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Current and future abundances of large vertebrate pests in the rangelands of Western Australia

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Summary

Feral goats (*Capra hircus*), feral camels (*Camelus dromedarius*), feral donkeys (*Equus asinus*), and emus (*Dromaius novaehollandiae*) are large vertebrate pest species that can cause economic and/or environmental damage to rangelands. Broad-scale aerial surveys were used to estimate the population sizes of these species in the southern rangelands of Western Australia. The southern rangelands were partitioned into three survey areas: Upper Gascoyne/Pilbara, Murchison and Goldfields/Nullarbor. Since 1987, there has been a general increase in the estimated size of the population for each species. Feral goats were the most abundant of the animals investigated, followed by emus. Feral camels and donkeys are currently in low numbers in the southern rangelands but their numbers are increasing. By examining the rate of increase (r) using two different methods, we predict that the populations of these species will continue to increase in numbers. Values of r, using least-squares linear regression, differed for each of the species and the three survey areas. These ranged in value from: -0.072 to 0.51 for feral goats, 0.025 to 0.135 for feral camels, 0.009 to 0.036 for feral donkeys and -0.015 to 0.062 for emus. Using r we predict that by 2010 the populations of these vertebrate pests will be far greater than current numbers and they are likely to require the development of new management strategies to reduce their potential detrimental impacts.

Background

Quantification of population size or animal numbers is often a prime ecological variable needed to understand ecosystem functionality at any scale (McCallum 2000). For the Australian rangelands, large introduced species and a few native herbivore species dominate the vertebrate biomass. Economic imperatives generally require that pastoral enterprises maintain a good understanding of the distribution and abundance of domestic animals, but for free-ranging herbivores, a lack of documented knowledge often precludes informed management decisions. Increasingly, society demands that non-domestic populations of vertebrates be quantified for conservation and biodiversity values (e.g. native fauna) or management and mitigation of threatening processes (e.g. vertebrate pests).

A number of introduced and native species can and do adversely impact the rangelands of Australia. In Western Australia, these species include feral goats (*Capra hircus*), feral donkeys (*Equus asinus*), feral camels (*Camelus dromedarius*) and emus (*Dromaius novaehollandiae*). Economic and environmental effects of introduced goats, camels and donkeys are substantial, even after taking into account the potential economic benefits of the commercial harvesting of feral goats (Parkes *et al.* 1996) or management programs (e.g. Department of Agriculture of Western Australia's Feral Goat Eradication Program 1993 to 1998). Likewise, under certain conditions, emu populations can increase such that they congregate in vast numbers on the State Barrier Fence, parts of which represent some of the former 'Rabbit Proof Fence' system in the state and now act as a barrier between pastoral and agricultural lands (Long and Tozer 1964, Riggert 1975). Feral goats, camels and donkeys also present biosecurity risks in terms of exotic disease, with feral goats and camels being susceptible to high-risk diseases such as foot and mouth disease (AUSVETPLAN 2000).

Southwell and Pickles (1993) and Southwell (1996) examined the distribution and abundance of feral goats in Western Australia. These authors collected opportunistic information on the abundance of feral goats during an aerial survey program, which had the prime objective of measuring kangaroo abundance. The minimum population estimates for feral goats at this time (i.e. numbers not corrected for any form of bias) ranged from 363,000 in 1987 to 596,000 in 1990 over a survey area of 1.2 million km^2 (Southwell and Pickles 1993). By examining the finite rate of increase at these two points of time, Southwell (1996) calculated a rate of increase (r) of 0.17. This indicated that the population was increasing by about 18% each year, even accounting for commercial harvesting (Parkes *et al.* 1996). In comparison to r, the alternative variable of the intrinsic rate of increase, r_m, provides a maximum growth rate when resources are unlimited and the age structure of the population is stable (Caughley 1977). For feral goats in the rangelands of Australia, this value (r_m) can be as high as 0.414 (Maas 1997) which is considerably greater than the value calculated by Southwell (1996).

In this paper, we revisit the data of Southwell and Pickles (1993) and extend the data set from 1990 to 2002. We examine whether Southwell and Pickle's (1993) rate of increase ($r = 0.17$) holds true for the period 1990 to 2002 and make predictions on future abundances of feral goat populations in the rangelands of Western Australia. Emus, feral donkeys and feral camels have also been included in our re-analyses and we examine the population trends of these large vertebrate pests with particular comment on the economic and environmental impact of these species, both now and in the future.

Aerial Surveys – Collecting the Information

Aerial surveys are routinely undertaken by the Western Australian Department of Conservation and Land Management (CALM) with the main objective of counting kangaroos. Censusing of kangaroo population forms an integral component of Western Australia's management plan for the commercial harvesting of kangaroos (Anon 2003a,b). As well as information on the two commercially harvested macropod species (the red kangaroo *Macropus rufus* and the western grey kangaroo *M. fuliginosus*), additional or opportunistic information is also collected on a number of large vertebrate species including feral goats, camels, donkeys and emus.

Southwell and Pickles (1993) and Southwell (1996) provide details on the strip transect methodology used in this study. In brief, a fixed wing aircraft (flown at 76 m altitude and at 185 km/h) flew two transect lines across each degree-block (1° latitude by 1° longitude) within the survey area. Animals were counted within 200 m strips on each side of the aircraft, giving a sampling intensity of around 0.7%. Some degree-blocks towards the more arid parts of the survey area only had one flight line (0.35% sampling intensity) per degree block. Analysis of animal counts followed the methods of Caughley and Grigg (1981) to derive measures of animal density and numbers.

Survey Areas

Between 1987 and 1993, aerial surveys were flown once every three years over the southern rangelands (areas south of 20°S latitude) of Western Australia. Approximately 1.2 million km^2 were covered in each these surveys (Southwell and Pickles 1993). This area was covered in two, three-week survey campaigns (Southwell and Pickles 1993). In 1995, due to budget constraints, CALM redesigned the manner in which the 1.2 million km^2 were surveyed. The revised survey strategy involved a three-zone survey campaign (Figure 1), where one zone (each of an area greater than 300,000 km^2) was surveyed triennially in a cyclic fashion. This equated to the same triennial system as the earlier aerial survey campaigns.

To allow for comparisons between the 1987-1993 data and the 1995-2002 data, the earlier data set was divided into the three survey areas, rather than the single block used by Southwell and Pickles (1993). This was possible because flight lines of the earlier surveys were in discrete degree-blocks. Some flight lines from the 1987-1993 surveys could not to be re-allocated to one of the three survey areas because they were outside the boundaries of the more recent survey areas. Because there was also some overlap in area between the three survey areas (Figure 1), some degree-blocks of the 1987-1993 surveys were included in the analysis of more than one survey area. These minor adjustments to the data sets had little impact on the population estimates.

Characteristics of the Western Australian Rangelands

Burnside *et al.* (1995) broadly classified the rangelands of Western Australia into three main categories: mulga shrublands, saltbush and bluebush, and sand plain. Mulga shrublands are the most common grouping making up about 60 % of the rangelands, characterised by open mulga and low shrubs with shallow and non-saline soils (Burnside *et al.* 1995). Saltbush and bluebush is the most favourable category for grazing but makes up about 20% of the rangeland area (Burnisde *et al.* 1995). It is characterised by chenopod shrublands and saline soils that are often eroded. The final category, sand plain, is characterised by non-saline, deep and sandy soils with dense tall shrubs, and perennial grasses (Burnside *et al.* 1995).

The Upper Gascoyne/Pilbara survey area (Figure 1) is characterised as being hot and arid, with rainfall averaging between 180 to 300 mm per year and mean monthly maximum temperatures ranging from 25.2 °C in July to 35.8 °C in January and February (Beard 1975a). The north-west part of this region, in particular, is influenced by tropical cyclones (average about 2.4 per year). As a guide to seasons in the Upper Gascoyne/Pilbara survey area, Gascoyne Junction has had 18 dry winters compared to 15 wet winters in 80 years of recording, with other years being 'average' (Burnside *et al.* 1995). In the survey area, rainfall was generally average for each of the survey years from 1987 to 1993. Annual rainfall was generally above average from 1995 to 2000, with the exception of 1996 which experienced average rainfall. From 2001, rainfall for the survey area returned to average conditions before declining into average to below average conditions for 2002.

The Murchison survey area (Figure 1) has a number of bioclimatic classifications, depending on distance from the coast. These range from dry-warm Mediterranean to desert with summer and winter rainfall (Beard 1976). Rainfall averages between 200 to 500 mm per year and mean monthly maximum temperatures in February range from 32.2 °C in Geraldton to 39.0 °C at Earaheedy Station near Wiluna (Beard 1976). As a seasonal guide for this area, Meekatharra had 33 dry winters and 14 wet winters from 1914 to 1993 (Burnside *et al.* 1995). During the study period, this survey area experienced average rainfall conditions in 1987, 1990 and 1993, and above average rainfall conditions from 1995 to 2001. In 2002, below to very much below average rainfall conditions prevailed in the Murchison survey area.

Similar to the Murchison survey area, the Goldfields/Nullarbor survey area (Figure 1) has a number of bioclimatic classifications, depending on distance from the coast. These range from warm Mediterranean near the coast to desert with non-seasonal rainfall inland (Beard 1975b). Rainfall averages between 150 to 600 mm per year and mean monthly maximum temperatures in February range from 25.3 °C in Esperance to 33.8 °C at Kalgoorlie (Beard 1975b). Using Leonora as the seasonal rainfall guide, 23 dry winters and 18 wet winters were recorded from 1914 to 1993 (Burnside *et al.* 1995). Rainfall in the Goldfields/Nullarbor survey area was generally average in the 1987 and 1990 survey years, with above average rainfall in 1993 and 1995 to 2001. Rainfall in 2002 was generally below average in the Goldfields/Nullarbor survey area.

Calculation of rate of increase

As did Southwell and Pickles (1993) we used the Caughley (1977) method to calculate a population's rate of increase (r) over two successive sampling periods. This uses the formula:

$$\ln N_t = \ln N_0 + rt$$

where N_t and N_0 are population counts at two time intervals (t). We calculated r for feral goats, camels, donkeys and emus for each successive pair of sampling periods. However, to minimise the effects of autocorrelation and to provide a more representative approach in examining r, we also considered the longer-term changes in population for the study period (r_{study}). That is, N_0 became the first survey (1987) and N_t

was the last survey for each region (between 2000 and 2002, depending on region) in solving the above equation for r_{study}.

Because the data are in the form of a time series, we also used the alternative method of Caughley and Sinclair (1994) to calculate *r*. This method uses the least squares linear regression of ln(*N*) versus *t*, with r being the slope of the regression (McCallum 2000). To differentiate between the two methods of calculating, we refer to the regression method as r_{reg} and our use of the Caughley (1977) method as r_{study}. The most obvious advantage of using r_{reg} over r is that it uses all the values of the time series rather than just the first and last values (McCallum 2000).

Feral Goats

In the period from 1987 to 2002, the feral goat population in Western Australia has generally increased (Figure 2a). For both the Upper Gascoyne/Pilbara and the Murchison survey areas, the feral goat populations have trebled in size since 1987. Although the Goldfields/Nullarbor feral goat population is still below 1997 numbers, this population is increasing (i.e. *r* is positive). This follows a significant population reduction in the early 1990's, in part attributed to control efforts (Table 1, Figure 2a).

The observed rate of population increase (*r*) was both positive and negative between these surveys (Figure 2b). This is likely the result of the combined effects of environmental variability (rainfall, forage availability etc.), natural population dynamics (births, deaths, migration) and the substantial influence of commercial harvesting and control efforts (Table 1). The overall negative rate of increase for the Goldfields/Nullarbor area (Table 2) can largely be attributed to the Feral Goat Eradication Program (1993 to 1998, Table 1) which was mostly confined to this area. When demographic and environmental stochasticity are 'smoothed out' through regression (Figure 2c), the feral goat population is generally still exhibiting a positive rate of increase in the rangelands of Western Australia.

If we assume that resources for feral goats were not limiting, extrapolating Southwell and Pickles (1993) *r* value of 0.17 from 1990 to 2002 gives an estimated 48 million feral goats in the rangelands of Western Australia. In reality, the long-term *r*-values for each of the regions are much less than 0.17 (Table 2). The mean of these three *r* values was $r_{study} = 0.035$ and $r_{reg} = 0.008$. These values represent a more pragmatic projection of the long-term feral goat numbers in Western Australia. They suggest that the population of feral goats in Western Australia is increasing, despite the negative impact of several stochastic events including harvesting. Therefore population estimates for 2010 should represent a minimum estimate of goat numbers (Table 2).

Feral Camels and Donkeys

The long-term population trend for feral camels in the southern rangelands of Western Australia is one of increasing numbers (Figure 3). Camels are currently at relatively low numbers compared to other large herbivores. As such, some of the variability in the *r*-values may be attributed to lack of survey sensitivity as well as general stochasticity in other environmental parameters (e.g. rainfall). Nonetheless, the available evidence suggests that the feral camel population is increasing in the southern rangelands of Western Australia (Table 2).

Feral donkeys are also at relatively low numbers in the southern rangelands of Western Australia (Figure 4). Numbers in both the Upper Gascoyne/Pilbara and the Murchison survey areas are increasing, but generally at a lesser rate than either goats or camels (Table 2, Figure 4). As for the feral camel, the sensitivity of the survey method may not be sufficient to reliably estimate changes in long-term population trends. Nevertheless the observation that the numbers of feral donkeys are increasing is consistent with our data and anecdotal reports.

Emus

Emu populations, distinct from the other pest animals, are very susceptible to stochastic events such as rainfall and food availability, which have both positive and negative effects on their population. This makes long-term generalisations about emu numbers using *r*-values tenuous at best. For example, the emu population of the Murchison survey area grew rapidly in size from 1987 to 1990 (Figure 5), followed by a period of relative stability. This initial rapid rate of increase during the study period resulted in a relatively large value for r_{study} and greatly influenced the value of r_{reg} for the Murchison survey area (Figure 5, Table 2). Emu populations also appear to be more dynamic in terms of *r* (Figure 5) when compared to a mammalian herbivore of similar body size (e.g. feral goats, Figure 2). Despite the relative population fluctuations, the interval between surveys (3 years) was not of sufficient resolution to detect the boom-and-bust population changes of 'emu plagues', which are a noted occurrence in the rangelands of Australia (Long and Tozer 1964, Riggert 1975).

Issues of Measuring Population Trends

Broad-scale aerial surveys clearly have some inherent problems in measuring the actual abundance of animal populations (e.g. Southwell 1996, Pople *et al.* 1998a, Pople *et al.* 1998b, Linklater and Cameron 2002). Southwell (1996) suggests that the estimates of Southwell and Pickles (1993) were likely to be negatively biased by about 30-40%. Despite their large size, feral camels and donkeys can sometimes be difficult to see during aerial surveys (S. Wheeler, *pers. comm.* 2003). It follows that the same level of negative bias, as a minimum, is likely to be present for estimates of each of the vertebrate pest animals presented in our paper. However, while these problems are acknowledged, our comparisons and predictions have been made using the minimum, uncorrected estimates. Uncorrected estimates act essentially as an index of true density (Choquenot 1991). Therefore, our uncorrected population estimates and predictions are in reality, likely to be underestimates of absolute animal numbers. However, such indicies provide a valuable indicator of the relative changes in animal abundance over time.

Another issue that is illustrated by our study is the problem of small population size when undertaking broad-scale surveys. Feral camels and donkeys are sparsely distributed in the southern rangelands of Western Australia and are currently at relatively low numbers (Figures 3 and 4). Their distribution is influenced by environmental variables including food and water availability (Choquenot 1991, Edwards *et al.* 2001). Small population sizes, small sampling intensity (0.35 to 0.7%) and large survey areas (around 300,000 km^2) for each region combine to make a low probability for the encounter of a feral camel or donkey. When these factors are considered collectively, it is likely they mask trends in population abundance and calculation of population parameters such as r.

Using r to predict future trends in the population demographics of these pest animals needs to be context-dependent, in terms of the ecology of the animal and its habitat (McCallum 2000). Influences such as environmental variability greatly affect the demography of these populations, which in turn affect the rate of increase. While useful, caution needs to be used when using Caughley's (1977) r. If we extrapolate the example of Southwell and Pickles (1993) of $r = 0.17$, a population estimate of 48 million feral goats would be predicted for 2002 based on the 1987 and 1990 feral goat population estimates. However, this prediction of an excessively large feral goat population did not eventuate. The estimate of Southwell and Pickles (1993) resulted from two values for N_t and N_0 at points of time when feral goat fecundity was high, mortality was low and environmental conditions favourable for population growth (Figure 2). When N_t and N_0 were selected at different points of time, the predicted value of r was quite different (Figure 2, Table 2). For our approach in using r_{study}, the autocorrelation effects of age-specific mortality and fecundity are minimised by selecting the extreme points of the time series (greater than 12 years; Parkes *et al.* (1996)) but the calculation still only relies on two variables. The least squares regression method of Caughley and Sinclair (1994) provides a better estimate of r because it utilises all the points of the time series. However, in our example with feral camels and donkeys, the regression model fails to account for populations with an estimate of zero, which in turn influences the value of r. Furthermore, the time series requires sufficient data such that the natural stochasticity of the population does not adversely influence the regression model and hence r (e.g. emus in the Gascoyne/Murchison, Figure 5).

Large Vertebrate Pest Populations

Feral goats have become an important economic resource to some members of the pastoral industry, with Western Australia dominating the live-export market. The results presented in our paper suggest that the current harvest rate in Western Australia of around 228,500 feral goats per year (average from 1990 to 2000) is sustainable. However, it is clear that the current harvest rate is not acting as an effective, albeit unmanaged, form of pest control because the feral goat population is continually expanding. As described above, good rainfall fell during some of the sampling period and the rate of harvest appears to closely match the natural fluctuations in the feral goat populations (Figure 2). Market forces have also driven the harvesting/commercialisation of feral goats, with average monthly prices (2002/2003) being around AUD$30 per head (domestic abattoir) and much higher for live export. Future market potential for feral goat products appears promising for the pastoral sector in the short to medium-term, particularly for managed herds. The real test for the industry will come if feral goat prices fall. A fall in feral goat prices may have a negative economic impact on producers that rely on income generated from the harvest of feral goats. This in turn could increase the already substantial burden of feral goats on the rangelands environment, as the economic incentive to harvest will be minimal or even negative. In contrast, if domestic and international markets can be further developed, feral goats could exceed their current economic value to the pastoral industry. This could encourage positive management practices towards feral goats.

Despite some positives associated with commercialisation and sustainable harvest of feral goats, this practice is perhaps not the best long-term solution for the management of rangelands. At best, commercial harvest will retard population growth but not prevent it (Parkes *et al.* 1996). Without concerted government and industry support for the control of these particularly well-adapted vertebrate pests, the issues associated with the loss of biodiversity and degradation of the rangelands directly caused by feral goats will become more apparent as the feral goat population increases. Current control practices (shooting, mustering and trapping combined) may not be sufficient to impact the already large population (Parkes *et al.* 1996), so alternative methods should be examined.

While the commercial benefits of retaining or controlling goats remain in doubt (Anon 1999), consideration also needs to be given to the impact that the goats have on other pastoral industries such as the production of valuable timber crops such as sandalwood (*Santalum spicatum*). Sandalwood production from the Western Australian rangelands amounts to *ca.* 5000 tonnes p.a. and the timber sells for around AUD$5,000 per tonne wholesale. Recent research in Western Australia indicates that feral goats are a major factor in preventing the successful recruitment of sandalwood seedlings in the rangelands (Brand 1999, Brand 2000).

The current density of feral goats is low (e.g. 1.11 goats per km^2 in the Upper Gascoyne/Pilbara survey area in 2001) compared to a potential carrying capacity of 20-40 goats per km^2 in semi-arid rangelands (Parkes *et al.* 1996). The estimates for the rates of increase of the feral goat population (Table 2) are conservative and are far below the reported maximum rate of increase (Maas 1997; $r_m = 0.414$). This suggests that our predictions regarding the long-term population trends for feral goats are conservative and probably represent a guide for the minimum population size. Our estimates predict that, under current conditions and regimes, there could be between 1.2 and 1.6 million feral goats in the rangelands of Western Australia by 2010. However, these estimates could vary by as much as 40% due to the survey methodology used (Southwell 1996). A feral goat population in excess of 2 million animals could be expected to detrimentally affect the rangelands significantly above their current influence. Some pastoral leases and conservation areas with high densities of feral goats could be rapidly degraded. When these habitats contain areas of high biodiversity value then these areas could be under significant threat from feral goats. If future control is required to limit the feral goat population then options for control will become an issue, and expense, for pastoralists and other land managers.

Feral camels are currently at relatively low densities in the southern rangelands of Western Australia, with a maximum recorded density of 0.016 camels per km^2 recorded in the 2001 Upper Gascoyne/Pilbara survey. Western Australia has the highest abundance of feral camels in Australia (Short *et al.* 1988, Edwards *et al.* 2001) but the areas of highest density are beyond the pastoral boundaries in the arid interior. Short *et al.* (1988) found camel densities ranging from 0.03 to 0.78 camels per km^2 in arid areas bordering our survey areas. Edwards *et al.* (2001) reported an intrinsic rate of increase for feral camels in the Northern Territory of 0.16, indicating that feral camels are increasing at a relatively rapid rate in the arid interior of Australia. This suggests that, in the medium to long-term, there is a high potential for feral camels to become a vertebrate pest of some significance to the pastoral industry, rangeland biodiversity and in the maintenance of biosecurity.

Feral donkeys in the southern rangelands of Western Australia are currently at very low densities, with a maximum density of 0.028 donkeys per km^2 in the 1998 Upper Gascoyne/Pilbara survey. When compared to similar uncorrected population estimates from aerial surveys in the Northern Territory of 1.5 to 3.3 donkeys per km^2 (Choquenot 1991) it is apparent that feral donkeys are not currently a major vertebrate pest of the southern rangelands of Western Australia. Rates of increase for feral donkeys in the Upper Gascoyne/Pilbara survey area compare favourably with those reported previously Choquenot (1990) indicating our calculated values of *r* were realistic. Theoretically, based on these *r*-values it is very possible that numbers in the southern pastoral region will reach the higher densities described by Choquenot (1991), but over a time frame of 40-80 years. Ongoing opportunistic control efforts may minimise the potential long-term environmental, economic and biosecurity risks of having an arid-adapted herbivore with high survival rates and rates of increase of over 20% per annum (Choquenot 1991).

Emus are capable of altering their breeding activity in response to environmental parameters such as rainfall (del Hoyo *et al.* 1992). Large population increases, in response to good conditions, often result in large congregations of emus along vermin-proof fences adjacent to agricultural areas (Sexton 1976). In response to these increases, damage licences are issued by CALM to the affected pastoralists. These build-ups, and associated large-scale migrations, can often occur within a single year but they rarely persist over two years. Because of the triennial cycle of surveys, a true 'boom' year wasn't identified in any of the three areas surveyed. Nonetheless, *r*-values and population fluctuations (Figure 5) demonstrate the variability in the emu numbers in the southern rangelands of Western Australia. In terms of pest status, emus are much less a real threat to the rangelands than their mammalian counterparts.

Conclusion

Feral goats, donkeys and camels are all increasing in abundance within the southern rangelands of Western Australia. Feral goats are the major pest species of concern in the southern rangelands causing damage to the environment and pastoral production. We predict that the deleterious impact of feral goats will increase significantly in the short to medium-term. However, some components of the pastoral industry perceive feral goats to be a sustainable resource in their own right. This perception is closely linked to market forces and without a market and sustained harvest, feral goats will become a more significant problem for land managers than they are at present. Furthermore, harvesting and commercialisation is not preventing population growth of feral goats. Feral donkeys and camels are currently at such low densities that they are not a major risk to the pastoral industry in the areas surveyed. Caution must be taken with feral donkeys and camels, as both species have the potential to be serious vertebrate pests in the southern rangelands and it is doubtful if our methodology enabled reliable explanations of changes in abundance of these species. Emus undergo such rapid growths and declines in population size that it is difficult to make predictions about future numbers. Emus will continue to be a vertebrate pest of annoyance to the pastoral industry, causing damage to infrastructure (e.g. fencing) but their long-term potential impact is much less than the introduced goat, donkey and camel. For preservation of biodiversity values, mitigation of threatening processes and minimisation of biosecurity risks in the rangelands, implementing ongoing proactive management of these species will reduce the impact of the high numbers of vertebrate pests that our study predicts.

only by maintaining a heavy regular pressure.

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Table 1. Number of feral goats harvested for abattoir processing and live export. A feral goat eradication program was conducted by the Department of Agriculture from 1993 to 1998.

Year	Number of Goats Processed[1]	Live Export[2]	Goats Destroyed in Eradication Program	Total
1987/88†	179,085	16,707		195,792
1988/89†	150,745	14,753		165,498
1989/90†	186,625	13,365		199,990
1990*	195,502	14,337		209,839
1991	237,144	48,212		285,356
1992	219,842	17,685		237,527
1993	189,763	14,793	48,985	253,541
1994	144,158	21,653	53,831	219,642
1995	93,460	10,998	49,551	154,009
1996	110,282	22,562	44,113	176,957
1997	159,753	35,385	23,198	218,336
1998	159,849	52,813	33,375	246,037
1999	176,154	28,989		205,143
2000	270,078	38,099		308,177
2001	259,809	69,326		329,135

† Financial year (July to June) figures from Southwell and Pickles (1993).

* Some overlap with 1989/90 financial year.

[1] Source: John James, Department of Agriculture, unpublished data.

[2] Source: Australian Bureau of Statistics.

Table 2. Predicted population sizes of four pest animal species in three rangeland regions by the year 2010. The rate of increase (r) was calculated using two different methods. The first followed the procedure of Caughley (1977), using the first (1987) and last year (2000, 2001 or 2002) of surveys to calculate r for the study period (r_{study}). The second method (r_{reg}) followed the least squares linear regression procedure of Caughley and Sinclair (1994), and uses all survey results.

Pest Animal	Region	Year of Last Survey	Last Survey Population Estimate	r_{study}	r_{reg}	2010 Population Estimate	
						with r_{study}	with r_{reg}
Goats	Upper Gascoyne/Pilbara	2001	352,838	0.090	0.046	764,192	530,610
	Murchison	2000	362,415	0.077	0.051	759,735	594,901
	Goldfields/Nullarbor	2002	57,919	-0.059	-0.072	35,575	31,810
Camels	Upper Gascoyne/Pilbara	2001	4,957	0.052	0.135	7,829	15,510
	Murchison	2000	2,738	0.032	0.025	3,761	3,501
	Goldfields/Nullarbor	2002	3,245	0.074	0.098	5,766	6,866
Donkeys	Upper Gascoyne/Pilbara	2001	7,372	0.031	0.036	9,709	10,133
	Murchison	2000	4,867	-0.023	0.009	3,849	5,313
	Goldfields/Nullarbor	2002	0	-0.009	0.011	0	0
Emus	Upper Gascoyne/Pilbara	2001	27,073	0.007	0.020	28,945	32,373
	Murchison	2000	74,521	0.086	0.062	169,966	135,902
	Goldfields/Nullarbor	2002	1,979	-0.143	-0.015	574	1,747

Figure 1. Three survey areas of the CALM aerial survey operation. Surveys are undertaken in a cyclic fashion, with each area being re-surveyed every 3 years. The names of the survey areas are representative of the areas and are not strictly geographical regions.

Figure 2. Changes in numbers of feral goats in the southern rangelands of Western Australia. The three plots represent:

a) Number (*N*) of feral goats in each of the three survey areas from 1987 to 2002. Population estimates are uncorrected and therefore represent the minimum number of animals present.
b) Rate of increase (*r*) calculated from successive surveys using the formula of Caughley (1977). Positive values of *r* represent positive population growths with negative values representing periods of population decline. The solid reference line of y = 0 represents a stable population size and the dashed reference line of y = 0.17 represents Southwell and Pickles (1993) value for *r*.
c) Least-squares linear regression calculation of the rate of increase (r_{reg}) following the method of Caughley and Sinclair (1994). The values of r_{reg} are: 0.046 (Upper Gascoyne/Pilbara), 0.051 (Murchison) and -0.072 (Goldfields/Nullarbor).

Figure 3. Changes in numbers of feral camels in the southern rangelands of Western Australia. The three plots represent:

a) Number (*N*) of camels in each of the three survey areas from 1987 to 2002. Population estimates are uncorrected and therefore represent the minimum number of animals present.
b) Rate of increase (*r*) calculated from successive surveys using the formula of Caughley (1977). Positive values of r represent positive population growths with negative values representing periods of population decline. The reference line of y = 0 represents a stable population size. Note that to calculate '*r*', successive population estimates need to be greater than zero.
c) Least-squares linear regression calculation of the rate of increase (r_{reg}) following the method of Caughley and Sinclair (1994). Note that this method excludes survey data with zero animals. The values of r_{reg} are: 0.135 (Upper Gascoyne/Pilbara), 0.025 (Murchison) and 0.098 (Goldfields/Nullarbor).

Figure 4. Changes in the numbers of feral donkeys in the southern rangelands of Western Australia. The three plots represent:

a) Number (*N*) of donkeys in each of the three survey areas from 1987 to 2002. Population estimates are uncorrected and therefore represent the minimum number of animals present.

b) Rate of increase (*r*) calculated from successive surveys using the formula of Caughley (1977). Positive values of r represent positive population growths with negative values representing periods of population decline. The reference line of y = 0 represents a stable population size. Note that to calculate '*r*', successive population estimates need to be greater than zero.

c) Least-squares linear regression calculation of the rate of increase (r_{reg}) following the method of Caughley and Sinclair (1994). Note that this method excludes survey data with zero animals. The values of r_{reg} are: 0.036 (Upper Gascoyne/Pilbara), 0.009 (Murchison) and 0.011 (Goldfields/Nullarbor).

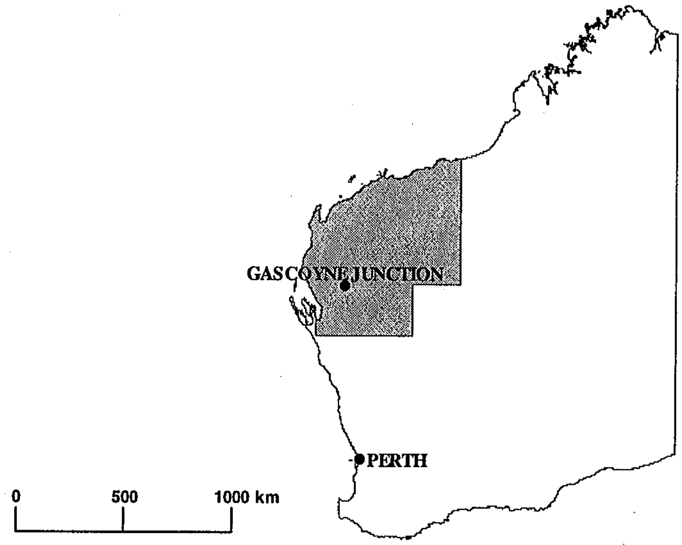
Figure 5. Changes in the numbers of emus in the southern rangelands of Western Australia. The three plots represent:

a) Number (*N*) of emus in each of the three survey areas from 1987 to 2002. Population estimates are uncorrected and therefore represent the minimum number of animals present.

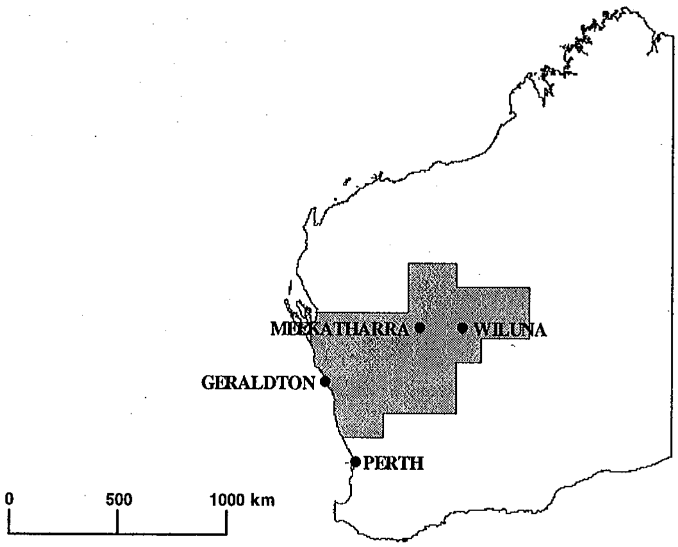
b) Rate of increase (*r*) calculated from successive surveys using the formula of Caughley (1977). Positive values of *r* represent positive population growths with negative values representing periods of population decline. The reference line of y = 0 represents a stable population size.

c) Least-squares linear regression calculation of the rate of increase (r_{reg}) following the method of Caughley and Sinclair (1994). The values of r_{reg} are: 0.020 (Upper Gascoyne/Pilbara), 0.062 (Murchison) and -0.015 (Goldfields/Nullarbor).

Upper Gascoyne/Pilbara



Murchison



Goldfields/Nullarbor

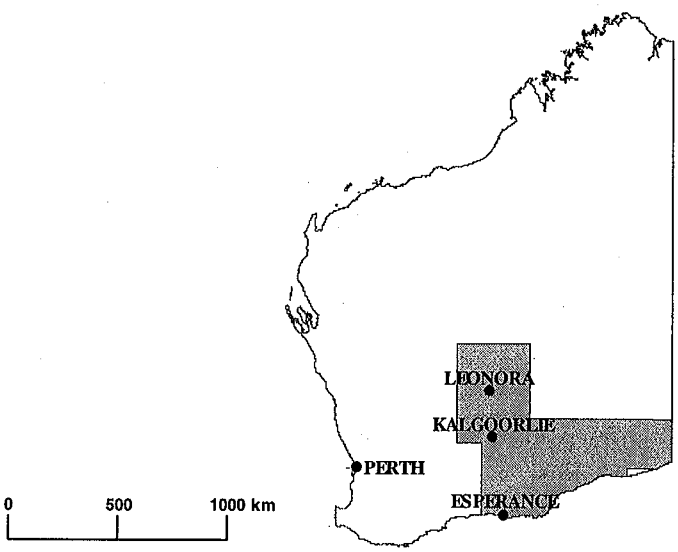


Fig 2.

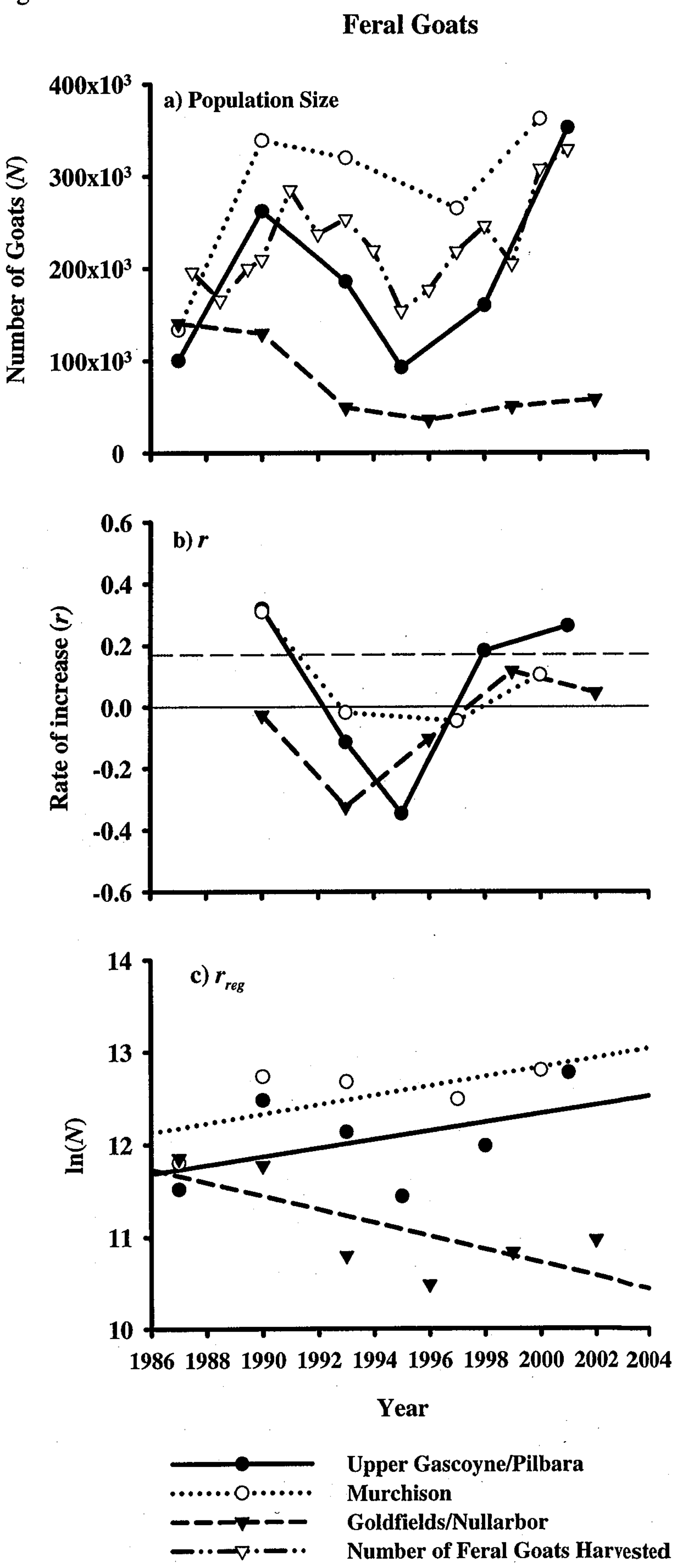
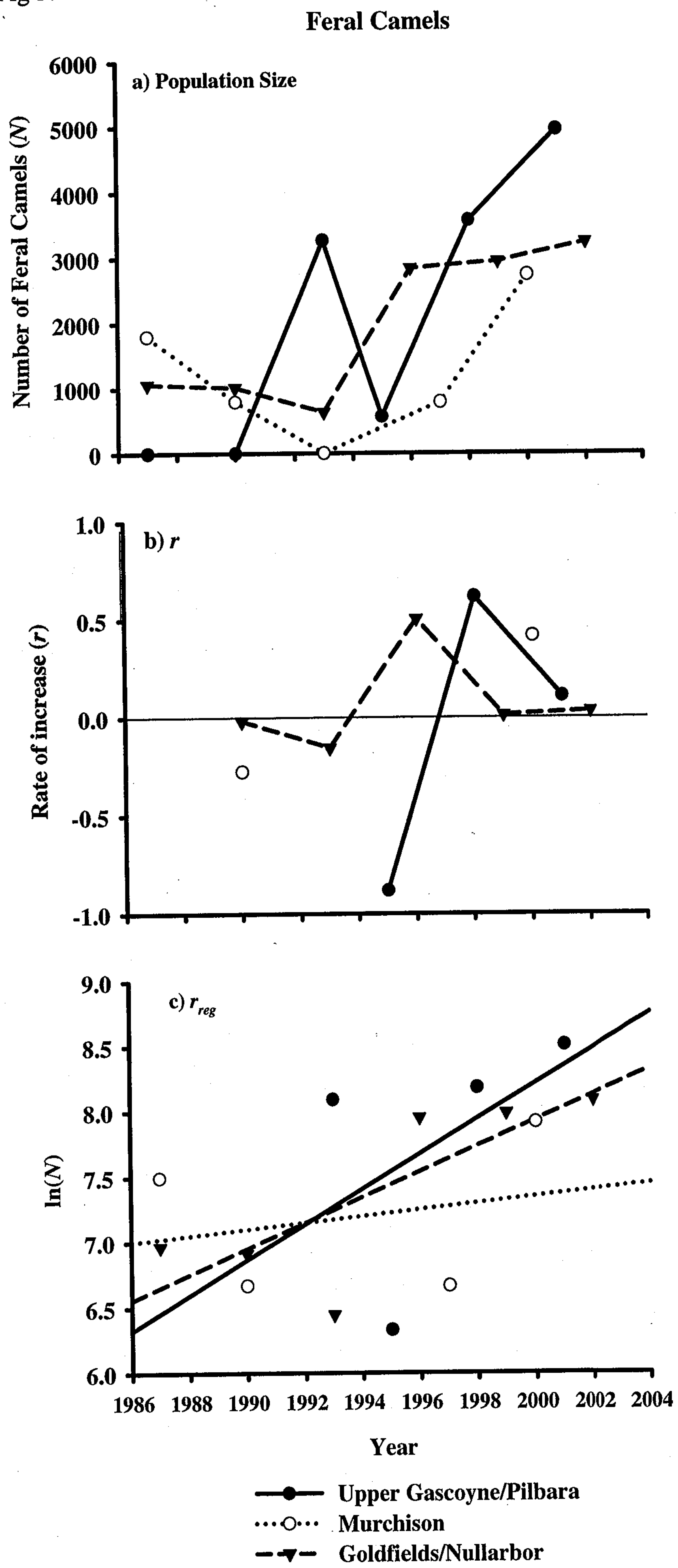

Feral Goats
a) Population Size
Number of Goats (N)
400x10³
300x10³
200x10³
100x10³
0
b) r
Rate of increase (r)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
c) r_reg
ln(N)
14
13
12
11
10
1986 1988 1990 1992 1994 1996 1998 2000 2002 2004
Year
Upper Gascoyne/Pilbara
Murchison
Goldfields/Nullarbor
Number of Feral Goats Harvested

Fig 3.



Feral Camels
a) Population Size
Number of Feral Camels (N)
6000
5000
4000
3000
2000
1000
0
b) r
Rate of increase (r)
1.0
0.5
0.0
-0.5
-1.0
c) r_reg
ln(N)
9.0
8.5
8.0
7.5
7.0
6.5
6.0
1986 1988 1990 1992 1994 1996 1998 2000 2002 2004
Year
Upper Gascoyne/Pilbara
Murchison
Goldfields/Nullarbor

Fig 4.

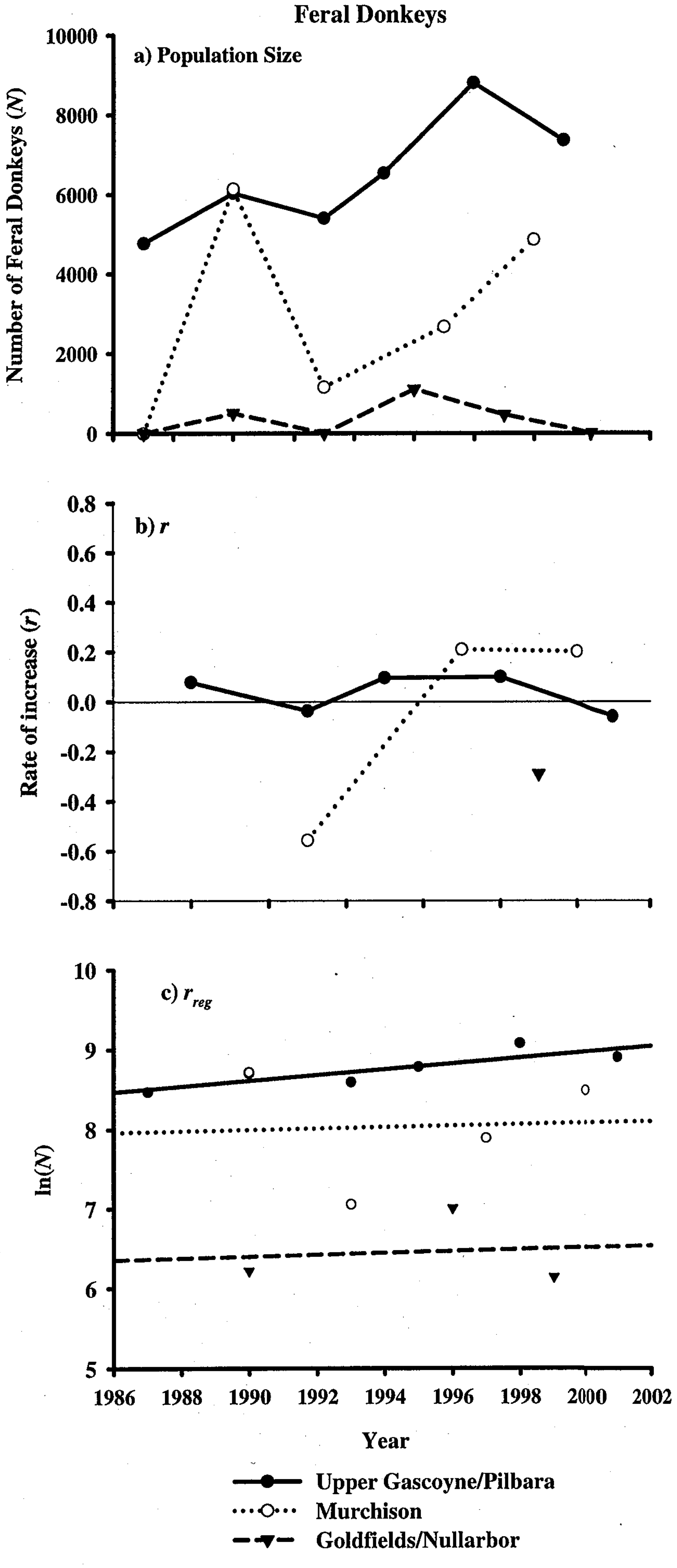
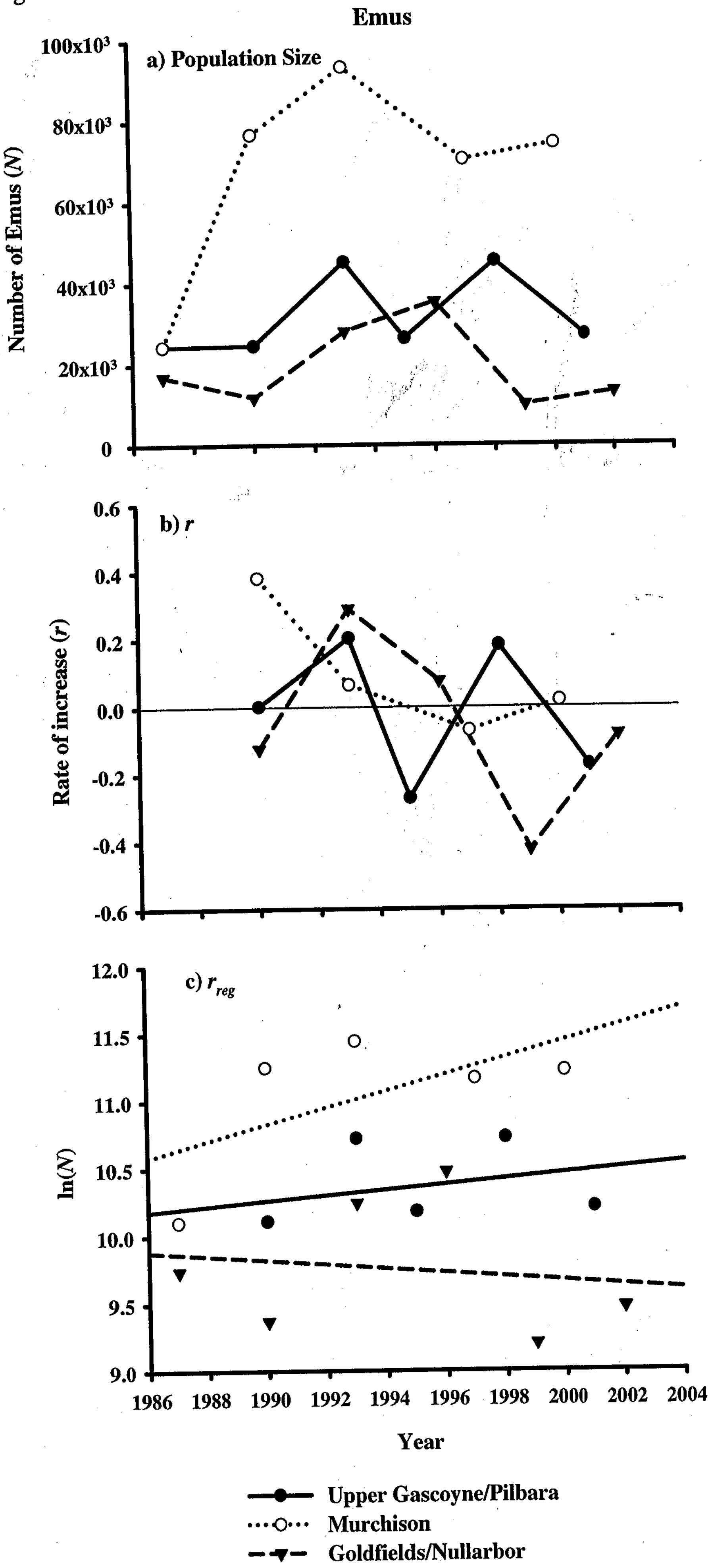

Feral Donkeys
a) Population Size
Number of Feral Donkeys (N)
10000
8000
6000
4000
2000
0
b) r
Rate of increase (r)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
c) r_reg
ln(N)
10
9
8
7
6
5
1986
1988
1990
1992
1994
1996
1998
2000
2002
Year
Upper Gascoyne/Pilbara
Murchison
Goldfields/Nullarbor

Fig. 5



Emus
a) Population Size
Number of Emus (N)
100x10³
80x10³
60x10³
40x10³
20x10³
0
b) r
Rate of increase (r)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
c) r_reg
ln(N)
12.0
11.5
11.0
10.5
10.0
9.5
9.0
1986 1988 1990 1992 1994 1996 1998 2000 2002 2004
Year
Upper Gascoyne/Pilbara
Murchison
Goldfields/Nullarbor