, suggesting that baiting was not a causal factor. Activity may have increased as a result of the onset of breeding, because all female cats and foxes had litters during the study period. The increase in activity is unlikely to be related to changes in rabbit abundance because quarterly rabbit spotlight counts indicated that rabbit abundance remained stable at 51–55 rabbits per square km between January and October 2006 (BHP Billiton Environmental Department, unpubl. data). Another possible reason for the conundrum was high reinvasion immediately
after baiting. Long-range movements including the movement of a radio-collared cat from the control area to inside the baited zone 3 days after baiting suggest that reinvasion could have been a factor contributing to the lack of a decline in cat spoor recorded on monitoring transects after baiting.

**Optimum bait uptake**

It total, 10 of the 11 cats and three of the four foxes tested would have encountered a bait within 3 days, by using the bait density formula (25 per km² for cats and 2 per km² for foxes), and the 11th cat would have encountered a bait on the fourth day. The estimate of optimum bait density should be used as a guide only, because calculations were based on minimum daily distance moved and direct linear travel between fixes was assumed. It is likely that actual daily distance moved is greater than that detected by 4-hourly fixes. Detection distances were only estimates, because of a lack of published information; considerably more work is required in this field. Seasonal conditions would also be likely to influence significantly the density of baits required for effective control.

The formula for the optimum bait intensity does not take into account non-target uptake; consequently, additional baits would be needed to compensate for removal of baits by other animals. Three previous trials on non-target uptake of sausage baits in the same area found that over a period of three nights, non-targets consumed 5%, 20% and 24% of baits respectively (Arid Recovery, unpubl. data). One other study in Western Australia found that non-target animals removed 22% of sausage baits each night; however, in that study baits were laid along the middle of roads in summer where they were conspicuous and easily accessible to corvids and varanids (Algar et al. 2007). More research is needed to test whether increasing the suggested bait density from 25 to 31 per km² in non-summer months will effectively compensate for an average non-target uptake of 25%.

Previous studies on optimum bait density for foxes found that baiting at a rate of 5 per km² was highly effective (Thomson et al. 2000) and just as effective as 10 baits per km² (Thomson and Algar 2000); however, lower bait densities were not trialled. Other studies have found high levels of bait caching when bait density is 12.5 baits per km² (Saunders et al. 1999) and our results also suggest that bait density at many sites may be too high. Fox densities in the study region (0.6 per km², Read and Bowen 2001) are considerably lower than those reported in more mesic environments (7.2 per km², Thompson and Fleming 1994) and we suggest that a bait density of 5 per km² should be trialled for foxes in arid South Australia, to take into account non-target uptake.

Optimum bait density also assumes that bait detection is the same as bait uptake; however, personal observations and previous studies (Risbey et al. 1997; Algar et al. 2007) have suggested that not all cats that encounter a bait will ingest it. Domestic cats are known to eat only when they are hungry (Bradshaw 1992) and other studies using sand plots at Arid Recovery found that feral cats consumed only 25% of encountered baits (Arid Recovery, unpubl. data). Algar et al. (2007) also found extremely variable bait uptake, with between 0 and 70% of detected baits consumed depending on season, although these values were often less than 10%. Even if baiting is timed to coincide with key periods of high nutritional stress, other factors could also contribute to low bait uptake, including a reluctance to eat unfamiliar foods, an aversion to scavenging and daily feeding patterns.

**Management implications**

Control of cats and foxes in arid Australia should target habitats with thick vegetation, particularly creekline and dune habitat or areas where there are rabbit warrens. Aerial baiting in arid Australia should ideally occur across areas of several thousand square kilometres because large home ranges and long-range movements increase the chance of rapid reinvasion. A baiting intensity of 30 per km² for cats and 5 per km² for foxes may be effective; however, more research is required into non-target uptake and the relationship between bait detection and uptake, particularly in feral cats.

Continual movement throughout their home range suggests that fixed trap or bait sites should be effective for cats and foxes, and because of the large variation in home-range size we concur with Edwards et al. (2001) that they should be placed at a minimum density of 1 every 1–2 km². Foxes should encounter them more quickly than cats, because foxes move further each day although they have similar home-range size.

The large intra-specific variation in home-range size, and sometimes small core home ranges, suggests that even small unbaited areas of 1–2 km² within treatment areas could lead to some cats not encountering baits. Cats and foxes can cause the failure of threatened species reintroductions in the arid zone, even when present at low densities (Christensen and Burrows 1995; Langford 1999; K. Moseby, pers. obs.), suggesting that care should be taken to ensure bait coverage is comprehensive even if it is less intensive in unfavoured habitats. When using radio-collared cats to monitor bait uptake it is recommended that cats are not first captured using food-based lures, to ensure results are not biased towards hungry, inefficient hunters that are likely to scavange baits.

Feral cats exhibited much higher intra-specific variation in activity patterns and home-range size than did foxes, rendering them a potentially difficult species to control by a single method. Long-range movements and continual movement throughout their home range also increases the chance of rapid reinvasion into control areas. Although successful baiting events for feral cats have been reported (Short et al. 1997; Burrows et al. 2003; Algar et al. 2007), baiting appears to be more effective on islands or when using familiar prey items such as birds, fish or mice (Short et al. 1997; Twyford et al. 2000; Mitchell et al. 2002). We concur with Risbey et al. (1997) who suggest that cats are difficult to poison with baits, and the long-term control of feral cats through poison baiting may be ineffective in the Australian arid zone where alternative food sources such as rabbits are available. Because of high intra-specific variability and extremely variable resource availability, long-term control of feral cats in inland Australia may be best achieved through a combination of control techniques.

**Acknowledgements**

Arid Recovery is a joint initiative between BHP Billiton, The University of Adelaide, SA Department for Environment and Heritage and the local friends of Arid Recovery. Funding was also provided by the South Australian Arid Lands Natural Resource Management Board through the Federal Government Natural Heritage Trust program. This study was conducted under animal
ethics permits 14-2002 and 9-2006 through the Wildlife Ethics Committee (SA Department for Environment and Heritage). We thank members of the Friends of Arid Recovery who assisted in the field and the local veterinary clinic for assisting with training in the use of anaesthetics. Gratitude also goes to Phil Goldsworthy and the Roxby Downs Aeroclub for assisting with radio-tracking and we are indebted to Ross Cunningham for his statistical support. John Read and the three referees provided insightful and useful comments on the manuscript.

References


Movement patterns of feral predators in an arid environment

Wildlife Research


Manuscript received 19 June 2008, accepted 23 April 2009

---


---

http://www.publish.csiro.au/journals/wr