Distribution, abundance and harvesting of feral goats in the Australian rangelands 1984-2011

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Summary

The Australian Collaborative Rangelands Information System (ACRIS), through Ninti One Ltd., commissioned Biosecurity Queensland to collate and analyse aerial survey data to determine trends in the abundance and distribution of feral goats and their commercial harvest over the past three decades in the rangelands of Australia.

Objectives

i. Collate a national rangelands dataset for feral goat abundance from available aerial survey data and calculate densities for IBRA bioregions.

ii. Investigate the need to correct for visibility bias and the potential to do this based on available data.

iii. Map goat densities for selected years in relation to IBRA bioregions.

iv. Map change in feral goat abundance over time.

v. Provide estimates of the proportion of the goat population in each survey area that is truly feral or is managed.

vi. Collate available regional data on numbers of goats harvested to supplement the survey data.

vii. Assess suitability and possibility of improvements to existing survey data for reporting change in feral goat densities and to existing harvest data for determining the impact of harvesting on feral goat populations.

Main findings

- Densities of feral goats in the rangelands of Australia have been estimated over the past three decades by aerial surveys for kangaroo management. Most surveys have involved counting goats in 100m or 200m strip transects surveyed by fixed-wing aircraft. These counts require correction for visibility bias. Various correction factors have been suggested for feral goats, based on double counting (i.e. mark-recapture), line transect methods using fixed-wing aircraft or comparisons with more accurate helicopter counts using line transect methods. Correction factors developed in Western Australia have been applied to counts in South Australia and Western Australia. Correction factors developed in New South Wales have similarly been applied to counts there. Unpublished data from Queensland were analysed in this project and applied to counts there. Correction factors of 1-2 were applied to the counts in all states.

- These surveys describe a feral goat population in Australia that has grown from 1.4 million in 1997 to 4.1 million in 2008. In 2010, there were an estimated 3.3 million feral goats in the rangelands of Australia.

- In Queensland, fixed-wing surveys were conducted annually over 1984-1992, and again in 2001, across an area of ~500,000 km^2. Since 1991, the area has been surveyed by helicopters in monitor blocks using line transect methodology. There has been an increase in feral goat numbers over the study period, particularly in the mulga lands where goats have increased almost five-fold over a 20-year period. However, numbers have been declining since 2006. A population of 491,000 feral goats was estimated in 2010.

- In New South Wales, fixed-wing surveys have been conducted annually since 1993 across an area of ~460,000 km^2. Goats are abundant in five bioregions and have increased in each at an average annual rate of 5-10% over the study period. Increases have been greatest in the mulga lands, Cobar peneplain and Murray Darling depression. Surprisingly, drought in the early 2000s did little to dampen this overall increase. An increasing proportion of Australia's feral goat population occurs in New South Wales, comprising 70% in 2010. In 2011, there were an estimated 2.95 million feral goats in the state.

- In South Australia, fixed-wing surveys have been conducted annually since 1989 across a core area of 290,000 km^2, but an area of ~490,000 km^2 was covered by all survey years combined. Goats are common in four bioregions, but particularly in the Murray Darling depression. There has been no obvious long-term, state-wide trend in abundance. In 2011, there were an estimated 322,000 feral goats in South Australia.

- In Western Australia, fixed-wing surveys of feral goats were flown in 1987, 1990 and 1993. Since 1993, a different third of the overall survey area of ~1,200,000 km^2 was flown each year. Goats are common in the Carnarvon, Murchison and Yalgoo bioregions. State-wide, numbers increased to a peak of 1.1 million in 2005, but have since declined to an estimated 150,000 in 2011. This decline has been most marked in the Murchison and Gascoyne bioregions.

- A caveat on these population estimates is that observers on aerial surveys cannot readily distinguish truly feral goats from domestic or managed goats. This problem has been exacerbated by an increase in the number of domestic goats in the rangelands and the practice of mustering feral goats and keeping them within fenced paddocks and managing them as domestic stock. Based on irregularly collected ABS data, there were 465,000 domestic goats in the rangeland survey area in 2008. Over 1983-2009, most (29-71%) domestic goats in the rangelands have been in New South Wales. The numbers of domestic goats relative to feral numbers are low, suggesting the problem of misidentification is low. However, the ABS data need validation. Surveys of processors suggest much larger numbers of domestic goats than those recorded by ABS.

- Surveys over larger areas in each state have indicated that the core areas that are surveyed regularly capture the bulk of the distribution. That distribution is largely restricted to the semi-arid rangelands where sheep grazing is or has been the predominant land use and, notably, where wild dogs are controlled. Changes in the pattern of distribution of goats within states over the study period have not been dramatic. Increases in density have been associated with expansions of distribution and decreases with contractions. Maps of the rates of increase over the study period show some variation, but trends have generally been uniform. An exception is the recent collapse in goat numbers in the eastern part of the feral goat distribution in Western Australia.

- Most harvested goats are processed at abattoirs. Based on the number of carcass inspections by AQIS, the Australia-wide slaughter has increased from 0.6 million in 1988 to 1.6 million in 2010. This is reflected in the steady increase in the export of goat meat over 1982-2011. It has been assumed that feral goats comprise ~90% of goats slaughtered and this is supported by ABS figures, although their data greatly underestimate the number of goats processed. The live export trade contributes a further 8% on average to the total goat offtake, but there has been little overall trend in the numbers exported live. These removal data suggest a commercial harvest rate that has fluctuated between 20% and 50% of the estimated population in Western Australia and eastern Australia (Queensland, New South Wales and South Australia combined) between 1990 and 2010. In Western Australia, non-commercial destruction increased the harvest rate to over 70% in 1992, but that declined to below 30% by 1997.

- Estimates of maximum age-specific survival and reproduction suggest feral goat populations can increase at a maximum annual exponential rate of r_m = 0.66, equivalent to almost doubling in a year. Empirical rates are lower than this theoretical maximum and so a more conservative value of r_m = 0.5 was included in the generalised logistical equation to indicate the likely impact of harvesting. Carrying capacity was varied in the model based on historical data. The maximum sustained yield occurs at a harvest rate of ~30% and results, in the long term, in a population reduction of just over 50%. The harvest rates reported here for goats fall around this figure.

Recommendations

1. In each state other than Queensland, the current aerial survey design provides adequate precision (<20%) to detect medium- to long-term changes in feral goat abundance. Precision is poorer in Queensland, averaging 36% using helicopter survey blocks, but will enable long-term changes to be detected. Goat life history and historical data presented here indicate that feral goat populations will not undergo large population fluctuations in the short term, with the exception of steep declines in response to drought. An improvement to the survey design would be to increase survey effort where population size is greatest. However, there would need to be good reason for this additional cost such as to monitor a greater control effort. Current surveys are undertaken by conservation agencies whose main interest is in kangaroo monitoring and not goat management.

2. Jurisdictions need encouragement to continue to count goats on aerial surveys for kangaroos and regularly analyse data on goats. Problems include the perception that feral and domestic animals cannot be distinguished and so the data are of little value, and the fact that the data are not used by the respective state government departments and so there is little incentive to analyse them.

3. The inability to distinguish feral from domestic goats compromises population estimates from these surveys. ABS data suggest that the domestic goat population is relatively small, but these data need validation. A few case studies examining property records would assist here.

4. Count data for all states are stored digitally, but most data required some manipulation before analysis. Ideally, each 5 km survey segment should be georeferenced to allow easy reanalysis of data in different areas of interest. Central storage of all states' data, kangaroo and goat, may be needed to achieve this. Only Western Australia maintains its survey data on a database, but all states should do this.

5. An improvement in methodology for fixed-wing surveys of goats would be to record individual clusters (i.e. groups) of goats as cluster size is an important influence on detection probability. This improvement aside, further work on correction factors is not a priority as the variation between different studies is not great. There may be biogeographic variation in detection probability as there is for kangaroos. It would be feasible and useful to collect mark-recapture data on current fixed-wing and helicopter surveys to address this.

6. Harvest data are reliable and readily available, but are limited by not knowing the region from which goats have been removed. Currently, the harvest data can only be allocated to eastern or Western Australia. Data from ABS could potentially provide the necessary information, but they are collected infrequently and appear unreliable. A further problem is again the inability to distinguish feral and truly domestic goats. Field data from representative sites as suggested in recommendation 3 above could address this.

Introduction

Feral goats (*Capra hircus*) are well recognised as agricultural and environmental pests in the rangelands of Australia (Parkes *et al*. 1996, DEWHA 2008). A necessary aspect of their management is the monitoring of (ideally) impacts and (more likely) abundance to evaluate past control and plan future action. This has not been regularly undertaken in the management of vertebrate pests in Australia (Reddiex *et al*. 2006). Monitoring the grazing impacts of goats is problematic as these can be difficult to disentangle from the grazing impacts of domestic and native herbivores that are also abundant across feral goats' distribution. Abundance has been considered a proxy for impact, but this is likely to be oversimplistic as it assumes a linear relationship between the two. In contrast to monitoring impact, goats are amenable to aerial survey and this has provided estimates of abundance over large areas of the rangelands (Pople *et al*. 1996, Southwell and Pickles 1993, Southwell *et al*. 1993, Grigg *et al*. 1999, Ballard *et al*. 2011). These data now represent a long time series that allow an assessment of not just past episodes of control but also long-term trend in pest abundance. This is particularly valuable as it allows consideration of temporal environmental variation, primarily rainfall in the semi-arid and arid rangelands, which can mask short-term effects of control and trends in abundance.

The Australian Collaborative Rangelands Information System (ACRIS), through Ninti One Ltd., commissioned Biosecurity Queensland to collate and analyse aerial survey data to determine trends in the abundance and distribution of feral goats and their commercial harvest over the past three decades in the rangelands of Australia. Specifically, the project addressed the following objectives:

1. Collate a national rangelands dataset for goat abundance from available jurisdictional data (1978-present) and calculate densities for regions (e.g. management zones, survey blocks, or ideally bioregions) as appropriate.
2. Investigate the need to correct for visibility bias and the potential to do this based on available data.
3. Map goat densities for selected years based on survey transects or blocks and, where possible, interpolate (spatially concord) to the Interim Biogeographic Regionalisation for Australia (IBRA) bioregional boundaries.
4. Map change over time either as trends (i.e. average rates of increase over survey periods) or against a base period, as ACRIS has done for livestock and kangaroo densities.
5. Based on available data, provide estimates of the proportion of the goat population in each survey area that is truly feral or is a managed herd possibly seeded from feral stock.
6. To the extent possible, collate available regional data on numbers of goats harvested to supplement the survey data. Such data could come from the Australian Quarantine Inspection Service (AQIS), Meat and Livestock Australia (MLA), abattoir statistics, or regional statistics compiled by natural resource management (NRM) bodies.
7. Provide advice to the ACRIS Management Committee on:
    i. the suitability of existing data for reporting change in feral goat densities
    ii. actions within jurisdictions that could improve the value of future data
    iii. the capacity of jurisdictions to undertake expanded activity in monitoring goats
    iv. the value of available regional harvest data and the potential to improve this data source
    v. a recommended protocol for standardising aerial survey to provide suitably robust data on goat densities.

Data on the density and distribution of feral goats come from broad-scale aerial surveys undertaken for kangaroo management (see Pople and Grigg 1998, Pople *et al*. 2011). A range of other large vertebrates has been counted on these surveys, including emus (*Dromaius novaehollandiae*) (Grice *et al*. 1985, Pople *et al*. 1991), bustards (*Ardeotis australis*) (Grice *et al*. 1986), feral camels (*Camelus dromedarius*) (Short *et al*. 1988), feral donkeys (*Equus asinus*) and feral horses (*Equus caballus*) (A. Woolnough, G. Martin, WA Department of Agriculture and Food, and P. Mawson, Western Australian Department of Conservation and Land Management, unpublished data), and feral goats. This project provides an overdue update on previously presented population data for feral goats, mostly from the 1990s. Concurrent data on goat sales, slaughter and export are also presented and considered here, rather than in isolation from the population data, which has compromised their presentation elsewhere (e.g. Forsyth and Parkes 2004, Forsyth *et al*. 2009, Schuster 2006, Swain 2011). These data thus allow assessment of both the status of an environmental and economic pest and the impact of commercial harvesting, which is the principal control method (Parkes *et al*. 1996).

Methods

Aerial surveys

The main study area that was regularly surveyed spans four states across a region where sheep grazing has been the predominant land use (Fig. 1). The relatively flat terrain and open vegetation makes the area suitable for aerial survey of large wildlife such as kangaroos and goats. The vast size of the core survey area (~2.4 million km^2) makes aerial survey the only feasible monitoring method.

Fixed-wing surveys

Surveys have been undertaken by fixed-wing aircraft in all states, but in Queensland helicopters have been used since 1991. Fixed, high-wing aircraft (Cessna) have flown transects at a ground speed of 185 km h^{-1} at 76 m above ground. An observer on either side of the aircraft counted feral goats in 200 m wide strips along 5 km segments (i.e. 1 km^2), each separated by a seven second break (i.e. 0.36 km) in counting. Since 2001, counts from fixed-wing aircraft have been made in 100 m wide strips in both New South Wales and Queensland. These counts need to be adjusted for visibility bias and their derivation is explained below.

In Queensland, surveys were flown in 1980, then annually from 1984 to 1992, then again in 2001. Survey transects were ~50 km apart (Caughley and Grigg 1982). Only the presence or absence (i.e. occupancy) of goats was recorded in surveys over 1980-1982. For 1984-1991 and 2001, the same transect lines were flown, covering an area of 495,000 km^2. The lower two degrees of latitude (i.e. 29-31^o) of the Queensland survey area was flown in 1983. The 1984 survey covered a larger area of 1,027,000 km^2, which mostly covered the areas surveyed in 1980-1982. Data for the latter surveys are therefore not reported here. In 1991, the southern third of the Queensland study area was not flown. Density was therefore interpolated for this area using the 1990 and 1992 surveys.

In New South Wales, survey transects were flown ~50 km apart (Caughley *et al*. 1977). Surveys have been flown in New South Wales since 1975, but raw data are only available since 1993 because earlier data were destroyed by a fire. Surveys were conducted annually across an area of 463,000 km^2 . Southwell *et al*. (1993) provide an uncorrected estimate of feral goat numbers in the survey area for 1992. Helicopter surveys are flown to the east of this area, outside the semi-arid and arid rangelands, to estimate kangaroo numbers, but the resulting data were not collated in this study.

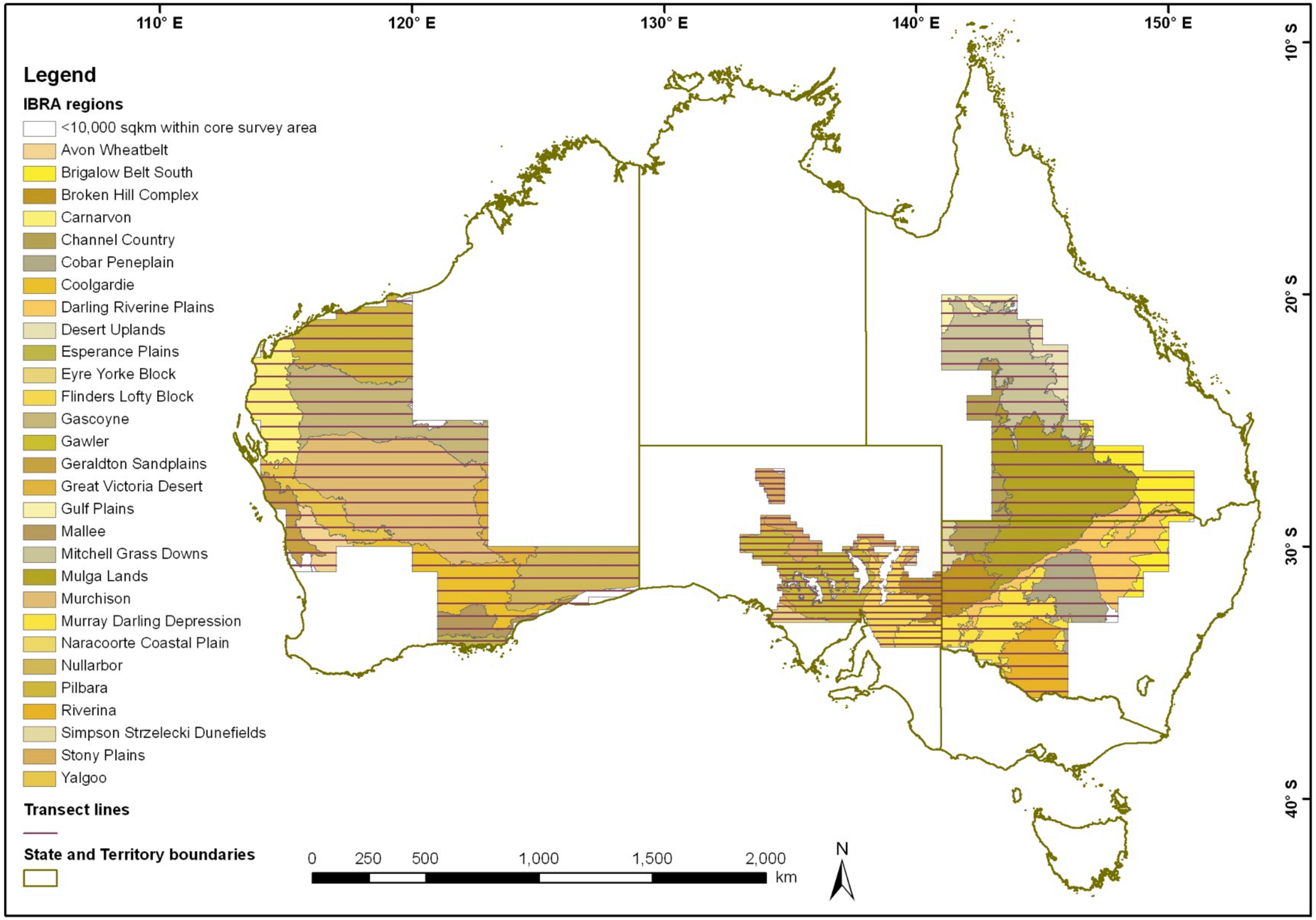

Figure 1. Core survey areas and transect lines for surveys of goats in Queensland (1984-2001), New South Wales (1993-2011), South Australia (1989-2011) and Western Australia (1987-2011). Bioregions >10,000 km^2 within these survey areas are also shown. Transect lines were flown outside this area in some years.

In South Australia, aerial surveys have been flown annually since 1978 along east-west transect lines that are 28 km apart (Caughley and Grigg 1981, Grigg *et al*. 1999). Only the occupancy of goats in survey segments was recorded over 1978-1988, but actual counts were made thereafter. Occupancy data have been reported by Pople *et al*. (1996) and so only the count data from 1989 were analysed here. A core area of 209,000 km^2 was surveyed each year, but surveys often extended over a larger area specific to that year. A survey area of 487,000 km^2 was covered with all survey years combined. Notably, the survey area excludes areas in the Flinders Ranges above 500 m where goat numbers in the 1980s and early 1990s were considered similar to those in the rest of the pastoral zone combined (Alexander 1992, Pople *et al*. 1996). Goat numbers in the South Australian rangelands are therefore underestimated by the survey data analysed in this report. Since the early 1990s, there has been a considerable non-commercial effort to reduce feral goat numbers in the Flinders Ranges, in addition to a relatively substantial commercial harvest there.

In Western Australia, the survey transects were also ~50 km apart (Short *et al*. 1983). Kangaroo surveys began in 1981, but goats were not counted until 1987. Only densities in degree blocks were available for 1987, 1990, 1993 (Fletcher and Southwell 1987, Southwell *et al*. 1990, Southwell 1993) and 1998, but raw data were available for other years. Given the vast size of the harvest area for kangaroos, the area was surveyed triennially, in 1987, 1990 and 1993. Since 1993, the survey area has been split into three zones and one zone surveyed each year to provide some annual monitoring and to maintain skills of the survey team. Zones were surveyed triennially starting in 1995 for the northern zone, 1996 for the southeast zone and 1997 for the central zone. In 2003, monitor blocks (~30,000 km^2) were also surveyed in the two zones not being surveyed to better follow trends in each zone. The three zones cover a core survey area of 1,187,000 km^2. A larger survey area of 1,399,000 km^2 was flown in 1987 and some of this additional area was again surveyed in 1990.

Correction factors for fixed-wing surveys

Several sources outlined below suggest adjustments for visibility bias in these fixed-wing surveys of goats. Sources iii-v were analysed as part of this study.

i. Southwell (1996) suggested three correction factors depending on the density of vegetation cover, based on line transect sampling using fixed-wing aircraft in the rangelands of Western Australia. These were 1 for open cover (i.e. no correction), 1.79±0.13 for medium cover and 1.96±0.15 for high cover. Estimates of cover are determined for survey segments for fixed-wing surveys in South Australia and Western Australia in order to correct counts of kangaroos (Caughley *et al*. 1976, Pople 1999). These correction factors were applied to goat densities estimated in South Australia and Western Australia.
ii. Ballard *et al*. (2011) initially suggested a single correction factor for goats counted in 100 m and 200 m strips based on mark-recapture sampling (i.e. double counting, Caughley and Grice 1982) in New South Wales. A reanalysis of this correction by the authors (P. Fleming, NSW Department of Primary Industries, personal communications) indicated a correction factor of 1.075 for counts in 100 m strips and 1.136 for counts in 200 m strips. These adjustments were applied to the New South Wales data.
iii. Pople *et al*. (1998a) recorded goats on fixed-wing surveys using line transect methods in the rangelands of Queensland in 1992. Similar correction factors to those employed by Southwell (1996) (i.e. i above) were calculated from these unpublished data.

iv. Pople *et al*. (1998a) also used mark-recapture sampling in 100 m and 200 m strips in fixed-wing surveys in the rangelands of Queensland in 1992. Similar correction factors to those used by Ballard *et al*. (2011) (i.e. ii above) were calculated from these unpublished data. Standard errors were calculated following the formula of Graham and Bell (1989).
v. Pople *et al*. (1998a,b) recorded goat density in a number of survey blocks using concurrent helicopter and fixed-wing surveys in the rangelands of Queensland in 1992. Helicopter surveys using line transect methods are considered a more accurate survey method than fixed-wing surveys using strip transect methods, at least for kangaroos (Clancy *et al*. 1997). The comparison of these unpublished data that are analysed in this report should therefore also provide a correction factor that possibly differs across regions.

Ideally, the error associated with correction factors should be incorporated into the overall standard error for the population estimate. This is done for line transect sampling, but is not standard practice for fixed-wing surveys, where the correction factor has been determined independent of the survey. Precision in these cases is therefore underestimated.

Helicopter surveys

Since 1991, kangaroo managers in Queensland have used helicopters and line transect (*cf*. strip transect) methods to annually survey kangaroo populations in non-contiguous monitor blocks (Fig. 2) (Lundie-Jenkins *et al*. 1999) and data on feral goats are available from 1992. The number of blocks surveyed has increased over time to provide a more representative coverage of the kangaroo harvest area, with only nine blocks flown in 1991 (Westmar, Roma, Bollon, Charleville, Hungerford, Windorah, Blackall, Longreach and Julia Creek). Under the current management program, four of the blocks (Charleville, Blackall, Barcaldine and Windorah) are surveyed annually, with the remainder flown every second year. The latter blocks are paired with another block in the same bioregion and one of each pair is flown in alternate years. All blocks are flown concurrently every five years. Each block contains 2-16 transect lines, each of which was 50-100 km long.

Line transect methods employed on helicopter surveys in Queensland provide survey-specific correction, unlike the correction factors suggested above. However, an important assumption of line transect sampling is that animals on the transect line are seen with certainty. This is likely to hold for large groups of goats in open areas, but may be violated for small group sizes and in timbered areas. Density is therefore likely to be underestimated to some extent.

Surveys were flown using a helicopter with two front and two rear seats (e.g. Robinson R44) with the doors removed, along transect lines at a ground speed of 93 km h^{-1} (50 kts) and at a height of 61 m (200 ft) above the ground. Navigation was by a global positioning system (GPS) receiver. Observers occupying the two rear seats of the helicopter counted the goats and other species seen on either side of the aircraft. Clusters of animals were recorded, using a digital hand held recorder, into distance classes, perpendicular to the transect line. Over 1992-2001, 25 m interval classes out to 125 m were used. Since 2002, distance classes were 0-20 m, 20-40 m, 40-70 m, 70-100 m and 100-150 m. As was stated earlier, a key assumption of line transect methods is that objects on the line are detected with certainty. This assumption can be extended to detection probability being almost certain near the line as well, resulting in a ‘shoulder’ in detection probability with increasing distance from the line. Interval width was increased with distance to reflect the greater importance of accurate measurements near the transect line, particularly to model the shoulder in the detection function (Buckland *et al*. 1993).Distance classes were delineated on aluminium booms extending from either side of the helicopter. Animals were recorded in the position in which they were first observed, which should avoid any problems with animals moving in response to the helicopter (Fewster *et al*. 2008).

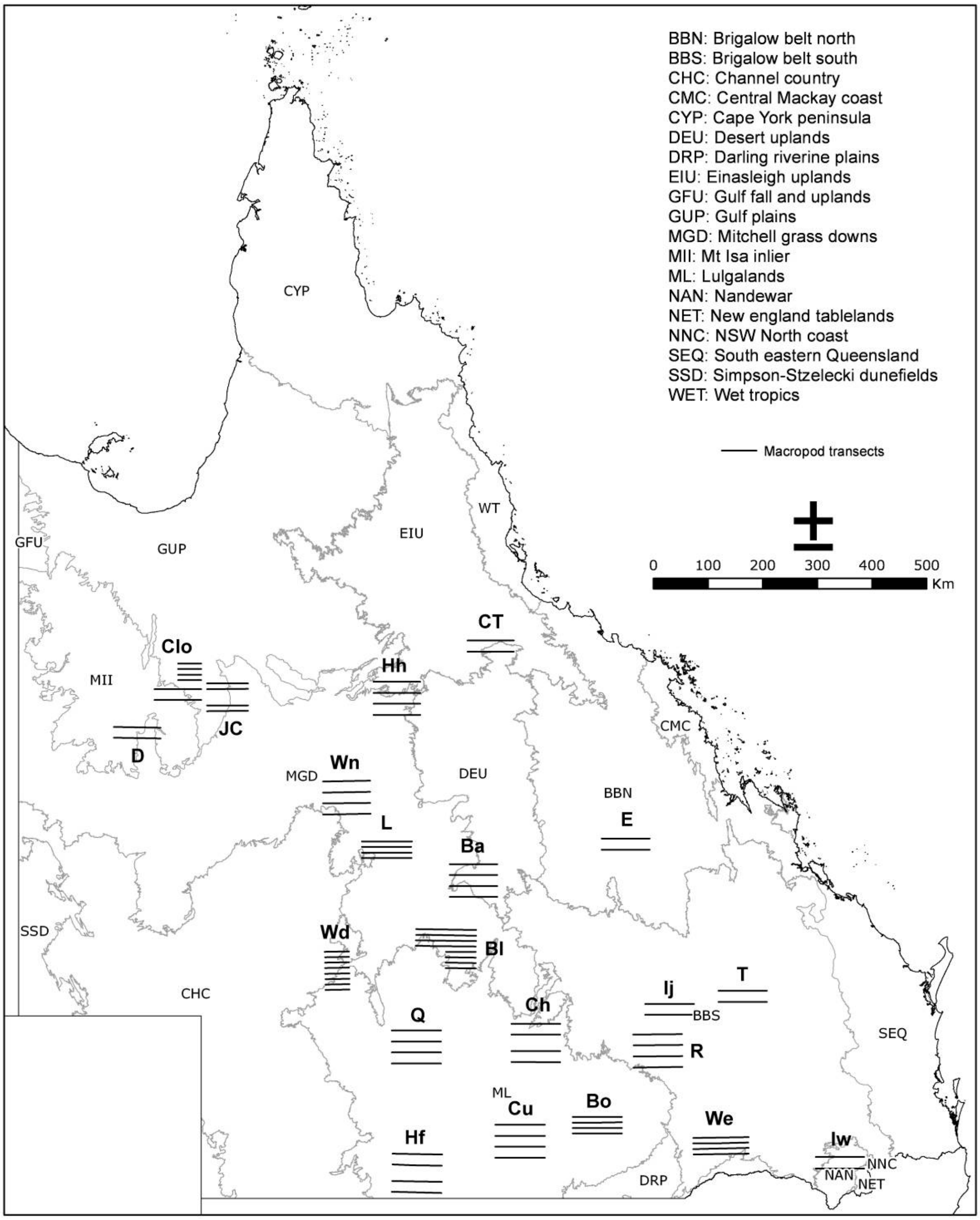

Figure 2. Survey lines (i.e. 'macropod transects') within helicopter survey blocks in Queensland. Biogeographic regions are shown as light grey lines and labelled with two-three capital letter codes that are explained on the figure. Codes for survey blocks are: D, Duchess; Clo, Cloncurry; JC, Julia Creek; Hh, Hughenden; CT, Charters Towers; Wn, Winton; L, Longreach; Ba, Barcaldine; E, Emerald; Wd, Windorah; Bl, Blackall; Q, Quilpie; Ch, Charleville; R, Roma; Ij, Injune; T, Taroom; Hf, Hungerford; Cu, Cunamulla; Bo, Bollon; We, Westmar; Iw, Inglewood.

In 2011, feral goats were not recorded on surveys because of a lack of confidence in distinguishing feral from ‘domestic’ or managed animals (N. Finch, Qld Department of Environment and Resource Management, personal communications). This problem is discussed further below.

Analysis of line transect data from helicopter surveys

The two sets of distance classes for the Queensland helicopter data required two separate sets of analyses. Sample size was invariably too low (n<50) to model detection probability in each block for each year separately. It was assumed that detection probability would vary primarily among blocks and secondarily among years. Detection functions were therefore determined for blocks pooled across years. However, small sample sizes on many blocks, particularly those with abbreviated time series, forced detection functions to be modelled by pooling data across nearby blocks.

Five detection function models were modelled in DISTANCE 6.0 (Thomas *et al*. 2009): a uniform key function, plus either a cosine or simple polynomial series expansion; a half-normal key function, plus a Hermite polynomial series expansion; and a hazard-rate key function, plus a cosine series expansion. The most parsimonious model and number of adjustment terms in the series expansion were selected in DISTANCE using Akaike’s Information Criterion (AIC) (Buckland *et al*. 1993). Detection functions with marked spikes at zero distance were rejected. Densities of goats were calculated as densities of clusters multiplied by mean cluster size. In line transect sampling, cluster density D is calculated as;

$$D = n/2wLP_a \qquad (1)$$

where n is the number of clusters sighted, $2w$ is the strip width (125 m or 150 m here), L is the total transect length and P_a is the probability of detecting a cluster in an area $a = 2wL$.

Population dynamics

Densities and population sizes of feral goats for each bioregion, based on the Interim Biogeographic Regionalisation for Australia (IBRA 6.1) (Thackway and Cresswell 1995, 1997, www.environment.com.au), were calculated for each survey in each core survey area of each state over the study period. Only the areas of bioregions within the survey area were used to calculate population size. For fixed-wing data, standard errors for these bioregional estimates were calculated using ratio estimation (Cochran 1977). Bioregional population estimates and standard errors based on helicopter surveys in Queensland were calculated by treating the survey blocks as replicate lines within bioregions (see Buckland et al. 1993 p92 formulae 3.13 and 3.14). Standard errors for the state estimates were calculated using stratified random sampling and treating bioregions as strata (McCallum 2000).

For Western Australia during 1995-2001, goat densities in unsurveyed zones needed to be interpolated. Bioregional densities for an unsurveyed zone in a particular year were estimated as the density from either the closest survey in time or the average of densities in adjoining years. From 2002, bioregional densities for unsurveyed zones were adjusted by the rate of increase in the zones’ monitor blocks. Bioregional population estimates were calculated each year by adding each zone’s population estimate within bioregions.

Patterns of distribution

Densities of goats obtained from fixed-wing surveys were calculated for all half-degree blocks (½° latitude × ½° longitude) in each year that they were surveyed. In South Australia these blocks were surveyed by two transect lines comprising approximately eighteen 1 km^2 segments. In Queensland, New South Wales and Western Australia, the blocks were surveyed by a single line comprising approximately nine 1 km^2 segments. Mean densities of feral goats were also determined for each block. Where goat densities were available only in one-degree blocks in Western Australia, goat numbers were apportioned across the four constituent half-degree blocks using the long-term average proportional abundance in those blocks.

Shifts in the pattern of distribution were assessed by comparing maps of half-degree block densities over time. Changes were also assessed by calculating average rates of increase of goats in half-degree blocks over the study period. Simple linear regressions were fitted for $\log_e$(density+0.01) against time in each half-degree block in each state for the available time series (Queensland, 1983-2001; New South Wales, 1993-2011; South Australia, 1989-2011; Western Australia, 1987-2011). While the slopes of these relationships in each block provide estimates of *r*, the average annual exponential rate of increase (Caughley and Sinclair 1994), they assume the only error is sampling error, but there is clearly considerable process error in these data as well (McCallum 2000). However, in this case, the focus is not an estimate of trend over time, but a comparison of trends across space. For this, comparisons of the slopes determined by simple linear regression were considered adequate.

A caveat for these analyses is that the time series within each block varies amongst states and between the core area and outside for each state. Comparisons across these areas must therefore be made cautiously.

Harvesting

Goats have commercial value as a source of meat, fibre, milk and as a control method for weeds. As identified by Forsyth and Parkes (2004), feral goats are harvested for four main commercial purposes, held and managed as domestic stock, processed through abattoirs, shot in the field and processed as game meat, or exported live. The number of carcasses inspected by AQIS at abattoirs, the weight of goat meat exported and the number of goats exported live has been reported by Ramsay (1994) and Forsyth and Parkes (2004). These figures are updated here. Ramsay (1994) reported 1981-2 to 1991-2 data in financial years. To be consistent with more recent data, these were allocated to the second year. These figures comprise both feral and domestic goats, with Forsyth and Parkes (2004) suggesting 70-90% of the goat meat processed is feral in origin. Schuster (2006), reporting a 2006 telephone survey of all Australian goat processors, suggests 90-95% of goat meat in Australia comes from feral (40%) or 'rangeland' (55%) animals. The latter were defined as re-domesticated feral goats, which is a recent practice. Collating numbers of both feral and domestic goats in Australia and comparing these with the slaughter data will allow an assessment of that percentage. AQIS amalgamate their abattoir data by state, but this does not necessarily reflect the source of goats, as animals are regularly trucked interstate for processing. Harvest data were therefore combined into eastern (Queensland, New South Wales, Victoria and South Australia) and Western Australia. Instantaneous harvest rates were calculated by dividing harvest numbers, assuming 90% feral, by estimates of population size.

Forsyth and Parkes (2004) recognised that, prior to 2001, the AQIS records of carcass inspections were much lower than those recorded by the Western Australian Department of Agriculture. These latter data (A. Woolnough and G. Pickles, WA Department of Agriculture and Food, unpublished data) were therefore used to estimate harvest rate. A large number of goats were also removed non-commercially, primarily by helicopter shooting, from the Western Australian rangelands over 1992-1997 (Parkes *et al*. 1996). These data were also included in an estimate of harvest rate (A. Woolnough and G. Pickles, WA Department of Agriculture and Food, unpublished data).

Sales of unmanaged goats in Australia were recorded in agricultural surveys undertaken by the Australian Bureau of Statistics (ABS) in 2004 and the 2006-7 financial year, where they were collated in statistical divisions (SDs), and in the 2005-6 financial year, but collated in finer-scale statistical local areas (SLAs). For each ABS survey, sales of unmanaged goats were determined for each state and for the survey area (Fig. 1) in each state. Survey area boundaries often intersected SD or SLA boundaries and so goat sales were allocated to the survey area if part of the SLA or SD was within the survey area. Based on their distribution, most feral goats within an SLA or SD were likely to have originated from the more arid section that was in the survey area and so this allocation avoided underestimating the harvest based on these data. Using the finer-scale SLA data from the 2005-6 financial year, feral goat sales were mapped to assess the variation in harvest effort and, in combination with feral goat density, the harvest rate.

The impact of harvesting was explored by determining a yield curve for feral goats in semi-arid and arid Australia. Firstly, the maximum exponential rate of rate increase r_m was calculated using the Euler-Lotka equation (McCallum 2000) and demographic data from the literature (Parkes *et al*. 1996). Simulation was used to generate a yield curve, since fluctuations in population size and species-specific, density-dependent growth would make it differ from the textbook logistic curve (Caughley and Sinclair 1994). A goat population was simulated using a generalised logistic equation (Eberhardt 1987),

$$r = r_m[1 - (N/K)^z] \quad (2)$$

where r is the actual exponential rate of increase, N is population size, K is carrying capacity and z indicates the nature of density dependence. Theory and field data from mammals with a similar life history (Eberhardt 1987, Fowler 1987, McCullough 1992) suggest a value of 1.5 for z. Higher values of z would be appropriate for larger mammals, where density dependence does not greatly affect growth until close to carrying capacity and so the maximum sustained yield (MSY) is pushed to the right. Stochasticity was introduced by drawing K from a lognormal distribution with a mean of 1,000 and coefficient of variation (CV, standard deviation/mean) based on historical population data. The population was modelled over 100 years in annual time steps. For each simulation, a starting population of 1,000 was harvested at varying isolated rates (Caughley 1977) to determine the average yield over 100 years and the average population size over that time period. 1,000 simulations were run for each harvest rate. Models were run in Excel with the add-in POP-TOOLS (Hood 2010).

Domestic goats

There are three reasons why numbers of domestic goats are relevant to this project:

1. During surveys, the identification and recording of feral goats by observers is based largely on colouration and herd size structure. Feral goat herds typically comprise a mixture of colours and sizes and, indeed, individual goats are often piebald. Domestic herds tend to comprise animals of uniform colour (usually white) and size, primarily nannies with or without kids. In recent years, there has been an increase in the number of domestic goats managed within fenced paddocks in the rangelands. As a result, observers have been forced to make more decisions on whether particular goats should be counted. This has been exacerbated further by the practice of mustering feral goats and keeping them within fenced paddocks and managing them as domestic stock (i.e. 'rangeland goats', Schuster 2006). There are thus animals that fall along a continuum from feral to domestic (Forsyth and Parkes 2004), and this uncertainty in identification obviously compromises estimates of feral goat numbers. One way of addressing this problem is to determine the number of domestic goats grazed in the study area. This should at least quantify the size and location of the problem.

2. Goats slaughtered for the domestic and export meat markets and for live export are considered to be mostly feral (Ramsay 1994). However, some domestic goats enter this trade and so their numbers need to be assessed if the size of the feral harvest is to be estimated from export and slaughter data (see above).

3. Domestic goats are the original and potentially on-going source of feral goats in the rangelands. Feral populations are clearly self-sustaining, but new wild populations could establish through domestic escapees. The location of domestic herds identifies areas at risk of recruitment from domestic goats.

Numbers of domestic goats in Australia were recorded in agricultural surveys undertaken by the ABS over 1982-3 to1998-9, 2004, 2005-6 to 2008-9. Data were again allocated to the second year of financial years. The SLAs in which data were collated have changed over this period, making comparisons difficult (John Carter Queensland Department of Environment and Resource Management, unpublished data). For 2004 and 2007-8 to 2008-9, data were recorded in only coarser statistical divisions. For each ABS survey, numbers of goats were determined for each state and for the survey area (Fig. 1) in each state. Survey area boundaries often intersected SLA and SD boundaries and so, in contrast to the ABS harvest data described above, goat numbers were allocated to the survey area according to the proportion of the SLA or SD within the survey area. This was because there was no reason to believe most domestic goats would have been in the more arid parts of a SLA or SD and so disproportionately allocated to the survey area. Using the finer-scale data, densities were mapped to assess shifts in distribution over time.

Results

Correction factors for fixed-wing surveys

Using source iii for correction factors from the Methods, there were 126 clusters of goats recorded on fixed-wing surveys using line transect sampling in six survey blocks (Longreach, Blackall, Windorah, Charleville, Bollon and Roma, Fig. 2) across the survey area in Queensland in 1992. Sample size was insufficient to model detection probability separately for each block, but 70% of the data were recorded in the Bollon and Charleville blocks. Detection declined steeply from the transect line (Fig. 3) and the overall probability of detection within a 200 m strip was 0.48 ± 0.07. This is comparable to Southwell's (1996) estimate of 0.51 ± 0.56 for detection probability in medium-heavy vegetation cover in Western Australia. These Queensland data suggest a correction factor of 2.08 ± 0.28, calculated as the reciprocal of detection probability.

Using source iv from the Methods, mark-recapture data (*n*=109) from 200 m strips were drawn from the same six blocks described above for line transect sampling. Data were recorded in 100 m strips on surveys in the Longreach, Blackall and Charleville blocks and constituted a smaller sample size (*n*=18). For 200 m strips, correction factors were 1.79 ± 0.13 and 2.00 ± 0.15 for the front and rear seat observers, respectively. As these estimates are not significantly different, an average correction factor of 1.90 can be used. For 100 m strips, the respective estimates are 3.25 ± 1.26 and 2.25 ± 0.72. These are counter-intuitively larger than the 200 m estimates, but the relatively large standard errors caution against their use.

Using source v from the Methods, goat densities recorded by three survey methods in the six survey blocks in 1992 are shown in Table 1. The densities based on a helicopter survey were only higher than the fixed-wing estimates in the two blocks where goats were at a relatively high density. This is likely due to low sample size for the helicopter surveys in the low density blocks. Similarly, few goats were counted in 100 m strips, making those density estimates again unreliable. These problems with low sample sizes are also reflected in the relatively large standard errors associated with the estimates in Table 1. Ignoring the blocks with low densities leaves an average correction factor for Bollon and Charleville for counts in 200 m strips of 2.96.

Table 1. Estimates of goat density (km^{-2}) in survey blocks in Queensland in 1992 using helicopter line transect surveys and fixed-wing counts in either 100 m or 200 m strips. Standard errors are given in parentheses.

	Helicopter	Fixed-wing	
Block	Line transect	100 m	200 m
Blackall	0.11 (0.09)	0.40 (0.26)	0.69 (0.35)
Bollon	8.26 (3.92)		2.96 (0.78)
Charleville	5.83 (2.74)	0.53 (0.43)	1.87 (0.81)
Longreach	0.00	1.77 (1.77)	2.63 (2.44)
Roma	0.07 (0.07)		0.25 (0.19)
Windorah	0.10 (0.07)		0.17 (0.09)

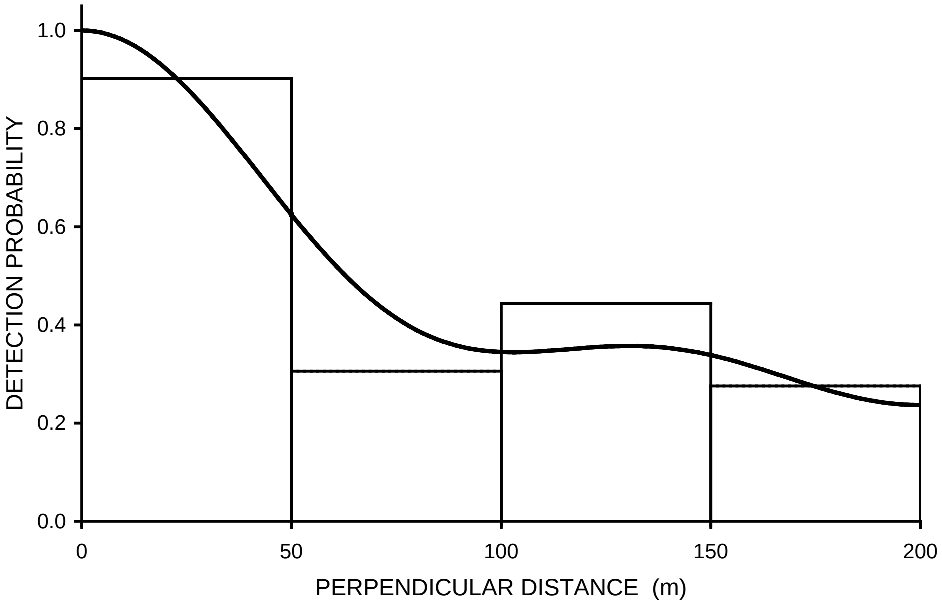

Figure 3. Modelled detection probability (black line) for goats recorded in four distance classes (histogram) away from the transect line during fixed-wing surveys in Queensland in 1992. See Pople *et al*. (1998a) for survey details. The modelled detection function is a uniform key series with three cosine adjustment terms.

The comparison of helicopter and fixed-wing estimates of goat density in Table 1 is inconclusive. Mark-recapture estimates of correction factors for counts in 100 m strips are similarly unreliable. An average of fixed-wing line transect (2.08) and mark recapture (1.90) correction factors of 2.00 was therefore used to correct counts of goats in both the 100 m and 200 m strips on fixed-wing surveys in Queensland.

Population dynamics

Queensland

Trends in corrected goat abundance in bioregions in the Queensland survey area are shown in Figure 4a. Densities in these bioregions are shown in Appendix 1. Estimates from 1993 onwards are based on helicopter surveys in survey blocks. Trends in goat density for the survey blocks are shown in Figures 5a-d. Survey block estimates were based on modelled detection probabilities (i.e. P_a in equation 1) shown in Table 2. Surprisingly, detection probability was similar among the blocks, which cover a range of vegetation types from open to heavy cover. The extremes of detection probability occurred as expected, with low detection probability in the woodlands around Bollon and high detection probability in the open areas around Windorah.

Combining fixed-wing and helicopter datasets shows an upward trend in abundance in the mulga lands, where goats have consistently been most numerous. Goats in this bioregion increased almost five-fold over a 20-year period. Other bioregions have shown fluctuations, an increase through the 1980s, but no strong long-term trend. There were notable declines in the mid-1990s associated with dry conditions in southern Queensland. There were also declines in the Mitchell grass downs and brigalow belt south in the early 2000s, coinciding with a major drought, but the declines were not matched in the mulga lands. The survey block data showed contrasting trends for the high density blocks of Bollon and Hungerford over 1993-2010 (Fig. 5b).

Figure 4 (overpage). Trends in the numbers of feral goats in the survey areas (Fig. 1) of (a) Queensland over 1984-2010, (b) New South Wales over 1993-2011, (c) South Australia over 1989-2011 and (d) Western Australia over 1987-2011. Estimates are given for each biogeographic region within the survey area. Region codes are defined in Figure 1. Population estimates are based on aerial surveys using fixed-wing aircraft in all states except Queensland, where helicopter-based estimates have been used since 1993. For each state, bioregions which typically have low numbers of goats (<10,000 animals) are not shown.

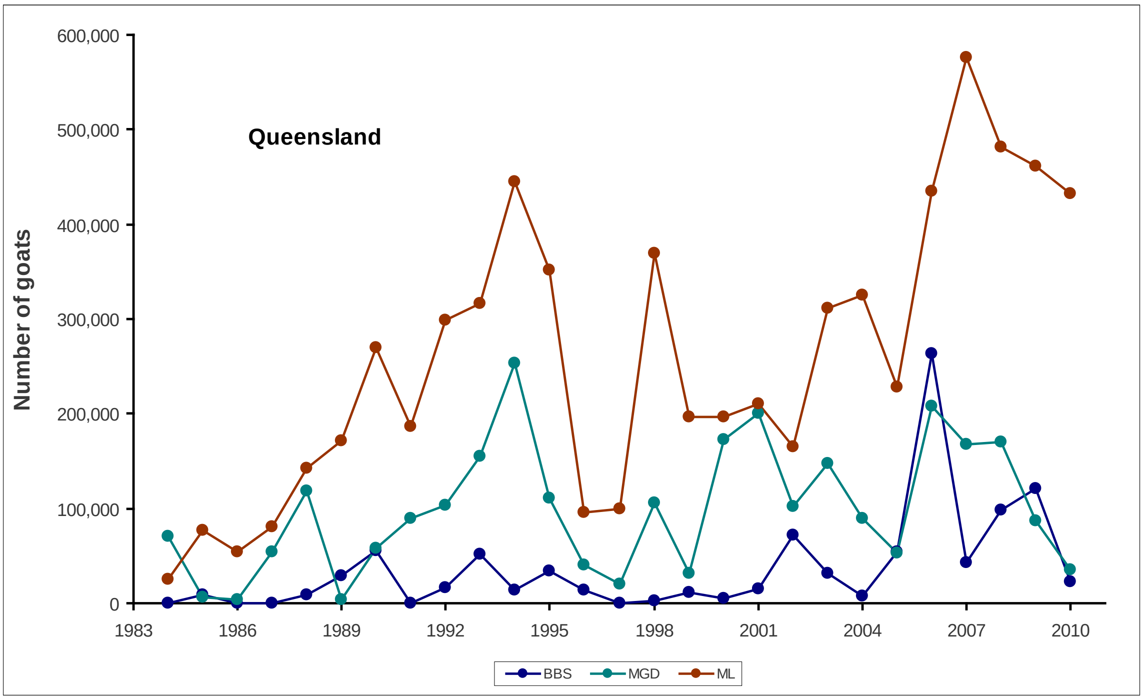

Figure 4a.

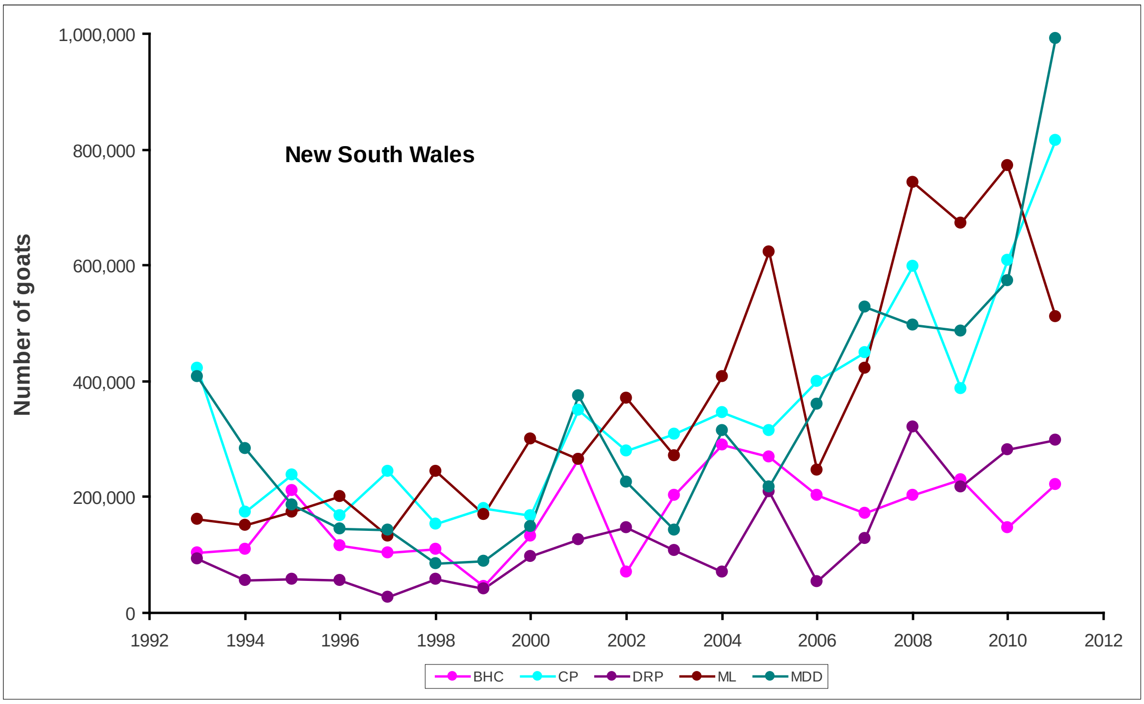

Figure 4b.

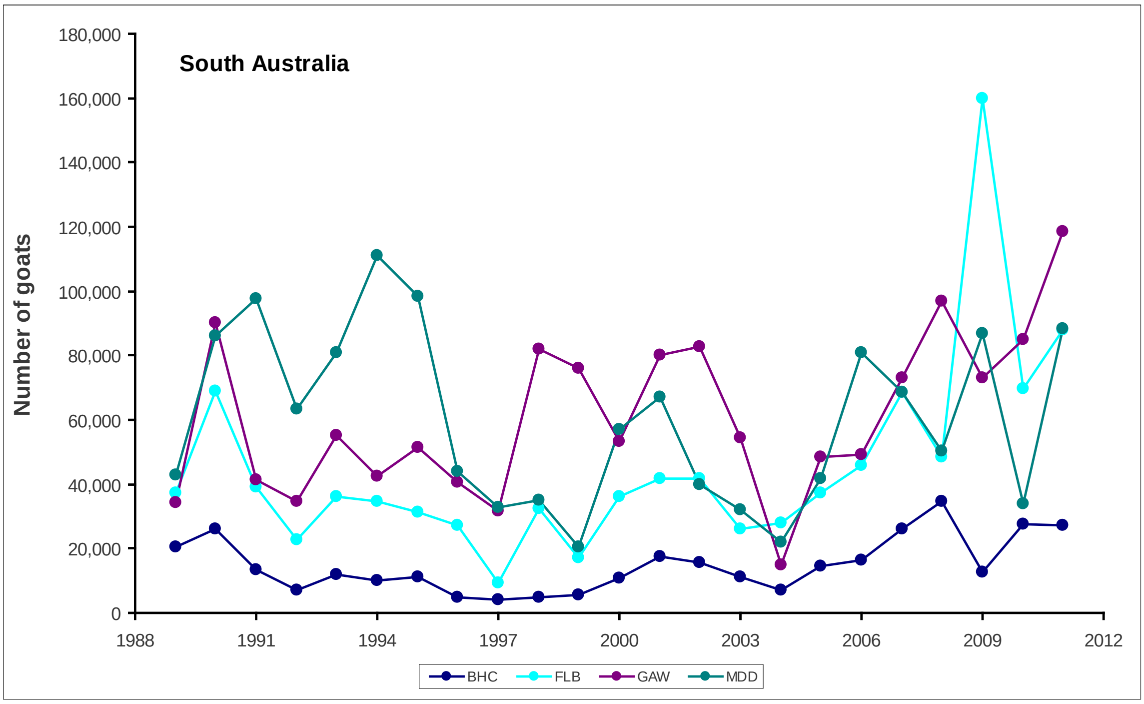

Figure 4c.

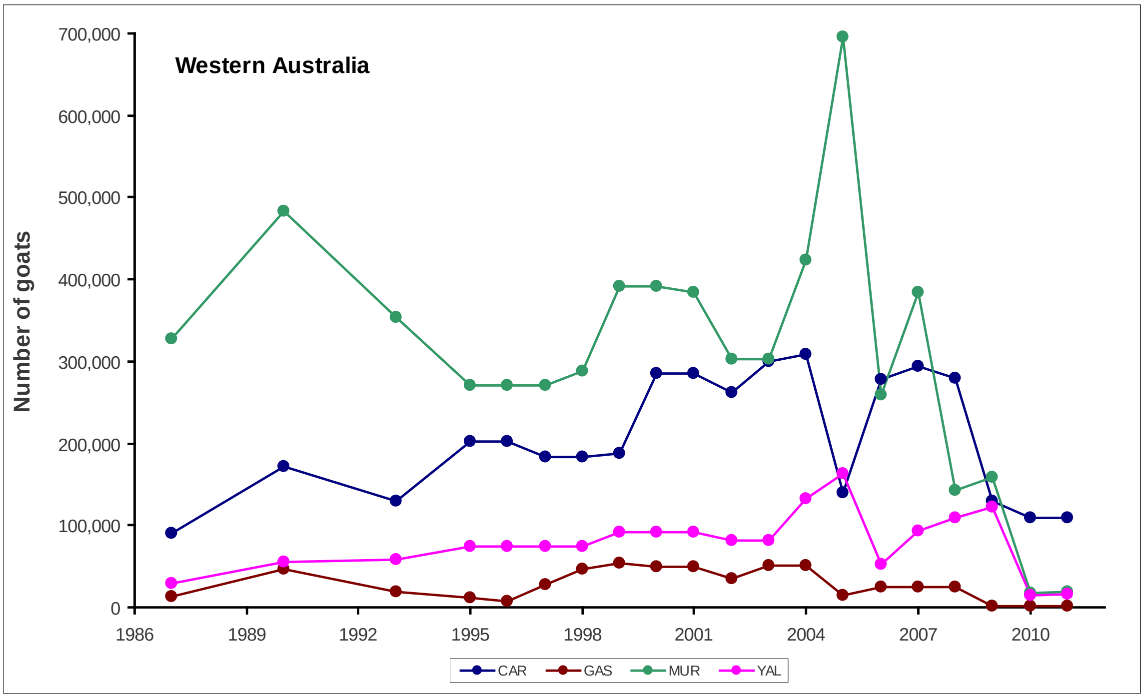

Figure 4d.

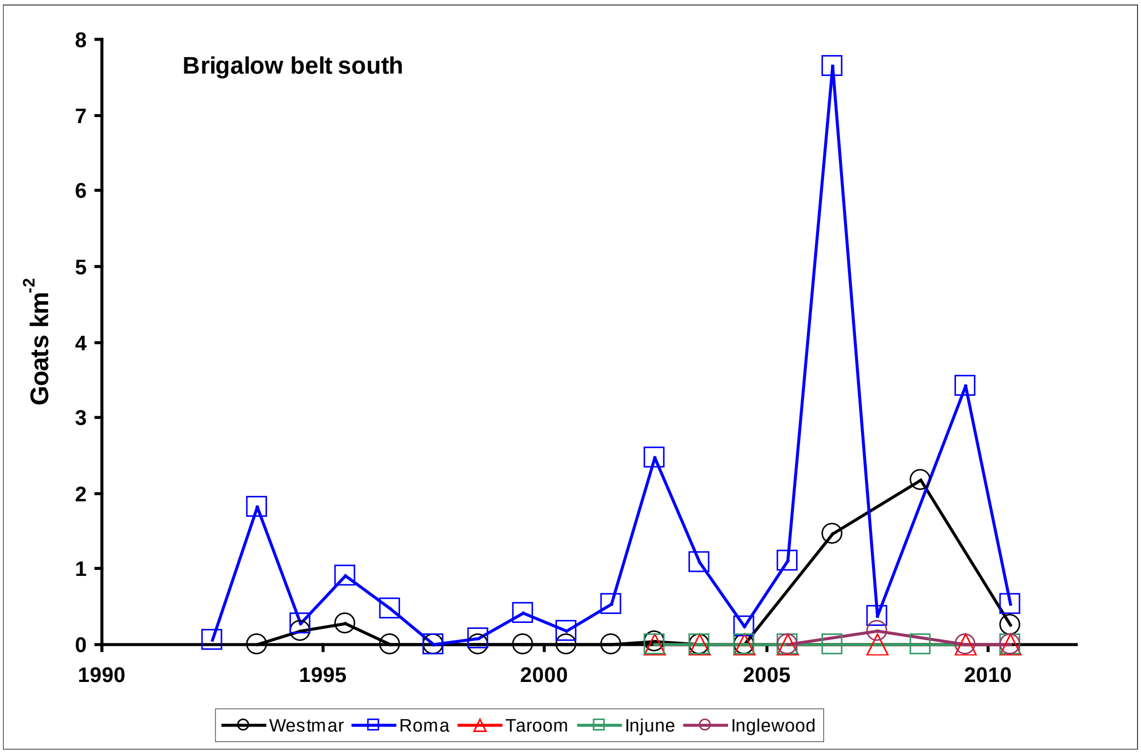

Figure 5a. Densities of feral goats in helicopter survey blocks in the brigalow belt south bioregion in Queensland (Fig. 2) for 1992-2010.

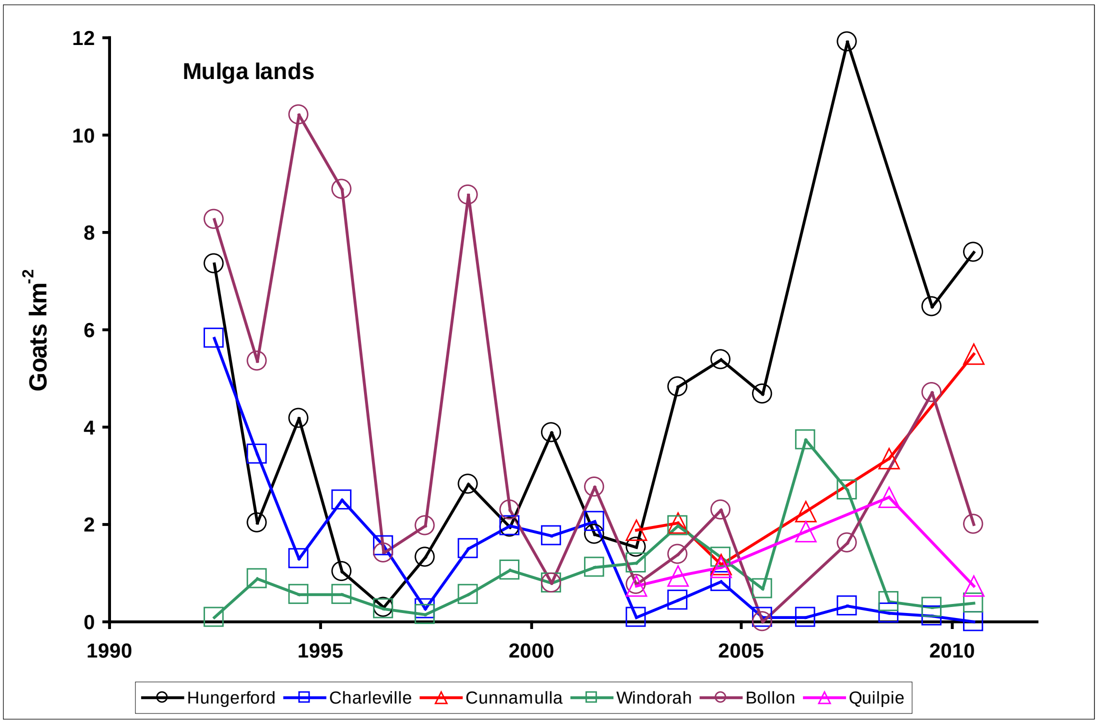

Figure 5b. Densities of feral goats in helicopter survey blocks in the mulga lands bioregion in Queensland (Fig. 2) for 1992-2010.

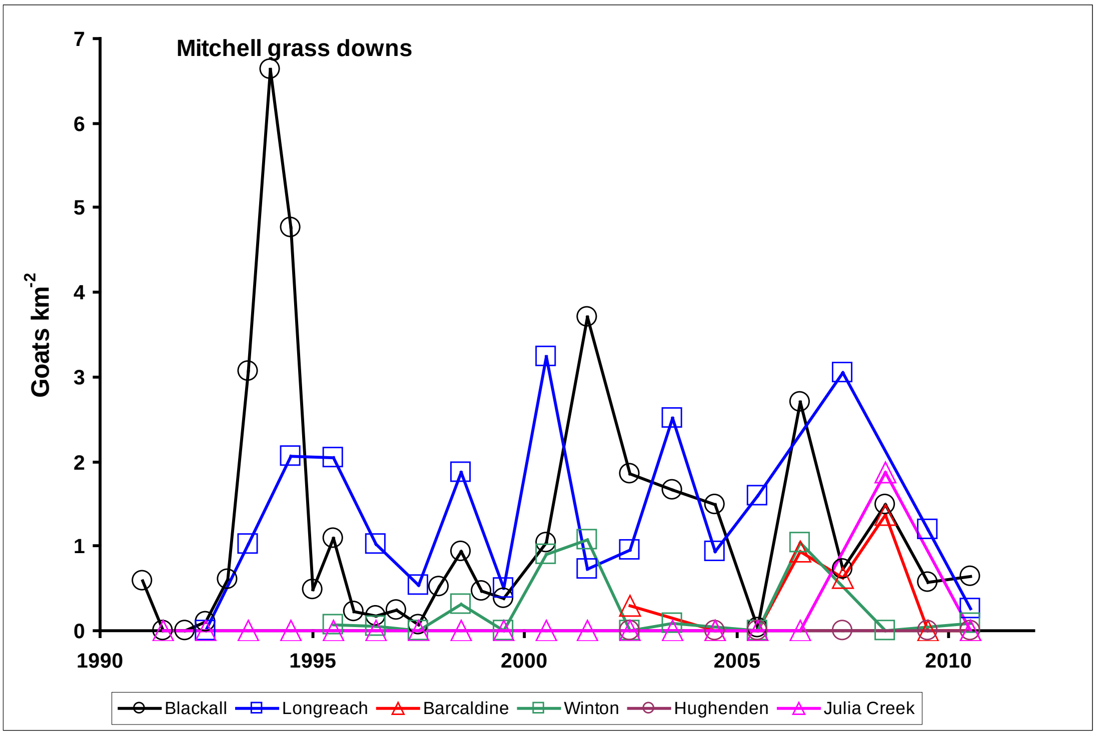

Figure 5c. Densities of feral goats in helicopter survey blocks in the Mitchell grass downs bioregion in Queensland (Fig. 2) for 1992-2010.

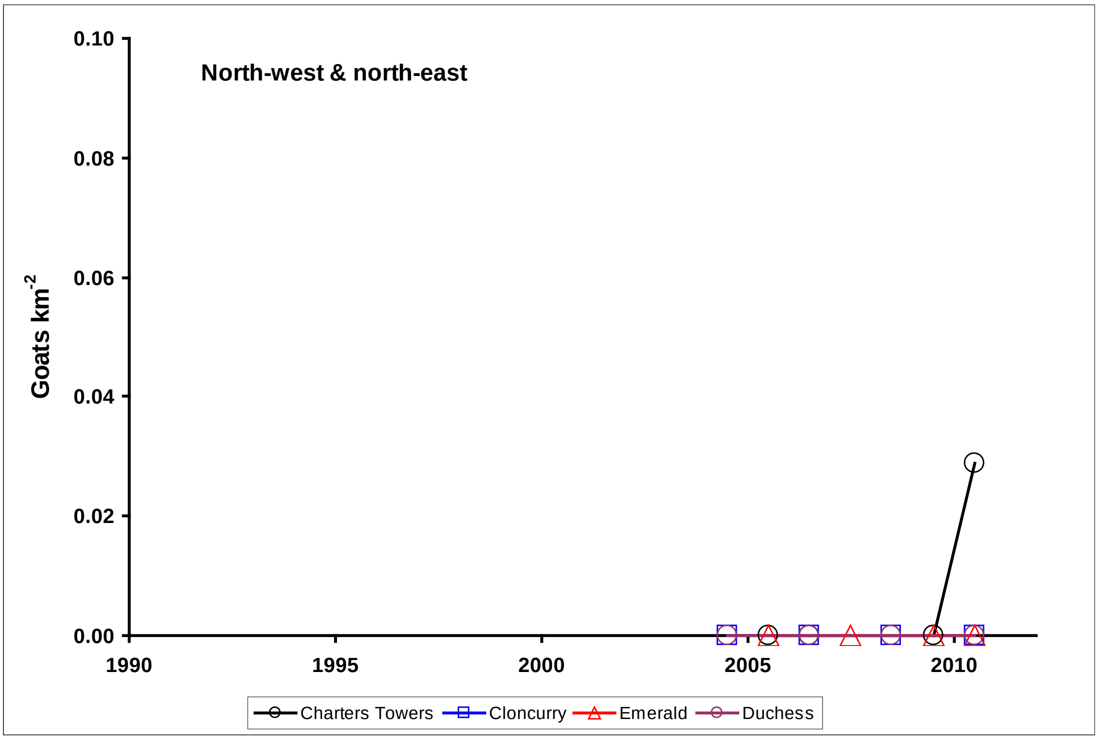

Figure 5d. Densities of feral goats in the north-western and north-eastern helicopter survey blocks covering a number of bioregions in Queensland (Fig. 2) for 1992-2010.

Table 2. Strip width and detection probability (i.e. P_a in equation 1) modelled using the program Distance for goats recorded on line transect surveys using helicopters in Queensland survey blocks. Where sample size was low (n<50), data for other blocks were included to model detection probability.

Block/s	Years	Strip width (m)	Detection probability	Other blocks included to model detection probability
Barcaldine	>2001	150	0.70	Blackall, Longreach
Blackall	<2002	125	0.81	
Blackall	>2001	150	0.62	
Bollon	<2002	125	0.45	
Bollon	>2001	150	0.71	
Charleville	<2002	125	0.82	
Charleville	>2001	150	0.74	
Cloncurry, Duchess, Julia Creek, Winton	>2001	150	0.71	Longreach
Cunnamulla	>2001	150	0.69	
Emerald, Hughenden, Charters Towers	>2001	150	0.81	Longreach, Barcaldine
Hungerford	>2001	150	0.75	
Hungerford	<2002	125	0.69	
Inglewood, Injune, Roma, Taroom, Westmar	>2001	150	0.52	
Julia Creek, Winton	<2002	125	0.66	Longreach
Longreach	<2002	125	0.63	
Longreach	>2001	150	0.72	
Quilpie	>2001	150	0.65	
Roma, Westmar	<2002	125	0.80	
Windorah	<2002	125	1.00	
Windorah	>2001	150	0.72	

New South Wales

Goats are abundant in five bioregions in New South Wales and populations in these have increased on average at 4-10% per year over the survey period (Fig. 4b), as estimated by regressing logged density over time (Caughley and Sinclair 1994). In particular, there have been relatively marked increases in the mulga lands, Cobar peneplain and Murray Darling depression. Again, drought in the early 2000s, has done little to curb that increase.

South Australia

Goats are common in four bioregions (Fig. 4c), but densities are considerably higher in the Murray Darling depression (Appendix 1c). There is no obvious long-term trend in numbers, although all four regions have seen an increase since 2004, after numbers had declined following drought in the early 2000s. Over the study period, this has resulted in average increases of 3-4% per year in Gawler, Broken Hill complex and Flinders Lofty block, but little change in the Murray Darling depression.

Western Australia

Goats are common and at similar densities in three bioregions, Carnarvon, Murchison and Yalgoo (Fig. 4d, Appendix 1d). Since 2008, numbers have declined to 6%, 20% and 49% of the 1987-2008 average in the Murchison, Yalgoo and Carnarvon bioregions, respectively. Numbers built up in the Gascoyne bioregion over 1997-2004, but have similarly declined to 3% of the 1987-2008 average. Over the study period, numbers have declined 8-9% per year on average in the Murchison and Gascoyne bioregions, but there is no trend in the Carnarvon and Yalgoo bioregions.

Fluctuations in numbers are less marked in Western Australia than other states. This is likely due to the smoothing effect of combining density estimates three years apart. The data become more labile when monitor blocks are used to adjust bioregional estimates. Calculating abundance over relatively large areas will also dampen fluctuations in the constituent, smaller areas.

Rangeland Australia

State-level population estimates for the survey area are shown in Figure 6. Australia’s feral goat population in the rangelands ranged from 1.4 (± 0.3) million in 1997 to 4.1 (± 0.4) million in 2008. The upward trends seen in bioregions in Queensland and New South Wales translate into state-wide increases for the rangelands, particularly for the latter. This increase is only relatively recent in South Australia. The decline in numbers in the Murchison also translates into a state-wide trend for the rangelands in Western Australia. The recent decline in Western Australia has also been mirrored in Queensland. As a result, the proportion of Australia’s growing feral goat population that resides in New South Wales has increased from 48 to 70% over 2007-10.

Patterns of distribution

Average densities of feral goats in half-degree blocks, based on fixed-wing surveys, are shown in Figure 7. They cover different time periods (Queensland, 1984-92, 2001; New South Wales, 1993-2011; South Australia, 1989-2011; Western Australia, 1987-2011) which affects comparisons between states. Because of increases in goat numbers over the past two decades, the Queensland estimates will be relatively low and, to a lesser extent, New South Wales estimates will tend to be relatively high. Comparisons are also affected by infrequent surveys of blocks outside the core survey area (Fig. 1) over the time period. However, few goats occur outside the core area.

Even with these qualifications, there are some striking features of the distribution of feral goats in the rangelands. The distribution is largely restricted to the semi-arid and arid ‘sheep rangelands’ (Caughley 1987), where sheep grazing is, or at least has been in recent history, the predominant land use, but it is not where most of the sheep occur in Australia. It coincides with an area where wild dogs are controlled to low numbers (Fleming *et al*. 2001), supporting the assessment of Newsome (1994) that, outside the dog fence, wild dogs keep feral goats and pigs at trace levels. Goat density within the distribution is obviously not uniform and densities are higher on average in New South Wales.

The distribution pattern in Figure 7 contrasts with that described by West (2008), based on expert opinion (Fig. 8). The distribution is well delimited by expert opinion although some outlying pockets have been missed by West's (2008) map. However, the high abundance of goats in Western Australia relative to other states suggested by expert opinion is not supported by the aerial survey data. The relative distribution within states does not match exactly, but that will be partly a function of timing of the respective surveys.

Changes in the distribution within states can be crudely assessed by comparing distributions in three individual years that span the time series, 1993 (1992 for Queensland), 2001 and 2011 (Fig.9a-c). The year-to-year variation in the distribution is not dramatic, although increases in density appear to be associated with an expansion in distribution. Similarly, the decline in numbers in Western Australia has been associated with a distributional contraction. These changes in distribution can best be seen in a map of the rates of increase over the study period (Fig. 10). The time series differs among the states, explaining the relatively high increases described by the Queensland data (i.e. last available comparable data were from 2001). There are distinct areas in each of the eastern states where goats have increased at a higher rate than elsewhere. However, the trends have generally been uniform. The collapse of feral goat numbers in the eastern part of the distribution in Western Australia in the Murchison bioregion (Fig. 4d) is quite clear in Figure 10.

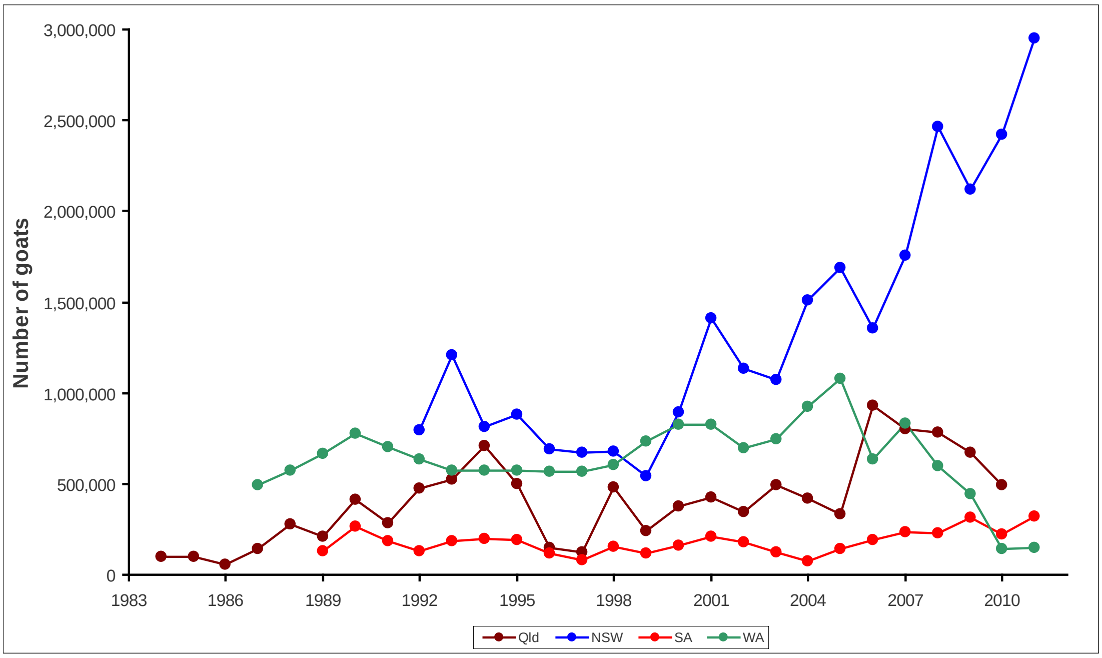

Figure 6. Abundance (± s.e.) of feral goats in the survey areas (Fig. 1) of each of the four states. Estimates are based on combining bioregional estimates shown in Figure 4. There were no surveys in Western Australia in 1988-9, 1991-2 and 1994.

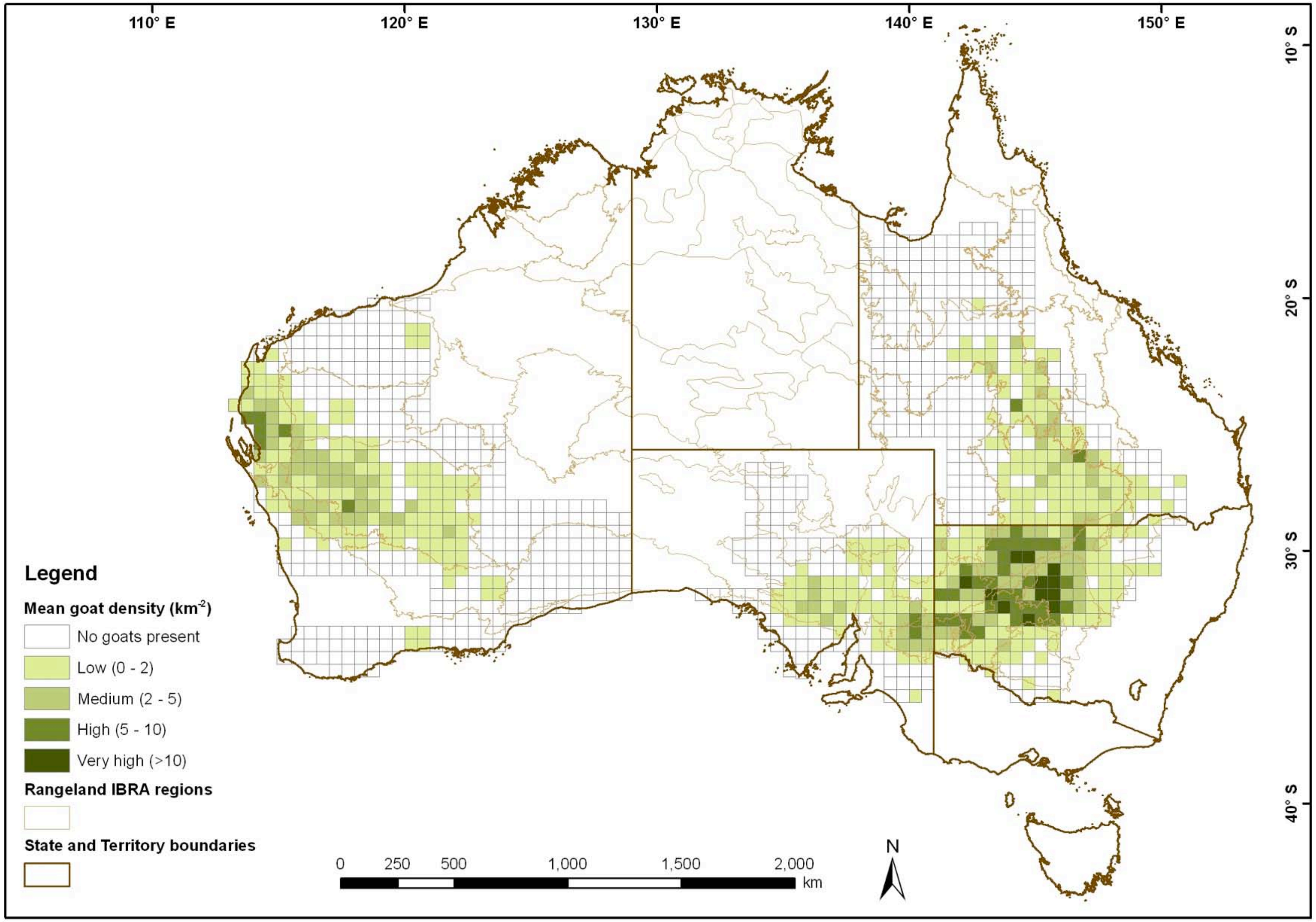

Figure 7. Average densities (km^{-2}) of feral goats in half-degree blocks surveyed by fixed-wing aircraft across Queensland (1984-92, 2001), New South Wales (1993-2011), South Australia (1989-2011) and Western Australia (1987-2011). Surveys in blocks outside the core area (Fig. 1) were infrequent. Rangeland bioregions are also indicated.

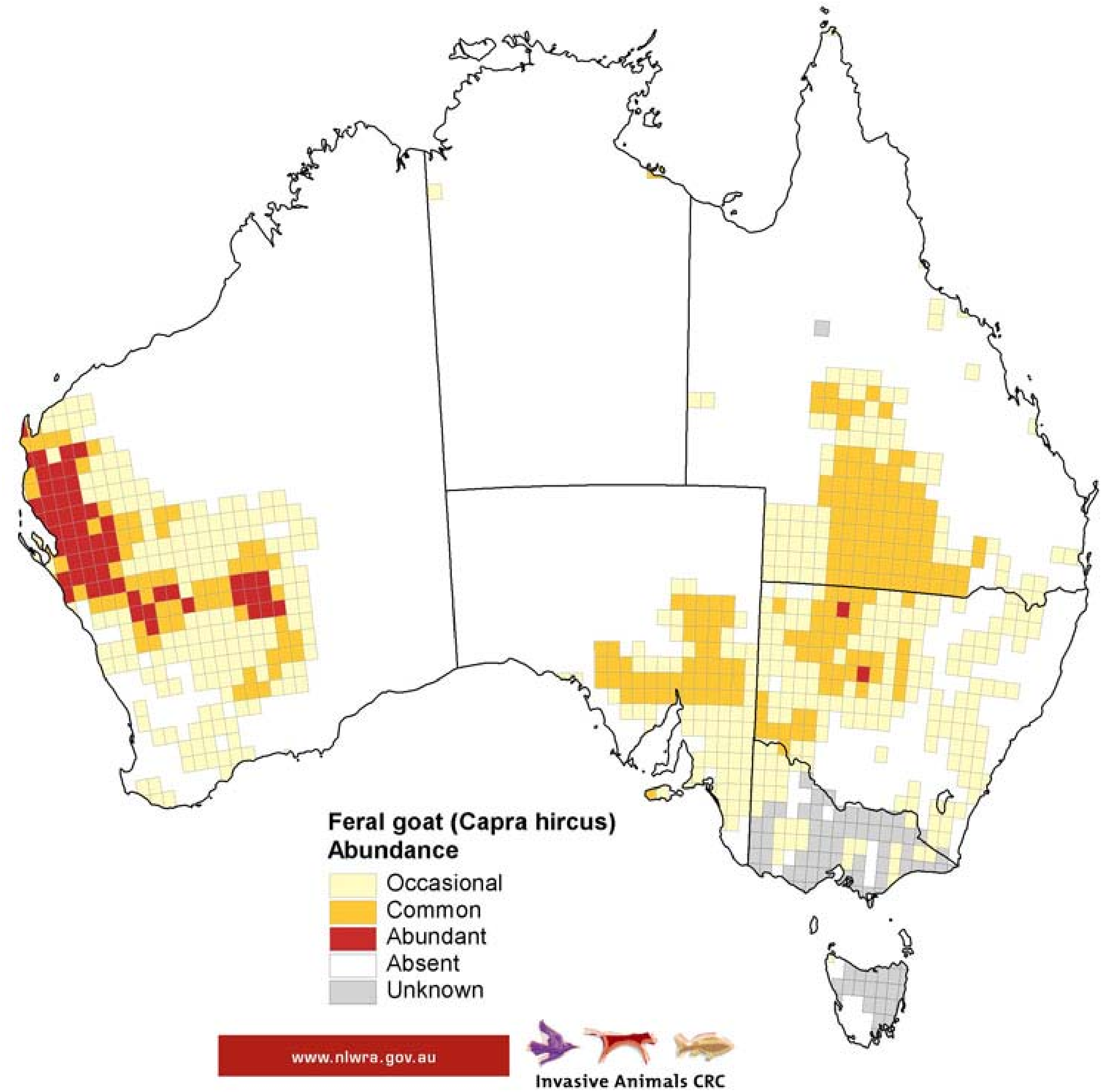

Figure 8. Distribution and abundance of feral goats in half-degree blocks in Australia in 2008, based on expert opinion. After West (2008).

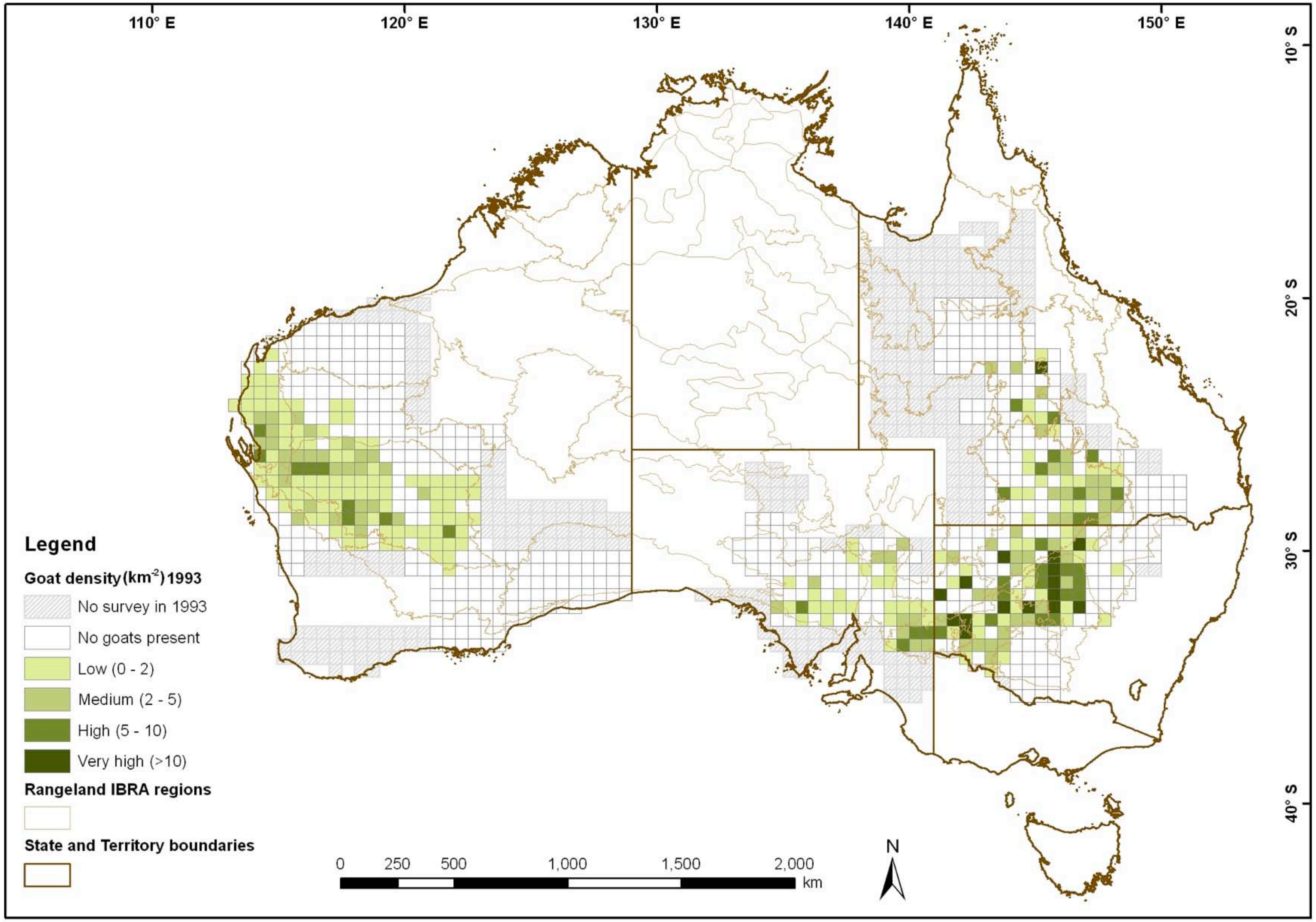

Figure 9a. Densities (km^{-2}) of feral goats in half-degree blocks surveyed by fixed-wing aircraft in 1993 (1992 for Queensland). Surveys in blocks outside the core area (Fig. 1) were infrequent. Rangeland bioregions are also indicated.

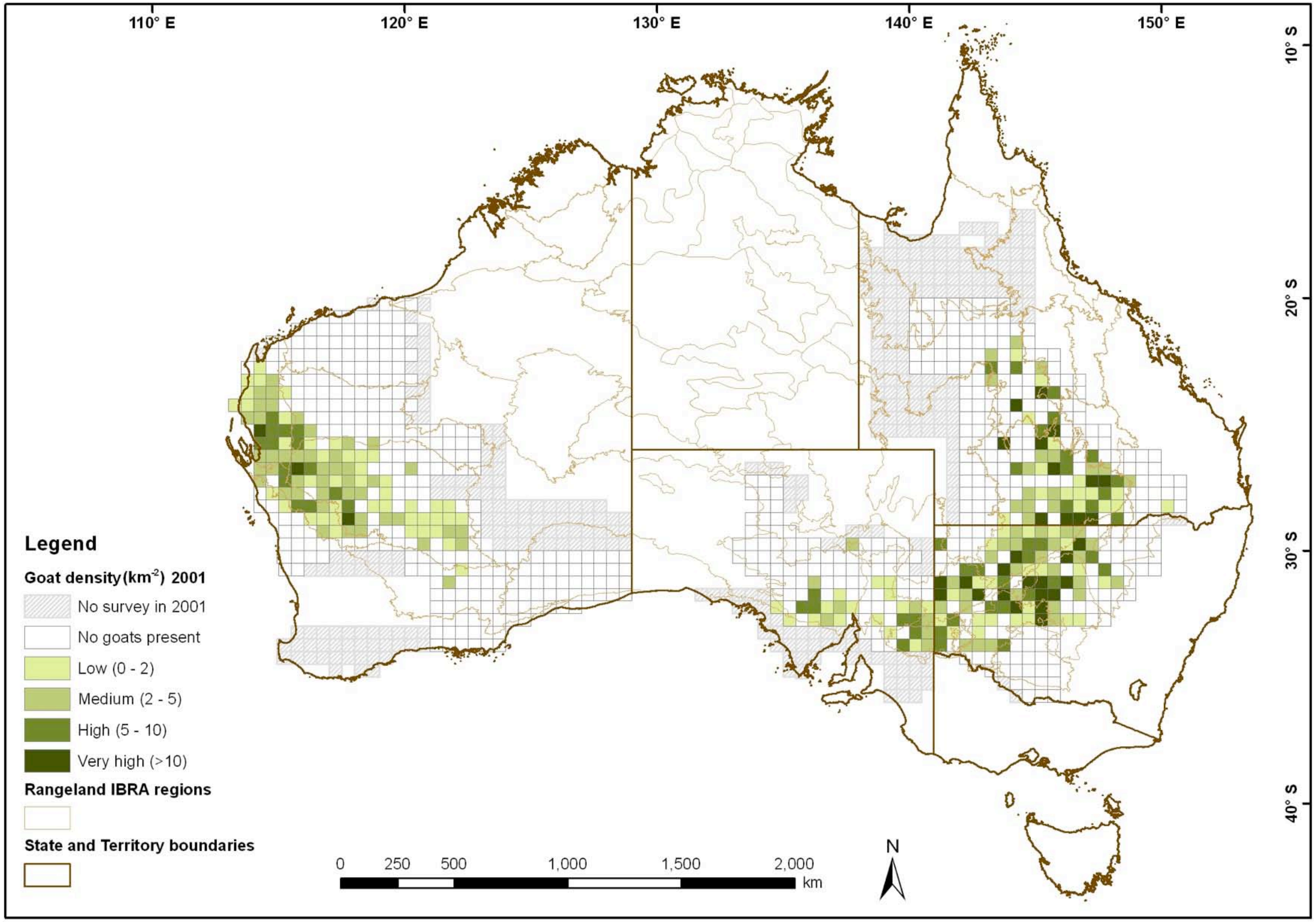

Figure 9b. Densities (km^{-2}) of feral goats in half-degree blocks surveyed by fixed-wing aircraft in2001. Surveys in blocks outside the core area (Fig. 1) were infrequent. Rangeland bioregions are also indicated.

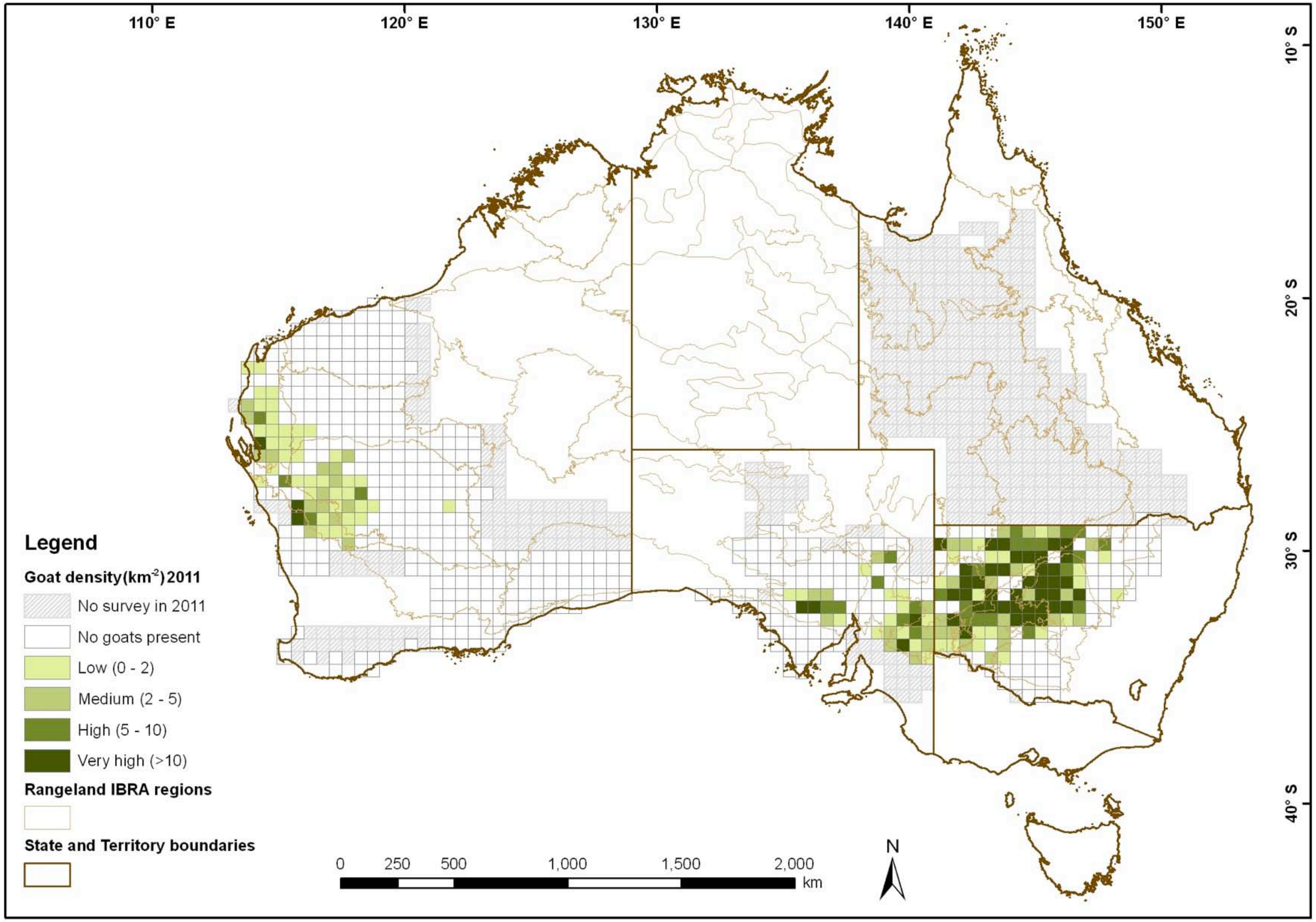

Figure 9c. Densities (km^{-2}) of feral goats in half-degree blocks surveyed by fixed-wing aircraft in 2011. Surveys in blocks outside the core area (Fig. 1) were infrequent. Rangeland bioregions are also indicated.

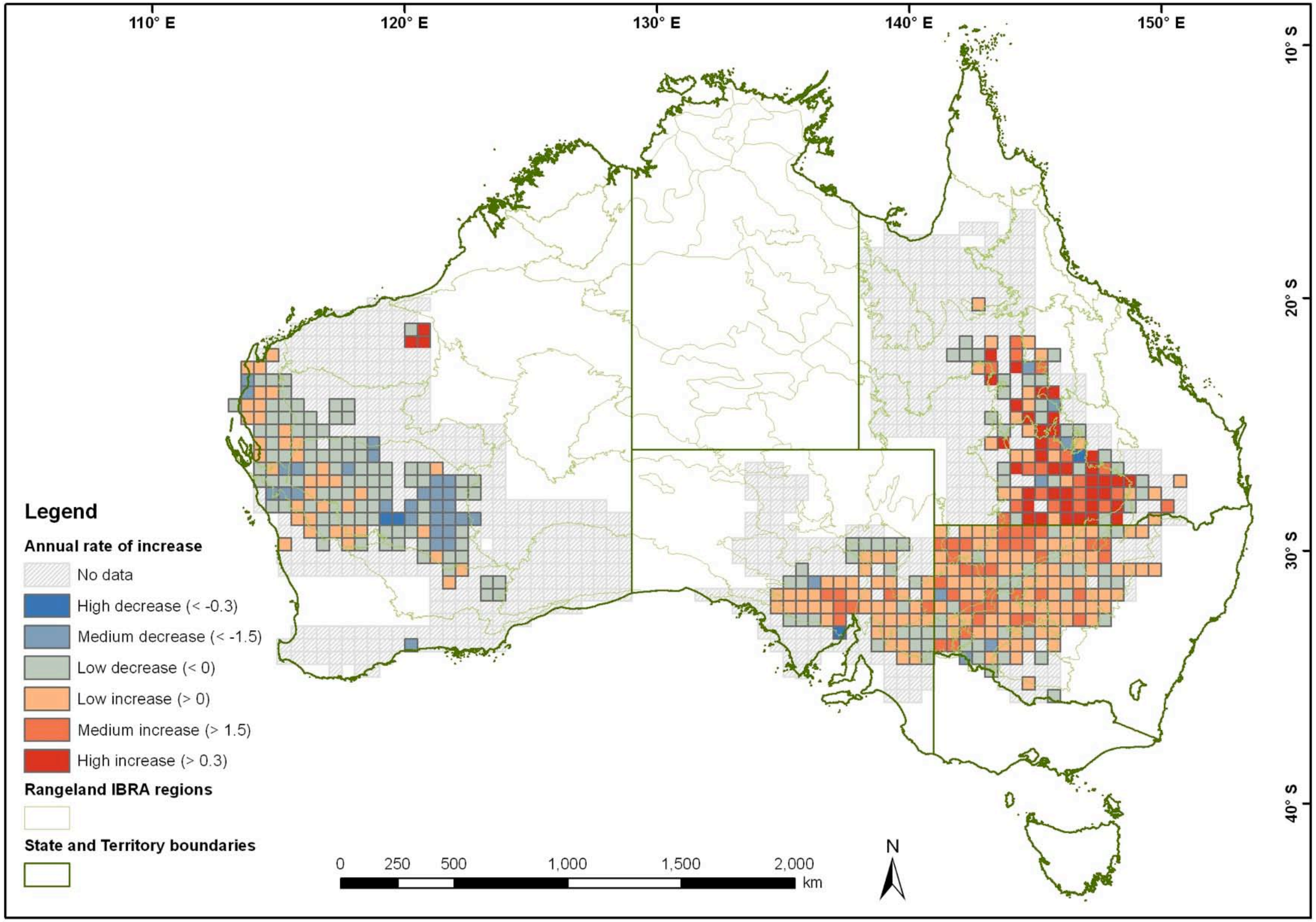

Figure 10. Annual exponential rate of increase of feral goats in half-degree blocks surveyed by fixed-wing aircraft across Queensland (1984-92, 2001), New South Wales (1993-2011), South Australia (1989-2011) and Western Australia (1987-2011). Surveys in blocks outside the core area (Fig. 1) were infrequent. Rangeland bioregions are also indicated.

Harvesting

Goats processed at abattoirs or exported live

The numbers of goat carcasses inspected by AQIS at abattoirs over 1988-2010 is shown in Figure 11a, which depicts an Australia-wide slaughter that has grown from 0.6 million in 1988 to 1.6 million in 2010. Numbers have increased dramatically in Victoria and Queensland. The contribution of Western Australia to goat meat production has dropped from 32% to 11% over this period. Data provided by the Western Australian Department of Agriculture fill a gap in the time series for goats processed at Western Australian abattoirs and show that a comparable number of animals were removed non-commercially (Fig.11b). The actual export of goat meat has shown a steady increase over the longer time period of 1982-2011 (Fig. 12). The live export trade has contributed a further 8% (range 5-14%), on average, to the goat offtake in Australia (Fig. 13). There has been an increase in the export of live animals from South Australia over the past 20 years, matched by a decline in the export from Western Australia.

Combining removal data (assuming 90% corresponded to feral goats) and dividing by population estimates for Western Australia and eastern Australia provides estimates of harvest rate over 1990-2010 (Fig. 14). Estimates fluctuate between 20% and 50%. Non-commercial destruction raised the overall rate to over 70% in 1992, but this declined steadily to below 30% in 1997.

Sales of unmanaged goats

Surveys of properties by ABS suggest 320,000-360,000 feral goats were removed in the survey area over 2004-06 (Fig. 15a). This is well short of the numbers suggested by the data presented in Figures 11-13. It is possible that survey respondents did not distinguish between managed and unmanaged goats. Combining sales of unmanaged and managed goat (Fig. 15b) still only accounts for 43-76% of the goats recorded as being removed for live export or processing at abattoirs in either Western Australia or eastern Australia over 2004-06.

Despite the apparent underestimate and misidentification, the ABS data provide an indication of the pattern of distribution of feral goat harvest. Figure 16 shows that most feral goats are harvested from within the survey area, with relatively smaller numbers taken outside, predominantly in the northern and southern tablelands of New South Wales.

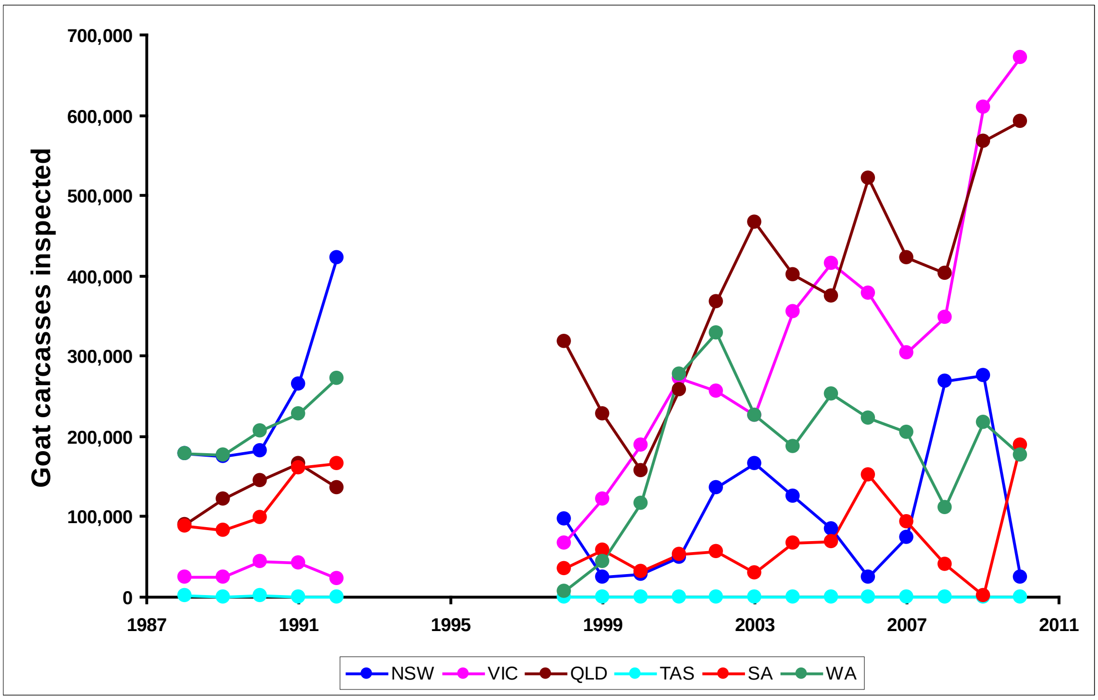

Figure 11a. Trends in the number of goat carcasses inspected by AQIS veterinarians at abattoirs in each Australian state over 1988-2010. Data from Ramsay (1994), Forsyth and Parkes (2004) and P. Smith (AQIS, Canberra, unpublished data).

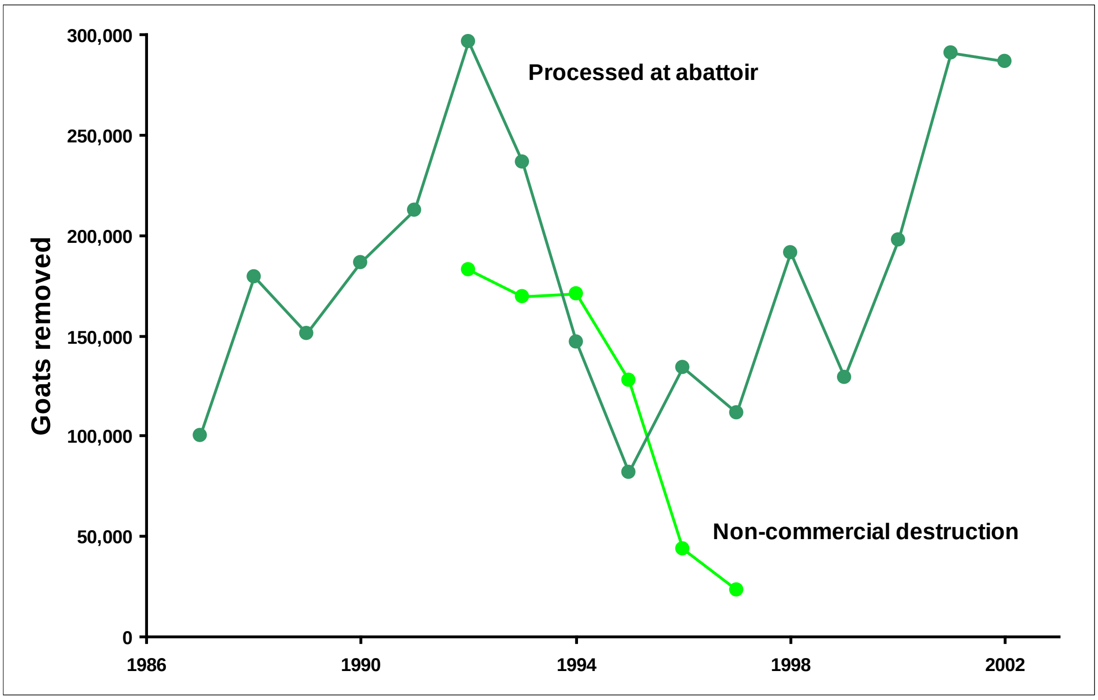

Figure 11b. Goats processed at Western Australian abattoirs and destroyed non-commercially over 1987-2002 (A. Woolnough and G. Pickles, WA Department of Agriculture and Food, unpublished data).

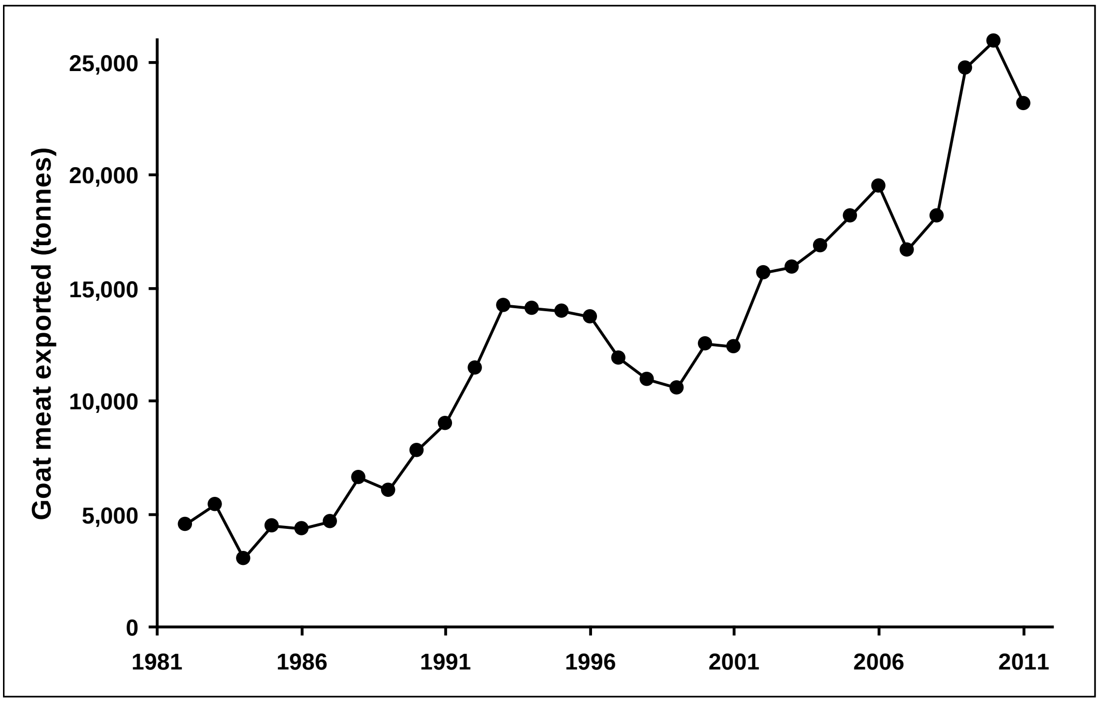

Figure 12. Tonnes of goat meat exported from Australia over 1982-2011. Data from Ramsay (1994), Forsyth and Parkes (2004) and Department of Agriculture, Fisheries and Forestry (http://www.daff.gov.au/agriculture-food/meat-wool-dairy/quota/red-meat/statistics2011/export-stats-1997-2009).

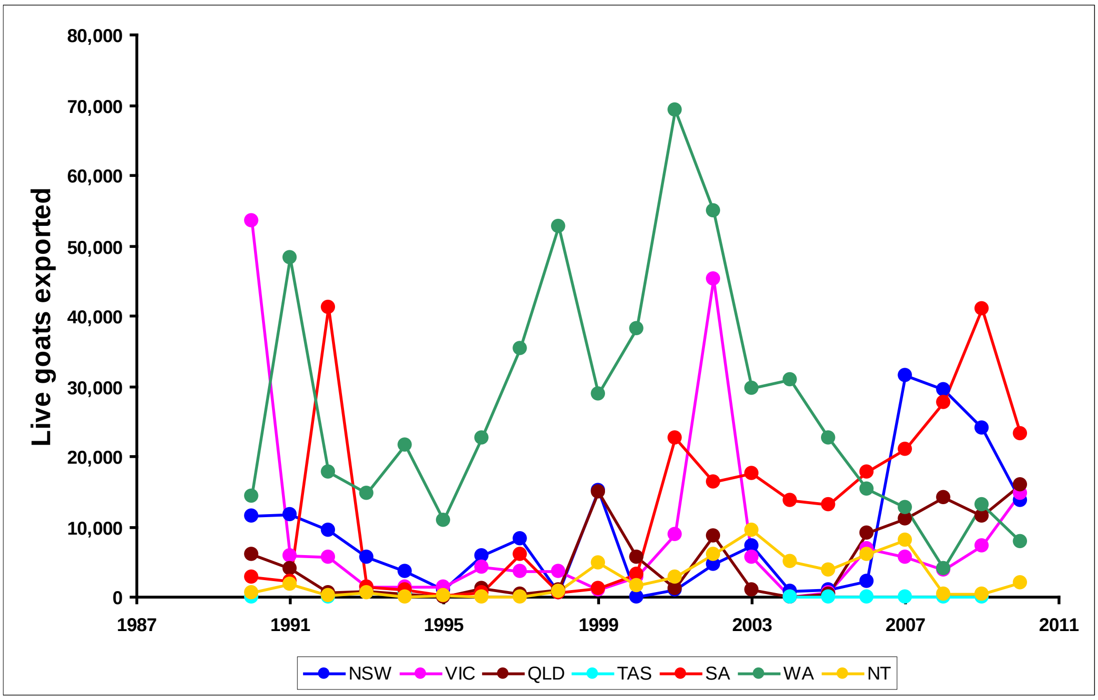

Figure 13. Number of live goats exported from Australia from each state 1990-2010. Data from Livecorp (http://www.livecorp.com.au/Facts_and_Stats/Statistics/Goats.aspx)

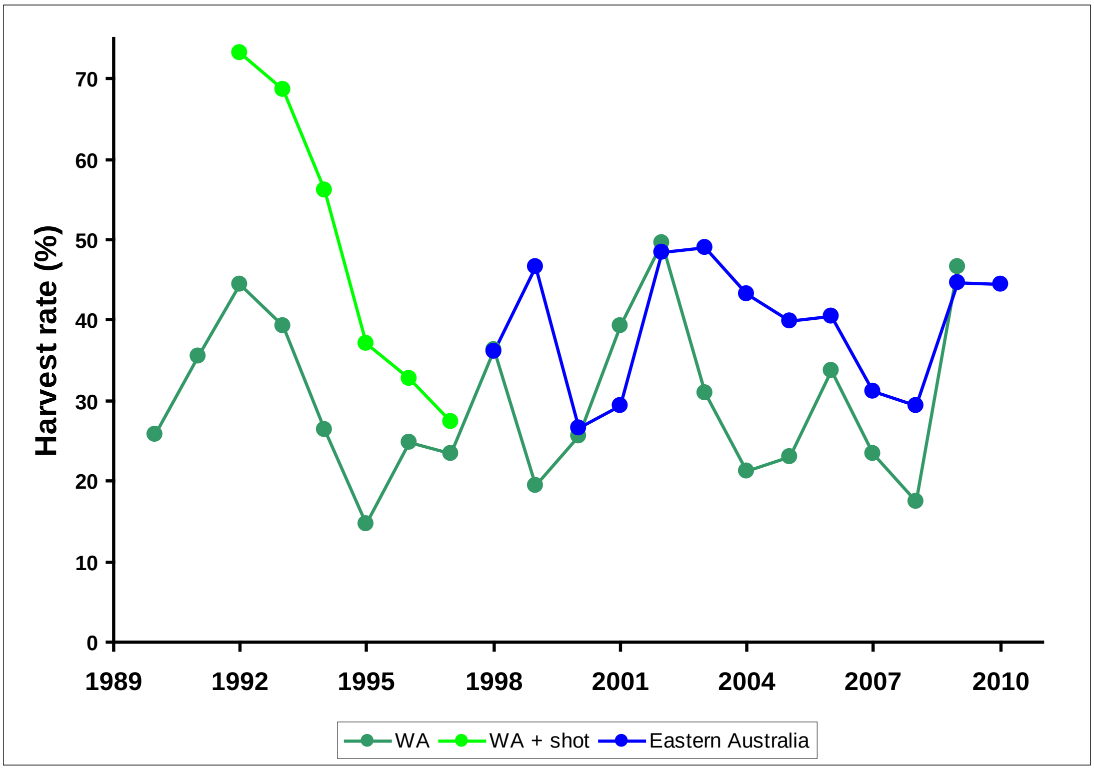

Figure 14. Instantaneous harvest rates for feral goats in Western Australia (dark green) and eastern Australia (Queensland, New South Wales and South Australia) (blue) based on numbers of goats exported live and processed at abattoirs and assuming 90% are feral. Also shown are the same harvest rates in Western Australia but including the number destroyed non-commercially (light green).

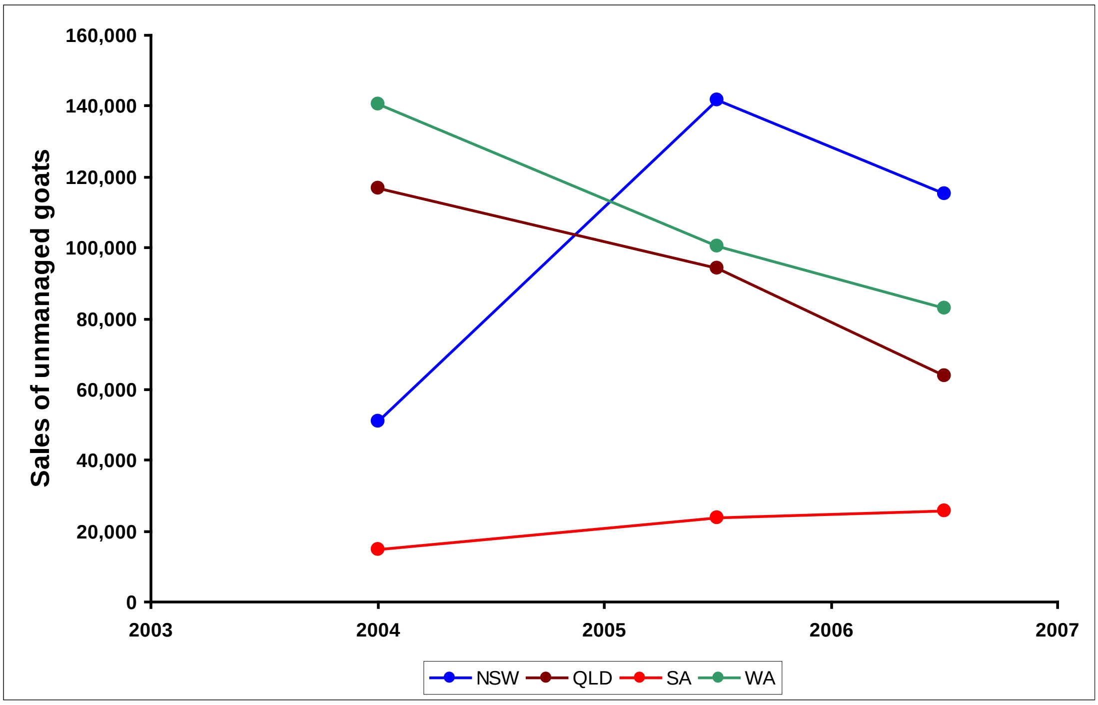

Figure 15a. Sales of unmanaged goats in the survey area. Based on ABS data.

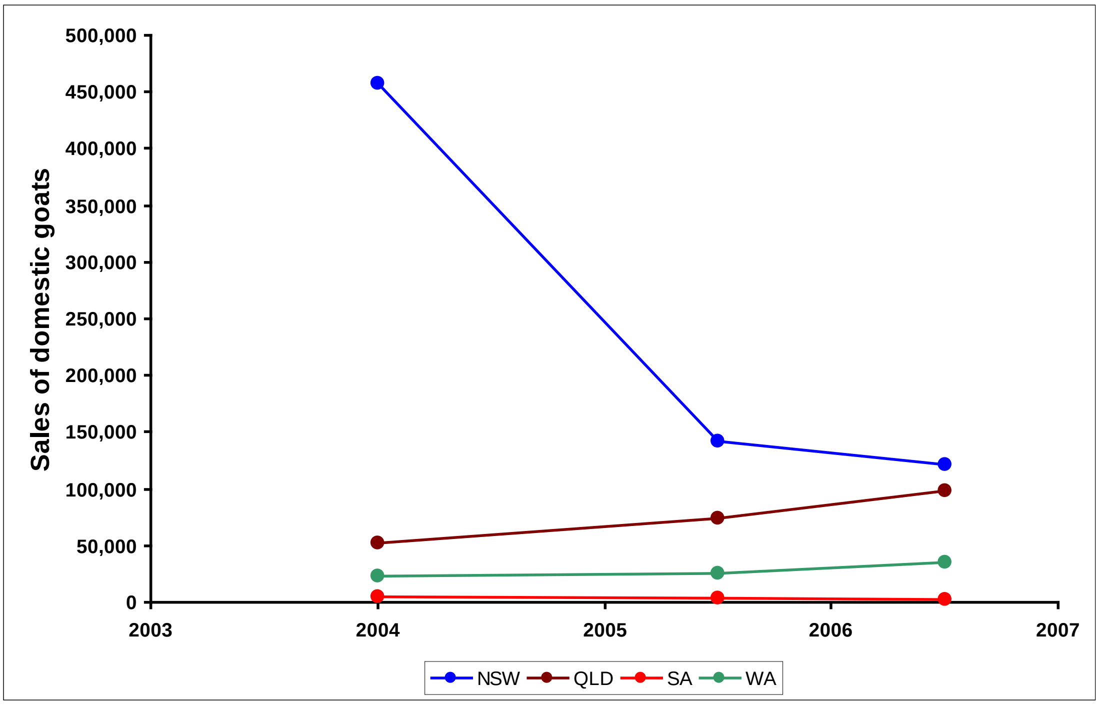

Figure 15b. Sales of domestic goats in survey area. Based on ABS data.

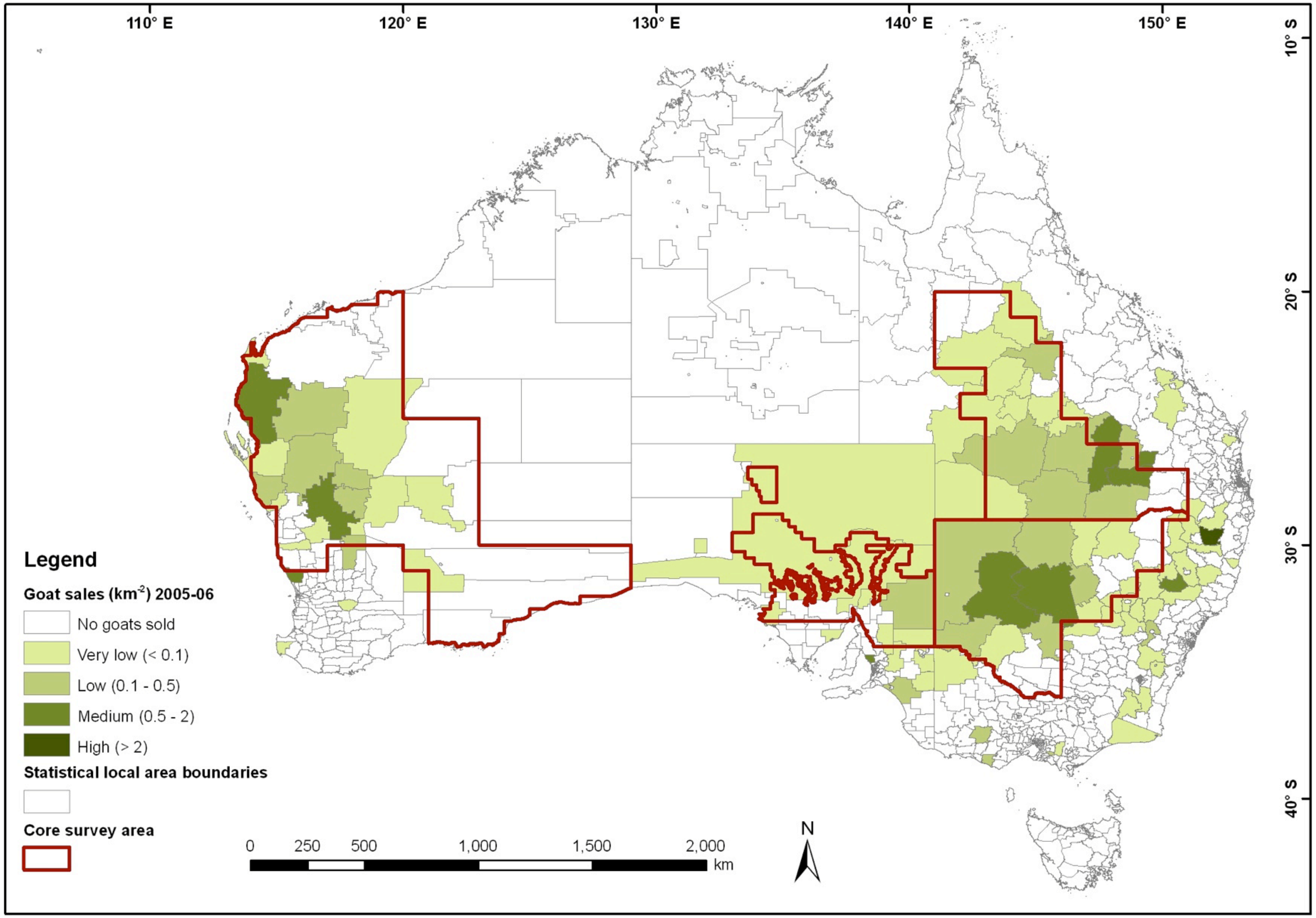

Figure 16. Distribution of sales of unmanaged goats in the 2005-6 financial year. Based on ABS data.

Modelling harvesting impact

Parkes *et al*. (1996) describe the following demographic parameters for use in the Euler-Lotka equation to estimate r_m:

- o 1.57 litters per year, 1.59 embryos per litter
- o 50% of first-year females breed, but only have a single young
- o Birth interval 9 months
- o Annual kid mortality 29%
- o Annual sub-adult and adult mortality 10% p.a.

These parameters translate to r_m = 0.66 or a finite rate of increase (λ) of 1.93, indicating that a goat population with a stable age distribution (and equal sex ratio) can almost double in size over a year. This is higher than maximum rates of ~ 0.4 suggested or recorded elsewhere (Parkes *et al*. 1996, Ballard *et al*. 2011). A compromise value of r_m = 0.5 was therefore used to model sustained yield and long-term population reduction. Historical data suggested a CV of 0.4 was appropriate to model variation in K.

The resultant sustained-yield curve (Fig. 17a) suggests a maximum sustained yield (MSY) at ~30%, resulting in a long-term reduction in population size of ~54% (Fig. 17b). The harvest rates shown in Figure 14, excluding those including non-commercial removal, have been close to the MSY. It is worth providing an explanation of sustained yield and associated reduction in population size, which are only theoretical constructs. The sustained yield refers to the yield taken each year when a population is harvested at a particular rate every year for many years. Lower rates in some years will reduce the long-term yield and result in higher average population sizes. Conversely, high harvest rates can drive populations to low densities (Figure 17b), but only if those rates are maintained. Figure 14 provides an example with the combined commercial and non-commercial harvest of feral goats in Western Australia being at long-term unsustainable rates (see Fig. 17) for only a few years (1992-4). Despite this brief heavy harvest, feral goat numbers did not decline appreciably in Western Australia (Fig. 6), with the exception of a brief decline in the Murchison bioregion (Fig. 4d).

Domestic goats

Domestic goats in Australia have fluctuated markedly, with two peaks since 1983 (Figure 18). Within the survey area, numbers reached ~170,000 in 1989 and 465,000 in 2008, with lows <40,000 in 1983 and 1994-95 (Fig. 18b). This pattern was mirrored across the country (Fig. 18b), with numbers fluctuating between 230,000 and 780,000 goats. Over 1983-2009, most domestic goats have been in New South Wales, both as a percentage of the Australia-wide survey area (Fig. 1) (29-71%) and the country (45-70%). The percentage of the national goat herd that is in the survey area has also increased from 15% in 1983 to 65% in 2009. The increase has been particularly marked in Western Australia (16 to 86%).

Within the survey area, feral goats have represented the main component of the overall (feral+domestic) goat herd. This herd comprised 96-99% feral goats in Western Australia over 1987-99 and comprised 94-98% in eastern Australia over 1993-99. The percentage has declined in recent years, comprising 86-95% in Western Australia and 90-92% in eastern Australia over 2006-09. This suggests that the assumption that 90% of goats processed at abattoirs and exported live are feral is conservative. Including domestic goats in the calculation of harvest rate (Fig. 14) has trivial effects of reducing rates by <3%.

The distribution of domestic goats in Australia for four years within 1983-2005 is shown in Figure 19. The shift in distribution into the survey area is evident, as is the recent increase in numbers overall. There is now considerable overlap between feral (Fig. 9) and domestic herds, although the latter are at lower density.

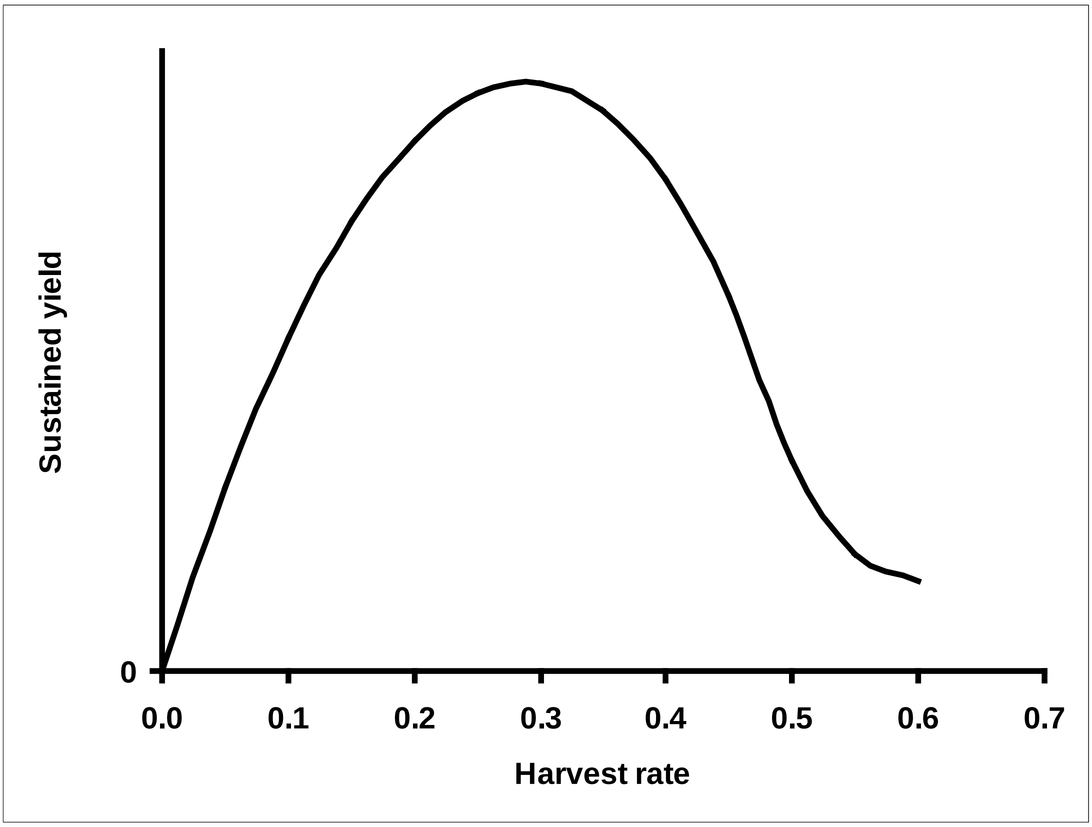

Figure 17a. Sustained-yield curve for feral goats. See text for explanation.

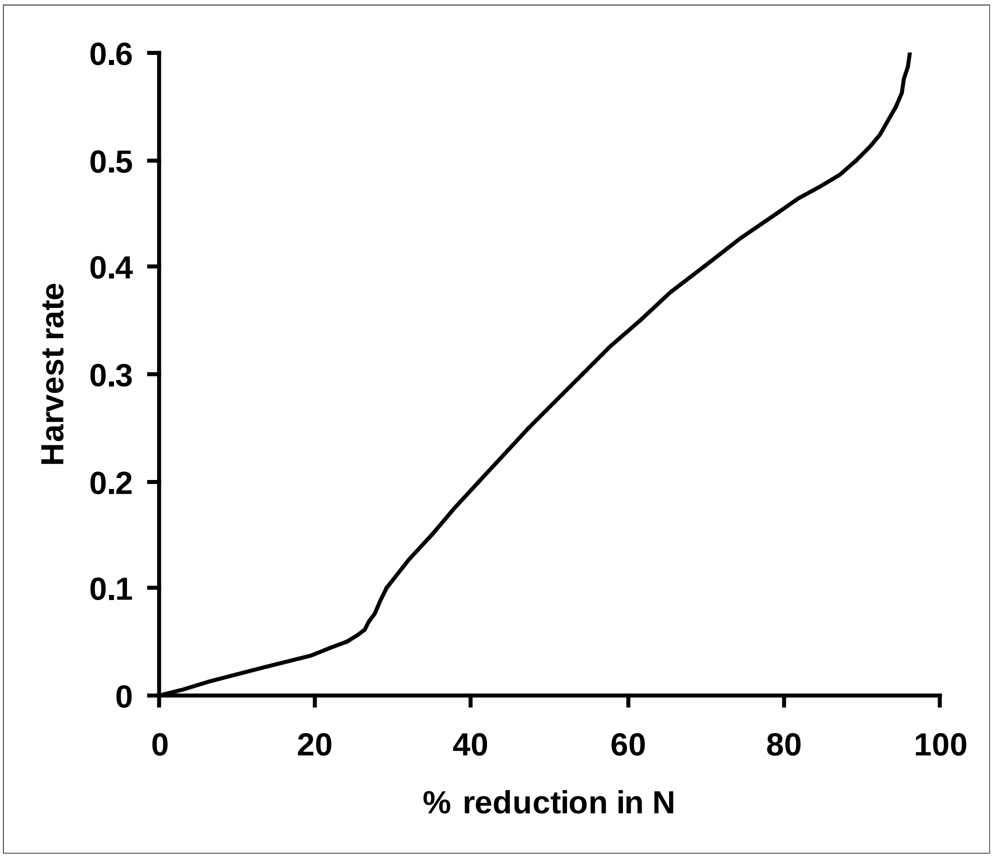

Figure 17b. Percentage reduction in population size from a range of long-term harvest rates. See text for explanation.

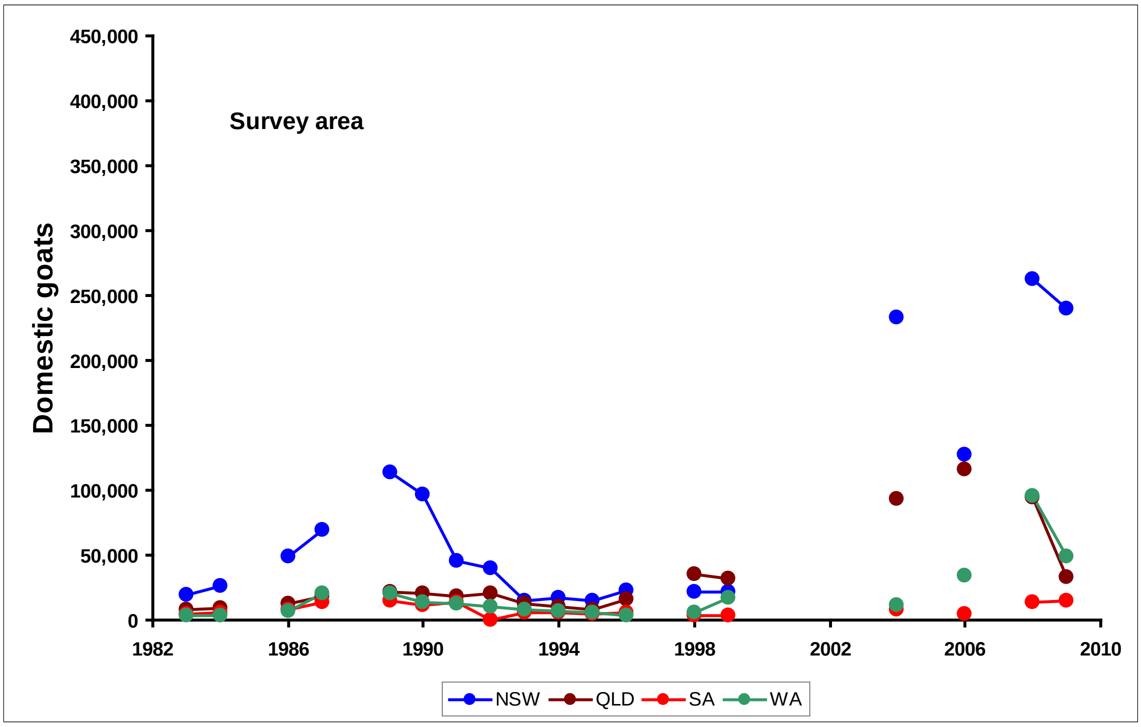

Figure 18a. Domestic goats in the survey area of each state (Fig.1). Data are from ABS and were collated for financial years, but have been allocated to the second year.

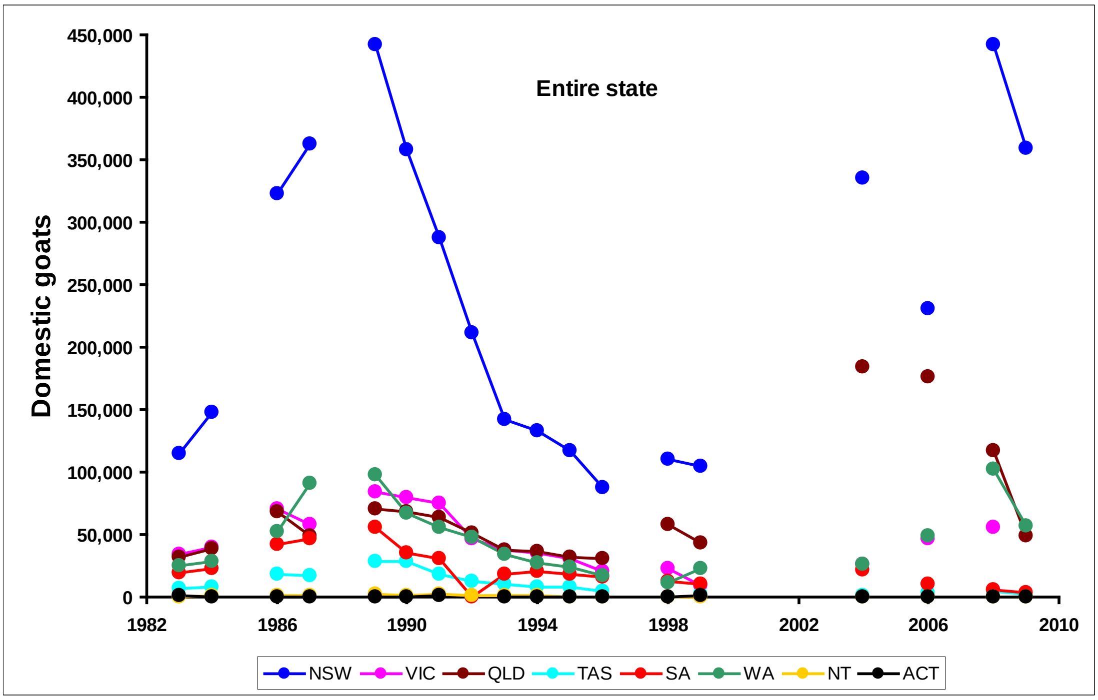

Figure 18b. Total domestic goats for each Australian state. Data are from ABS and were collated for financial years, but have been allocated to the second year.

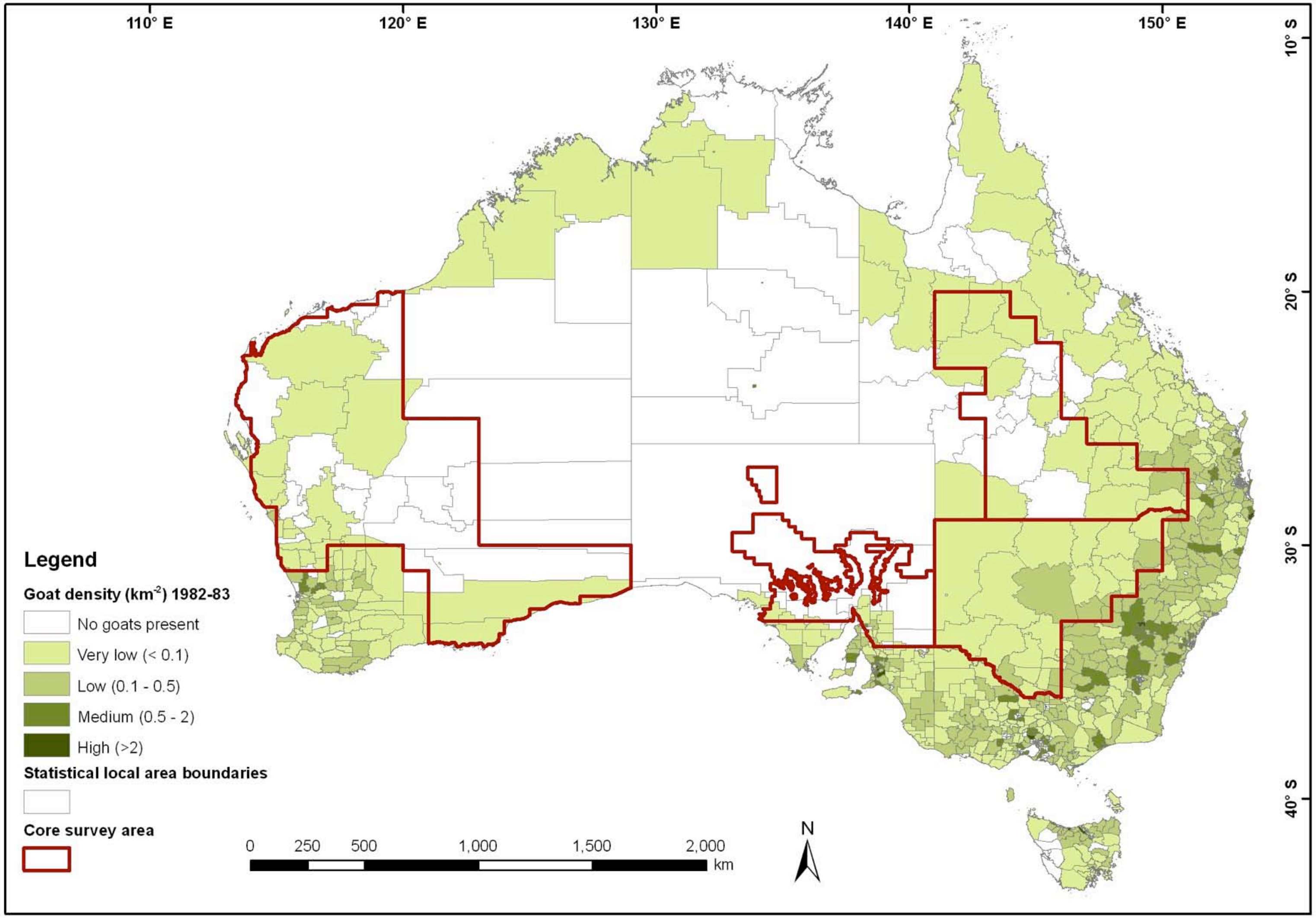

Figure 19a. Distribution of domestic goats in the 1982-3 financial year. Data from ABS.

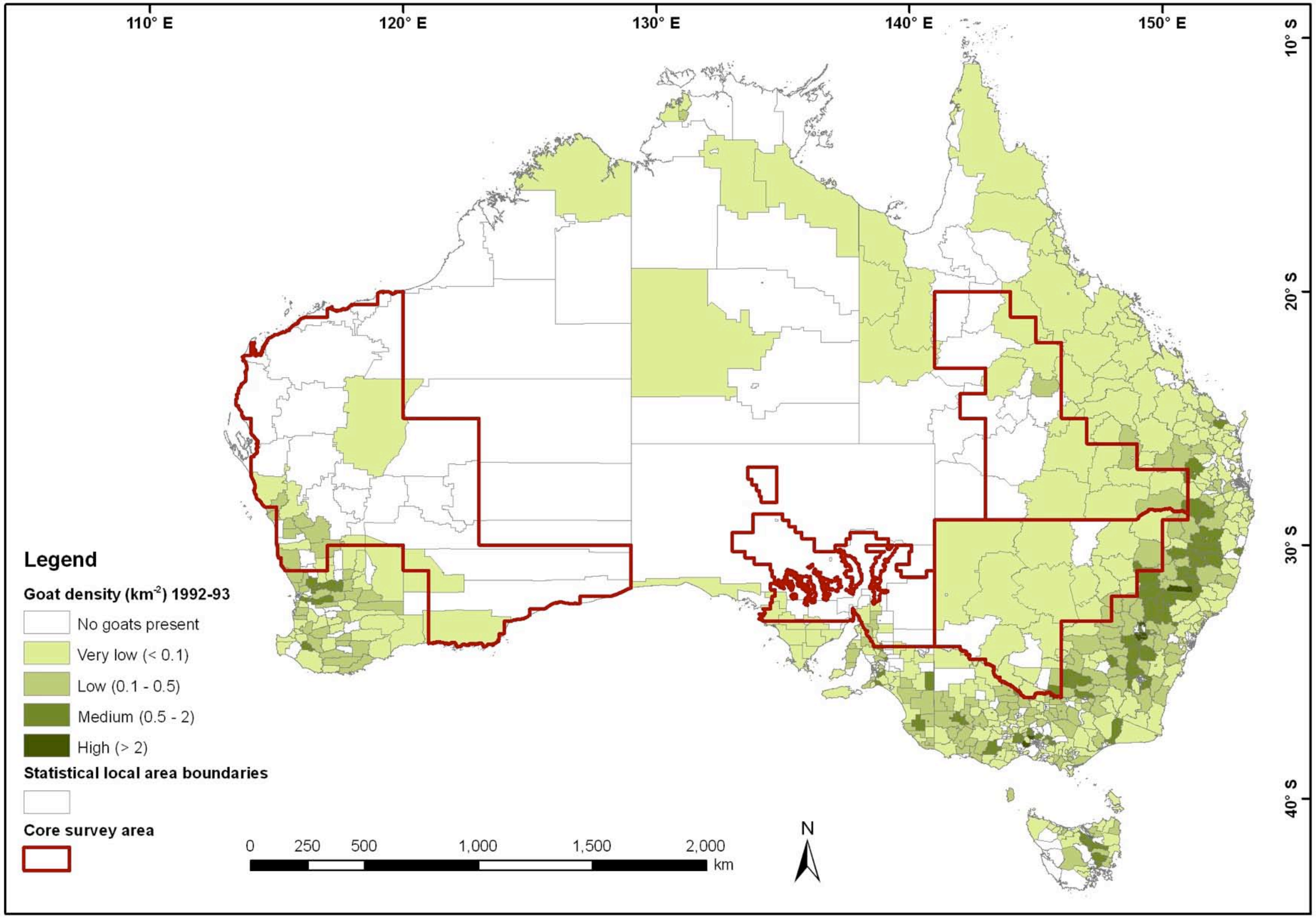

Figure 19b. Distribution of domestic goats in the 1992-3 financial year. Data from ABS.

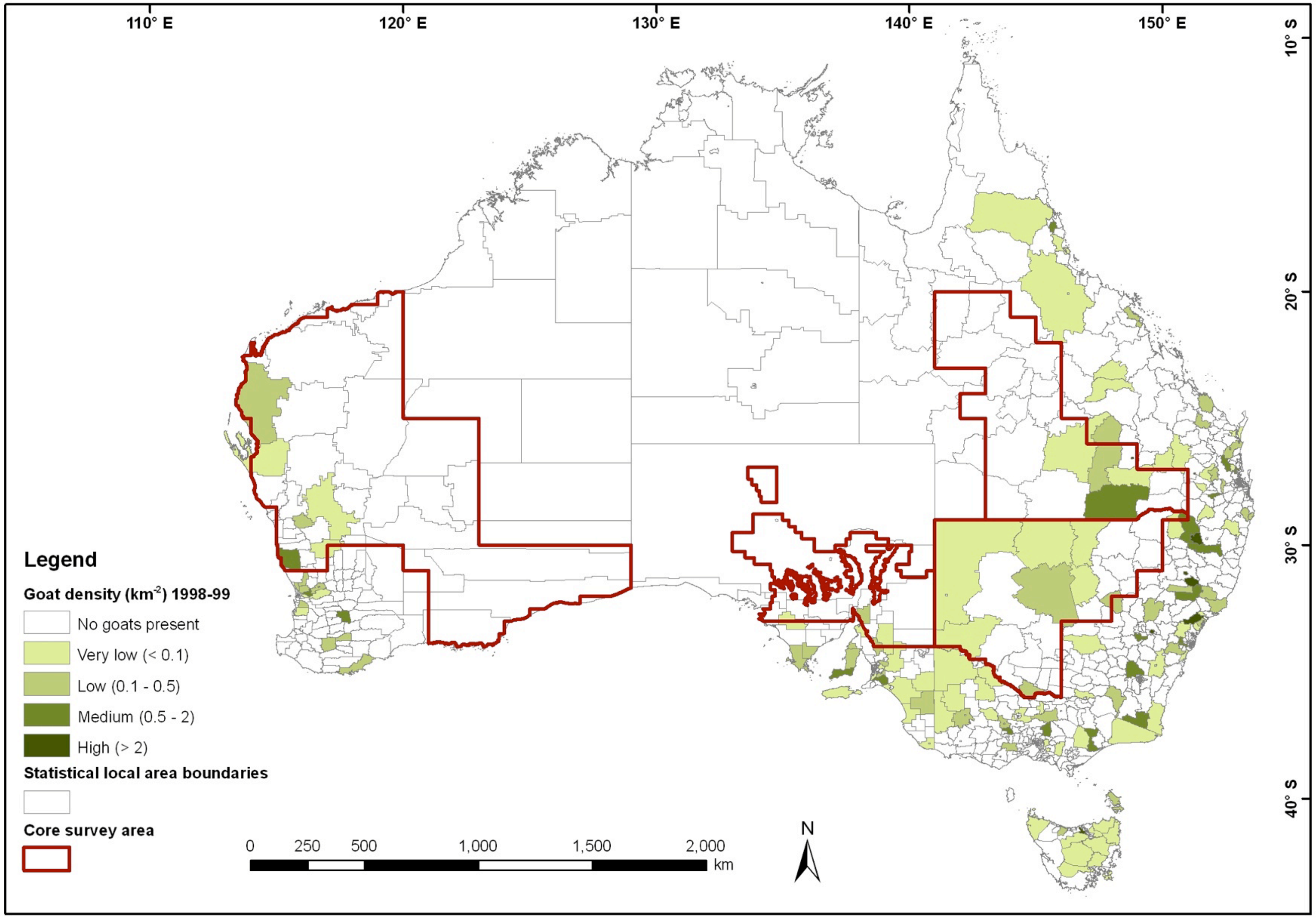

Figure 19c. Distribution of domestic goats in the 1998-9 financial year. Data from ABS.

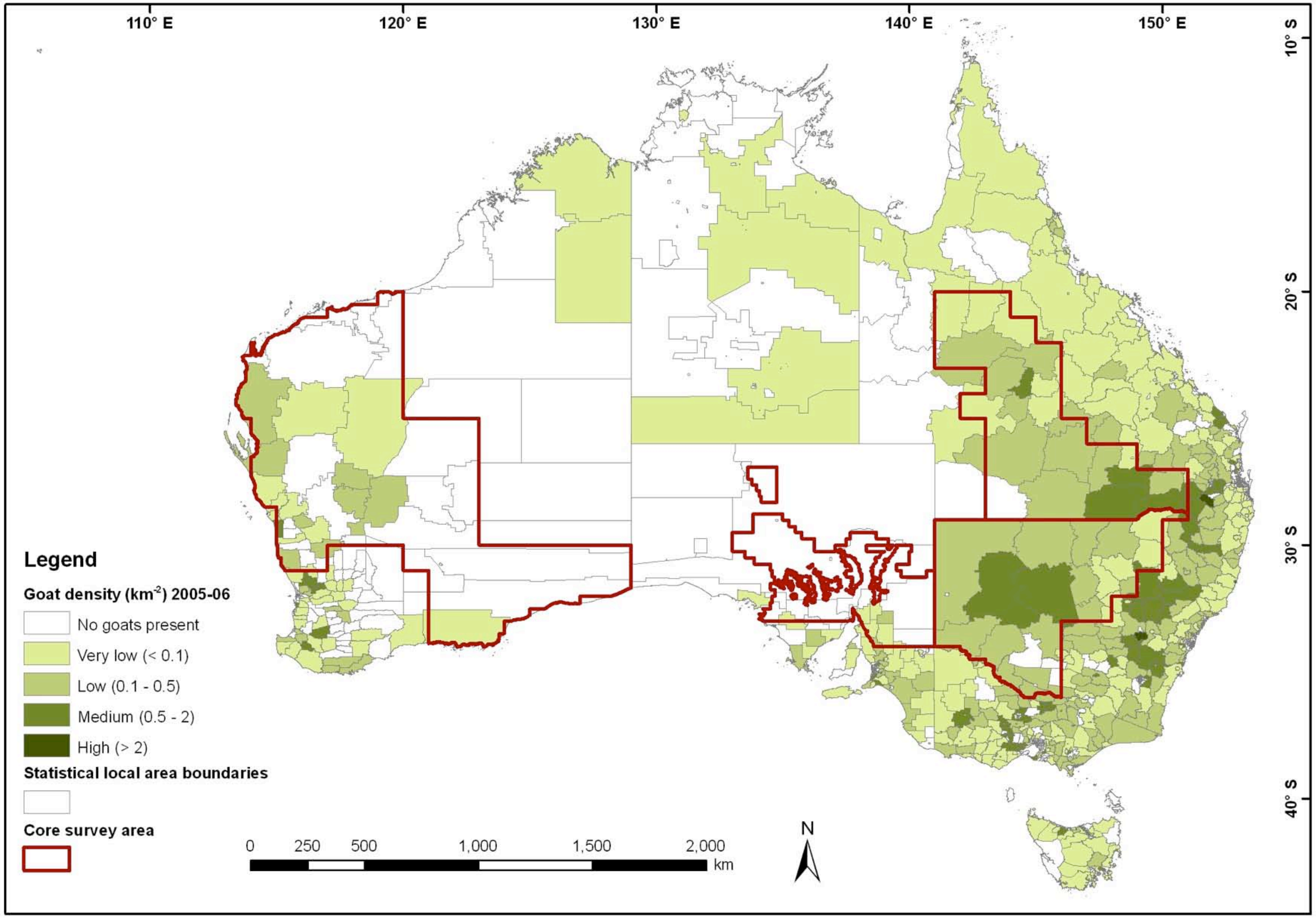

Figure 19d. Distribution of domestic goats in the 2005-6 financial year. Data from ABS.

Discussion

Historically, the value of feral goats was always seen as a constraint to their commercial harvest (Parkes *et al*. 1996). An increase in the value of goats in the mid-1990s (Forsyth *et al*. 2009) was widely thought to be a trigger for an increased harvest and a reduction in abundance. This certainly coincided with an increase in the number of goats processed at abattoirs in the eastern states (Fig. 11a), early on in Western Australia (Fig 11b) and the volume of goat meat exported (Fig. 12). The link between price and the size of the harvest in Western Australia was demonstrated statistically by Forsyth *et al*. (2009). However, this increased harvest has not lead to a decline in numbers (Fig. 6). Harvest rate increased over the latter half of the 1990s in Western Australia and possibly in eastern Australia, but the higher rate has not been maintained. More importantly, numbers have increased in all states since the mid-1990s, particularly New South Wales. The exception has been a decline in Western Australia since 2005 which has been pronounced in the east of the Murchison bioregion. This decline was not associated with particularly dry conditions with roughly average annual rainfall over the past seven years and only moderately wet or dry periods.

By its very nature, broad-scale monitoring of pest abundance and impact is difficult. Expert opinion can assist, but qualitative data will be poor at detecting trend unless it is substantial. Maps based on expert opinion (West 2008) adequately describe the broad-scale distribution of feral goats and even some of the patterns of distributions within states. Comparisons across states are poor, indicating a mismatch in the subjective estimates of abundance by the respective experts. This is likely to also occur over time in the one location, where one expert subjectively estimates current density differently from how another expert has estimated past density.

In terms of advice for the ACRIS Management Committee, their five requests can be addressed in turn.

i. Suitability of data for reporting change

Aerial surveys in all four states provide data that are sufficiently precise (standard error/mean × 100) for monitoring medium- to long-term changes in feral goat abundance. In New South Wales and South Australia, precision of state-wide estimates is ~10-15%, but in Western Australia, triennial surveys reduce precision to ~20%. In Queensland, fixed-wing surveys resulted in a precision of 13-26%, but this has been reduced with the use of helicopter survey blocks to 27-48% because of the lower sampling intensity (i.e. shorter total transect line length). An increase in the number of blocks in recent years has improved precision. To be statistically significant, a percentage change in abundance needs to be greater than roughly twice the precision. Thus small to moderate changes in goat abundance are unlikely to be detectable. Large mammals, because of their life history with relatively high adult survival (Gaillard *et al*. 1998), will not undergo large population fluctuations in the short term, with the exception of steep declines in times of drought (e.g. Caughley *et al*. 1985) or similar catastrophic events. Goats fall somewhat short of being large mammals, but have a similar life history. Change in abundance is therefore expected to be gradual and this is supported by survey data (Figures 4-6). Short-term changes in numbers may not be well monitored, but longer-term changes should be detected with this survey design.

ii. Actions to improve future data

There are five areas of improvement for data collection and analysis and there is a role for ACRIS in at least the first two.

Firstly, kangaroos rather than goats are the target species for the surveys. Observers may thus not count the latter as diligently. This is exemplified in Queensland, where feral goats were not even counted in 2011, largely from the perception that they could not be distinguished from domestic animals. It is further exemplified by the fact that most jurisdictions have not analysed their goat data for over a decade. Jurisdictions need to be encouraged to regularly analyse their count data on goats to estimate regional and state numbers. This should be done annually when the specifics of a particular survey are fresh in the mind of the survey team. The procedures are little different to the analysis of kangaroo data. It is just that there is little incentive. ACRIS could improve this situation by arguing the importance of these data and reporting the data as collated and analysed here.

The second concern is that each jurisdiction has a different method of storing aerial survey data and consequently a different method of analysis. All data are maintained digitally. Ideally, counts in each 5km survey segment should be georeferenced, allowing estimates of density in different areas of interest. This has now been done for goats in this project as it has been done previously for kangaroos (Pople *et al*. 2011). In Queensland, line transect data from helicopter surveys are maintained in various forms in Excel files. Georeferencing data in survey blocks is probably not necessary, as long as transect lines and blocks are well identified. These data have now been collated in a Distance file, to which future data can be added. Ideally, Queensland helicopter survey data for all species should be maintained on a database. ACRIS could encourage jurisdictions to make these improvements, probably with the support of the kangaroo management arm of the Federal Department of Sustainability, Environment, Water, Population and Communities.

Thirdly, only the total numbers of goats in a fixed-wing survey segment are recorded. Previous work (Pople *et al*. 1998c, Ballard *et al*. 2011) suggests that cluster size influences detection probability. An improvement in methodology would be to record individual clusters of goats to allow appropriate corrections to be applied.

Fourthly, the correction factors applied here to the fixed-wing counts are not definitive. Different corrections were applied in the various states, but they were broadly similar, which is encouraging. Pople *et al*. (1998c) suggested correction factors of 1-2, which is similar to those used here. That work also suggested no need for a correction for temperature which is applied to kangaroo counts. Corrections were applied at the scale of a survey unit in South Australia and Western Australia, but they were not determined at that scale. In contrast, correction factors were applied across the state in Queensland and New South Wales. In New South Wales, biogeographic correction factors over a wide range of 2-13 are applied to kangaroo counts as these were determined by comparisons of helicopter and fixed-wing surveys at that scale (Cairns and Gilroy 2001). Correction factors based on line transect surveys in Western Australia (Southwell 1996) and Queensland in 1992 (Pople *et al*. 1998a) embody the assumption that all animals are seen on the transect line. This could well be violated, suggesting the correction factors are too low. Similarly, the helicopter surveys in Queensland have the same untested assumption. Correction factors have been developed for line transect sampling of kangaroos (Fewster and Pople 2008) and pigs (Gentle *et al*. 2011) by helicopters, based on mark-recapture distance sampling. Further work on correction factors would be useful, but is probably not a priority as the variation amongst likely corrections does not appear great. Opportunistic collection of mark-recapture data on present fixed-wing and helicopter surveys would be the most efficient means of making progress.

Finally, misidentification of feral goats as domestic animals is problematic. ABS data on domestic goat densities in the survey areas suggest their numbers are low relative to the numbers of feral goats and so the problem is minor. However, the ABS data need validation, particularly as other ABS data on feral goat sales are lower than those recorded from abattoirs. Schuster's (2006) processor survey suggested much larger numbers of 'rangeland' goats than the equivalent managed goats reported by ABS. A few case studies where actual property records are collated would be a realistic way of addressing this. The ABS survey questions for goats may also need revision.

iii. Capacity to expand monitoring activity

An improvement to the survey design for goat monitoring would be to increase survey effort where population size is greatest. Such stratification of survey effort is roughly optimised to improve precision if it is in proportion to population size (or more formally, the variance). However, there would need to be good reason for improving precision, such as monitoring increased control effort. Increasing monitoring effort for goats seems unlikely given that it is undertaken by conservation agencies whose primary interest is kangaroo monitoring. Additional survey effort directed at goats would presumably need to be supported by the relevant agencies managing invasive species. An exception would be if survey effort were to be directed onto the National Park estate.

iv. Value of harvest data

AQIS data on carcass inspections and Livecorp's records of live export numbers have the advantage of being readily available and currently reliable. A check on the AQIS figures comes from the weight of goat meat exported provided by DAFF. What these data lack is a link to the region where the goats have been removed. Presently, they can only be split between the eastern states as a whole and Western Australia. A further disadvantage is the inability to distinguish feral and truly domestic goats. ABS surveys could potentially resolve this, but these data too have shortcomings. The problem is in how feral and domestic goats are defined and separately recorded. Ground assessment of these data from representative sites as suggested in *ii* would again be valuable.

v. Protocol for aerial survey of goats

If goats are treated with a greater value by aerial survey teams and the data routinely analysed, reported and safely stored, as recommended in *ii*, then the current aerial survey protocol for kangaroos can provide reliable goat data too. Kangaroo monitoring has been supported by a substantial research effort, resulting in population estimates of sufficient accuracy and repeatability for defensible harvest management (Pople 2004, Pople 1999). Feral goats can be successfully monitored off the back of this work.

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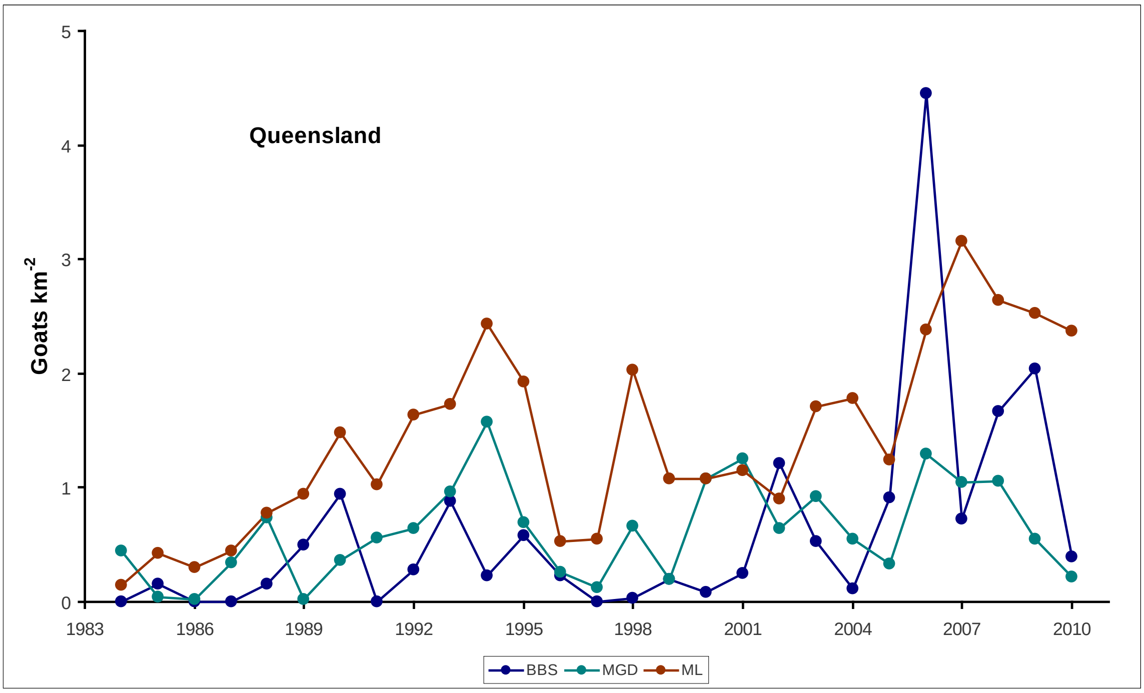
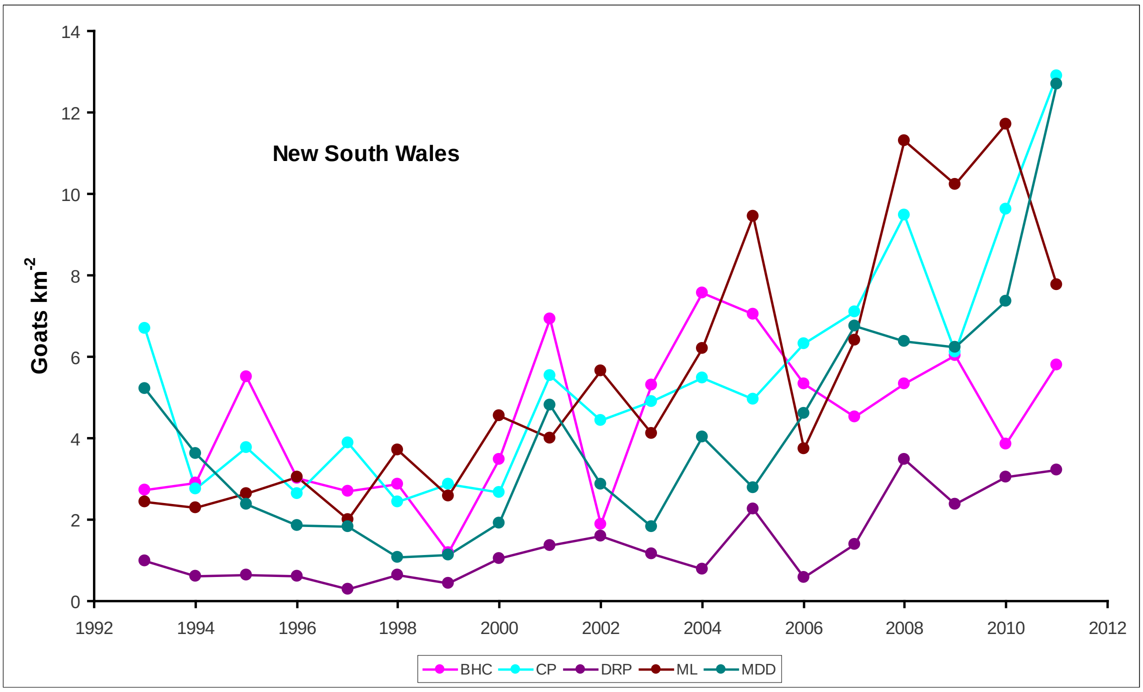
Appendix 1 (overpage). Trends in the densities (km^{-2}) of feral goats in the survey areas (Fig. 1) of (*a*) Queensland over 1984-2010, (*b*) New South Wales over 1993-2011, (*c*) South Australia over 1989-2011 and (*d*) Western Australia over 1987-2011. Estimates for the biogeographic regions within the survey area are given separately. Region codes are defined in Figure 1. Densities are based on aerial surveys using fixed-wing aircraft in all states except Queensland, where helicopter-based estimates have been used since 1993. For each state, bioregions which typically have low numbers of goats (<10,000 animals) are not shown, with the exception of Geraldton sandplains in Western Australia, where low numbers translated to a relatively moderate density of goats.



Appendix 1a.



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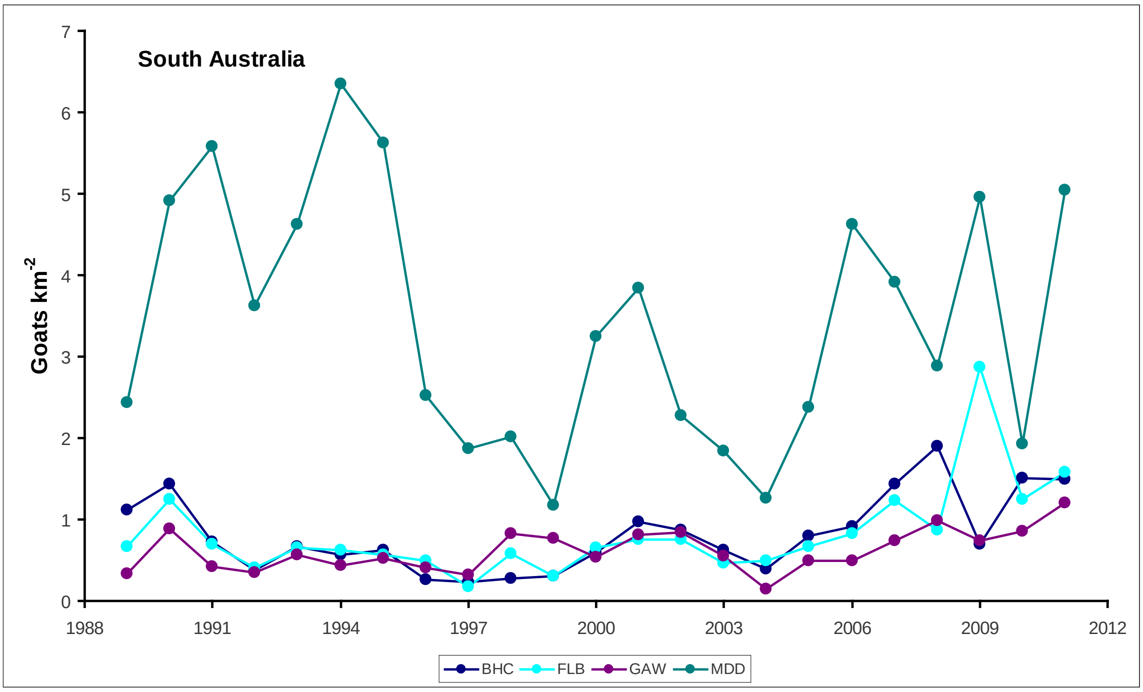
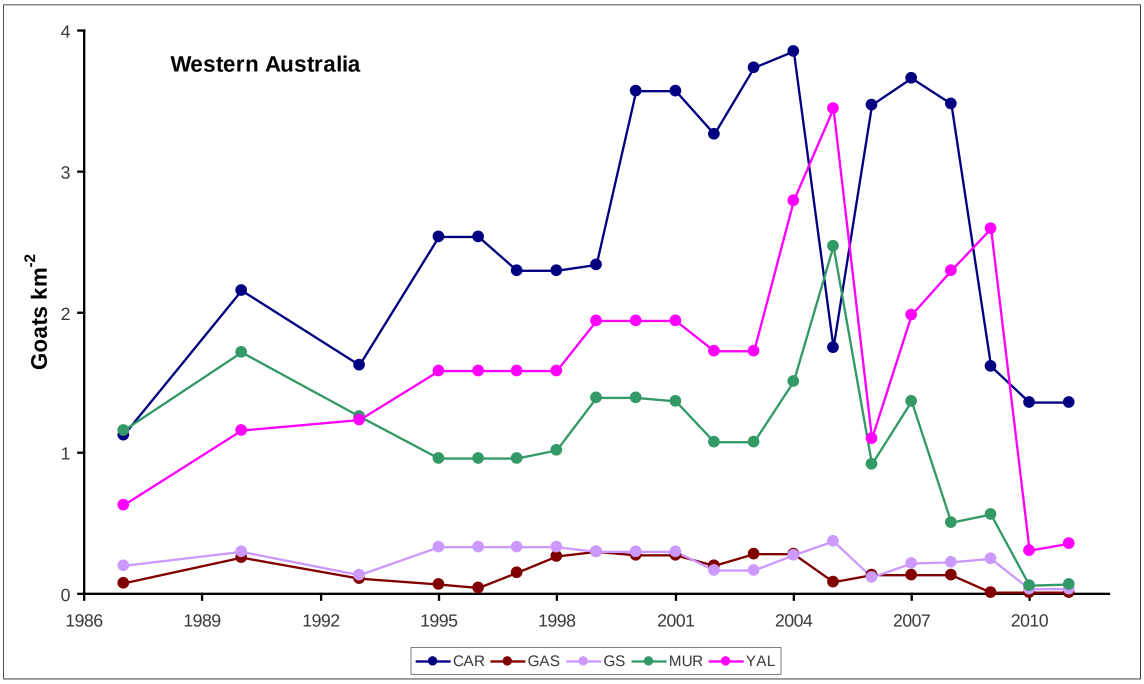


Appendix 1c.



Appendix 1d.