

Low-density koala (*Phascolarctos cinereus*) populations in the mulgalands of south-west Queensland. IV. Abundance and conservation status

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Abstract. Urban encroachment on dense, coastal koala populations has ensured that their management has received increasing government and public attention. The recently developed National Koala Conservation Strategy calls for maintenance of viable populations in the wild. Yet the success of this, and other, conservation initiatives is hampered by lack of reliable and generally accepted national and regional population estimates. In this paper we address this problem in a potentially large, but poorly studied, regional population in the State that is likely to have the largest wild populations. We draw on findings from previous reports in this series and apply the faecal standing-crop method (FSCM) to derive a regional estimate of more than 59 000 individuals. Validation trials in riverine communities showed that estimates of animal density obtained from the FSCM and direct observation were in close agreement. Bootstrapping and Monte Carlo simulations were used to obtain variance estimates for our population estimates in different vegetation associations across the region. The most favoured habitat was riverine vegetation, which covered only 0.9% of the region but supported 45% of the koalas. We also estimated that between 1969 and 1995 ~30% of the native vegetation associations that are considered as potential koala habitat were cleared, leading to a decline of perhaps 10% in koala numbers. Management of this large regional population has significant implications for the national conservation of the species: the continued viability of this population is critically dependent on the retention and management of riverine and residual vegetation communities, and future vegetation-management guidelines should be cognisant of the potential impacts of clearing even small areas of critical habitat. We also highlight eight management implications.

Introduction

In the latter part of the 20th Century the koala (*Phascolarctos cinereus*) has become a conservation icon and national symbol. Yet since European settlement of Australia management of the species has been mostly *ad hoc*, often incidental to land management, and based on few data about population size.

Despite the lack of data there have been numerous public and institutional expressions of concern for the future of the species. In 1992 the International Union for the Conservation of Nature (IUCN) Scientific Australian Marsupial

and Monotreme Specialist Group classified the national conservation status of the koala as 'Potentially Vulnerable'. The draft Action Plan for Australian Monotremes and Marsupials (Maxwell *et al.* 1996) assessed its conservation status as lower risk ('near threatened') using the 1994 IUCN criteria. It estimated that there were more than 50000 koalas in Australia, but gave no indication of an upper limit. However, the koala is not listed by the Australian Federal *Endangered Species Protection Act 1992*. Recently the non-government organisation (NGO), Australians for Animals, successfully lobbied policy makers in the United

States of America and the koala is now listed as a threatened species under the *United States of America Department of the Interior, Fish and Wildlife Service, Endangered Species Act*.

It is generally acknowledged that the koala's former geographic range has contracted by more than 50% since European settlement (Phillips 1990; Maxwell *et al.* 1996). However, organisations have vastly different views on national and statewide abundance and conservation status. For example, the NGO Australian Koala Foundation estimates that the national population is 45 000–80 000 (25–50 000 in Queensland and 10–15 000 in both New South Wales and Victoria (Sharp 1995). This contrasts sharply with other estimates, for example 170 000 in Queensland alone (G. Gordon, Queensland National Parks and Wildlife Service, personal communication), up to 10 000 in New South Wales (Lunney *et al.* 2000), and 75 000–130 000 for the Strathbogie Plateau in Victoria (Melzer *et al.* 2000). The uncertainty of population estimates is further illustrated by Phillips (2000), who estimated koala abundance for the Strathbogie Ranges by modelling population growth from a known history of introductions and an expected rate of increase. These models suggested a best-case scenario of <30 000 koalas, without accounting for assumptions of habitat homogeneity, non-limiting food resources, mortality and stochastic events.

Around 40% of the natural distribution of the koala occurs in tropical, subhumid and semi-arid regions of the continent (Phillips 1990), and almost all of that is in Queensland. However, little is known of the abundance of koala populations in these areas (Melzer and Lamb 1994). Their current distribution in Queensland has largely been derived from questionnaire surveys, and many local koala populations in northern, central and western Queensland may remain unreported or unknown (Patterson 1996).

The most significant threat to the long-term conservation of koalas is habitat loss, although drought, wildfire, disease, predation and vehicle strikes are also serious threats (Melzer *et al.* 2000). Despite these threats and the level of uncertainty regarding the abundance of koalas, it has been suggested that conservation intervention should be taken now, since there is clear evidence of decline in some populations while the existence of other robust populations offers the possibility of a variety of creative solutions (Sherwin *et al.* 2000). The primary aim of the National Koala Conservation Strategy is to conserve koalas by retaining viable populations in the wild throughout their natural range (ANZECC 1998). However, the lack of reliable, or even generally agreed, national estimates of abundance for this species presents clear difficulties (Cork *et al.* 2000). Until a nationally recognised standard (with regionally specific and compatible survey methodologies) is adopted to derive an acceptably precise estimate of koala abundance across all states, *ad hoc* estimates and best guesses will continue to cause controversy and retard practical koala conservation initiatives.

The first paper in this series (Sullivan *et al.* 2002) detailed the development and statistical validation of our pellet-sampling protocol and the second (Sullivan *et al.* 2003a), the diet and distribution of koalas within the study area. The third paper in the series (Sullivan *et al.* 2003b) applied GIS technology, a relative habitat-utilisation index and logistic regression modelling based on the presence/absence of pellets to identify broadscale habitat utilisation, and discussed the biotic factors that appear to determine these patterns.

In this, the final paper in the series, we report regional density estimates, and describe the application of a geographic information system (GIS) to convert broadscale survey density data to regional estimates of koala abundance, derive bootstrapped variance estimates for those abundances and discuss the conservation significance of our findings. Given that Queensland is likely to have the largest koala populations, determining their abundance in regional Queensland is a critical component to the success of the National Koala Conservation Strategy and will help to place the management of the species on a more informed footing.

Methods

Study area

This study was conducted in the Queensland portion of the mulgalands biogeographic region (Fig. 1), which covers more than 190 000 km² and is described in detail by various authors (e.g. Neldner 1984; Thackway and Cresswell 1995; Wilson 1999).

Application of the faecal standing-crop method

Koala density estimates are derived from data collected from a multi-scaled, stratified survey of the mulgalands. The sampling rationale and location of the sampling sites is provided in detail in Sullivan *et al.* (2003a, 2003b).

We calculated koala density using the faecal standing-crop method (FSCM, as used by Johnson and Jarman 1987; Latham *et al.* 1996).

$$\text{Koala density} = P/da, \quad (\text{Eqn 1})$$

where P = pellet abundance, d = daily pellet production and a = maximum pellet age. The methods used to estimate P and a are described in detail in Sullivan *et al.* (2002).

By adapting a method used to capture koalas (Hasegawa and Carrick 1995) we estimated daily pellet production rates (d) in 8 free-ranging koalas (3 males and 5 females) of different ages located in a range of habitats in different seasons. A 1.5-m-high sheet of metal was placed in a circle ~2 m from the base of a tree in which a koala was found, forming a barrier that the koala could not climb. In this way an animal was confined to a single tree for 24 h. Black plastic sheeting was placed under the entire canopy to separate any previously deposited pellets from those deposited during the period of confinement, and to ensure that vegetation or litter did not hinder pellet collection.

Once estimated with 95% confidence limits, this parameter (d , Eqn 1) was applied to calculate density estimates for all sites, for the duration of the study. However, the age (a) at which pellets reached the threshold between the 'new' and 'old' class varied depending on seasonal weather conditions and was applied to data collected at that time only (Sullivan *et al.* 2002).

Table 1. Vegetation visibility class characteristics

Visibility class	% ground cover of litter/pebbles	% visibility of ground through vegetative cover
1	<20 light litter/pebbles	>80
2	100 light litter/pebbles	51–80
3	100 light to dense litter	21–50
4	100 dense litter	up to 20
5	100 extremely dense litter	0

The density of koala faecal pellets was estimated from quadrat counts under trees (see Sullivan *et al.* 2002 for details). Ground vegetation and cover greatly affected the time taken to search any quadrat, and had the potential to bias estimates of pellet density if pellets were missed in quadrats placed in different vegetation cover. To minimise this potential source of bias we recognised five vegetation visibility classes (Table 1), and developed correction factors and standard search times for quadrats in each one.

We quantified the number of pellets obscured in each visibility class by conducting a thorough search under litter and/or vegetative growth present in the quadrat, as would be conducted under normal field conditions (standard count). All vegetation and litter were then removed from the quadrat, using hedge trimmers when necessary, and all pellets in the quadrat were counted. Linear regression was used to compare several models for predicting the actual number of pellets from the standard count in each visibility class.

To calculate site-specific pellet abundance, the data from each individual sampling quadrat (Sullivan *et al.* 2002) were adjusted to account for differential pellet detectability due to variable vegetation ground cover. For estimates in residual, floodplain and plains landforms, the adjusted densities were then multiplied by the estimated canopy area of the tree under which they were found. For riverine communities, where trees often had large and asymmetrical canopies, the pellet density was calculated by multiplying the corrected density in quadrats in each quarter of the tree canopy by the area of that quarter, then summing the four estimates for each tree (see Sullivan *et al.* 2002). We then calculated P for each site by summing adjusted data from each tree.

We used Equation 1 to estimate a range of koala densities for each site. Maximum density was calculated using minimum figures for daily pellet production and pellet age, and the minimum density used the respective maximum figures.

Habitat loss (aerial photographic interpretation)

Since the only available GIS coverage of the mulgalands was based on 1969 aerial photography, it was necessary to estimate the area of each habitat unit that had been cleared since that time. We did this by aerial photograph interpretation (API). Most of the most recent photographs available were taken since 1994. However, for a few very small areas the most recent photos were taken in the early 1990s.

In the last thirty years considerable habitat clearance and fragmentation has taken place across the entire region. For example, between 1991 and 1995, 633 km² of vegetation per year was cleared in the mulgalands biogeographic region, which represents 0.34% of the total area per year (SLATS 1999a).

At 207 randomly selected API sites a 100-cm² grid consisting of one hundred 10-mm² cells was placed over the photograph, with the selected site located in the centre of the grid. The vegetation in each cell was categorised as being either cleared or uncleared. If a selected site did not occur within one of our defined habitat units, another site was randomly selected. The same process was followed to select sites within each habitat unit in approximate proportion to their relative area. Finally, we used a maximum-likelihood estimator, weighted according

to sample size, to estimate the ‘current’ area of each habitat unit within each sampling zone (SZ):

$$\sum(x_i - qy_i)^2 / (n - 1) (\sum y)^2, \quad (\text{Eqn 2})$$

where x_i = units in original state, y_i = units assessed and $q = x / y$.

These adjusted figures were then used to extrapolate koala densities across the study area.

Density extrapolation across the region

All density data were extrapolated using the API-adjusted area estimates for each of the 10 primary sampling units (habitat units). Each habitat unit was formed by combining similar vegetation associations on the basis of their floristic and edaphic composition (see Sullivan *et al.* 2003a). Koala abundance across the study area was estimated using a data interpolator to assign values to points for which there were no data. Given the high degree of variation in density estimates and the broadscale nature of the survey, we chose to apply an inverse distance weighting (IDW) interpolator because it assumes that the influence of an observation is inversely related to its distance from the point to be estimated (Watson and Philip 1985).

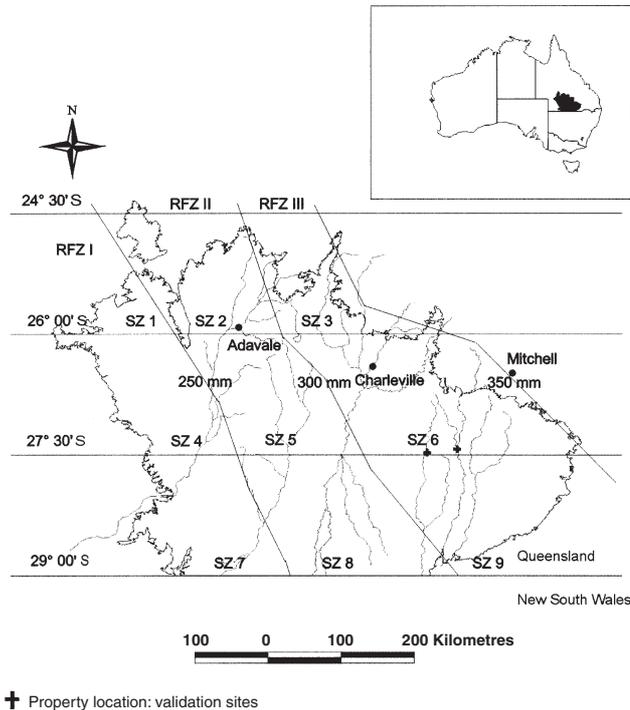
The precision of any weighted average interpolation exercise depends on the function used, or its parameters, and on the size of the domain or area from which sample points are chosen (Hodgson 1992). Our multiscaled stratification process consisted of dividing the study area into three rainfall zones (RFZ) based on annual median rainfall and overlaying three latitudinal zones to form nine SZs (Fig. 1) (see Sullivan *et al.* 2003a, 2003b for details). We then chose a global approximation interpolator (Chou 1997) to create separate IDW surfaces for each habitat unit in the six sampling zones from which ‘new’ pellets were recovered.

The distance parameter of IDW models has historically been 1.0 or 2.0 (Hodgson 1992). We chose a weighting of 2.0 to assign a greater weight to nearby points to capture local-scale density variations.

We generated a separate IDW surface for minimum-, mean- and maximum-density estimates. Density categories for each IDW surface were determined by inspecting a histogram of the estimated densities for each habitat unit in each SZ. Habitat units with a regular distribution of densities were assigned equal density categories and those with an irregular distribution were assigned density categories by Jenk's optimisation formula, which generates classes based on natural breaks in the data (ESRI 1996). For habitat units with only one site with new pellets per SZ we generated a surface for a 50-km radius around the point.

Variance estimates

We used the method outlined by Efron and Tibshirani (1986) to generate 500 bootstrap estimates of pellet abundance for each of the 149 sampling sites, which generated a site-specific measure of the potential range of pellet numbers present. Next, we converted these data into koala densities (via the FSCM) and conducted a Monte Carlo simulation to generate a variance estimate of koala abundance. This was achieved by randomly selecting 100 bootstrap estimates for each site and generating density estimates for each. Then 50 randomly selected



† Property location: validation sites

Fig. 1. The study area; including the three rainfall zones (RFZs), nine sampling zones (SZs), validation sites, major towns and rivers (inset: location of study area).

estimates were used to run a Monte Carlo simulation to generate 50 koala abundance estimates for each habitat unit in each SZ. We considered 50 simulations for each (per SZ) to be adequate to determine the variance of the abundance estimate as samples as small as 25 can give reasonable standard error estimates (Efron and Tibshirani 1986). However, it is desirable to have a much larger sample size to generate confidence intervals (Efron and Tibshirani 1986). Because we manually inspected the distribution of estimated densities for each coverage to decide on the method used to generate density categories, the computation time to generate so many coverages using Arcview (Spatial Analyst) was enormous. Therefore it was not feasible to generate more than 50 coverages for each habitat unit in each SZ. The Monte Carlo simulation was not run for 6 habitat units with an abundance estimate of <100 koalas.

We calculated both the standard error of the mean estimate and 95% confidence intervals of the estimate. Confidence intervals for the mean Monte Carlo simulation were estimated by multiplying the estimated standard error by the appropriate tabulated t .

Field validation of sampling protocol

In addition to the statistical validation of the pellet-sampling protocol (see Sullivan *et al.* 2002), the accuracy of koala densities derived from the protocol were assessed in the field by comparing them with density estimates derived from direct animal counts obtained on belt transects.

Our data were collected at two sites in the eastern portion of the study area (Fig. 1). Both sites consisted of a linear riverine community dominated by river red gums surrounded by plains communities dominated by scattered poplar box (*Eucalyptus populnea*) trees and *Eremophila mitchellii* shrubs. At both sites a 150-ha quadrat, 3 km long and 500 m wide (250 m either side of the riverine habitat), was

Table 2. Pellets collected from confined koalas to determine mean defaecation rates

All data were collected between July 1996 and July 1997

Sex	Age class	Landform	Season	No. of pellets recovered
F	Adult	Riverine	Spring	169
F	Adult	Residual	Spring	134
F	Sub-adult	Riverine	Summer	147
F	Adult	Floodplain	Winter	139
F	Sub-adult	Plains	Summer	131
M	Adult	Riverine	Summer	157
M	Adult	Floodplain	Winter	162
M	Sub-adult	Residual	Autumn	167

delineated using aerial photography and subsequently ground-truthed and marked using flagging tape.

Initially, new pellets were sampled as described above at both sites in one 1-ha transect (1 km × 10 m) positioned along the river bed and another placed perpendicular to the river in the surrounding plains habitat. These data were extrapolated over their respective habitat areas (i.e. riverine and plains) to estimate the number of pellets present. Then the FSCM was used to estimate the number of koalas within the site.

To conduct the direct counts 7 people were positioned abreast to search every tree within the clearly defined riverine habitat at both sites. The riverine community at Nebine Creek (Site 1) was, on average, 30 m wide and at Mungallala Creek (Site 2) it was 40 m wide, so it was possible to position people such that every tree was searched by a minimum of 2 people (often 3 or 4) observing from different angles. The plains habitat on both sides of the creek was searched in the same way. At Site 1 it was possible to spread 7 people at 30-m intervals to cover the 250 m on either side of the creek in one pass. However, at Site 2 the density of trees in the plains communities necessitated the spread of 7 people over 125 m, so 2 passes were made on each side of the creek.

Results

Application of the FSCM

The mean daily pellet production for free-ranging koalas was 150.75 ± 12.55 (95% CI) (Table 2).

We fitted a parallel-lines model to predict the actual pellet count from the standard count for quadrats in four of the five visibility classes, since allowing the slope to vary between classes did not significantly improve the model. Based on this model, a correction factor was applied to the number of pellets recorded in each quadrat in each visibility class (Table 3). No correction was necessary for Visibility Class 1 (Table 3).

Habitat loss (aerial photographic interpretation)

In this study no new pellets were found anywhere in RFZ I (which contained SZs 1, 4 and 7), so habitat loss was not measured there. The total estimated percentage of cleared land for each SZ follows a general increasing trend from RFZ II to RFZ III, with a marked peak in SZ 6 (Fig. 2). We estimate that over the last 30 years in RFZs II and III there has been a 32% reduction in the vegetation associations that comprise our habitat units. This reduction has been markedly higher in RFZ III (Table 4).

Table 3. Correction factors applied to each visibility class

Visibility class	Sample size	Correction factor (s.e.)
1	1380	$0.00 + 1 \times \text{observed}^A$
2	2193	$-0.0194 + 1.090 \times \text{observed}$ (0.2490)
3	771	$0.3969 + 1.090 \times \text{observed}$ (0.2958)
4	97	$4.276 + 1.090 \times \text{observed}$ (0.3205)
5	34	$1.934 + 1.090 \times \text{observed}$ (0.0197)

^ANo correction necessary.

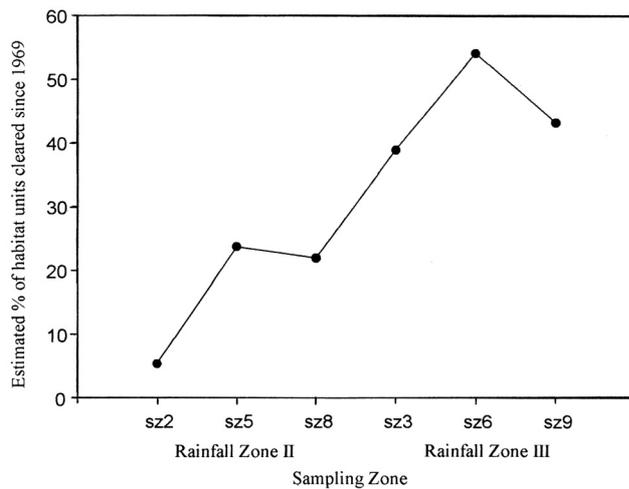


Fig. 2. Estimated percentage of habitat units cleared since 1969 (based on aerial photography interpretation) in each sampling zone (SZ).

The estimated percentage of cleared vegetation varied greatly for the same habitat units in different SZs. The maximum extent of clearing, relative to the 1969 base, was ~80% in Habitat Units 5 and 7 in SZ 3, Habitat Units 4 and 7 in SZ 6 and Habitat Unit 8 in SZ 9, all of which are located in RFZ III. In contrast, the highest estimated extent for RFZ II was ~30% in Habitat Units 3 and 6 in SZ 5.

Koala density estimates

Estimated densities across the study area for all sites with 'new' pellets ranged from 0.0007 to 2.513 ha⁻¹. The highest densities were typically recorded in Habitat Unit 1 in SZs 3, 6 and 9 (RFZ III), and the next highest in Habitat Unit 9 in SZs 3 and 6. The lowest densities were recorded in Habitat Units 1 and 6 in SZs 8 and 5.

Koala abundance estimates

Using data collected at 149 sites and the adjusted habitat area figures we derived a population estimate of 59 500. The bootstrap Monte Carlo simulation was that koala abundance in the study area ranges from 44 900–81 100 ± (95% CI) with a mean estimate of 63 000 ± 1280 (s.e.).

Abundance estimates varied greatly between habitat units (the dominant floristic components of the 10 habitat units is

Table 4. Estimated reduction of vegetation associations that comprise habitat units in RFZs II and III

	RFZ II	RFZ III
Area in 1969	5 566 557	5 067 365
Area in 1995	4 565 419	2 576 914
Estimated reduction	18%	49.1%

detailed in Sullivan *et al.* 2003a) and SZs (Table 5). As no new pellets were collected in RFZ 1 (Sullivan *et al.* 2003a), no koala-density estimates were possible for any habitat units in SZ 1, 4 and 7. Habitat Unit 1 in SZ 6 had considerably more koalas than any other habitat unit. The next highest abundance estimate was obtained in Habitat Unit 10 of SZ 2. At the scale of RFZ, SZ and habitat unit, riverine communities (Habitat Unit 1) are the single habitat unit with the highest estimated number of koalas, and SZ 6 has considerably more koalas than all other SZs combined. At the RFZ scale, RFZ III has more than double the estimated number of koalas than RFZ II (Table 6).

However, the combined abundance of koalas in residual habitat units (Habitat Units 9 and 10) suggests that residual landforms had slightly more koalas than riverine landforms. Residual and riverine communities combined accounted for ~94% of the total abundance estimate (Table 7).

Assuming that the direct loss of habitat was the only factor causing a reduction in koala numbers, on the basis of our density estimates ~66 300 koalas would have been found in the region in 1969 (Table 8). That represents a possible reduction of ~10% in the last 30 years.

Field validation of sampling protocol

No pellets were recovered in the plains communities surrounding the riverine communities at either site, so the pellet-based density estimates were extrapolated only over the homogenous riverine habitat. For both validation sites the upper density estimate of the pellet-sampling protocol under-estimated <20% compared with the direct koala count densities (Table 9).

In western Queensland, riverine communities provide optimum koala habitat (Gordon *et al.* 1988, 1990; Witt and Pahl 1995; Munks *et al.* 1996). We therefore concentrated our field validation effort in riverine communities, where the precision of the protocol was deemed to be most critical.

Discussion

In recent times pellet-sampling methods are frequently used to survey koala populations (e.g. Hasegawa 1995; Munks *et al.* 1996; Pahl 1996; Lunney *et al.* 2000; Phillips *et al.* 2000). Barnes (1996) noted that for elephants, direct count methods have been validated and fine-tuned, whereas dung counts are still evolving. A similar situation occurs in Australia where pellet-count methods, particularly those for arboreal mammals, are relatively untested compared with more

Table 5. Estimated abundance of koalas in each habitat unit and sampling zone

Sampling zone	Habitat unit	Abundance estimate on 1995 vegetation areas		
		Minimum	Mean	Maximum
2	10	10323	13007	16097
	1	526	815	1137
3	10	2245	2766	2814
	9	1558	2521	3573
	7	126	160	188
	3	8	13	16
	2	27	34	54
5	1	1026	1329	1777
	10	1271	2114	2588
	9	51	69	87
	5	23	23	23
6	3	706	806	1064
	1	1597	1621	1888
	10	1133	1375	1559
	9	5340	7408	9787
	8	61	99	130
8	5	612	1236	2246
	2	570	648	796
	1	16281	21492	26739
	1	33	42	48
9	7	227	296	355
	1	849	1681	2671

traditional direct count methods. While some studies have identified limitations to counting accumulations of koala pellets to determine tree-species preferences (Hasegawa 1995; Pahl 1996), these studies were based on arbitrarily sampling an unknown proportion of pellets beneath a tree, or using presence/absence of pellets around the base of trees to derive a habitat-utilisation index (Phillips *et al.* 2000). Ours is the first method to validate the use of pellet searches around the base of trees (basal pellet searches: Sullivan *et al.* 2002) as a means of identifying trees with and without pellets, and to develop correction factors to account for varying levels of pellet detection. These data were critical in estimating both pellet and koala abundance. We also provide a measure of variance of this estimate, which has previously been a deficiency in regional koala-abundance estimates.

Faecal standing-crop method

Of the three parameters required for the FSCM (pellet abundance, maximum pellet age and daily pellet production), the last was the final variable to be quantified (for details of the other two see Sullivan *et al.* 2002). Our estimate of daily pellet production of 150.75 ± 12.55 (95% CI) concurs well with the only other published estimate of mean daily pellet production of 174 ± 29 pellets day⁻¹ for captive koalas fed *Eucalyptus* browse *ad libitum* (Ellis *et al.* 1998), especially considering the potential differences in pellet production from free-ranging to captive koalas. However, the digestion processes of koalas are likely to be regular rather than episodic, because the koala has evolved to

the physiological limits possible for a mammal to survive on a sclerophyllous diet that is low in nutrients and protein and high in potentially toxic constituents (Cork and Sanson 1990). Thus pellet production is likely to be fairly uniform across habitats and even geographical regions.

Land-management practices

Habitat clearance

The vastly different estimated percentage of habitat units cleared in RFZs II and III (Fig. 2) are a consequence of the different land-management practices in the two regions. The greater level of clearing in the eastern portion of the study area (RFZ III, Fig. 1) is a reflection of the perceived level of economic return to graziers obtained by increased pasture cover in this region, and possibly the higher rates of regeneration (thickening) that have occurred in many vegetation associations. The critical importance of protecting habitat in RFZ III is emphasised by a range of indicators. The area has the most homogenous distribution of koalas in the mulgalands (Sullivan *et al.* 2003a), and koalas in the area potentially have the opportunity to access significantly more habitat units than koalas in the other two RFZs (Sullivan *et al.* 2003b), which would potentially increase resource access. RFZ III also has the highest densities of koalas, which translates to approximately twice the estimated koala abundance of RFZ II (Table 6).

The relative importance of residual and riverine habitats to koalas is clear from the estimated abundance of koalas in

Table 6. Summary of koala abundance estimates at the RFZ, SZ and habitat unit levels
zr = zero new pellet records

	Abundance estimate		
	Minimum	Mean	Maximum
Rainfall zone			
1	zr	zr	zr
2	14530	18490	22930
3	30060	41050	52700
Sample zone			
1	zr	zr	zr
2	10849	13822	17234
3	4990	6823	8422
4	zr	zr	zr
5	3648	4633	5650
6	23997	32258	41257
7	zr	zr	zr
8	33	42	48
9	1076	1977	3026
Habitat unit			
1	20312	26980	34260
2	597	682	850
3	714	819	1080
4	zr	zr	zr
5	635	1259	2269
6	zr	zr	zr
7	353	456	543
8	61	99	130
9	6949	9998	13447
10	15298	18769	22358

each landform class (Table 7). The relative habitat-utilisation index (H_i) presented in Sullivan *et al.* (2003b) also highlights the importance of these communities, and suggests a trend of decreasing relative importance of residual communities associated with an increasing relative importance of riverine communities in a southerly direction (and *vice versa*) in RFZ II and III. Riverine communities comprise only 5.6%, and residual habitat units (Habitat Units 9 and 10) ~19% of the total area of habitat units in RFZs II and III. We estimate that if 10% of the riverine communities in RFZ III alone were cleared it could reduce koala abundance in the study area by ~9%, even though these communities comprise only 0.9% of the total study area (including all vegetation communities).

The likely reduction in koala numbers over the last 30 years that we postulate here (Table 8) seems low compared

with the amount of land cleared; however, most land cleared was plains communities that typically either do not have resident koala populations (e.g. *Acacia*-dominated communities) or have extremely low-density koala populations. Estimates of broadscale clearing of eucalypt woodland may overestimate koala habitat loss because they include eucalyptus communities beyond the natural range of the koala (Melzer *et al.* 2000). However, in reality, the reduction in koala numbers due to habitat clearance may have been considerably higher because of the further fragmentation of habitat.

Critical thresholds in landscape connectivity illustrate that fragmentation is not a linear function of habitat loss. Above the threshold the primary consequence of habitat removal is a decrease in the area of available habitat, and below the threshold the landscape is effectively disconnected into isolated patches of habitat (With *et al.* 1997). This depends not only on the size of habitat patches and their degree of isolation (Dunning *et al.* 1992; Andren 1994), but also on the dispersal characteristics of the species utilising the patches (Fahrig and Paloheimo 1988). During this study many sightings of koalas and their signs (pellets and tree scratches) were made in isolated trees and traversing cleared land and grasslands. Landholders and clearing contractors reported similar sightings. We also heard several accounts from landholders/bulldozer drivers of koalas moving through vast tracts of *Acacia* plains communities with no *Eucalyptus* trees. This suggests that koalas move and/or disperse through both cleared and uncleared vegetation communities that are apparently unsuitable for resident populations.

Protection of koala habitat

The Statewide Landcover and Trees Study (SLATS) Reports (SLATS 1999a, 1999b, 2000) provide the most recent summary of broadscale vegetation clearing practices in Queensland. The Mulgalands biogeographic region was the second most heavily cleared area within Queensland, accounting for 22% of the total area cleared in Queensland between 1991 and 1995, 17% between 1995 and 1997, and 20% between 1997 and 1999. The SLATS 2000 report shows that the rate of vegetation clearing is greatest in the eastern higher-rainfall areas of the Mulgalands biogeographic region. For example, between 1997 and 1999 the annual rates of vegetation clearance were 384 km² for the west Balonne

Table 7. Estimated abundance of koalas by landform class

Landform class (habitat units)	Estimated current (1995) abundance			% of mean estimate
	Minimum	Mean	Maximum	
Riverine (1)	20312	26980	34260	45.4
Floodplain (2, 3)	1311	1501	1930	2.5
Plains (4–8)	1049	1814	2942	3.0
Residual (9, 10)	21921	29260	36505	49.1
Total	44593	59555	77567	

Table 8. Current and indicative 1969 koala abundance estimates

Date	Minimum	Mean	Maximum
Pre-'recent' clearing	50300	66300	83000
1995/96	44500	59500	75600
Change (%)	-5800 (11.5)	-6800 (10.3)	-7400 (8.9)

plains (SZ 9), 147 km² for the eastern mulga plains (SZ 6), 11–40 km² for the Nebine plains, Warrego River plains and west Warrego plains (all three in SZs 2, 5 and 8), and 0.2–7 km² for the Paroo sand sheets and west Bulloo plains (SZs 1, 4 and 7).

The figures on vegetation clearance presented in this study and in the more recent SLATS reports are not the only statistics that should be considered when determining changes in the extent of koala habitat following a century or more of pastoral industry land use in the mulgalands. Significant areas of regrowth and woody plant thickening exist in the mulgalands, adding sizeable areas of woody vegetation to this biogeographic region. The vegetation of the mulgalands mapped by the SLATS reports consists of all perennial woody plants of all sizes that can be distinguished with Landsat TM imagery (woody vegetation with a foliage projective cover of 5% or greater), and includes remnant native vegetation, disturbed native vegetation and regrowth (SLATS 2000). One-third of the native vegetation cleared between 1997 and 1999 was regarded as regrowth, with the other two-thirds regarded as remnant vegetation (SLATS 2000). Remnant vegetation is defined in the *Vegetation Management Act 1999* as vegetation with more than 50% of the undisturbed predominant canopy, 70% of the vegetation's undisturbed height, and composed of species characteristic of the vegetation's undisturbed predominant canopy. Consequently, remnant vegetation may also include regrowth that has occurred after a previous clearing event, and woody vegetation that is a result of shrub and tree thickening that has occurred over several decades. Witt and Beeton (1995) noted considerable thickening of woody plant cover in a mulgalands National Park in south-west Queensland. They found that the woody cover in a number of land systems increased from 2–10% in 1952 to 20–50% in 1992. In particular, Witt and Beeton (1995) noted major increases in woody cover after 1969, corresponding with the 1969 aerial photography that was the basis of the GIS coverage used in this study to determine loss of koala habitat. Thus, changes

in the extent of koala habitat since 1969 documented by aerial photo interpretation in this study and more recently by SLATS, only represent losses in habitat. Significant additions through regrowth and thickening have not been accounted for.

The management of the vegetation remaining in the mulgalands falls under the control of recent state legislation. In September 1997, 34 sets of Local Tree Clearing Guidelines for leasehold land in Queensland received Ministerial approval. The Broadscale Tree Clearing Policy was finalised and Part 6 of the *Land Act 1994* was proclaimed in October 1997. The mulgalands has been covered by 9 sets of Local Tree Clearing Guidelines (St George–Dirranbandi, Eastern Warrego, Warrego Floodplain, Western Warrego, Far Western Mulga, Maranoa, Northern Uplands, Blackall, and Isisford–Barcoo). These are now being reviewed, and will soon be replaced by the *Regional Vegetation Management Plan for the Mulga Lands Bioregion*. Under this new plan riverine communities (Habitat Unit 1) throughout the mulgalands will be protected by varying buffer widths, depending on stream order. In general, buffer widths for both sides of rivers, creeks and gullies are 200 m, 100 m and 50 m respectively. Riverine vegetation communities and all other forms of riparian and wetland vegetation, hard mulga and residual land systems will all be completely protected under the new vegetation-management plan (P. Voller, personal communication). Consequently, the vegetation that is most important for koalas, accounting for 94% of the koala population in the mulgalands (Habitat Units 1, 9 and 10), will be retained under the new legislation.

Impacts of grazing

The degradation of semi-arid rangelands is a global phenomenon that has received increasing attention in recent years (Walker and Steffen 1993). Evidence of such degradation includes a change in species dominance from palatable perennial grasses to woody shrubs and a reduction in landscape uniformity as native pastures become increasingly interspersed with scalded areas, woody weed infestation and erosion (Passmore and Brown 1992). Land-management practices in the mulgalands associated with grazing of introduced and native herbivores have caused a change in species dominance from palatable perennial grasses to woody shrubs and trees in some areas,

Table 9. Koala abundance and density (koalas ha⁻¹) estimates from direct counts and pellets counts

All koalas were recorded in riverine habitat. Minimum and maximum pellet age were measured in days. For the pellet protocol range estimates, the maximum is calculated using minimum figures for daily pellet production and pellet age, and minimum uses the respective maximum figures

Site	Area (ha)	Direct visual counts		Pellet age	Pellet protocol range estimates	
		Numbers	Density		Numbers	Density
Nebine Creek	9.3	3	0.32	17–19	2.13–2.82	0.23–0.30
Mungallala Creek	13.2	6	0.45	16–18	3.63–4.82	0.27–0.36

predominantly mulga (*A. aneura*), and species of *Eremophila*, *Dodonaea* and *Cassia*, leading to reduced ground cover and a subsequent reduction in fire frequency (Passmore and Brown 1992). Fire has been identified as one of the major threats to koalas throughout their range (Lee *et al.* 1990; Reed and Lunney 1990).

There is substantial evidence that the recruitment of many long-lived perennial tree species by seed or vegetative suckers is inhibited under grazing pressure (Lange and Graham 1983; Auld 1995). It has long been suggested that in Australia the major cause of reduced regeneration of perennial trees and grasses were rabbits, goats (Lange and Graham 1983) and domestic stock (Auld 1995), particularly in riverine communities (Reid and Fleming 1992). However, anecdotal evidence collected throughout this study suggests that *Eucalyptus* species in riverine communities regenerate well in comparison to some residual communities. Many riverine communities had trees that fitted into a range of size classes, which indicates at least some recruitment. In many residual communities, particularly Habitat Unit 10, little evidence of recruitment of *Eucalyptus* species was recorded, with most trees being of similar DBH. This suggests that these communities are not stable in the long term, and could decline, as too few recruits are available to replace mature trees that die (*sensu* Auld 1995).

The apparent suppression of regeneration in these communities could be caused partially by domestic stock, but is likely to be primarily caused by feral goats, which occur in high densities in these areas. Aerial surveys of the semi-arid rangelands of western New South Wales and Queensland indicate a minimum feral goat population of ~1 million, with the eastern portion of the mulgalands having an estimated mean density of 1.1–2.0 goats km⁻² (Southwell *et al.* 1993). While they may be reasonably accurate on a regional scale, localised groups of goats within many residual communities far exceed these reported densities (BJS and LP, personal observations). We suggest that the suppression of regeneration in these communities is one of the most serious long-term threats to koala populations, and potentially other taxa of native species (e.g. birds, scansorial lizards), within the mulgalands.

We suggest that it is possible that koala populations in the study area have accrued benefit from other land-management practices such as the provision of artificial water and the control of dingoes (*Canis familiaris*). However, specific studies would be required to support this argument.

Field validation exercise

On the basis of validation results obtained in riverine communities, our estimate of koala abundance should be conservative. There are two likely explanations for this slight underestimate. First, pellets were sampled only from beneath eucalypts (see Sullivan *et al.* 2002) so pellets deposited

beneath non-eucalypt tree species were not included in our abundance estimate. While non-eucalypt trees form only a minor part of koala diet in the study area (Sullivan *et al.* 2003a), it stands to reason that some faecal pellets would be deposited under such trees. Second, the method for detecting the presence/absence of pellets beneath riverine trees is only 90% accurate, so it is possible that some trees with pellets were excluded from the dataset. However, the estimates are sufficiently accurate to justify their use in the context of the study where an estimate of koala abundance and relative habitat utilisation is being derived for a 19200-km² biogeographic region, and where no other such estimates have been attempted.

Conclusions

Koala populations in the mulgalands occur at the western edge of their northern distribution, and may be considered peripheral populations. Peripheral populations can be geographically or ecologically marginal. The former are separated from central populations by distance and the latter experience different abiotic and biotic conditions. However, these two types of peripheral populations are not mutually exclusive (Lesica and Allendorf 1995). Considering the geographical location of koala populations within the mulgalands and the apparent climatic control of the edge of their westerly distribution (Sullivan *et al.* 2003a, 2003b), it is likely that in the mulgalands koalas are both geographically and ecologically marginal. Genetic data has shown that populations in New South Wales and Queensland consist of multiple management units (*sensu* Moritz 1994; Houlden *et al.* 1996, 1999). Considering that koala conservation should aim to maintain the species' current ecological amplitude (Sherwin *et al.* 2000), the peripheral nature and estimated size of the mulgaland's koala population (63000 ± 18000) should afford them special consideration in future conservation initiatives.

Prior to our study and that of Witt and Pahl (1995) the widely held view regarding koalas in the study area was that they are largely restricted to riverine communities dominated by river red gum and coolabah. While these communities are undoubtedly critical, our study has highlighted the wide variety of vegetation communities utilised by koalas and has emphasised that conservation strategies within the mulgalands must strive to ameliorate the adverse impacts of habitat clearance and fragmentation and conserve a representative mosaic of vegetation with a high level of connectivity.

Management implications

In this series of papers we have quantified the number of koalas in the mulgalands, defined their geographic range, determined relative habitat preferences, and described their dietary preferences. Regional management of the species can now proceed on a much more informed and coordinated

basis. On the basis of our findings we highlight the following management implications:

- (1) The size of the koala population within the mulgalands suggests that it is important in the overall conservation of the species. The results of this study (which provides the first inland estimate of regional abundance) may be used to help clarify the conservation status of the koala and develop practical conservation initiatives, at a regional, state and national level.
- (2) Conservation and land-use management strategies within the mulgalands should strive to protect vegetation associations that are otherwise considered to have low fauna conservation values. The residual communities are particularly important in maintaining viable low-density koala populations. Plains communities may also be important for their low-density populations and/or for their potential to act as a conduit between populations.
- (3) The high level of protection for riverine communities should be maintained because they sustain the highest-density populations (and ~45% of estimated abundance) and act as refugia for koala populations in adverse climatic conditions (*sensu* Gordon *et al.* 1988; Munks *et al.* 1996).
- (4) Given the flagship nature of koalas, their future management could be crucial in the development of future land-management (e.g. tree clearing) guidelines to engender an increased conservation ethic within the mulgalands.
- (5) As a result of our findings, future research can become much more clearly targeted. Key questions are: do koala populations function as a metapopulation, and if so, do source–sink populations occur? If so, where are they?
- (6) As proposed by Sherwin *et al.* (2000), genetic studies should be conducted to identify the degree of demographic independence of populations within the mulgalands.
- (7) Mulgaland koala populations should receive special consideration in koala conservation because of the benefits of maintaining the current ecological amplitude of the species throughout its range (Sherwin *et al.* 2000).
- (8) The abundance, sex ratios and fecundity of a representative selection of populations should be monitored over the long term to develop an understanding of the stability of populations throughout the region.

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