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ORIGINAL PAPER

Rapid recolonisation by the European red fox: how effective are uncoordinated and isolated control programs?

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Abstract Uncoordinated and isolated control programs are often used by land managers, property owners and recreational hunters to control numbers and reduce the impacts of European red foxes (*Vulpes vulpes*). However, decades of such attempts to eradicate this significant agricultural and biodiversity pest in many countries have failed. We investigated the effectiveness of an uncoordinated and isolated shooting program to determine if it caused any change in red fox population density. We also determined whether shooting is more cost effective than poison baiting for fox control. First, we estimated the density of foxes on an agricultural study property using distance sampling and rates of bait uptake before and after a control program. Second, we estimated the costs associated with undertaking the control program and compared it to the estimated costs of undertaking poison baiting. Prior to control, we estimated a density of 4.18 foxes per square kilometre. After the control exercise, which removed 47 individuals in 12 nights, we estimated a density of 3.26 foxes per square kilometre. Our results provide evidence that one-off control programs are not effective in greatly reducing red fox density, even if the control effort is intensive. Where large-scale control programs cannot be coordinated, isolated programs should therefore involve follow-up campaigns to reduce population recovery. On a local scale, combinations of shooting and baiting may also provide maximum control impact at minimal cost.

Keywords Fox control · Pest management · Recreational hunting · *Vulpes vulpes*

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Introduction

The European red fox (*Vulpes vulpes*) (Linnaeus 1788) is regarded as a pest where it has been introduced in many parts of the world and as one of Australia's most significant vertebrate pests (McLeod 2004). With no specialised food requirements, the fox thrives in fragmented agricultural landscapes that provide a wide range of cover, food and den sites (Saunders et al. 1995). Foxes in agricultural lands are subject to various levels of population control because they depredate livestock (Greentree et al. 2000; Heydon and Reynolds 2000); in protected areas, they are often managed to reduce their impacts on native fauna, including endangered species (Coman 1973; Burbidge and McKenzie 1989; Glen et al. 2011). However, foxes remain populous in many regions despite intensive and extensive management efforts to control them.

Territoriality is arguably one of the most important behavioural traits affecting the spatial organisation of animal populations, although its application to fox populations is the subject of some debate. For example, Doncaster and Macdonald (1991) found that territories of foxes living in Oxford City continually drifted; this appeared to be a rapid behavioural response to social instability and changes in the pattern of food resources. In contrast, White et al. (1996) found a high degree of spatio-temporal stability in the home ranges of foxes living in Bristol City. Either way, rapid behavioural changes, including the turnover of territories to transient or subordinate animals (Baker et al. 2000), may limit the effectiveness of fox control. Therefore, understanding how foxes respond to control programs is critical to developing sound management strategies.

Coordinated landholder participation in landscape level control programs benefits agricultural productivity in some areas (McLeod et al. 2010; Towerton et al. 2011). In contrast, uncoordinated attempts to control foxes generally cause little change in fox density over the long term (Harding et al. 2001; Baker and Harris 2006; Gentle et al. 2007). For example, Baker and Harris (2006) suggested that driving foxes to guns using dogs and rifle shooting across 44 sites in Wales did not reduce fox numbers. Similarly, Gentle et al. (2007) suggested that immigration of foxes onto farms negated any long-term effects of uncoordinated baiting operations in Australia. Yet, many landholders and recreational hunters still undertake isolated and uncoordinated control programs on agricultural properties. A potential problem is that previous studies have focused on landscape-scale responses of foxes to control programs, thus making it difficult to infer what happens at the individual property level. Therefore, specific studies are crucial to quantify whether uncoordinated fox control programs, carried out by an individual landholder, can be effective.

One way to approach this question is to carry out an uncoordinated and isolated control program in which fox density is measured before and after treatment. This would permit assessment of the effectiveness of the program and the costs associated with it. The timing of control could also influence whether the program reduces fox density (Coman 1988; Hone 1999; Harding et al. 2001). For example, high recruitment rates could render useless any population control prior to pup rearing. Understanding when to implement a control program is therefore integral to ensuring maximal disruption to the population at minimal cost.

We explored the effectiveness of an uncoordinated and isolated fox control program by undertaking a 12-day hunt, with rifles. We did this on an agricultural property where there was no concurrent control, on or around the property, to maximise our ability to test explicitly whether a one-off shooting campaign could reduce fox density in the short term. We predicted that the effectiveness of the program would be limited because of foxes reinvading the control area and because of recruitment of new animals into the population after breeding. As baiting is widely used to control foxes, we also undertook a cost-benefit analysis to compare the associated costs of baiting against those of shooting. We use the results to provide recommendations on how to optimally use hunting as a management tool.

Materials and methods

Study site

Our study was conducted on Arthursleigh, a 7,900-ha sheep and cattle grazing property 200 km southwest of Sydney, south-eastern Australia (34° 37′ S, 150° 01′ E) (Fig. 1). This site experiences hot summers and cold winters, with temperatures ranging from −8 °C to 40 °C. The mean annual rainfall is 666 mm. About 3,000 ha of remnant dry sclerophyll woodland provides shelter for foxes and native wildlife on the property, whereas the remainder is characterised by low, cleared, undulating hills, which provide excellent visibility for spotlighting (Vine et al. 2009). No fox control had occurred on the property for the 3 years preceding our study, and there were no concurrent control programs on neighbouring properties.

Control exercise

Foxes were shot from a vehicle using a 0.22, 0.205 or 0.243 centre-fire rifle over 12 consecutive nights in October 2005. This coincided with the end of the breeding season to target juveniles (dispersing or within den sites) and adult foxes (including lactating females), potentially providing maximum disruption to the population. Shooting was conducted on or near main trunk roads of the property. Spotlighting commenced at 20.00 h and continued until early morning. The time of death, sex, approximate age status based on body size (juvenile<12 months old and adults>12 months old) and GPS location of each shot animal were recorded.

Density estimates—distance sampling

We used distance sampling (Buckland 1985; Buckland et al. 1993) based on line-transect sampling and spotlight counts as our first method to assess fox density before and after the control exercise. Thirteen straight line transects were chosen along existing vehicle tracks or open areas, varying in length from 1 to 5 km (Fig. 2). Each transect was driven at five random times between 21.00 and 02.00 h to coincide with peak activity times for foxes. Sampling commenced 2 weeks before and continued for 2 weeks after the control exercise with a continual rotation between transects. For each transect, at least two observers were used. Foxes were detected using two handheld 1 million candlepower spotlights mounted on the roof of a 4WD vehicle driven at 10–15 km per hour depending on terrain. To minimise the risk of missing animals on the centreline, each observer would scan only one side of each transect, but frequently scan the road or track ahead for foxes running away from the vehicle. When a fox was detected, the perpendicular distance from the centre of the road to the fox was measured using a laser telemeter (Bushnell optics, Brookvale, NSW). Detection distances and detection angles were recorded where it was difficult to accurately measure perpendicular distance.

Transects of varying lengths, L, with fixed boundaries were used. In the absence of obstructions, foxes are detectable up to at least 350 m under a spotlight (Heydon et al. 2000). However, in this study an estimated effective strip width (or truncation distance) of 300 m was used due to occasional

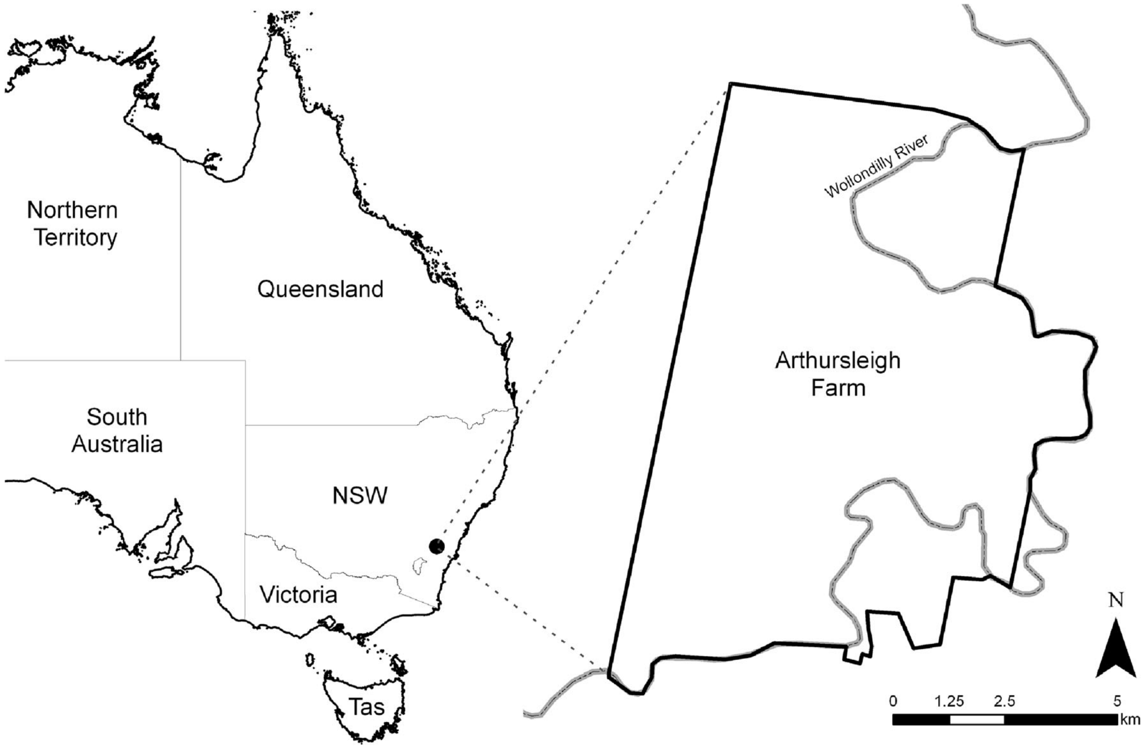


Fig. 1 Location of Arthursleigh in relation to the surrounding states of Australia

obstructions and undulating topography that decreased visibility on either side of the vehicle. Distance data for each transect, before and after the control exercise, were pooled over each night, and DISTANCE v6 (Thomas et al. 2010) was used to estimate the probability density function of the perpendicular distances, evaluated at zero ($f(0)$).

Because foxes mainly forage solitarily, distance data were analysed as individuals rather than clusters (Buckland et al. 1993). For model selection, we used the robust models recommended by Thomas et al. (2010): a uniform key with cosine adjustments, half-normal key function with cosine adjustments, and half-normal key function with hermite polynomial adjustments. The hazard-rate key with simple polynomial adjustments was not included because it yielded an implausible shape and an improbable density estimate after the control exercise. We used the Akaike Information Criterion (AIC), goodness-of-fit statistics and visual assessment of the ability of each model to fit the data, especially near the centreline where the detection function should have a 'shoulder' (Buckland 1985).

Density estimates—bait uptake rates

A bait station web was set up to act as a second method to assess fox abundance and to compare with density estimates obtained from spotlighting. Lukacs et al. (2005) suggested that webs should contain at least 90 locations, that sampling should occur on 5–7 occasions and that movement rates of animals have little impact on density estimates when animals are confined to home ranges. However, a fox could potentially walk along a line of bait stations and take as many baits as desired if they are spaced relatively close together. Each bait station therefore must be placed far enough apart to cover a large area and multiple home ranges, but still be close enough to maximise the number of trapping stations for adequate data analysis. Initially, we placed bait stations 1 km apart to satisfy these requirements. However, a pilot study using this design within the confines of the study area allowed a trapping web consisting of only eight lines (from the centre) with two traps per line to be set up on some lines. Therefore, we increased the number of bait stations by decreasing the distance between each trap from 1 km to 500 m, giving a total of 64 trap stations to analyse (Fig. 2).

Bait stations consisted of 1-m^2 raked areas with three chicken winglets buried 10 cm deep in the centre. Baits were buried to minimise uptake by non-target species. Bait stations were checked after 3 days, and where it was obvious that a fox had taken the bait (identified by the presence of tracks, the size of any diggings, the size and presence of toe-nail marks in the diggings and the distribution of dirt away from the bait), a successful bait uptake was recorded. The bait station web was baited for two periods, using the same locations, about a week apart before and after the control exercise. Chi-squared was used to test for a difference in the number of baits taken before and after the control exercise.

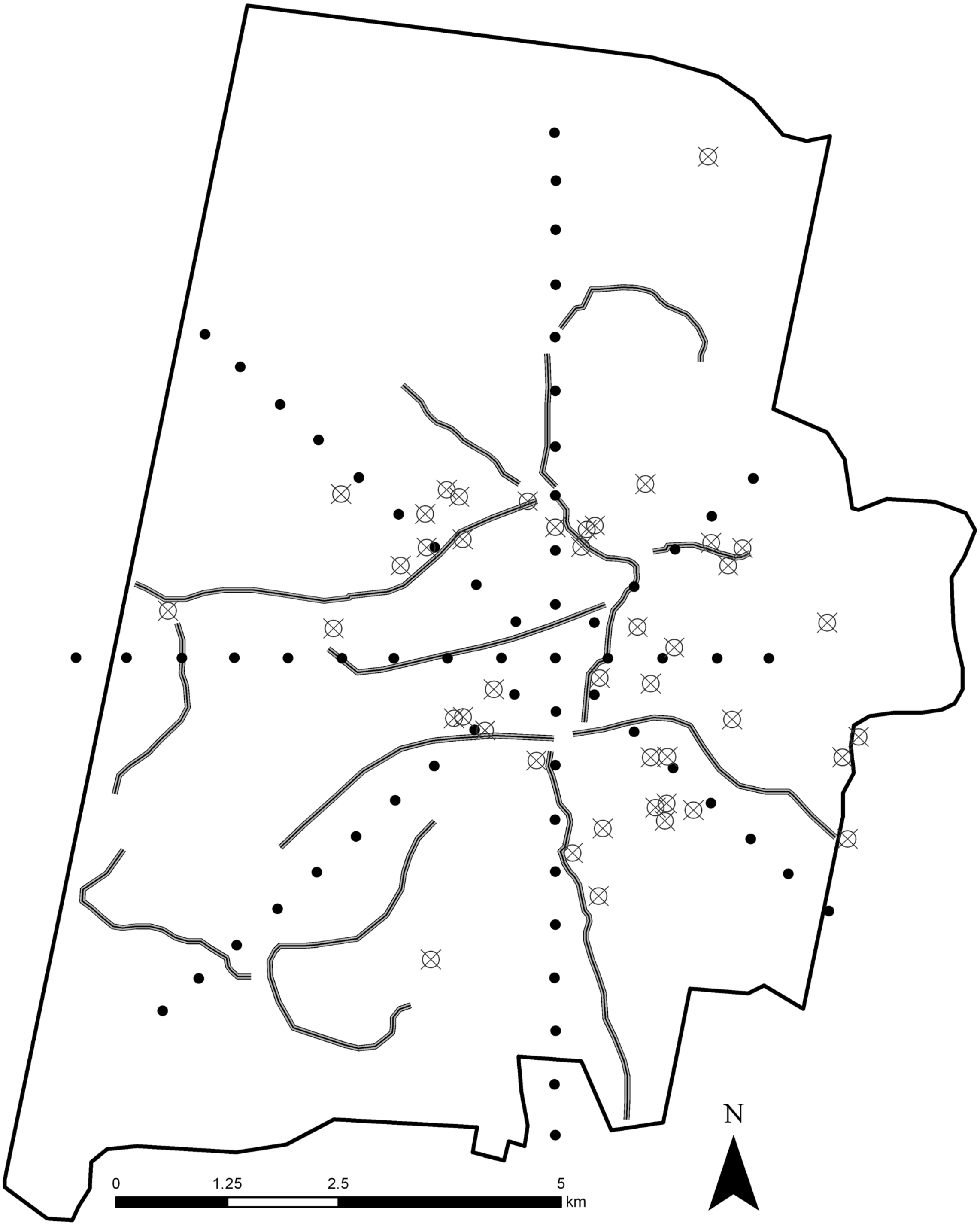


Fig. 2 Location of distance sampling line transects (*shaded lines*) and bait uptake stations (*black dots*) used to assess the effectiveness of a fox control exercise between October and November 2005 on Arthursleigh, south-eastern Australia. The *open circles with crosses* represent the location of foxes shot during the control exercise

Cost-benefit analysis

During the control exercise, we recorded the number of hours spent spotlighting per night, the number of bullets used and the kilometres driven using either a 4WD vehicle or quad bike. These data were used to calculate a kill-per-unit-effort value and to compare costs against poison baiting. The costs of poison baiting were based on Gentle (2005), who assessed the relative cost of baiting using three different bait types, Foxoff® (a commercially manufactured bait), euthanased day-old chicks and chicken wingettes (wings of chicken meat sold for the catering industry) over a period of 3 to 4 weeks. All costs were based on 2012 ($AUD) prices. The estimates from Gentle (2005) were scaled using the Reserve Bank of Australia inflation calculator, which provides a guide to the current value of a basket of goods and services based on previous costs.

Ethics

Research was undertaken under Animal Care and Ethics Authority from the University of Sydney (L04/6-2003/2/3770). We adhered to all conditions related to the study.

Results

Control exercise

Forty-seven foxes (36 adults and 11 juveniles) were shot over 12 nights. Forty-six percent of these were shot within the first three nights, with the number of foxes shot each night generally decreasing thereafter (Fig. 3). However, the number of hours spent spotlighting each night was not consistent, and the number of foxes shot per hour varied inconsistently from 0.17 to 1.33 (mean 0.85±0.04 s.e.). The number of foxes shot per kilometre also varied each night (Fig. 4).

Density estimates—distance sampling

Seventy sightings of foxes were made on the 13 transect lines (total length 18 km) before the control exercise. Data pooling over five nights allowed sufficient sightings to model a detection function *f(0)* for our three chosen models (Table 1). The AIC values for the three models were similar, but the visual assessments and goodness-of-fit tests suggested that the half-normal key function with a hermite polynomial or cosine expansion best fitted the data before the control exercise (Table 1). With a truncation point of 300 m, four sightings were removed from the sighting histogram. Sighting frequencies were generally low near the centreline, with a peak at around 130 m (Fig. 5). Thus, with a sample size of 66 after truncation, DISTANCE estimated a density of 4.18 foxes per square kilometre (with a lower 95 % confidence interval limit of 2.7 and upper limit of 6.4) (Table 1).

Thirty-one sightings of individual foxes were made after the control exercise. Buckland et al. (1993) suggested that to produce a reliable estimate of *f(0)* at least 60–80 objects need to be sighted. A sample size of 30 sighting distances after truncation for this survey does not meet this criterion. However, a half-normal key function with a hermite polynomial expansion provided a good fit of the distance frequencies (Fig. 5). For example, for this model, the *P* value corresponding to the χ^2 goodness-of-fit was 0.01 (Table 1). In the other models, the *P* value corresponding to the χ^2 goodness-of-fit tests were much higher, making them poor models to select. Thus, with a sample size of 30 after truncation, DISTANCE estimated a density of 3.26 foxes per square kilometre (with a lower 95 % confidence interval limit of 1.7 and upper limit of 6.2).

Density estimates—bait uptake rates

Fewer baits were taken after the control exercise ($n=30$) in comparison to before ($n=43$), but the difference was not statistically significant ($\chi^2=2.31$, $P=0.128$).

Shooting—costs associated with the control exercise

During the control exercise, a total of 391 km was driven whilst spotlighting and shooting, 109.3 km on a 4WD quad bike (14.9 h) and 281.7 km (43.6 h) in a diesel 4WD. An additional 100 km (1.5 h) in a diesel 4WD was added to account for travel time to-and-from site and collecting supplies such as ammunition. An additional half hour was also spent setting up and putting away gear before and after each night. In total, 58 bullets were used to shoot the 47 foxes. A further 20 bullets were used to sight in the rifles accurately. In total, 66 h were spent on the control exercise, which removed 47 foxes at a total cost of $1,506.55 (Table 2). This equates to a kill-per-unit-effort value of $32 per fox.

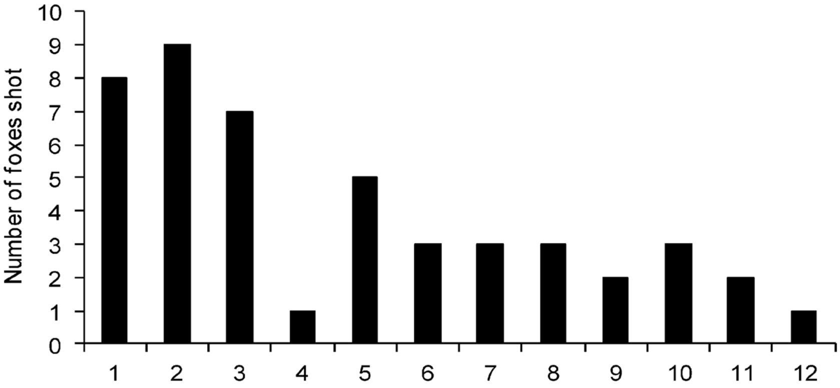


Fig. 3 The number of foxes shot each night (1–12) during the control exercise between October and November 2005 at Arthursleigh, south-eastern Australia

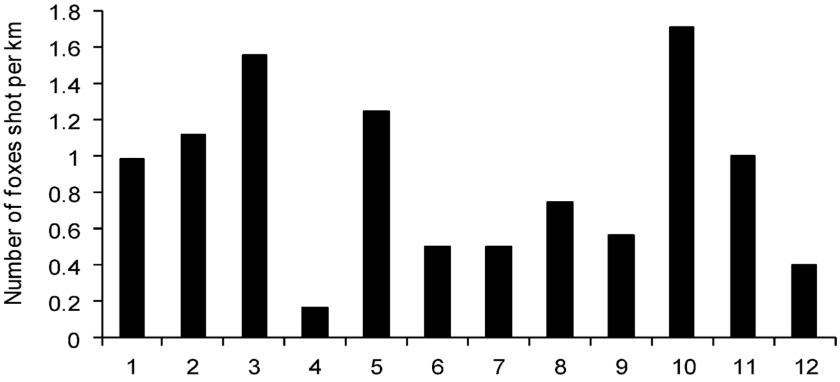


Fig. 4 The number of foxes shot per kilometre on each night (1–12) during the control exercise between October and November 2005 at Arthursleigh, south-eastern Australia

Estimated cost of baiting on Arthursleigh

Under the estimates of Gentle (2005), higher kill rates than those obtained during the control exercise at Arthursleigh could be achieved with bait uptake rates of 50 % after a 14-day campaign using day-old chick/wingettes and with bait uptake rates of 50 % after a 28-day campaign using Foxoff®. Costs of these campaigns would be $912.69 and $1,278.66, respectively.

Discussion

Our control exercise, designed to simulate a single fox control event typifying such exercises on mixed grazing properties in eastern Australia and elsewhere in the world, successfully removed 47 foxes in 12 nights. Despite these foxes being shot relatively close to each other (Fig. 2), the cull resulted in a decline in estimated fox density of only 0.92 individuals per square kilometre. Given that higher kill rates can be achieved using baiting for less cost, our study does not provide compelling support for isolated hunting programs being an efficient or cost effective technique for fox control in the short term.

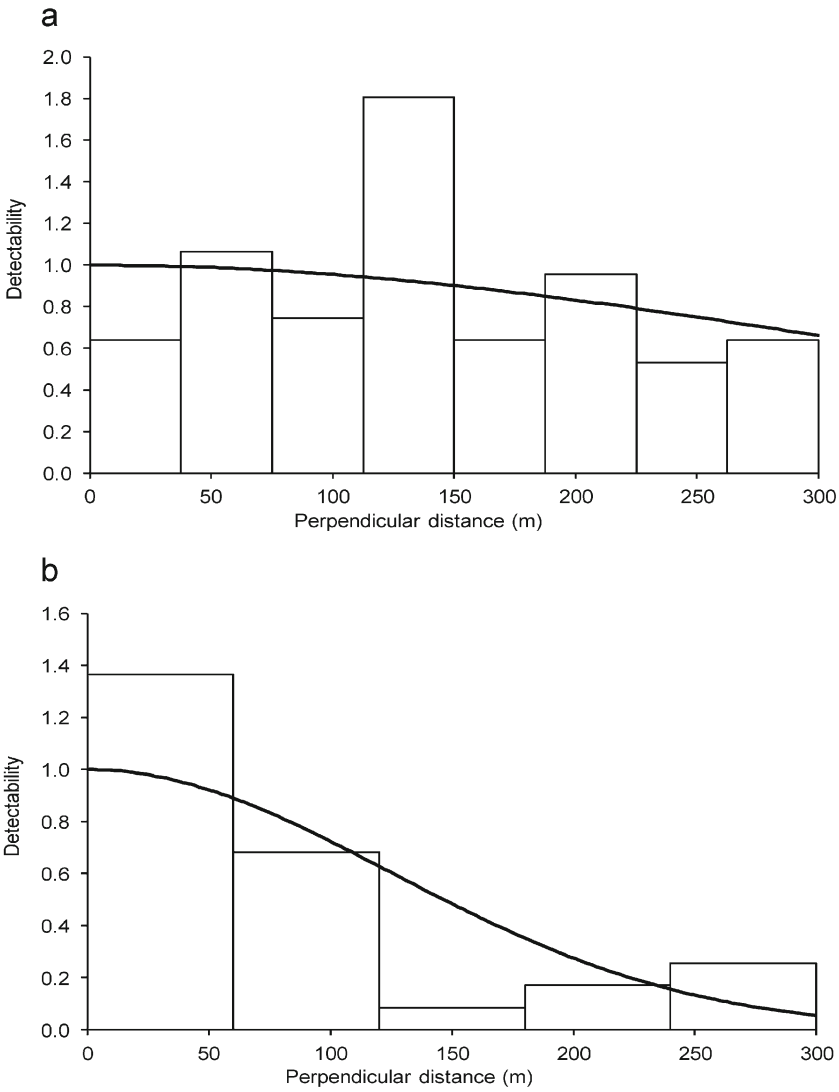
Our results are not surprising in one respect; numerous studies have demonstrated or concluded that uncoordinated control programs do not effectively reduce fox density (Gentle et al. 2007; McLeod et al. 2010, 2011; Saunders et al. 2010; Towerton et al. 2011). However, as opposed to prior studies that have assessed the effectiveness of uncoordinated fox control over large areas, our study confirms that isolated one-off control programs at the individual property level are also not effective, with only a small reduction in fox density achieved in our study. Overwhelmingly, rapid immigration of foxes from neighbouring uncontrolled areas is cited as the key reason why control programs fail (Harding et al. 2001; Rushton et al. 2006; Gentle et al. 2007). Although our study was conducted over a relatively short period, it would not have precluded rapid immigration. It demonstrated further that, even though our control program was conducted when juveniles were becoming active, either around the den or dispersing, many still survived as indicated by frequent sightings of juveniles around dens during our post-control spotlighting. Our kill rate of less than one fox per hour was therefore not high enough to counter high rates of recruitment within the control area, let alone any potential immigration from outside.

The behavioural responses of surviving foxes also may have limited the effectiveness of our control program. Foxes are generally regarded as territorial and as using exclusive home ranges either individually or in family groups (Goszczynski 2002). However, foxes also have a highly flexible social system, and territory areas may change if there is social instability and a high turnover of the population (Doncaster and Macdonald 1991). Hence, as fox populations decline, surviving animals may increase (or change) the area over which they forage in response to the availability of a vacant territory. Settlers may also assess the environmental factors that determine habitat and territory quality, and intruder

Table 1 Line transect density estimates for foxes (*D*) before and after a control exercise at Arthursleigh, south-eastern Australia, and model selection results based on the Akaike Information Criterion (AIC) and goodness-of-fit statistics (χ^2 and corresponding *P* value)

Key function	Series expansion	Before control						After control					
		AIC	χ^2	df	*P*	*D*	95 % CI	AIC	χ^2	df	*P*	*D*	95 % CI
Uniform key	Cosine	752.90	8.39	4	0.08	3.67	2.6–5.2	326.68	7.73	1	0.19	4.69	2.3–9.5
Half-normal	Cosine	753.95	7.59	3	0.06	4.18	2.7–6.4	325.91	2.40	2	0.30	4.74	2.3–9.5
Half-normal	Hermite polynomial	753.95	7.59	3	0.06	4.18	2.7–6.4	330.82	6.82	1	0.01	3.26	1.7–6.2

Fig. 5 Number of fox sightings (*bars*) and detection probability (*lines*) at intervals from the centre line (*0*) at Arthursleigh, south-eastern Australia, before (**a**) and after (**b**) the control exercise. Data were fitted with a half-normal key function with a hermite polynomial expansion



pressure, and then adjust territory sizes and spacing patterns accordingly (Bubela 1995). Depending on the circumstances, this could compromise fox control programs if newly vacant areas are favoured by neighbouring and surrounding individuals. Alternatively, Baker et al. (2000) found that foxes consistently increased the area over which they ranged as

Table 2 Costs ($AUD) of parameters associated with vehicle usage and labour during a fox control exercise conducted at Arthursleigh, south-eastern Australia

	Travelling cost			Labour cost			Total cost
Task	Vehicle cost (per km)	Distance travelled (km)	Total	Time (h)	Hourly rate	Total	
Spotlighting (quad bike)	$0.20	109.30	$21.86	14.9	$15.96	$237.80	$259.66
Spotlighting (diesel 4WD)	$1.02	281.70	$287.30	43.6	$15.96	$695.86	$983.19
Procuring ammunition	$1.02	100.00	$102.00	1.5	$15.96	$23.94	$125.94
Preparation time				6.0	$15.96	$95.76	$95.76
Ammunition							$42.00
Total			$411.2			$1,053.36	$1,506.55

Diesel 4WD running costs were based on the total average running cost for a Toyota Landcruiser (National Road and Motoring Association 2011). 4WD quad bike running costs were based on the amount of fuel used during the controlexercise and associated costs of unleaded petrol. Labour costs were based on Australian minimum hourly wages in 2012 competitors in neighbouring groups died. If this occurred in our study, we would have expected a large decrease in population density post-control, which was not the case. However, detailed home-range data on surviving foxes would be needed to confirm if there was an increase, decrease or shift in home range following the control exercise.

It is possible that spotlighting, due to its low precision, may not have detected small changes in fox abundance (Sharp et al. 2001). However, we also used bait uptake rates as a secondary method of estimating fox activity or abundance. Based on this method, there was no major change in bait uptake rates detected pre- and post-control, which supports our density estimates via spotlighting. Alternatively, it is possible that foxes avoided our spotlight post-control (e.g. foxes became wary of the vehicle and spotlight because it was associated with the shooting campaign). However, if there was any behavioural avoidance of the spotlight post-control, we would have underestimated the population size as opposed to overestimating it, making the control program seem more effective. Therefore, our ability to detect foxes post-control did not appear to be influenced by avoidance of the spotlights by foxes.

Taking these observations together, the fact that our control program did not greatly reduce fox density provides support for the idea that foxes can rapidly recruit and compensate for losses within a population, or swiftly recolonise vacant territories. The only other explanation for our results is that our distance sampling incorrectly estimated fox population densities. For example, the confidence intervals surrounding our density estimates were large (Table 1), potentially indicating that a more intense and longer survey effort was required. However, our estimates are typical of those found elsewhere. In the agricultural grazing lands of the northern tablelands of New South Wales, for example, fox density ranges from 4.6–7.2 foxes per square kilometre (Thompson and Fleming 1994). Slightly lower fox density has been estimated in central Victoria (3.0 foxes per km^2) (Coman et al. 1991), and even lower densities (less than two foxes per km^2) have been recorded in semi-arid and arid areas (Marlow et al. 2000; Sharp et al. 2001). Thus, our density estimates are comparable to those in agricultural systems elsewhere. The fact that 47 foxes were removed (and that 44 were shot within a relatively small area, equating to 2.6 foxes being removed per km^2) should have made a great impact on the population size, but our results suggest that it did not. Therefore, when considering the use of shooting or recreational hunting as a management tool, there are a number of factors that should be considered.

First, high recruitment rates coupled with rapid recolonisation of vacant territories after control could render useless one-off control programs. The rapidity with which this occurred in our study suggests that follow-up control programs are absolutely necessary. Second, the impact of shooting can be greater during the beginning of the control program. For example, during the first five nights of the control exercise 30 out of 47 foxes were removed from the property (Fig. 3). Therefore, if shooting is to be deployed, consideration needs to be given to its duration. Third, the timing of a control exercise could influence success in terms of its impact on fox populations. For example, our control exercise was initiated after the onset of fox breeding and during the stage when fox cubs were dispersing. Longer term and sustained control would undoubtedly have been more effective to reduce fox numbers. Finally, our results suggest that baiting is a more cost effective strategy that can achieve higher kill rates with 50 % bait uptake rates by foxes. Therefore, combinations of shooting and baiting may provide maximum impact at minimal cost.

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