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How can warren destruction by ripping control European wild rabbits (*Oryctolagus cuniculus*) on large properties in the Australian arid zone?

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Abstract

Context. For over 100 years, control efforts have been unable to stop rabbits causing damage to cattle production and native plants and animals on large properties in arid parts of Australia. Warren destruction by ripping has shown promise, but doubts about long-term success and the perceived expense of treating vast areas have led to this technique not being commonly used.

Aims. This study measured the long-term reduction in rabbit activity and calculated the potential cost saving associated with treating just the areas where rabbits are believed to survive drought. We also considered whether ripping should be used in a full-scale rabbit control program on a property where rabbits have been exceptionally resilient to the influence of biological and other control measures.

Methods. Rabbits were counted along spotlight transects before warrens were ripped and during the two years after ripping, in treated and untreated plots. Rabbit activity was recorded to determine the immediate and long-term impact of ripping, up to seven years after treatment. The costs of ripping warrens within different distances from drought refuge areas were calculated.

Key results. Destroying rabbit warrens by ripping caused an immediate reduction in rabbit activity and there were still 98% fewer rabbits counted by spotlight in ripped plots five months after ripping. Seven years after ripping no active warrens were found in ripped plots, whereas 57% of warrens in unripped plots showed signs of rabbit activity. The cost of ripping only the areas where rabbits were likely to seek refuge from drought was calculated to be less than 4% of the cost of ripping all warrens on the property.

Conclusions. Destroying rabbit warrens by ripping is a very effective way of reducing rabbit numbers on large properties in arid Australia. Ripping should commence in areas used by rabbits to survive drought. It is possible that no further ripping will be required.

Implications. Strategic destruction of warrens in drought refuge areas could provide an alternative to biological control for managing rabbits on large properties in the Australian arid zone.

Additional keywords: European rabbit, pest control, warren ripping, arid Australia.

Introduction

In 1995, the biological control agent rabbit haemorrhagic disease virus (RHDV, otherwise known as rabbit calicivirus disease) spread across Australia, rapidly reducing rabbit populations to very low levels (Cooke 2002; Mutze *et al*. 2002; Story *et al*. 2004). The impact of rabbit haemorrhagic disease (RHD) was monitored (the Rabbit Calicivirus Monitoring Program) at sites selected throughout Australia (Cooke 2002; Henzell *et al*. 2002; Story *et al*. 2004). One of these sites was established at Bulloo Downs cattle station in south-west Queensland. Field surveys conducted between 1996 and 1998 (Story *et al*. 2004) showed Bulloo Downs to be the only arid site in the national and state monitoring programs that still had high rabbit numbers three years after RHDV arrived. The virus was killing rabbits at Bulloo Downs, and suppressing the population, but rabbit numbers were still unacceptably high (Story *et al*. 2004).

Rabbits at Bulloo Downs had also coped relatively well with myxomatosis (Bowen 1987) after the successful introduction of the myxoma virus in 1950 (Reid 1953; Williams *et al*. 1995). Rabbits recovered or were still in high numbers on Bulloo Downs in the 1960s when the property supported 102 commercial rabbit hunters (Bowen 1987). In the 1980s, rabbits infested most of the property in densities as high as 11 000 km^{-2} (Cantrill, unpubl. data). This estimate was derived from spotlight counts in which over 1000 rabbits were counted per kilometre of spotlight transect. It is hard to imagine that there were ever higher numbers of rabbits on Bulloo Downs even before myxomatosis arrived.

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Losses incurred to cattle production on Bulloo Downs were over AU$250 000 per year prior to the arrival of RHDV (Berman 2001), and the damage to biodiversity was probably considerable (Berman, unpubl. data). It was clear that actions in addition to the passive spread of biological control agents were required to reduce the damage caused by rabbits on Bulloo Downs. In 1999, the manager of Bulloo Downs, believing that RHD was not working, requested that virulent myxoma virus (Lausanne strain) be introduced into the wild rabbit population. This was the usual practice in the region, each year in spring. Nevertheless, there was no noticeable reduction in rabbit numbers on Bulloo Downs after the introduction of virulent myxoma virus in 1999. Within the local rabbit population, field strains were found to be derived from the original strain released in 1950, not the Lausanne strain (Berman *et al*. 2006), suggesting that regular releases of the Lausanne strain had been ineffective.

Combined, myxomatosis and RHD certainly suppressed the rabbit population at Bulloo Downs (Story *et al*. 2004), but not enough to stop extensive damage to cattle production and the environment. Rabbit-proof fencing, rabbit harvesting (Bowen 1987), and poison baiting (Strong, pers. comm.) have all been used on Bulloo Downs, but have failed to achieve any long-term reduction in the negative impact of rabbits. Therefore, another control technique was required.

In addition to the combination of suitable soil (for building warrens and growing rabbit feed) and flooding from the Bulloo River, the abundance of permanent or long-lasting natural waterholes may be an important factor causing Bulloo Downs to be continually infested by large numbers of rabbits. Arid Australia is characterised by unpredictable rainfall. There are sequences of years with above average rainfall that cause periods of substantial plant production; however, these are separated by droughts of irregular length, in which animal populations contract to more moist or fertile areas (Morton 1990). When the moisture content of the vegetation becomes too low, rabbits require water to drink (Cooke 1982), so they move towards water during drought (Parer 1982). Rabbits were observed drinking out of Booka Booka waterhole on Bulloo Downs in 2001 (Brennan, pers. obs.). Rabbits also require warrens for protection and to keep cool (Myers and Parker 1975*a*; Williams *et al*. 1995). Rabbits that find suitable drought refuges, with both warrens and drinking water, presumably have a greater chance of surviving. At Bulloo Downs, destruction of the large numbers of rabbit warrens along the banks of permanent or long-lasting natural waterholes by ripping was proposed as a strategy to control rabbits.

In arid or semiarid areas, destruction of rabbit warrens by ripping was effective for rabbit control in the late 1970s and through the 1980s (Foran *et al*. 1985; Wood 1985; Cooke and Hunt 1987; Mutze 1991; Williams and Moore 1995), but the method was not economically viable (Burley 1986; Parer and Parker 1986). Only with funding support from the Federal Government in the early 1990s did warren ripping become an option for some properties in arid areas (Linton 1995; Ferraro and Burnside 2001; Edwards *et al*. 2002*a*). Warren ripping over large areas in arid Australia through the early 1990s dramatically reduced rabbit numbers on properties in western New South Wales, South Australia and the Northern Territory (Croft *et al*. 1997; Ferraro and Burnside 2001; Edwards *et al*. 2002*a*). Prompted by the success of ripping elsewhere, the management of Bulloo Downs ripped some warrens in an area close to the homestead. While this was successful, and rabbits did not reopen the warrens, no further ripping was conducted because of the sheer size of the area to be treated.

Treating drought refuge areas has been recommended as a priority, but the belief was that all warrens on the property needed to be ripped to prevent reinvasion (Williams *et al*. 1995). However, there are often too many warrens on arid properties for all to be ripped. Given that rabbits are confined to relatively small areas during drought (Myers and Parker 1975*a*; Wood 1980), we considered whether effective control over entire properties could be achieved by just ripping warrens in drought refuge areas.

This trial was conducted to decide whether ripping should be used in a full-scale rabbit control program on Bulloo Downs. The aim was to determine whether warren destruction by ripping provides a long-term reduction in rabbit activity where the rabbit population has proven to be exceptionally resilient compared with other rabbit populations in the arid zone of Australia. The cost and effectiveness of ripping was determined at different warren densities to allow calculation of the cost of a full-scale control program. The association between warren density and distance from long-lasting natural waterholes was investigated as an aid to identifying priority areas for treatment and to calculate the cost of treating these areas.

Materials and methods

Site description

The study was conducted on Bulloo Downs Station, a 10 000 km^2 property used for cattle production. Bulloo Downs is located ~100 km south-west of Thargomindah in south-west Queensland (Fig. 1). Experimental sites were selected in the centre of the property (Fig. 2), in an area heavily infested by rabbits, and where there was a good understanding of the ecology of rabbits from previous work in the area (Story *et al*. 2004; Berman *et al*. 2006).

There is a large area of sand dunes intersected by clay flats that can be inundated by local rainfall or flooding of the Bulloo River caused by rain falling up to 400 km away. Although the mean annual average rainfall is around 200 mm, the property is relatively less arid than surrounding areas. The soil is favourable for warren construction and there is, at least along the water courses, a predictable supply of green feed available during the cooler seasons (Story *et al*. 2004). These factors are conducive to long and productive breeding seasons (Williams *et al*. 1995), which have resulted in rabbit numbers being consistently higher than in other arid areas.

Rainfall

Prior to the ripping experiment, there were five consecutive good rainfall years (1996–2000) with average or above average rainfall, followed by a run of extremely dry years (2001–06). The first above average rainfall year after ripping was 2007 (data interpolated from point observations by the Bureau of Meteorology) (Jeffrey *et al*. 2001).

Description of the design and treatments

Square kilometre plots

At four sites, a treated (ripped) plot and an untreated (unripped) control plot were established (Fig. 2). Plots were square (1 km^2),

Fig. 1. Bulloo Downs (black) is a 10 000 km^2 property south-west of the town of Thargomindah at the lower reaches of the Bulloo River catchment (dark grey) in the state of Queensland in the arid zone of Australia (grey).

and pairs of treated and untreated plots were established ~500 m apart. Each plot contained a mixture of sand dune and clay flats. Rabbit warrens occurred mainly in the sand dunes and were usually absent from the clay flats. Pairs of treated and untreated plots were considered close enough to experience similar environmental conditions, such as rainfall and grazing by stock, but far enough apart to be independent with regard to short-term rabbit movements. Sites containing pairs of plots were spaced 3–8 km apart (Fig. 2). One pair of plots was selected near Booka Booka Waterhole, which only dries up in the most severe droughts. The other plots were selected at varying distances up to 10 km from Booka Booka Waterhole.

At the end of April 2001, spotlight counts, footprint counts and warren activity counts were conducted in ripped and unripped plots before treatment. Ripping commenced 2 May 2001 and finished 12 May 2001. Four days later, 16 May 2001, the activity of rabbits was assessed using footprint counts in ripped and unripped plots. Five months after ripping, in September 2001, rabbits were counted by spotlight in ripped and unripped plots. Spotlight counts were repeated in April 2002, September 2002,

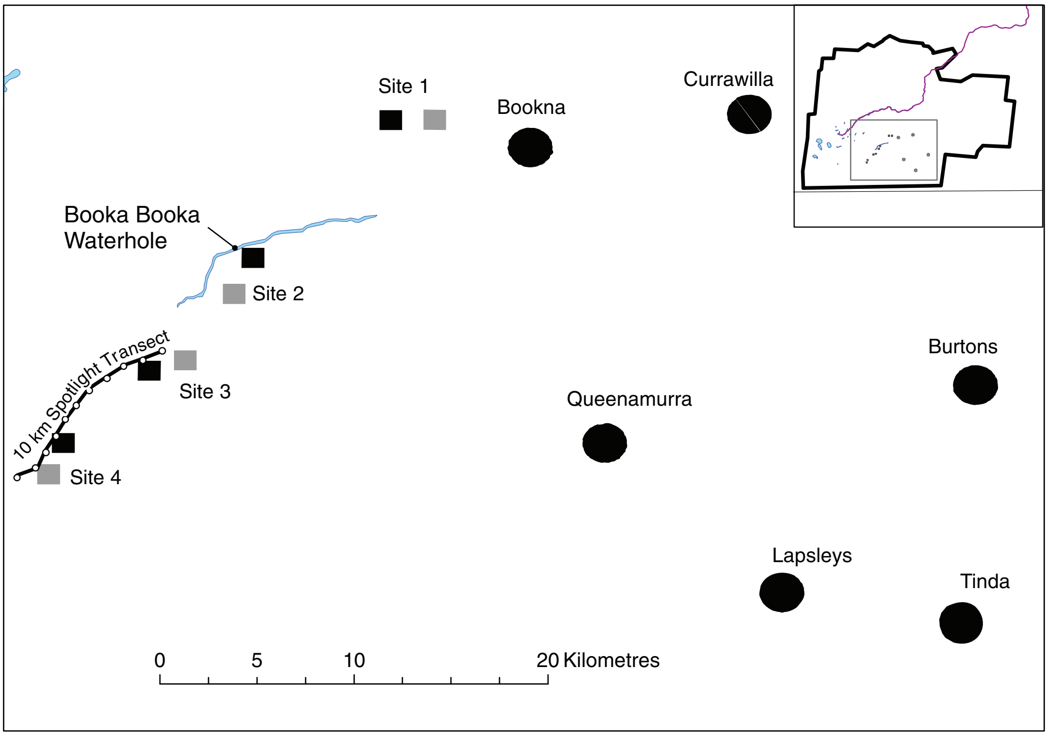

Fig. 2. Treatment sites where rabbit warrens were ripped (black) and untreated control sites (grey) on Bulloo Downs cattle station. Sites 1 to 4 have paired ripped and unripped plots established at different distances from the long-lasting Booka Booka Waterhole. Circular plots were at six man-made watering points. The 10 km spotlight transect was established as part of the rabbit calicivirus monitoring program in 1996 (Story *et al*. 2004) and was used throughout this study.

and April 2003. The initial plan was to conduct spotlight counts twice a year for three years until September 2003. However, thorough searches of all plots on foot and by spotlight failed to detect any sign of rabbits in the area in April 2003. Low rainfall in 2001, followed by an exceptionally dry year in 2002, is believed to have caused rabbits to die in or leave the study area. From April 2002 to September 2008, spotlight counts were considered unsuitable for comparison of the plots due to the overall low rabbit density.

Searches for signs of rabbit activity in warrens confirmed the similarity of treatment and control plots prior to ripping in May 2001. Searches for signs of rabbit activity in warrens were conducted again in September 2008 to measure the reopening rate seven years after ripping.

Circular plots

Prompted by the initial success of ripping in the treatment plots, we commenced a broader rabbit control program to rip all warrens within 1 km of long-lasting water. A further six sites were chosen, 10–40 km from long-lasting natural waterholes, but located at man-made watering points (<100 m long by 50 m wide when full). All warrens were ripped within 1 km of these man-made waterholes, each plot covering an area of ~3.14 km^2. They were not permanent supplies of drinking water, except for Currawilla, which was equipped with a bore. While these waterholes could support a small number of rabbits during drought, there were relatively low numbers of warrens, suggesting that they were less useful as drought refuges than the long-lasting natural waterholes, such as Booka Booka.

Ripping at four circular plots (Bookna, Queenamurra, Lapsleys and Tinda) was conducted between the end of May 2001 and the beginning of July 2001. The other two circular plots (Burtons and Currawilla) were ripped in April 2002. Unlike the square plots, there were no control plots of a similar size and shape. For comparisons with ripped areas we selected unripped areas just outside a circle of 1 km radius from the water point. Searches for sign of rabbit activity in ripped and unripped warrens measured the difference in September 2008, seven years after ripping.

Ripping technique

A grader marked the boundary of each site so that it was clearly visible for the observing ‘spotter’ while searching for and marking warrens. A warren was defined as one burrow or a group of burrows that appeared connected. If two groups of burrows were separated by 5 m or more they were recorded as two separate warrens. The spotter rode a four-wheel motorbike in a systematic pattern, searching for, flagging and GPS-marking warrens. A 220 HP rubber-tracked Cat Challenger dozer (AGCO Australia Limited, Melbourne) with five curved tines (70 cm ripping depth) destroyed flagged warrens, and then each was GPS-marked by the driver. At the end of each day GPS points were downloaded onto a laptop computer and a map was created showing areas of the plot that may have been missed. Warrens were not cross ripped in the sand dunes, because one pass generally damaged the warrens sufficiently, with the dry sand funnelling into the deeper cavities. Some larger warrens in harder soil required cross ripping.

Each site was covered in 20 to 30 m wide strips, with the spotter beginning in one corner of a square plot and slowly moving along the 1 km graded boundary line on the first strip and then back ~20 to 30 m from this first strip. For circular sites the search strips were from the centre out to the 1 km radius. Ripped warrens and dozer tracks also provided reference points for the spotter when searching an untreated area of the site. The spotter did not venture too far ahead of the dozer, making certain that no flagged warrens were missed. The spotter tried to keep about five to 10 warrens marked ahead of the dozer. Once warrens were ripped, the spotter checked for missed burrows.

Cost of ripping

The path of travel was also recorded for both the spotter and dozer, ensuring a thorough coverage and providing data on time spent travelling between warrens and time spent ripping. The amount of diesel used was also recorded. Warren density, distance between warrens, and number of warrens ripped per hour were determined from data collected by GPS. These data were used to calculate the cost of ripping. Calculations were based on a cost of \$100 hour^{-1} for the dozer plus \$0.51 L^{-1} for diesel and \$60 day^{-1} for the spotter.

Monitoring procedures

We used three different rabbit monitoring techniques, each with various strengths and weaknesses. Spotlight counts are the most commonly used for rabbit studies in Australia and produce repeatable results (Ballinger and Morgan 2002; Poole *et al*. 2003), but at very low densities rabbits may not be detected with a spotlight. Footprint counts are commonly used in arid areas for a variety of wildlife species (Mahon *et al*. 1998; Edwards *et al*. 2002*b*; Southgate *et al*. 2005) and rabbit tracks can be detected at very low rabbit densities. Counts of active warren entrances can rapidly and reliably provide an estimate of abundance of rabbits (Williams *et al*. 1995) and provide an excellent measure of the effectiveness of ripping, given that the aim of ripping is to reduce the number of warren entrances available to rabbits.

Footprint counts

Footprint counts were conducted at square ripped and unripped plots. Two-metre-wide paths were cleared using a piece of heavy steel dragged along four internal paths, each 1 km long, and around a 4 km perimeter path of each plot. Rabbit footprints were recorded while riding a four-wheel motorbike along the paths the next morning. The presence or absence of footprints in each 100 m section of the cleared paths was recorded. Individual rabbit tracks were not recorded.

Pre-ripping

Footprint counts were conducted at square plots on 3 and 4 May 2001 just before ripping.

Post-ripping

On 15 and 16 May 2001 rabbit footprint counts were conducted at all ripped and unripped square plots.

Warren activity

Pre-ripping

A survey was conducted in April 2001 just before ripping to count the number of active and inactive entrances in a sample of warrens at square plots. The number of entrances and the presence or absence of signs of rabbit activity was recorded for each entrance. Signs of rabbit activity in a warren entrance included fresh rabbit tracks or pellets. Sites were surveyed on a four-wheel motorbike commencing at the edge of the site and continuing through until at least 40 and no more than 100 warrens at any one plot had been visited. The location of each surveyed warren was recorded using a GPS.

Post-ripping

Five months after ripping, the square plots were checked for missed or reopened warrens, in October 2001. The number of missed or reopened warrens was recorded. Sites were resurveyed on a four-wheel motorbike using a GPS. The locations of missed or reopened warrens were recorded using a GPS and they were treated with fumigant (Pestex tablets).

Four of the circular sites (Bookna, Queenamurra, Lapsleys and Tinda) were also checked for missed and reopened warrens in December 2001, approximately five months after ripping. All ripped warrens at these four sites were revisited. There was insufficient time to check warrens at the other two circular sites.

Seven years after ripping, in September 2008, a survey was conducted to measure the relative availability of warren entrances for rabbits in ripped and unripped plots. A sample of warrens in untreated square plots was compared with a sample of warrens in treated square plots. A sample of warrens in treated circular plots was compared with a sample of warrens in untreated areas up to 500 m from the ripped circular plots. At all square plots and circular plots, with the exception of Tinda (time did not permit sampling), a search was conducted in a vehicle with a driver and passenger both looking for warrens. At least a 1 km search path was driven through both the ripped and unripped areas. The numbers of warren entrances (active and inactive) were recorded for all warrens within 10 m of the search path. There was insufficient time to sample random points. Ripped warrens were still clearly visible at most sites, but where they were not visible their location was determined using a GPS.

Spotlight counts

General description

A trained observer standing in the tray of a vehicle being driven along permanently marked transects at ~15 km h^{-1} searched for rabbits with a 100 W, 500 000-candle power spotlight. Spotlight counts were conducted at square ripped and unripped plots and along the 10 km RCV monitoring transect (see below) (Fig. 2).

Ten-kilometre RCV monitoring transect

A 10 km transect established in 1996 to monitor the influence of RHD (at that time known as rabbit calicivirus RCV disease) on rabbit populations ran through the area. Data from counts conducted along this transect provided a good indication of rabbit abundance at the time of the experiment relative to previous periods. The transect sampled areas that were not ripped, except for 500 m that ran through site 4 (ripped), and the counts were used to show the influence of rainfall on rabbit numbers independent of ripping. Counts were conducted at least once every year between 1996 and 2007.

Square plot spotlight transects

Counts at each square plot were conducted along four permanently marked 1 km transects once in April 2001, before ripping commenced, and then on four occasions after ripping in September 2001, April and September 2002, and April 2003. The last two collection dates were excluded from the formal analysis due to a lack of variability resulting from all zero counts for at least one treatment. By removing the last two time points, the residual plots did not show any extreme deviation from the regression assumptions.

Initially, a repeated-measures analysis was applied to the data. An autoregressive model allowing for heterogeneity over time was used to assess the correlation between time points. The deviance test from the model allowing for heterogeneity did not show significant improvement over a model not allowing for heterogeneity. Since correlation between time points was weak and heterogeneity was not significant, a simpler model of a split plot ANOVA was used to compare the treatments. The ANOVA was generated using GENSTAT 12th edition (Payne *et al.* 2009).

Extensive spotlight counts

To determine the relative abundance of rabbits across the entire property, 600 km of 'rapid' spotlight counts were conducted along existing tracks approximately two years after warrens were ripped. Observations were made by a driver and passenger in the cabin, travelling between 30 and 50 km h^{-1}. The passenger used a spotlight to supplement the headlights. The location of each rabbit seen was recorded using a GPS.

Results

Ripping

Square kilometre plots

Starting 2 May 2001, it took 11 days to rip a total of 2427 warrens in the four square plots. The total time spent ripping and travelling between warrens was 87 h, and 1900 L of diesel were required (22 L per hour and 0.8 L per warren). Table 1 shows the number of warrens ripped in each plot. Warren ripping removed most warrens from the plots. Five months after ripping, 0.9–4% of warrens were found reopened or not ripped (Table 1). The cost per warren varied from \$3.62 to \$6.31, and the cost per plot varied from \$1343 to \$3922 per km^2.

Circular sites

Ripping commenced 27 May 2001 and finished 6 July 2001. It took 10 days to rip 1350 warrens at the first four circular sites. A further 206 warrens were ripped at two other circular sites 7 and 8 April 2002. The cost per warren varied from \$7.20 to \$13.70 and the cost per plot varied from \$432.67 to \$1136.75 per km^2 (Table 1). The total cost for the six sites was \$14 626.30 and 18.9 km^2 was treated by ripping.

Warren density and distance from water

The density of ripped warrens was highest at site 2 (1082 warrens km^{-2}), which was the closest site to the Booka Booka waterhole (Fig. 2). Sites with the lowest density were furthest from long-lasting natural water and closest to man-made watering points. Warren density decreased with distance from natural long-lasting water and this decrease was particularly rapid within 5 km of the water (Fig. 3). There was a significant correlation between distance from natural long-lasting water and warren density ($r = 0.78$, $P = 0.009$) but no significant correlation between distance from nearest water (natural or man-made) and warren density.

Warren density and cost of ripping

There was a significant correlation between cost of ripping per km^2 and the $\log_e$ of distance from long-lasting water ($r = 0.95$, $P < 0.00001$) (Fig. 4).

The equation for the curve fitted to the points in Fig. 4 is:

$$\text{Cost}(\$) = 3660 - 971 \times \log_e(\text{distance from long-lasting water (km)})$$

Table 1. The density of ripped warrens, the cost of ripping, and the reopening rate for square and circular plots five months after treatment

Site	Ripped warren density (km^{-2})	Cost (\$ $warren^{-1}$)	Warrens ripped ($hour^{-1}$)	Cost (\$ km^{-2})	% of warrens missed or reopened	Missed or re-opened warren entrances (km^{-2})
Site 1	349	5.37	23	1874	0.9	10
Site 2	1082	3.62	32	3922	0.6	5
Site 3	783	4.20	28	3291	0.6	6
Site 4	213	6.31	19	1343	4.2	37
Bookna	158	7.20	25	1137	3.0	–
Queenamurra	138	7.50	23	1031	3.7	–
Lapsleys	70	11.90	15	837	2.7	–
Tinda	64	11.80	15	754	6.5	–
Burtons	34	13.60	21	462	–	–
Currawilla	32	13.70	28	432	–	–
Mean	292	8.52	23	1508	2.8	15

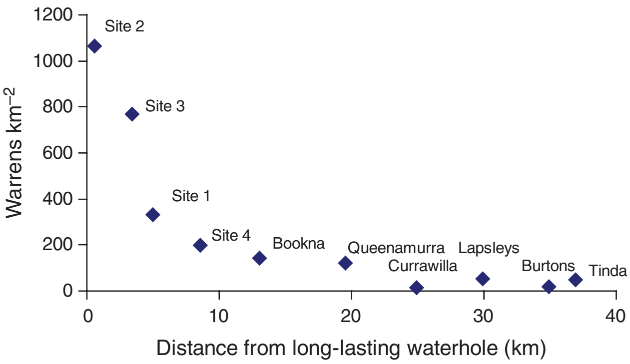

Fig. 3. The density of warrens ripped at each of the 10 ripped sites decreased with distance from the long-lasting Booka Booka Waterhole.

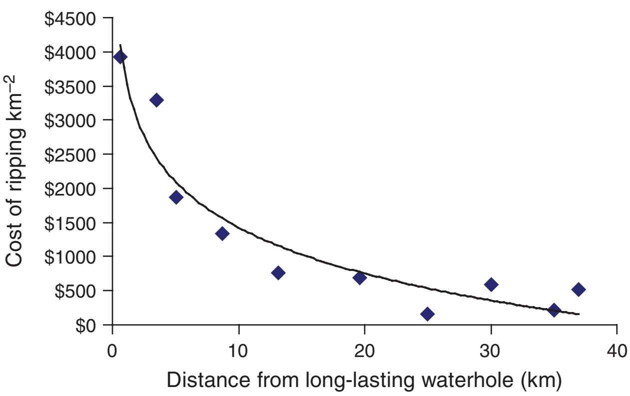

Fig. 4. The cost of ripping per square kilometre at each of the 10 ripped sites decreased with distance from a long-lasting waterhole.

This equation was used to calculate the cost of ripping warrens at different distances from long-lasting water. The area to be treated within 1 km wide buffers at different distances from long-lasting water was determined and then the cost of ripping all warrens at different distances from long-lasting water was calculated using the above equation (Fig. 5). Ripping all warrens on the property within 15 km of water was calculated to be \$6 million; however, to rip all warrens within 1 km of long-lasting water was estimated to cost around \$250 000 (Fig. 5).

Although the cost of ripping per km^2 was highest at sites close to long-lasting water, the cost of ripping per warren was lowest (Table 1). The higher cost of ripping per warren in areas more distant from long-lasting water may have been due to greater diesel use as warren density decreased ($r = 0.83$, $P < 0.01$) and the distance travelled between warrens increased.

Monitoring

Footprint counts for rabbits

Pre-ripping. There was no difference between the internal paths and perimeter paths in the proportion of 100 m sections with rabbit tracks present before ripping. The activity of rabbits was evenly spread across the whole plot. There were 12 ± 3 (s.e.) sections with rabbit tracks around the perimeter and 15 ± 3 with rabbit tracks on internal paths of plots to be treated and there were

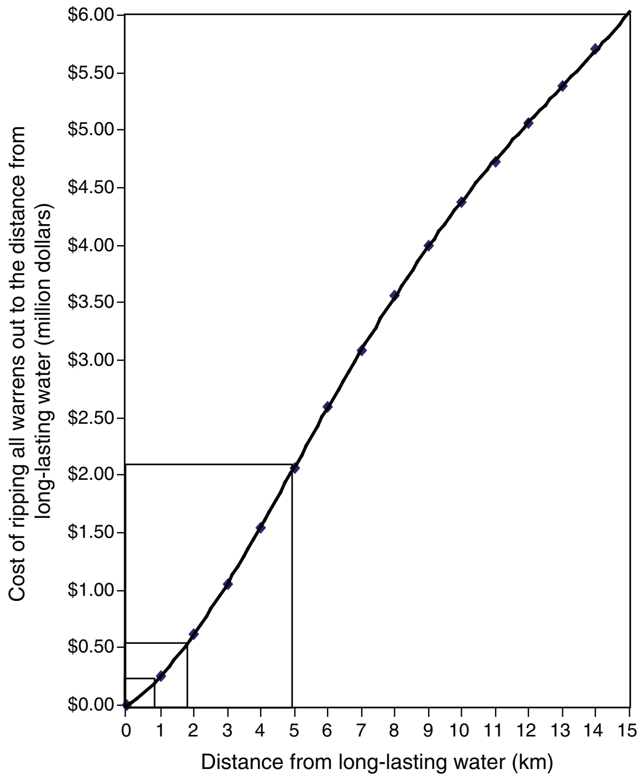

Fig. 5. The cost of ripping all warrens out to various distances from long-lasting water. The cost of ripping was determined using the equation for the curve shown in Fig. 4.

12 ± 3 sections with rabbit tracks around the perimeter and 14 ± 4 with rabbit tracks on internal paths on plots to remain untreated.

Post-ripping. Two months after ripping there were 16 ± 4 (s.e.) sections with rabbit tracks around the perimeter and 17 ± 3 sections with rabbit tracks on the internal paths at the untreated plots. In contrast, there were 11 ± 3 sections with rabbit tracks around the perimeter and 4 ± 1 sections with rabbit tracks on the internal paths at the treated plots after ripping. Ripping appears to have reduced the activity of rabbits, indicated by footprint counts in ripped plots, not so much around the perimeter, but along the internal paths. In untreated sites, two months after ripping, rabbit tracks occurred over as much as 70% of the area, whereas in treated sites rabbit tracks occurred in less than 10% of the area.

Warren activity

Pre-ripping

In April 2001, just before ripping, there was no significant difference between the mean number of warren entrances per warren in square plots selected to be treated (7.2 ± 0.4 s.e., $n = 232$) and square plots to remain untreated (7.4 ± 0.4 s.e., $n = 237$). Nor was there a difference in the mean number of active entrances per warren in plots to be treated (3.3 ± 0.3 s.e.) and in plots to remain untreated (3.9 ± 0.3 s.e). Of the 469 warrens surveyed, 318 (68%) showed signs of rabbit activity. There were 1062 km^{-2} warren entrances in square plots before ripping.

Post-ripping

Five months after ripping. The percentage of missed or reopened warrens ranged from 0.6% to 6.5% approximately five months after ripping (Table 1) and there was a negative correlation between the density of warrens and the percentage of missed or reopened warrens ($r = -0.85$, $P = 0.01$). There were 15 warren entrances km^{-2} in square plots five months after ripping.

Seven years after ripping. In September 2008 the mean number of warren entrances available for use by rabbits was 795 ± 265 km^{-2} (s.e.) in untreated areas, whereas in treated areas the mean was much lower at 10 ± 5 km^{-2} (s.e.) (paired $t = -3.67$, d.f. = 8, $P = 0.0063$). A total of 291 warrens were checked (7% of the 3983 warrens ripped) in treated sites and only two holes potentially suitable for rabbit use were found (Table 2). These holes were created by cattle hooves pushing through the surface into a tunnel below and, although they could be used by rabbits for shelter, there was no sign of rabbit activity. There were therefore no signs of reopening of ripped warrens, whereas there were 240 warren entrances found in 60 warrens checked in untreated areas. Signs of rabbit activity were recorded in 66 (28%) of these 240 entrances, but 57% of the 60 warrens checked had signs of rabbit activity. Rabbits needed to travel a long way (5 km) to find a warren entrance in ripped areas whereas they could find on average 80 entrances in the same distance (5 km) in unripped areas (Table 2).

Spotlight counts

Ten-kilometre RCV monitoring transect

Figure 6 shows the number of rabbits seen along the 10 km RCV spotlight transect before and after ripping. The figure also indicates the influence of lack of rainfall on rabbit numbers, independent of ripping. The number of rabbits seen along the 10 km RCV transect correlated with the number of rabbits

Table 2. The distance travelled and the number of warrens checked seven years after warrens were ripped

Site	Search distance (km)		Number of warrens checked		Warren entrances per linear kilometre	
	Ripped area	Unripped area	Ripped area	Unripped area	Ripped area	Unripped area
Site 1	11.4	5.1	33	7	0.0	6.8
Site 2	3.9	3.3	95	6	0.0	5.4
Site 3	3.2	4.4	52	10	0.0	4.6
Site 4	3.2	3.2	25	12	0.0	18.4
Bookna	1.0	1.0	15	5	0.0	30.0
Queenamurra	1.0	1.0	24	6	0.0	24.0
Lapsleys	1.0	1.0	16	5	0.0	39.0
Burtons	1.0	1.0	31	5	2.0	11.0
Currawilla	1.0	1.0	0	4	0.0	4.0
Total	26.7	21.0	291	60		
				Mean ± s.e.	0.2 ± 0.1	15.9 ± 5.3

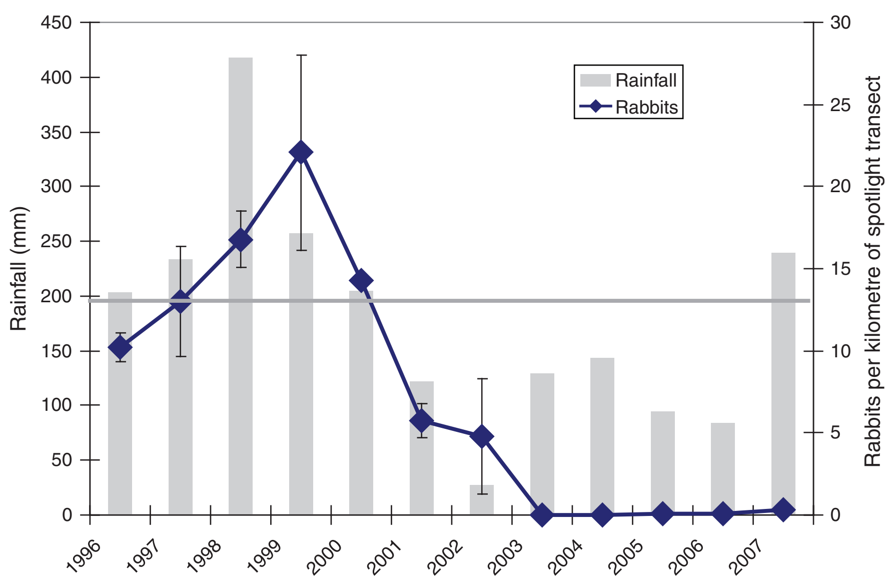

Fig. 6. Mean (line) and total annual rainfall for Bulloo Downs. Rabbits seen along a 10 km spotlight transect established as part of the RHDV monitoring program (means and standard errors are shown for years when more than one count was conducted). These counts represent unripped areas.

counted along spotlight transects in unripped plots ($r = 0.93$, $P < 0.02$) but not with the number of rabbits counted along spotlight transects in the ripped plots. There was a significant correlation between the mean number of rabbits per kilometre of spotlight transect and the rainfall for the previous year ($r = 0.91$, $P < 0.0001$) (Fig. 7). By November 2002 no rabbits were seen along the 10 km RCV transect. After the better than average rainfall in 2007, rabbits were again seen in low numbers along the 10 km RCV transect.

Square kilometre plot spotlight transects

Prior to ripping in April 2001 there was no statistically significant difference between the numbers of rabbits seen in ripped and unripped plots. The mean number of rabbits seen in spotlight counts before ripping was 7.5 per km (±3.7 s.e., $n = 4$). This number dropped to a very low level (<1 km^{-1}) in the treated sites after ripping. In September 2001, four months after ripping, 200 rabbits were counted during spotlight counts (11.4 per km ± 2.2 s.e., $n = 4$) in the untreated sites and only three (0.2 per km ± 0.1 s.e., $n = 4$) were observed in treated sites (Fig. 8).

There was a significant difference between treated and untreated plots ($F_{2,1} = 55$, $P = 0.018$) and distance from long-lasting water was a significant covariate in the model ($F_{2,1} = 24$, $P = 0.04$). There was also a significant interaction of treatment with time ($F_{12,2} = 4$, $P = 0.046$), indicating the effectiveness of ripping in September 2001, but no effect in April 2002. Figure 8 shows mean indices of rabbit abundance for the first three time points using this model.

A higher number of rabbits than expected were seen in ripped sites in April 2002, but there was no evidence that they were reopening warrens and perhaps were not attempting to re-establish permanently but were moving through seeking food or heading towards drought refuge areas. By November 2002 thorough searches for rabbit sign (pellets or tracks) indicated there were no rabbits in the ripped and unripped plots presumably because of the extreme drought conditions.

Extensive spotlight counts

Although rabbits were not detected by spotlighting in the trial sites or along the 10 km transect from September 2002 to 2007. They were present in parts of the property close to long-lasting water. Spotlight counts conducted in 2003, two years after ripping, over 600 km of tracks covering most of the rabbit habitat on Bulloo Downs showed that 71% of 119 rabbits seen were within 1 km of long-lasting water. There were 0.2 rabbits per km over the entire 600 km, but the highest density (1.1 km^{-1}) occurred along the edge of the large lake.

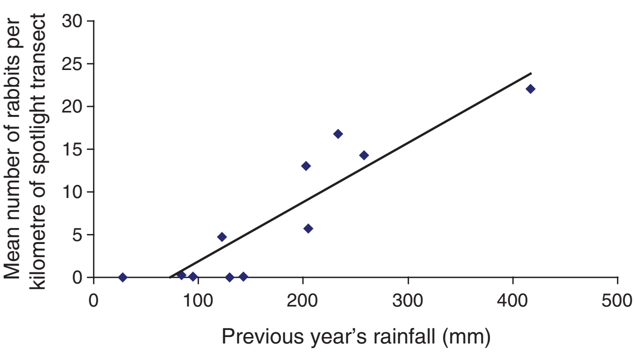

Fig. 7. The mean number of rabbits seen per kilometre in a year along the 10 km spotlight transect in unripped areas depended on the total amount of rainfall during the previous year.

Discussion

Destroying warrens by ripping reduced rabbit numbers by at least 98%. Even though the rabbits that infested surrounding areas had free access to the ripped areas, they did not readily re-establish warrens. The absence of reopened warrens seven years after ripping indicates that this treatment is long-lasting, and may only need to be done once. The cost of ripping and the vast areas to be treated make this method too expensive to treat all warrens on large properties like Bulloo Downs, at least in the short term. Nevertheless, the low reopening rate may mean that ripping can be spread out over many years and eventually all affected areas could be treated. Ripping programs could strategically treat areas important for cattle production or biodiversity. Furthermore, ripping areas close to long-lasting or permanent water may destroy the rabbits' drought refuge (Myers and Parker 1975*b*) and, after the inevitable dry periods, suppress rabbit numbers over the entire property for a fraction of the cost of ripping all warrens.

Release of virulent myxoma virus into wild rabbit populations has been viewed since the 1960s as the only useful form of rabbit control in south-west Queensland. Unfortunately, the releases were probably, in most cases, having no influence on rabbit numbers (Berman *et al*. 2006). In stark contrast to this, ripping warrens rapidly reduced rabbit numbers in the experimental plots on Bulloo Downs, strongly supporting other studies in South Australia (Mutze 1991), the Northern Territory (Edwards *et al*.

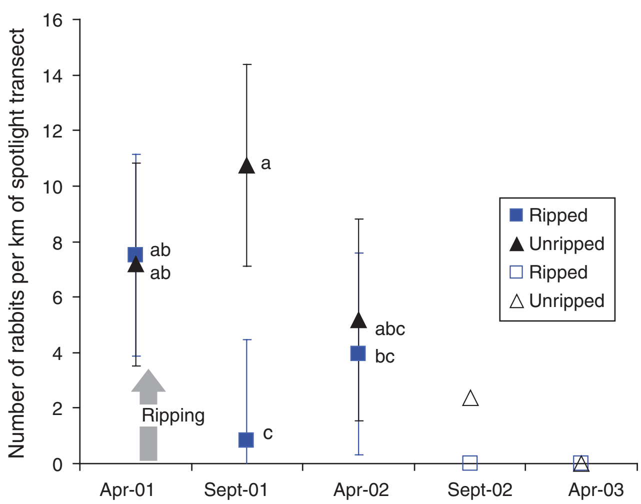

Fig. 8. Mean indices of rabbit abundance for spotlight counts at square plots for the first three time points from an ANOVA adjusted for the distance from long-lasting water covariate. Means with the same subscript are not significantly different at the 0.05 level. Confidence intervals around these means have been included to aid comparison with values from the last two time points (not included in analysis). Data for the last two time points (open symbols) were not included in the ANOVA.

2002*a*), and New South Wales (Wood 1985; Parer and Parker 1986), showing the value of ripping warrens for managing rabbits in arid or semiarid areas.

On a property near Yunta, in semiarid South Australia, there were still 98% fewer active warren entrances 10 years after ripping than before treatment (Mutze 1991). In our study at Bulloo Downs there was a very low initial rate of reopening and, seven years after ripping, there had been no further sign of reopening of treated warrens. Ripping, however, must be done well (McPhee and Butler 2010). Much higher reopening rates have been reported in north-western New South Wales (Martin and Eveleigh 1979; Wood 1985) and South Australia (Cooke 1981). In these cases not all warrens were ripped, because of economic or environmental contraints, the tractors used were too small, or the ripping depth was too shallow (Martin and Eveleigh 1979) to destroy the structure of the warrens adequately. In north-western New South Wales, only warrens with greater than four entrances were ripped, to reduce the cost, but the small warrens that were not treated proved to be a source of reinfestation (Wood 1985). In our study we attempted to rip all warrens in the treatment plots thoroughly with a large machine, which appeared to be effective. Monitoring will, however, need to continue to see if the reopening rate increases when ripped warrens are exposed to high rabbit densities after a sequence of high rainfall years.

The effectiveness of managing rabbit populations by warren destruction has been demonstrated in this study as it has elsewhere in arid Australia (Wood 1985; Mutze 1991; Edwards *et al*. 2002*a*), but the expense of treating vast areas makes this technique unviable for large arid properties. The cost of warren destruction per warren at Bulloo Downs was similar to that reported for South Australia but lower than for the Northern Territory or Victoria (Table 3) (Linton 1995; Dobbie 1998; Westhead 1998). However, the cost per km^2 on Bulloo Downs was higher than that found in other studies, probably because of the higher warren density. Based on the ripping conducted in 2001, and considering the relationship between distance from long-lasting water and warren density, we estimated it would cost over \$6 million to rip all warrens on Bulloo Downs Station. The management of the property were not willing to invest such a large amount, particularly as there was no guarantee at that time that ripping would be effective in sand dune country.

However, since the long-term survival of rabbits on Bulloo Downs may depend on the large numbers of warrens close to long-lasting water, we suggested that effective control might be achieved by ripping only these drought refuge areas. The cost of ripping areas within 1 km of long-lasting waterholes was estimated to be \$250 000 (Fig. 5). This is less than 4% of the cost of ripping all warrens on the property. If ripping only drought refuge areas successfully controlled rabbit populations, many millions of dollars would be saved through reduced cost of control and reduction in the damage caused by rabbits. Ripping warrens in drought refuge areas is not a new proposition (Myers and Parker 1975*b*), and has been shown to be effective in at least one other study (Mutze 1991).

Encouraged by the success of the experimental ripping, the manager of Bulloo Downs commenced a broad-scale rabbit control program in 2002. (The estimates of ripping costs reported here were used to secure funds from the Federal and State Governments.) By 2003 all warrens within 1 km of long-lasting water had been ripped on Bulloo Downs. The results suggest that treating drought refuge areas has indeed suppressed rabbit numbers over the entire property (Brennan and Berman, unpubl. data). However, to further demonstrate the long-term effectiveness of ripping we may need to monitor reopening rates through a sequence of years with above average rainfall when rabbit numbers are likely to be high (Fig. 7).

In this study, it was important to use more than one method for monitoring rabbit activity. Footprint counts clearly showed changes in the distribution of rabbit activity at treated plots immediately after ripping, at least in the internal parts of the plots. Rabbits, presumably from warrens in surrounding areas, were using the edges of ripped plots but were rarely seen in the central areas. Spotlight counts clearly showed the difference between treated and untreated plots, but provided less information about the distribution of rabbit activity at ripped plots. Counts of active warren entrances showed that rabbits were not reopening warrens in the ripped plots even though they lived in surrounding burrows and were moving into the plots. Rabbits had the opportunity to re-establish warrens in the ripped areas during a period of at least two years of the study, but they did not. The combination of sampling techniques provided a more complete understanding of the impact of ripping on rabbit activity than just one technique, but we were unable to continue using all techniques throughout the study due to lack of staff and time. The most appropriate technique was chosen for each circumstance.

There were 15 rabbits per km at Bulloo Downs (mean for the years 1999 to 2001) before ripping. At the same time in other arid areas, rabbit numbers were less than one rabbit per km of spotlight transect, having been reduced by RHDV (Neave 1999; Story *et al*. 2004). One exception to this was the area around Coongie Lakes in north-eastern South Australia where there were 16 rabbits per km (mean for the years 1999 to 2001) (South Australian Department of Environment and Natural Resources, unpubl. data). Like Bulloo Downs, Coongie Lakes receives flood water from rain falling in river catchments over 400 km away and

Table 3. Warren density at Bulloo Downs and three sites in other parts of Australia showing the number of warrens that were ripped per hour and the cost of ripping per warren and per square kilometre

Site	Warren density (km^{-2})	Warrens ripped (hour^{-1})	Cost (\$ warren^{-1})	Cost (\$ km^{-2})
Bulloo Downs, Queensland (square plots)	607	28	4.88	2607
Flinders Ranges, South Australia (Linton 1995)	329	23	3.29	1071
Harcourt, Victoria (Westhead 1998)	227	13	7.30	1657
Northern Territory (Dobbie 1998)	59	7	9.89	579

has a large number of long-lasting natural waterholes. Along the many kilometres of sand dunes lining the banks of natural waterholes, there are high densities of rabbit warrens. This probably allows rabbit numbers to remain high even through severe drought periods. The high density of rabbit warrens close to natural long-lasting waterholes is assumed to be due to the importance of these areas for rabbits to survive drought. During prolonged droughts the few surviving rabbits live in refuge areas (Myers and Parker 1975*a*, 1975*b*). Once food becomes abundant (i.e. not limiting) after each drought we believe most rabbits would stay and breed where they are, in the drought refuge areas. Once warrens become fully occupied, some rabbits may disperse but if there is still abundant food, new warrens would be dug, particularly if digging was easy, as it is in sandy soil. Thus, after each drought period, the density of warrens in drought refuge areas could increase. This process would explain the exceptionally high density of warrens reported here compared with other parts of Australia (Linton 1995; Dobbie 1998; Westhead 1998).

The presence and density of warrens can be influenced by vegetation cover (Myers and Parker 1965; Myers *et al*. 1975; Martins *et al*. 2002), local topography (Myers *et al*. 1975; Parker 1977), and soil type (Parer and Libke 1985). In our study area, the vegetation cover, topography and mix of soil types were consistent over a large area up to 50 km from long-lasting natural waterholes. Warrens were present only in the sandy soil and absent from the clay flats but overall the distance from long-lasting natural waterholes appears the major factor influencing warren density.

The areas to be treated first by ripping in a control program were identified as being within 1 km of long-lasting water where the highest densities of warrens were found. Although some rabbits have been reported travelling up to 1.5 km to drink during severe drought (Newsome *et al.* 1989), most are unlikely to regularly travel further than 500 m from their warren to water (Cooke 1982; Williams *et al*. 1995). Therefore ripping all warrens out to 1 km from water should ensure very few rabbits have access to both warrens and water during severe drought.

In other arid or semiarid areas, drought refuges for rabbits may not be so obvious and may be in stony soil where there are large, deep warrens (Myers and Parker 1975*b*), often along drainage lines but not necessarily associated with long-lasting waterholes. The higher nutrient quality of the soil along drainage lines (Morton 1990) may contribute to high warren densities there. These areas are considered important for the survival of native animals (Morton 1990) and are important for cattle production. Controlling rabbits in these areas first is therefore not only important for effective rabbit control but also for protection of biodiversity and cattle production.

The reliance on biological control in arid areas was based on the belief that it was the only economically viable technique because of the vastness of the areas to be treated by ripping and the concern that ripped areas may need to be re-treated. Since reopening rates are very low, ripping warrens in country such as Bulloo Downs can be considered to be a long-term solution. Each year, new areas can be ripped without the need to repeatedly rip the areas treated in previous years. The expense can be spread out over many years until all areas with significant rabbit infestations are ripped. It is also possible that by ripping areas close to long-lasting water, other drought refuge areas or areas with highest warren density may be all that is required to control rabbits over entire properties or even regions in the arid zone of Australia.

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