Review of Scientific Literature Relevant to the Commercial Harvest Management of Kangaroos

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Table of Contents

1. Executive Summary 1
   1.1 Population Monitoring 1
   1.2 Relationship between Kangaroo Populations and Climate 1
   1.3 Kangaroo Population Genetics and Potential Effects of Harvesting 2
   1.4 Kangaroo Reproduction 2
   1.5 Other Threats to Harvest or Population Sustainability 2
2. Aim 4
3. Background 4
   3.1 Recent Kangaroo Population and Harvest Statistics 5
4. Reproductive Physiology 10
   4.1 Reproductive seasonality 10
   4.2 Reproductive Success 12
5. Population Dynamics 13
   5.1 Measuring population demographics 13
   5.2 Estimating Abundance 13
   5.2.1 Helicopter survey techniques 15
   5.3 Modelling population dynamics 18
   5.4 Spatial Patterns 19
   5.5 Genetic Population Structure 22
6. Population Health (Diseases, Parasites and Pathogens) 23
7. Other threats to population (or harvest) sustainability 28
   7.1 Genetic Impacts 28
   7.2 Climate Change 30
   7.3 Drought 32
   7.4 Interactions between Kangaroos and Other Species 36
   7.5 Habitat Loss and Modification 38
8. References 39

1. Executive Summary

Over the last five years a wealth of information relevant to the commercial harvesting of kangaroos has been published, especially within the field of kangaroo population dynamics. Most of this research stems directly from programs that were established to monitor kangaroo populations and set sustainable commercial harvesting quotas. This highlights the commitment of Australian wildlife management agencies to the principles of active adaptive management. The key findings of this review are outlined in point form below.

1.1 Population Monitoring

- A large number of papers have evaluated kangaroo population monitoring methodologies and sought to develop more cost effective, indirect methods of accurately estimating kangaroo abundance. However, despite the advances in these methods, variation in their performance over broad ranges mean that they are unlikely to be an effective management option that could replace existing population survey methodologies.
- Kangaroo monitoring programs should consider new population estimation methodologies and apply them as appropriate, particularly if they offer enhanced precision. Ideally, any significant changes to survey methodologies should be introduced in a way which allows for a degree of benchmarking between methods, thereby facilitating rigorous assessment of long-term population trends.
- Analysis of population and harvest data for wallaroos within the Northern Tablelands of NSW suggests that the current triennial helicopter survey technique does not offer adequate precision for managing the commercial harvest of this species within this environment. It is recommended that the survey design and/or the percentage allocation should be reassessed.

1.2 Relationship between Kangaroo Populations and Climate

- Kangaroo populations in NSW experienced significant declines in response to the 2001-2003 drought and have not yet recovered to pre-drought levels, presumably because of the record sequence of below average rainfall years. The long-term response of these populations to this drought should continue to be monitored, including analyses of the factor(s) which have limited population recovery over the last decade.
- Advances have been made in the development of complex stochastic models that aim to predict kangaroo population responses to rainfall and resource availability. While these models are often able to make confident predictions for species within localised regions, we still do not have a model that can predict population responses to resource variability over broad geographical ranges. This highlights that there is still much that we do not know about the relationship between kangaroo density and rainfall. Having a better understanding of this relationship will be essential if we want to be able to better predict the responses of kangaroo populations to climate change.
- There have been very few studies investigating the likely impact of climate change on kangaroo populations, but the predicted effects are negative. Climate change models

suggest that we may see significant range contractions for some species, at least in the northern areas of Australia. Generalised widespread reductions in rainfall, or increased variability of rainfall, may influence the sustainability of the commercial kangaroo harvesting industry. However, the current population monitoring and proportional quota system should provide adequate safeguards for kangaroo populations.

- The current kangaroo monitoring program may provide a valuable source of long-term data capable of detecting changes in the range and density of kangaroo populations throughout NSW in response to any observed changes in climate.

1.3 Kangaroo Population Genetics and Potential Effects of Harvesting

- A recent publication describing the genetic structure of western grey kangaroo populations has established that western grey kangaroos in NSW represent a single genetic unit, therefore supporting the current state-based management system. Similar conclusions were made for eastern grey and red kangaroos in the last review, but closer analysis of the data in these publications indicates that there is a need for additional analyses for these two species.
- The wallaroo was the only species for which there is definitive evidence of significant genetic structuring within NSW. Further studies should investigate the extent of fine-scale structuring within individual Kangaroo Management Zones for this species.
- The potential for selective harvesting to have negative genetic effects in vertebrate species has received increasing attention in the scientific literature over the last five years, highlighting the perception that the genetic consequences of selective harvesting may be significant in some instances. While the available evidence for kangaroos suggests that harvesting is unlikely to alter genetic structure, it would be remiss of us to rule out the potential for negative genetic effects given the heightened awareness of this issue in the scientific community. It would be prudent for wildlife managers to incorporate an element of phenotypic and genotypic monitoring into management plans, so that any deleterious effects of harvesting can be identified.

1.4 Kangaroo Reproduction

- Knowledge of the reproductive seasonality of the commercially harvested kangaroo species could be used to inform shooters of periods when there is the greatest risk of orphaning young. Recent studies have highlighted the fact that the timing and degree of reproductive seasonality varies between regions and species, so there is a need for regional, species-specific reproductive data.

1.5 Other Threats to Harvest or Population Sustainability

- There is currently no evidence that disease may affect the long term viability of kangaroo populations.

- While dingo predation may limit kangaroo populations, there is still no conclusive evidence of a regulatory effect. There is little evidence of competition between kangaroos and domestic livestock. Overall, there is no evidence that competition or predation will affect long-term sustainability of kangaroo populations.
- Habitat modification has generally been beneficial for kangaroo populations, facilitating range expansions for three of the commercially harvested kangaroo species.

The major findings of this review do not alter the over-riding conclusions of the previous two reviews. All of the available evidence suggests that the current commercial harvest strategy, which sets quotas between 15 and 17% of estimated population size, is successfully achieving the dual goals of facilitating sustainable resource utilisation and maintaining viable populations of the harvested species.

In the last review, Olson and Low concluded their executive summary by posing the question: "*…now that knowledge of levels of harvesting that can be sustained is well established,… is kangaroo monitoring a priority for conservation agencies?"* (p. 8). This question has both scientific and philosophical elements. From a scientific stand-point, although we support their assertion that the scientific and wildlife management community now have a good understanding of sustainable harvest levels, the research published in the last five years highlights that there is still much that we do not understand about kangaroo population dynamics and their response to resource availability. It has clearly been demonstrated that we cannot accurately predict kangaroo population size over broad geographical ranges, therefore direct population surveys remains a necessary component of setting harvest quotas. From a more philosophical stand-point, it is important that the harvest management system is transparent to all stakeholders, from the general public to commercial harvesters.

2. Aim

The aim of this document is to provide a review of recent scientific literature that is relevant to the commercial harvest management of kangaroos. The scope of the review is limited to recent works published since the preparation of the previous comprehensive review of literature (Olson and Low 2006) and publication of the New South Wales Commercial Kangaroo Harvest Management Plan 2007-2011 (Department of Environment and Conservation (NSW) 2006). This review focuses on aspects of kangaroo biology and harvest management that are relevant to the commercial harvest of kangaroos in NSW and is therefore not intended to be as broad in scope as the two previous reviews (Olsen and Braysher 2000; Olson and Low 2006). The term "kangaroo" is used throughout this report to collectively refer to the four commercially harvested macropod species.

3. Background

The management of kangaroos for commercial harvest in NSW is currently undertaken in accordance with the NSW Commercial Kangaroo Harvest Management Plan (KMP) 2007-2011 (Department of Environment and Conservation (NSW) 2006) approved by the Australian Government under the *Environment Protection and Biodiversity Conservation Act 1999*. The current KMP has approval from the 1 January 2007 to 31 December 2011. Before its expiry, the current KMP will be reviewed in preparation for the subsequent development of a new KMP. As a part of this process we have prepared a review of the current state of scientific knowledge on issues relevant to the commercial harvesting of kangaroos in NSW.

Four species of kangaroo are currently harvested in NSW. These are the red kangaroo (*Macropus rufus*), the eastern grey kangaroo (*M. giganteus*), the western grey kangaroo (*M. fuliginosus*) and the common wallaroo or euro (*M. robustus*). These animals are harvested for pet meat, human consumption and for their skins. In order to commercially harvest a kangaroo species, the Australian Government (under the *Environment Protection and Biodiversity Conservation Act 1999*) must approve a Wildlife Trade Management Plan such as the KMP. This management plan details harvest quotas, expressed as a proportion of the estimated population size, and the requirement for annual quota reports to ensure that the commercial harvest of kangaroos in NSW is ecologically sustainable (Kelly 2008).

Beginning with the 2002-2006 KMP, there has been no reference to the culling of kangaroos on the basis of damage mitigation, as damage is difficult to monitor, predict and prove empirically (Lunney 2010). As a result some topics of interest in previous literature reviews (Olsen and Braysher 2000, Olsen and Low 2006), including alternate methods of controlling kangaroo populations, have been omitted in this document as they are no longer relevant to the KMP.

This document will review recent scientific literature (published since 2005) relating to aspects of kangaroo ecology and harvest management. The major areas of interest outlined by the Kangaroo Management Advisory Panel include, but are not limited to:

- Reproductive physiology
- Population dynamics
- Population health (diseases, parasites and pathogens)

- Other threats to population or harvest sustainability, including climate change and interactions between kangaroos and other species.

3.1 Recent Kangaroo Population and Harvest Statistics

The relevance of any new scientific literature to the commercial harvest of kangaroos should be assessed within the context of the latest KMP and recent kangaroo population and harvest statistics.

Kangaroo population sizes are estimated using direct survey techniques for the purposes of setting harvest quotas. In the western plains of NSW, fixed wing surveys are used to estimate population size annually. In the Northern and Southern Tablelands and Barrier Ranges, helicopter surveys provide population estimates every three years (Department of Environment and Conservation (NSW) 2006). Commercial quotas are set annually based on the most recent population estimate for each species within particular regions, termed Kangaroo Management Zones (KMZ). There are 14 KMZ in NSW, plus a non-commercial zone that predominantly stretches along the east coast and covers approximately 20% of the state (for details of these zones see Department of Environment and Conservation (NSW) 2006). Quotas are set at 15% of the population for eastern and western grey kangaroos and wallaroos, and 17% of the population estimate for red kangaroos within each KMZ. Not all species are harvested within all zones (Department of Environment and Conservation (NSW) 2006). In addition to these proportional quotas, an addendum to the KMP 2007-2011 (Action 10A) states that "*If kangaroo populations decline to specific trigger points, the commercial harvest of particular species in particular zones will be suspended*". The current population triggers are set at the lowest population size recorded since the year 2000 for each species in each KMZ (Department of Environment and Conservation (NSW) 2008).

Figure 1 shows the change in kangaroo population size from 1989 – 2010, along with the numbers of harvested animals for each of the four commercially harvested species. The variation in population size each year reflects natural fluctuations in kangaroo abundance, which are most often linked with variations in rainfall (see discussions on the effects of drought in section 7), and variations in the number of KMZ which had commercial quotas set in each year (Figure 2). For example, In the case of eastern grey kangaroos, this species is commercially harvested in every NSW KMZ, but additional zones were added to the commercial harvest in 2004 (southeastern NSW) and 2009 (Central Tablelands, north and south). For western grey kangaroos, the number of KMZ with commercial quotas declined from eight in 2001 to six in 2010. Similar reductions in harvest zones were seen for wallaroos (from six to three), while the red kangaroo commercial harvest zone remained constant throughout the last ten years (Figure 2). Given these variations in the geographical range of "populations" in each year, it is not possible to draw conclusions about the underlying population size using the graphs in Figure 1. The number of animals commercially harvested also fluctuates from year to year (Figure 1). The harvest figures presented in these graphs reflect to the number of animals actually harvested, not the quota size, and they are therefore influenced by the overall population size and other market factors influencing the demand for kangaroo products.

Table 1 shows the annual kangaroo harvest statistics (2001-2010) as a proportion of the total population size within the commercial harvest zone of NSW. The greatest proportion of the population that was harvested in any one year across the entire commercial harvest zone was 15%

for eastern grey kangaroos (in 2006), 17% for red kangaroos (in 2001), 14% for western grey kangaroos (in 2006) and 12% for wallaroos (in 2006). These figures are in line with the maximum proportional quotas of 15% for eastern and western grey kangaroos and wallaroos and 17% for red kangaroos. The average proportion of the population that was harvested over the 10 year period is significantly lower than this, ranging between 7.6% (wallaroos) and 10.8% (eastern grey kangaroos) (Table 1). During this 10 year period, it was very rare for the entire allocated quota throughout the commercial harvest zone to be taken (Table 1), but there were some individual KMZ that approached the total quota in some years (data not shown).

The raw data that was used in the calculations presented in Table 1 can be accessed at: http://www.environment.nsw.gov.au/wildlifemanagement/TagAllocationsAndCommercialTakeReports.htm

Figure 1. **Estimated population size (grey) and harvest statistics (white) for the four commercially harvested kangaroo species in NSW from 1989 – 2010.**
(a) eastern grey kangaroos, (b) red kangaroos, (c) western grey kangaroos and (d) wallaroos
[Data supplied by the Kangaroo Management Program, Office of Environment and Heritage, Department of Premier and Cabinet (NSW)]

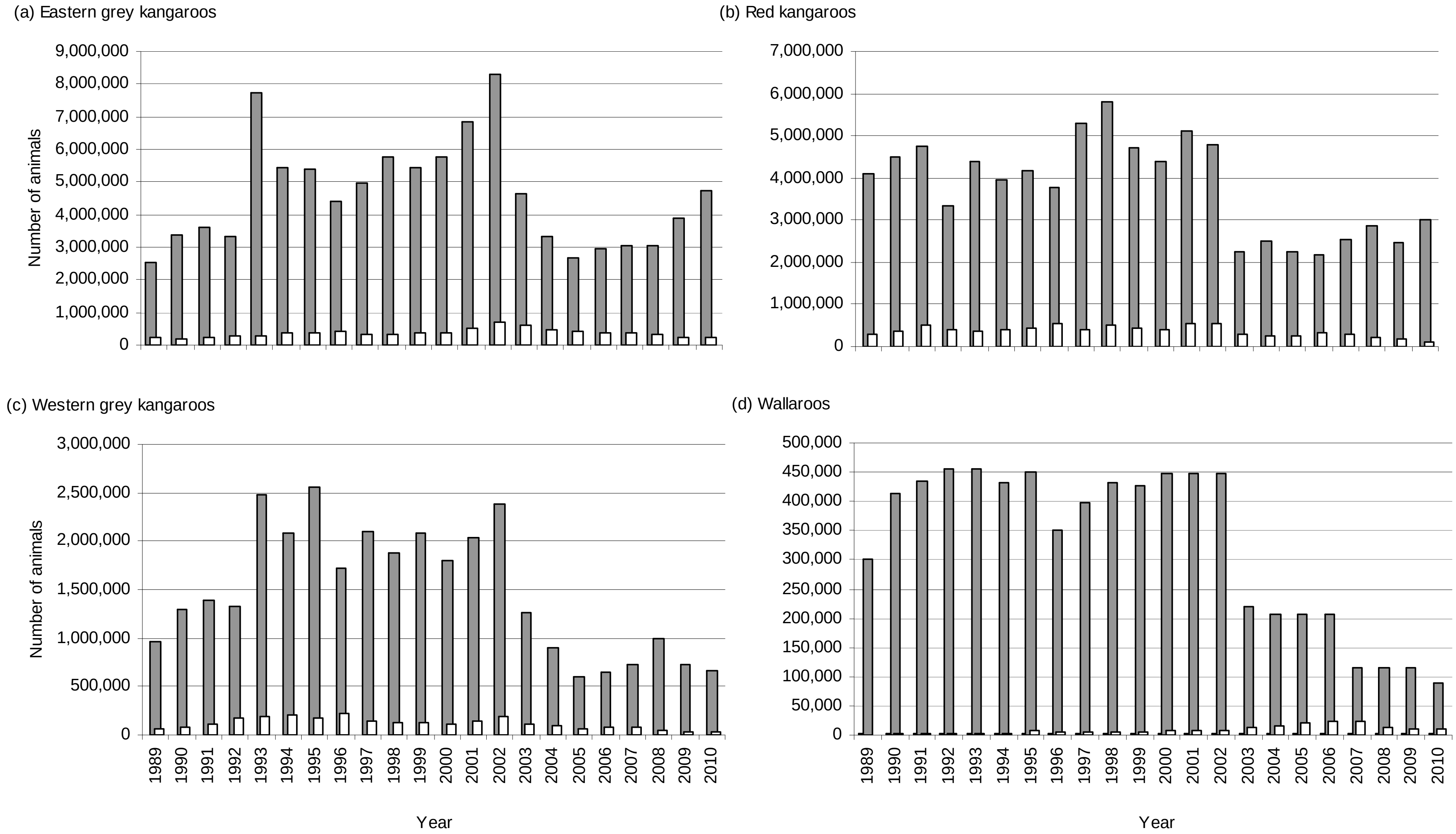

Figure 2. **Schematic showing the Kangaroo Management Zones (KMZ) which had commercial quotas set (shaded grey) for each species from 2001-2010.**

KMZ: 1, Tibooburra; 2, Broken Hill; 4, Lower Darling; 6, Cobar; 7, Bourke; 8, Narrabri; 9, Armidale; 10, Coonabarabran; 11, Griffith; 13, Glen Innes; 14, Upper Hunter; 16, SE NSW; 48, Central Tablelands N; 49, Central Tablelands S.
[Data compiled from http://www.environment.nsw.gov.au/wildlifemanagement/TagAllocationsAndCommercialTakeReports.htm**]**

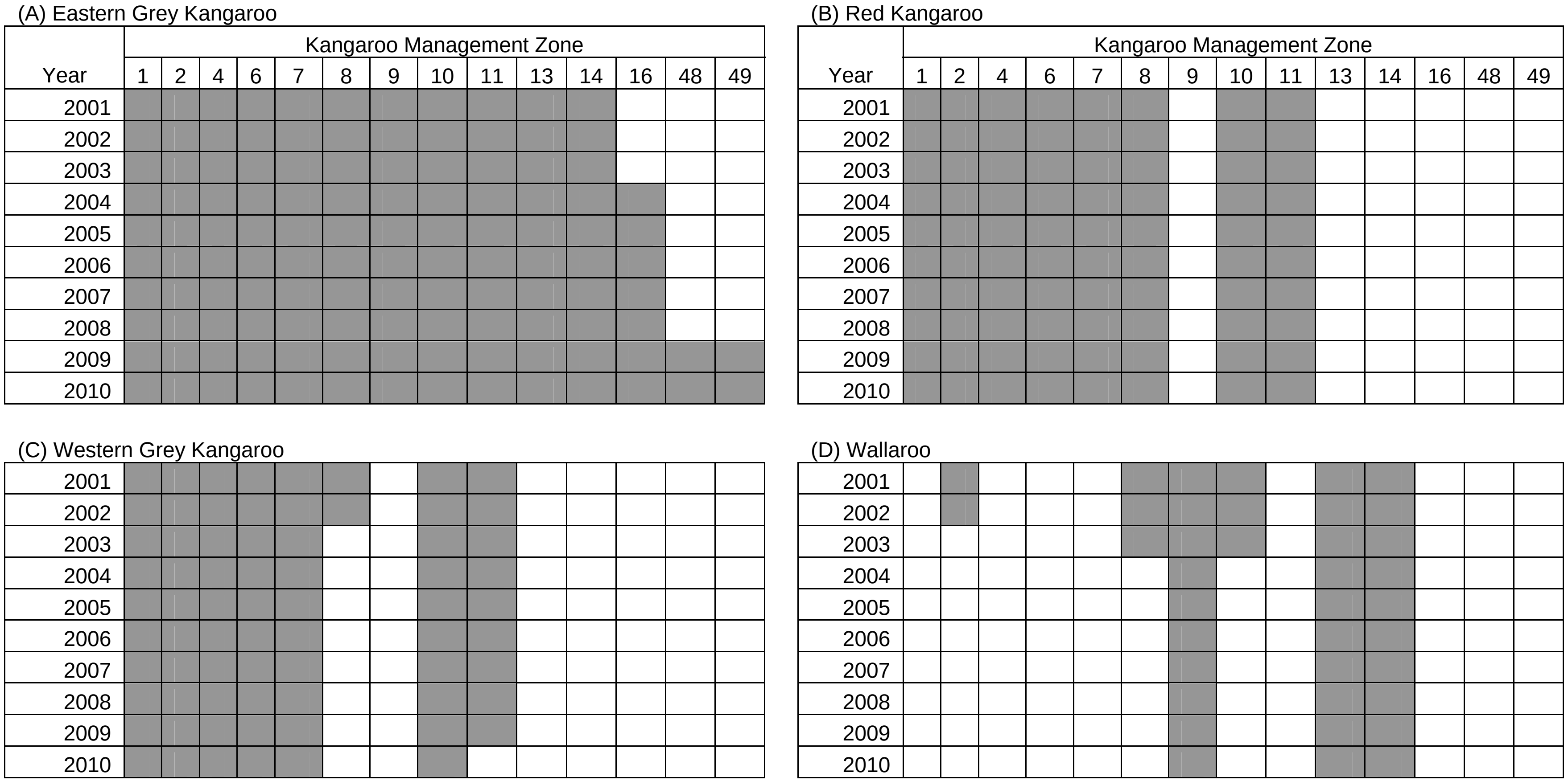

Table 1. **Annual harvest statistics from 2001 – 2010 for the four commercially harvested kangaroo species.** For each species, the left hand column shows the percentage of the entire NSW population (within the commercial harvest zone) that was commercially harvested in that calendar year. The figures in brackets show the maximum and minimum values that were reported in any one individual Kangaroo Management Zone.

[Source: http://www.environment.nsw.gov.au/wildlifemanagement/TagAllocationsAndCommercialTakeReports.htm (downloaded 7 June 2011)]

	Eastern grey kangaroo		Red kangaroo		Western grey kangaroo		Wallaroo	
Year	Take as % Population*	% Quota taken	Take as % Population*	% Quota taken	Take as % Population*	% Quota taken	Take as % Population*	% Quota taken
2001	14 (9-21)	80	17 (11-20)	86	12 (4-18)	70	3 (1-12)	48
2002	10 (4-23)	79	11 (6-18)	69	9 (1-16)	66	3 (1-7)	51
2003	9 (1-18)	60	6 (4-13)	46	5 (2-11)	40	3 (2-4)	60
2004	11 (5-15)	71	11 (8-16)	64	7 (1-14)	49	7 (5-13)	46
2005	14 (6-15)	84	10 (7-15)	57	8 (1-14)	53	10 (10-11)	68
2006	15 (13-15)	97	15 (13-17)	89	14 (12-15)	92	12 (10-12)	79
2007	13 (7-15)	90	14 (12-16)	82	12 (8-14)	83	11 (10-12)	72
2008	11 (5-14)	70	8 (6-15)	49	7 (2-13)	50	10 (9-12)	70
2009	5 (1-13)	37	6 (5-9)	37	4 (1-6)	31	9 (6-12)	58
2010	6 (0-13)	43	5 (1-8)	28	4 (0-6)	31	8 (5-12)	53
Mean	10.8±1.1	71.1±6.2	10.3±1.3	60.7±6.6	8.2 ±1.1	56.5±6.6	7.6±1.1	60.5±3.6

* Number represents the % of the total NSW population harvested (the lowest and highest figures for individual kangaroo management zones).

4. Reproductive Physiology

There has been very little scientific literature published on the reproductive physiology of the commercially harvested kangaroo species since the last review. The research that has been published falls into two categories; reproductive seasonality and reproductive success.

4.1 Reproductive seasonality

The seasonality of breeding activity in commercially harvested kangaroo species may have important implications for sustainable population harvesting and animal welfare. In highly seasonal species, harvesting during times when there are peak numbers of pouch young and/or young at foot may influence population dynamics. In addition, the fate of orphaned pouch young and young-at-foot is a serious animal welfare concern (Oogjes 2005), as these animals will likely perish if they elude capture when their mother is killed. The Code of Practice for the Human Shooting of Kangaroos and Wallabies for Commercial Purposes (Commonwealth of Australia 2008) states that "*Shooters should avoid shooting female kangaroos and wallabies where it is obvious [they] have dependent young… If a female kangaroo or wallaby is shot then any dependent young at foot must be shot as soon as possible to avoid dispersal…*" (p. 10-11). Therefore, knowledge of the reproductive seasonality of local populations of the target species could be used to inform shooters of the periods when there is a greater risk of orphaning dependent young.

The reproductive seasonality of several western grey kangaroo populations in the outer suburbs of Perth was described by Mayberry *et al.* (2010). They found that there was no evidence of breeding between June and September, with most conceptions occurring from December to February. This pattern of breeding differed significantly from previous studies in the eastern extent of their range (Shepherd 1987; Norbury *et al.* 1988), and may reflect adaptations to the local climate. The lower than average reproductive rate in the population that comprised the bulk of the sample size in the study reported by Mayberry *et al.* (2010) may be indicative of population under environmental stress. For example, only 39% of sexually mature females from Thomson's Lake Reserve had young. This enclosed population was culled to alleviate grazing pressure on native vegetation, so the timing of reproduction may not be indicative of free-living populations in the broader regional area.

Seasonal breeding activity in sympatric western grey and red kangaroo populations in semi-arid north-western Victoria was discussed by MacFarlane and Coulson (2005). Mating activity occurred synchronously in western grey kangaroos, with over 50% of adult females observed with either a large pouch young or a small young at foot during the spring. In late summer, culled females were more likely to have a small, unfurred pouch young. In comparison, mating activity in red kangaroos occurred less synchronously, but there was evidence of weak seasonality, with approximately 40% of females observed with either a large pouch young or a small young at foot during autumn. Samples from culled animals further supported the observation of limited synchrony of breeding in red kangaroos at this site. Furthermore, this study found that the degree of sexual segregation in these species varied throughout the year, and was presumably related to the frequency of sexually attractive females. In western grey kangaroos, mixed-sex groups occurred more often during spring, with single-sex groups predominating during autumn, when there were fewer females likely to be entering oestrus. Moreover, during autumn, male and female western grey kangaroos differed significantly in their distribution across the landscape. The trend was similar for red kangaroos, but the timing of segregation was reversed, i.e. there was significant spatial and habitat segregation in spring, but not autumn. The phenomenon of sexual segregation is discussed in more detail in section 5.4.

Nave (2002) reported on the reproductive seasonality of eastern grey kangaroos in western Victoria between January 1998 and March 2001. Much of the work reported in this thesis has not yet been published, and hence it was not included in the previous literature review (Olson and Low 2006). There have been very few other peer-reviewed accounts of reproductive seasonality in kangaroos over the last decade, so it is important to review this work here.

Nave (2002) reported that eastern grey kangaroos in Victoria are capable of breeding at all times of year. The majority of births (81%) occurred between October and April, with a peak in December. On average, females attained sexual maturity at 22 months, which was later than published accounts from southern Queensland (17 months, Kirkpatrick 1965) and central NSW (20 months, Poole 1973). Males attained sexual maturity between 23 and >32 months of age (n=25), which was also later than previous accounts for males in the north of their range. It is possible that this reflects a latitudinal effect on sexual maturity, with the age at sexual maturity increasing with increasing latitude.

Male testosterone concentrations varied throughout the year, with peaks observed to coincide with the peak breeding activity. Bachelor groups of males occurred at all times of year. These males tended to venture further into open farmland than males in mixed sex groups, and they were in better body condition. Nave (2002) hypothesised that males in mixed sex groups had higher metabolic demands in terms of maintaining dominance and procuring consorts with females, resulting in reduced body condition, while the tendency for mixed sex groups to remain closer to bushland was related to the need for females with dependent young to be able to rapidly retreat to shelter if necessary.

Overview

While there has been very little published on reproductive seasonality since the last review, the work reviewed above highlights the need for regional, species-specific knowledge of reproductive seasonality. There is a lack of knowledge about reproductive seasonality of grey kangaroos in NSW. Several large studies were conducted on grey kangaroo reproduction in the 1960s and 1970s (Poole 1973; 1975; 1983; Poole and Catling 1974). However, much of this research was conducted before it was recognised that there were two taxonomically (and reproductively) distinct species, subsequently referred to as the eastern and western grey kangaroo (Kirsch and Poole 1972; 1967). As a result, these intensive studies do not provide an understanding of subtle reproductive differences between the two species. What is known from recent and historic studies is that breeding (in the grey kangaroos especially) is seasonal and that the peak and degree of synchronisation likely vary with latitude (Coulson; pers. comm.). However, more data is needed over a broader range of latitudes.

As we accumulate information on the reproductive seasonality of kangaroos, the question is, how can this information be used to produce better animal welfare outcomes whilst maintaining the goals of a commercial industry? At a minimum, such data could be used to inform harvesters of the periods when there is the greatest risk of orphaning a young-at-foot or large pouch young, so that they can alter harvesting strategies to avoid females with dependent young as required. If studies reveal that there are variations in the timing of reproduction in sympatric species, as reported in MacFarlane and Coulson (2005), then it may be possible to selectively harvest different species at different times of year, thereby facilitating continual supply for the commercial industry whilst reducing the potential negative animal welfare outcomes that may result from orphaning young. However, most studies have shown that all four commercially harvested species have the capacity to breed throughout the year, so harvesters need to be cognisant of the potential for young to be orphaned at any time of year.

4.2 Reproductive Success

The relative reproductive success of different cohorts within the population is relevant to any evaluation of the extent to which selective harvesting of animals of a particular phenotype or age group may influence population structure and therefore the sustainability of harvesting activities.

Recently, Miller *et al.* (2010) determined a number of factors which influenced the reproductive success of male eastern grey kangaroos in three captive, semi-free-ranging populations. The dominant, alpha males were shown to sire the most offspring (54% on average), with the dominant male in one population siring over 80% of the young. Male dominance and reproductive success were strongly linked to body weight, body size and testosterone concentrations, with the most successful males being the largest, heaviest and having higher testosterone concentrations than less successful males. There was some evidence that females chose males that were more genetically distinct from them, suggesting that females exhibit a degree of mate choice aimed at promoting enhanced genetic diversity in their offspring.

Pople *et al.* (2010a) investigated the variance in reproductive success between female red kangaroos of different age groups. They found that while maternal age did influence reproductive success, with older females having 7-20% greater breeding success, female body condition and environmental conditions accounted for most of the variance in reproductive success (30 and 60% respectively). The impact of changes in age structure on rates of recruitment within the population is therefore believed to be slight and should not compromise harvest sustainability.

Overview

The work of Miller *et al.* (2010) demonstrates that, in semi-captive environments at least, the largest males father the majority of the offspring. Larger skins and heavier carcasses are more valuable to the commercial industry, but selective harvesting of the most reproductively successful animals in the population has the potential to alter population structure or select for smaller individuals. The extent to which kangaroo harvesting eliminates these fitter, reproductively successful individuals from the population needs to be determined before a thorough assessment of the likely population effects can be established. The potential effects of size-selective harvesting are discussed in more detail in section 7.1. Further research should focus on measuring male reproductive success under varying ecological conditions.

The work of Pople *et al.* (2010a) suggests that selective harvesting of larger (older) female red kangaroos is unlikely to affect recruitment rates within populations, and should therefore not affect long-term population viability in response to harvesting. The extent to which these findings hold true for the other commercially harvested species should also be established.

5. Population Dynamics

Kangaroo population dynamics have been widely documented within scientific literature both historically and recently. Advances in knowledge can be readily traced back through the literature to evaluate our progress towards a comprehensive knowledge of the subject area. Coulson (2009) reviewed the recent advances in behavioural ecology and their relevance to kangaroo management.

5.1 Measuring population demographics

Assessing harvest statistics and predicting the potential effects of harvesting on population demographics requires knowledge of the age structure of a population. Current age estimation methods include analysis of morphometric characteristics, dentition and protein content of eye lenses (reviewed by McLeod *et al.* 2006). Morphometric analysis (for example, leg length) is a useful and versatile technique because it is quick and can be performed on live or dead animals. However, it is only useful for assigning animals to broad age groups, as there is little correlation between morphometric characteristics and age when animals are over three years old. Analysis of dentition is a technique that has been widely used to estimate the age of dead animals by analysing their skull and calculating the molar progression index. However, harvesting kangaroos under the Code of Practice for the Humane Shooting of Kangaroos (Commonwealth of Australia 2008) requires animals be head shot, which often damages the skull rendering this technique for age analysis problematic. To overcome this problem, McLeod *et al.* (2006) proposed a method of age estimation using dried eye lens weight. This method was found to be a simple, cheap and easy method for determining age in western grey, eastern grey and red kangaroos. It enhances the potential for substantial data sets to be obtained, as samples may be collected from the commercially harvested kangaroo population, thereby allowing for a greater understanding of harvesting effects on age demographics in future studies. However, there is still the need for a non-destructive method of aging live animals in the field so that comparisons can be made between harvested and un-harvested populations.

5.2 Estimating Abundance

Much of the recent literature regarding population dynamics comes as a result of adaptive kangaroo management programs, which require ongoing monitoring to ensure that harvest levels are not adversely impacting on the natural populations. It is therefore little surprise that a large portion of the literature discusses the appropriateness of techniques for estimating kangaroo population size. Harvest quotas are set as a proportion (e.g. 15%) of the estimated absolute population size in winter of the previous year (Pople 2008). Considerable research effort has gone into improving the accuracy of aerial survey methods, initially sampling in strip transects in fixed-wing aircraft, but now also using line transect sampling in helicopters. Imprecision in population estimates is also important as it creates a risk that the quotas will be set too high or too low, therefore influencing the sustainability or profitability of the industry respectively.

The limitations of aerial line-transect surveys have received particular attention recently (Cairns *et al.* 2008; Fewster and Pople 2008; Fewster *et al.* 2008). New sample methodologies that combine mark-recapture and distance-sampling methodologies are believed to reduce potential bias in density estimation using aerial surveys. Fewster and Pople (2008) compared three mark-recapture distance-sampling methodologies and found that the point-independence Method *P* outlined by Borchers *et al.* (2006) performed best. However, there were still limitations to this method in that observers needed to be aware of responsive movement of kangaroos so that it could be detected and accounted for. In southern Queensland, mark-recapture distance sampling indicated that helicopter surveys of eastern grey kangaroos, currently using only line transect sampling, were underestimating abundance by 10-30%. This is relevant obviously to helicopter surveys in eastern NSW, but also fixed-wing surveys in the western plains, where correction factors have been based on comparisons of helicopter and fixed surveys (Cairns and Gilroy 2001). Cairns *et al.* (2008) described the design of a helicopter survey for population estimates of eastern grey kangaroos and wallaroos in the Northern Tablelands of New South Wales. The use of helicopter surveys is described in more detail in section 5.2.1.

Population monitoring is a necessary component of sustainable harvest management, but can prove very costly and logistically difficult given the large range of the commercially harvested kangaroo species. Numerous studies have investigated potential options for reducing the cost of population monitoring, whilst ensuring that the precision of population estimates does not compromise decisions about harvest management and long-term population viability.

Imprecision in population estimates creates a risk that the quotas will be set too high or too low, therefore influencing the sustainability or profitability of the industry respectively. Using a risk-assessment framework, Pople (2008) modelled the effects of varying precision, survey frequency and harvest rate on the risk of observing a significant population decline (termed “quasi-extinction” in the literature) for kangaroos inhabiting drier (arid) and wetter (mesic) environments. He concluded that an appropriate management regime could involve regular surveys in areas where the harvest rate is set close to the maximum sustained yield. Outside of these major harvest areas, survey frequency could be reduced in relatively wet areas. In arid areas, where population size and resource availability are more variable, a reduced survey frequency would need to be combined with reduced harvest rates to compensate for the added risk of overharvest due to rapid population change. Hauser *et al.* (2006) suggested a framework where a decision to survey or not is taken each year, dependent on the state of the system; i.e. in some years it may be possible to predict population abundance using a population model, data from previous surveys, and relevant covariates such as rainfall.

Another potential strategy to reduce the costs associated with population monitoring may be to use harvest statistics to generate estimates of population size when modelled as a function of a number of explanatory variables. This approach was evaluated by Pople *et al.* (2010b), who concluded that harvest statistics may be useful in supplementing direct monitoring methods, but further assessment is required. The relationship between harvest statistics (e.g. average weight, sex ratio) and population statistics (i.e. kangaroo density and harvest rate) varied among regions and species. There was no single model that could predict population density for all areas of a state, or for any particular species. This is likely to limit the usefulness of this form of indirect monitoring over a broad scale, as it will require multiple different models in different areas.

5.2.1 Helicopter survey techniques

In the Northern Tablelands of NSW, wallaroo and eastern grey kangaroo population size is currently estimated using helicopter surveys, as the terrain in this area is too steep to permit the use of fixed-wing aircraft. Furthermore, fixed-wing surveys are particularly inaccurate in more heavily timbered country and in surveys of wallaroos. Helicopter surveys have proven to be acceptable in these situations (Clancy *et al*. 1997, Pople *et al*. 2003). Surveys are conducted once every three years and harvest quotas are established based on the most recent population estimate (Department of Environment and Conservation (NSW) 2006). The reduced survey frequency is related to both the greater intensity of these surveys and the higher cost of helicopter surveys over fixed wing surveys.

Prior to 2001, population densities in the Northern Tablelands were estimated from walked line transects conducted in 1989/90, with annual adjustments based on environmental variables and densities measured in surrounding areas. Triennial helicopter surveys began in 2001, and the survey process was redesigned in 2004 and again in 2007 in response to information gained from previous surveys and advances in survey design software (Payne 2008). The survey methodology employed since 2004 involves dividing the terrain into three strata (categories), reflecting areas with high, medium and low densities of kangaroos (i.e. wallaroos and eastern grey kangaroos collectively). In areas where there are both high and medium density strata, the low density strata are generally not surveyed. The average population estimates for each stratum are then used to estimate the entire population within each KMZ. Because the low density strata are usually not surveyed, the population density for this stratum is assumed to be zero, but this is unlikely to be the case. As such, the population densities within each zone are conservative estimates (Payne 2008).

Cairns *et* al. (2008) reported on the design of helicopter surveys for macropod population estimation within the Northern Tablelands. They concluded that helicopter surveys could be considered a good surrogate for walked line transects for eastern grey kangaroos, but because of the difficulty of counting wallaroos from helicopters (Clancy *et al*. 1997), wallaroo population densities are multiplied by a correction factor of 1.85. It is difficult to objectively evaluate the accuracy of helicopter surveys in this area because the only available benchmark for comparison purposes was walked line transect data collected over a decade earlier. The coefficients of variation (CV) for population estimates varied between KMZ and between the two species. While the CV for eastern grey kangaroos varied between 18.1 and 23.5% for the three Northern Tablelands KMZ, the CV for wallaroo population estimates varied between 23.0 and 60.8% between KMZ (Cairns *et al.* 2008), suggesting that wallaroo population estimates in some areas do not have the same level of precision as seen for eastern grey kangaroos within the same zone.

A key risk associated with triennial surveys is that a population may decline significantly in the time between consecutive surveys and the quota system will not be able to take account of this. This type of situation is highlighted by the wallaroo population estimates and harvest statistics within the Northern Tablelands of NSW. Figure 3A is a modified version of the data presented in Figure 1D, showing the harvest and population statistics in relation to the timing of triennial surveys and the subsequent three-year period for which these estimates were used to set harvest quotas. The 2007 quota year occurred at the end of a three year block; hence the quota was based on the 2004 population estimate of 208,000 wallaroos. Approximately 24,500 wallaroos were harvested in 2007, representing 10.8% of the 2004 population estimate (Figure 3A). However, wallaroo populations had apparently declined during this three year period, with a subsequent population estimate of 115,000 calculated in the winter of 2007. Therefore, the number of wallaroos harvested in 2007 was almost 20% of the population, despite the fact that quotas were calculated according to methods approved in the current KMP. While a 20% take is almost certainly sustainable, even if it were taken every year, the current survey methodology makes it difficult for wildlife managers to ensure they stay within the targeted harvesting rate outlined in the current KMP. Whether the declines depicted in Figure 3A are real declines or an artefact of survey methodology cannot be determined with the available data. The higher CVs for wallaroo population estimates reduces the power to detect significant changes over time. Moreover, changes to survey methodology as part of the adaptive management process mean that strict statistical comparisons between years are not possible.

Comparable data for eastern grey kangaroos in this area are presented in Figure 3B. The variance in absolute population size between years is not as high as observed for wallaroos, which may partly reflect the greater precision of helicopter surveys for eastern grey kangaroos. There is also much less variance in the absolute number of eastern greys commercially harvested from year-to-year (Figure 3B).

Overview

The wealth of information that has been published on this topic recently clearly demonstrates that wildlife management agencies have seriously undertaken their commitment to adaptive harvest management. Kangaroo monitoring programs should consider new population abundance estimate methodologies and apply them where appropriate, particularly if they reduce the risk of setting inappropriate harvest quotas. However, any changes to population estimation methodologies should take into account the need for consistent long-term monitoring using comparable methodologies that will allow long-term trends to be measured, and comparisons to be made between different KMZ. Ideally, new survey methodologies should run concurrently with old methodologies for at least one year to enable some degree of benchmarking between methods.

The available data for wallaroos within the Northern Tablelands suggests that the current triennial survey and quota system does not offer the precision required to maintain harvest levels within the 15% limit outlined in the KMP. As such, either the survey design or percentage quota allocation should be reassessed. One option may be to supplement triennial surveys with estimates derived from regional models based on harvest statistics, as described in Pople *et al.* (2010b), or possibly rainfall-driven population models. It should be noted that although wallaroo populations appear to have declined within the Northern Tablelands, this represents only a small portion of the total range of this species.

A number of advances have been made in the development of indirect population survey methods. However, variation in the performance of models among zones means that different management systems would need to be employed in different zones. Employing these methods is likely to be administratively difficult as models are less able to demonstrate sustainability than surveys returning estimates of abundance.

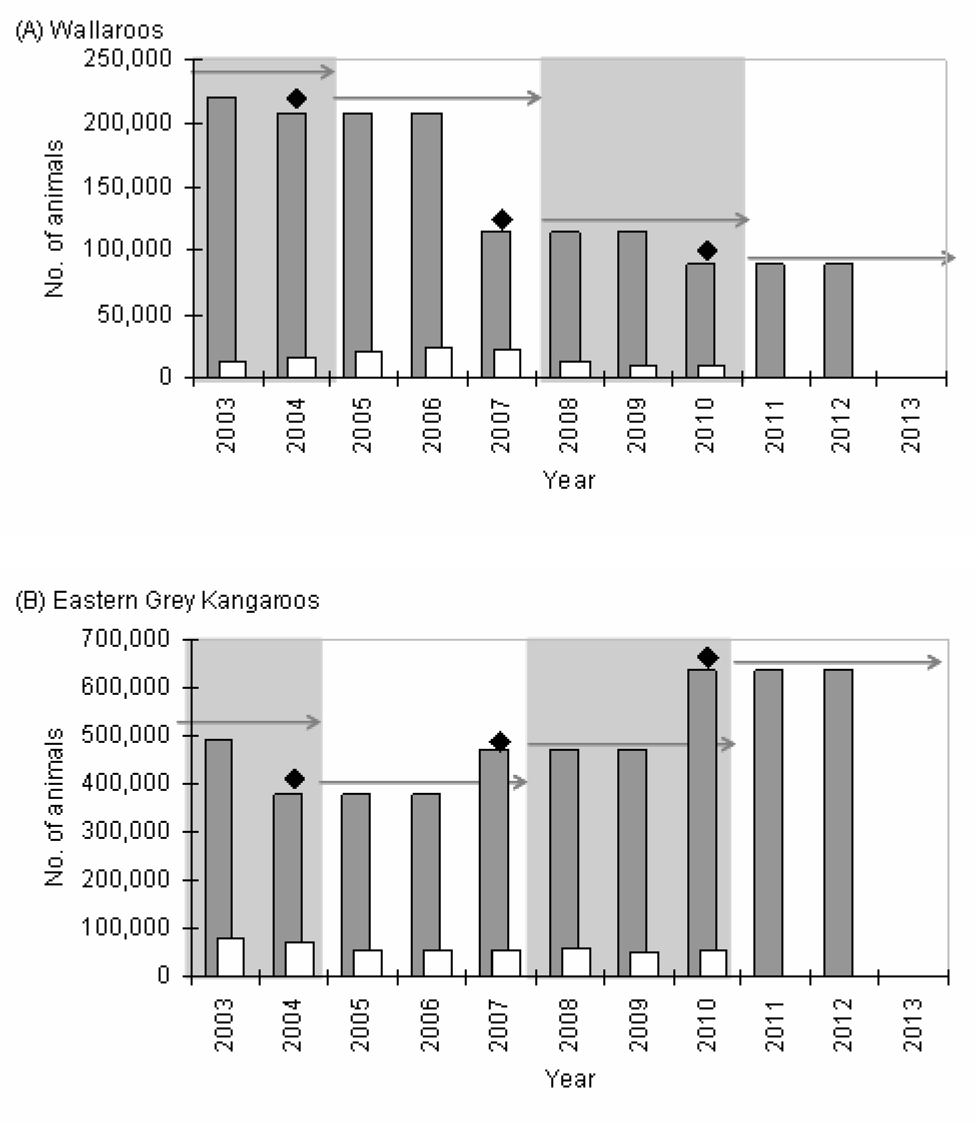

Figure 3. **Population (grey box) and harvest (white box) size for (A) wallaroos and (B) eastern grey kangaroos within the Northern Tablelands of NSW 2003 – present.**

The timing of each triennial helicopter survey is indicated (black diamonds), as well as the subsequent three-year block for which this estimate was used to set commercial harvest quotas (horizontal arrows). Each three-year block is highlighted by alternating grey and white shaded boxes.

[Data supplied by the Kangaroo Management Program, Office of Environment and Heritage, Department of Premier and Cabinet (NSW), with additional data from Payne 2010; http://www.environment.nsw.gov.au/wildlifemanagement/TagAllocationsAndCommercialTakeReports.htm]

5.3 Modelling population dynamics

Stochastic models have been extensively employed by ecologists to capture the random variation experienced by wildlife populations and to test ecological theories and the consequences of human activities, such as harvesting and climate change (Jonzen *et al.* 2010). Studies of the erratic fluctuations between kangaroo abundance and rainfall feature predominantly in the literature and have influenced the way many ecologists think about herbivore population dynamics. The relationship between rainfall, resource availability and kangaroo population dynamics continues to stimulate the development of complex models that aim to predict population responses to resource availability and these models increasingly include the capacity to factor in other biotic and abiotic influences on population density. As the precision of these models improves, they become an increasingly powerful tool for predicting the outcomes of different wildlife management scenarios.

Rainfall has long been recognised as one of the key driving factors in kangaroo population dynamics as it gives an indication of food supply. Pople (2006) used rainfall to generate population models for all four commercially harvested kangaroo species in their respective states. In South Australia, Pople (2006) used satellite imagery as a more direct measure of pasture biomass rather than simply including rainfall as an indirect measure of food supply. Pople found that the most effective population models differed from state to state. In NSW the rate of increase of kangaroo populations correlated most strongly with rainfall. Jonzen *et al.* (2005) created a model that described the effect of rainfall, harvesting, intraspecific competition and interspecific competition with domestic herbivores on red kangaroo populations in the South Australian pastoral zone. They found that while rainfall, sheep and cattle density vary between areas, populations respond to the variation in a similar way. The amount of total variation explained by this model however, ranged between 60% in one area to only 7% to another area, therefore highlighting that there is still much to learn about the relationships between these herbivores and their resources. Similarly, in a recent review of temporal dynamics of kangaroo populations, Pople *et al.* (2010c) concluded that despite the great promise of early numeric models relating rainfall to kangaroo density, we still do not have a model that can predict population responses for different species in different areas over time.

Jonzen *et al.* (2010) used a stochastic environment model of female red kangaroos to predict the effect of changes in rainfall on survival and fecundity in different age classes. Juvenile survival and adult reproductive rates fluctuated considerably in response to varying rainfall patterns. They found that a reduction in average rainfall may have detrimental effects on the population by reducing survival of both juveniles and adults, with mean adult survival having a much greater effect on the population than juvenile mortality. Similarly, increased variability of rainfall was also likely to have a detrimental effect on the population. This result may have implications for future harvest management. While current harvest quotas are sustainable under the current rainfall pattern, any level of harvesting may be unsustainable if average rainfall drops by more than 10% (Jonzen *et al.* 2010).

Modelling techniques have also been used to assess factors that influence species' distributions. A criticism of previous species distribution models was that they fail to consider the effects of biotic interactions, including competition. In response to this weakness, Ritchie *et al.* (2009) developed a model to quantify how environmental factors and interspecific competition affect the distribution and abundance of macropods in tropical northern Australia. The best-supported models showed that antilopine wallaroo (*M. antilopinus*) and eastern grey kangaroo abundance were dependent on both habitat variables and the abundance of the other species, providing evidence of interspecific competition. Specifically, eastern grey kangaroo abundance was influenced most by climate and the abundance of antilopine wallaroos and cattle. However, the abundance of common wallaroos was largely influenced by climate rather than interspecific competition. A benefit of such models is that they allow quantification of species' interactions for which competition may be difficult to demonstrate experimentally.

Overview

Despite advances in the development of complex stochastic models over the last five years, the complexity of highly variable natural systems limits the potential for these models to accurately predict kangaroo population density over broad geographic areas. As such, these models could not be confidently used in place of traditional, direct observations of animals to estimate absolute population size. However, these models are likely to prove quite valuable as a predictive tool to model the response of kangaroo populations to different scenarios, such as the interaction between predicted climate change and harvesting (as demonstrated by Jonzen *et al.* 2010). Although the models cannot predict population responses with certainty, they provide wildlife managers with an indication of the likely population responses, which should aid in the development of appropriate monitoring regimes to ensure harvest sustainability.

5.4 Spatial Patterns

Since the last review, numerous studies have investigated spatial patterns of kangaroo abundance. Spatial variation in species abundance and in the distribution of different sex and age classes across the landscape may influence the sustainability and/or profitability of harvesting at a local, individual property, scale.

Pople *et al.* (2007) used estimates of population size in small sampling segments to determine spatial patterns of red and western grey kangaroo density in the South Australian pastoral zone. Variations in spatial patterns of kangaroo density were seen from year to year, although the broad pattern of distribution remained stable. There was some evidence of immigration from surrounding areas, as annual rates of increase over large areas were too high to be explained by births and deaths alone. During dry seasons, red kangaroos became more aggregated, but this trend was not observed for western grey kangaroos. This modelling technique provides greater resolution of the spatial distribution of kangaroos, as densities can be estimated at the individual property level, and predictions of changes to kangaroo distribution as a result of climatic factors (e.g. rainfall) may also be made.

Pople *et al.* (2010c) also discusses the spatial patterns of kangaroos. Information from surveys of red, western and eastern grey kangaroos over the last 30 years was used to assess changes in their patterns of distribution over time. While densities of these species have fluctuated over time, all three have expanded their range. Eastern grey kangaroos have expanded westward into more arid areas and their pattern of density behind this front has continued to shift westwards. Red kangaroos have expanded eastwards into more mesic areas and the pattern of density of western grey kangaroos has shifted northwards into more arid areas of South Australia. Rainfall did not provide a simple explanation for the changes in distribution patterns and was absent in many of the regression models. This shift in distribution may be considered a result of land clearing for red kangaroos, while an increase in artificial watering points has been implicated in the expansion of eastern grey kangaroos into arid rangelands (Dawson *et al.* 2006). Vegetation changes have also been associated with heavy grazing pressure, which has provided extra resources for kangaroos. The spread of eastern grey kangaroos may be limited to habitats providing essential tree and shrub cover (Dawson *et al.* 2006).

Viggers and Hearn (2005) discussed spatial patterns of kangaroos on a finer scale, and looked at the home ranges of eastern grey kangaroos using radio-tracking techniques. They also discussed the implications of their findings for kangaroo management, concluding that population density, presence of cover and reluctance to disperse across cleared landscapes were the key factors influencing kangaroo home range size. They also stated that as kangaroos readily use areas of remnant vegetation and surrounding farmland, there may be little incentive for farmers to conserve remnant vegetation. This study has caused much debate, with Martin *et al.* (2007) critiquing the outcomes of the study due to perceived shortcomings in study design, home range analysis, biomass assessment and other aspects of the work. Viggers and Lindenmayer (2007) refuted these criticisms, and stated that the outcomes of the original paper were still valid. Notwithstanding questions about the validity of the work, Viggers and Hearn (2005) highlight an important question which is worthy of research attention, i.e. what factors influence the movement of macropod species. Further research should investigate the extent to which factors such as sex, age, reproductive status and culling influence movement patterns.

Wiggins and co-workers used scat surveys (Wiggins and Bowman 2011) and radiotelemetry (Wiggins *et al.* 2010) to measure the response of two Tasmanian macropodid species (Bennett's wallabies, *M. rufogriseus rufogriseus* and Tasmanian pademelons, *Thylogale billardierii*) to management interventions in different habitat types. They found that these species showed a preference for agricultural land, but the extent of preference varied throughout the year. Shooting was an effective technique for reducing densities at a localised scale, especially in agricultural areas (Wiggins and Bowman 2011), but individual animals that remained after culling adjusted their home range to increase their use of agricultural land (Wiggins *et al.* 2010), presumably in response to the reduced density in this preferred habitat. Although these studies were conducted on different macropod species inhabiting a very different environment to the NSW commercial harvesting scenario, they highlight the importance of considering how management operations may alter the behaviour of the remaining individuals within a population, with resultant effects on management goals. The altered movement patterns observed by Wiggins and co-authors may be viewed in a positive or negative light, depending on the specific management goals. In the Tasmanian Forestry scenario, where culling is performed for pest management and damage mitigation, such responses could be viewed as negative. However, within the context of sustainable commercial harvesting in NSW, such individual behavioural responses could be viewed in a positive light. Increased movement of animals in response to culling would facilitate the maintenance of gene flow within a population and may positively influence population recruitment.

Sexual segregation is a phenomenon seen in many species, with segregation occurring along behavioural or ecological dimensions. Sexual segregation in western grey and red kangaroos in semi-arid Victoria has been the subject of intensive investigations since the last review. As discussed in section 4, MacFarlane and Coulson (2005) investigated the effects of mating activity, group composition, spatial distribution and habitat selection on sexual segregation in western grey and red kangaroos. The synchrony and timing of mating activity was seen to influence the magnitude and timing of social segregation in these species, with mixed sex groups predominating during the breeding season. Spatial segregation and habitat segregation were also seen. Although the magnitude of these types of segregation were weaker, they were both still significantly influenced by synchrony and timing of breeding. Coulson *et al.* (2006) discussed sexual segregation at three levels (habitat, social and dietary) and confirmed that both size and sex influence segregation. MacFarlane and Coulson (2009) showed that the need for males to maintain contact with other males (perhaps to develop important fighting skills, evaluate rivals and establish a dominance hierarchy) might also promote sexual segregation. Similarly Nave (2002) reported evidence of sexual segregation in eastern grey kangaroos in Victoria (discussed in section 4).

Overview

Numerous studies have investigated the spatial distribution of kangaroos over the last six years. At a broad scale, the distribution of the commercially harvested kangaroo species has changed over the last 30 years, with eastern grey, western grey and red kangaroos showing range expansions across the continent. At the other end of the spectrum, Pople *et al.* (2007) developed a model that allows for fine-scale estimates of kangaroo density across the landscape. This method has the advantage that it can assess kangaroo density at the same spatial scale with which harvest quotas are allocated, i.e. at the individual property level. However, such fine scale population management may be unnecessary from a biological standpoint. Pople *et al.* (2007) identified immigration as an important factor in species distribution in response to resource availability, suggesting these animals have the ability to move reasonably large distances over relatively short periods of time. Moreover, the extent to which individual animals and discrete populations range across numerous properties probably negates the need for such fine-scale analysis.

Studies of western grey, eastern grey and red kangaroo populations in Victoria have demonstrated that the distribution of different age and sex classes is not uniform across the landscape, with group composition and location predominantly influenced by the reproductive status of females. The extent to which this may influence harvest demographics is unknown. Spatial “clumping” of animals may mean that animals of a specific demographic may be over- or under- represented on a local scale, for example, if bachelor groups of lower ranking male eastern grey kangaroos spend more time in open paddocks, they may be more likely to be harvested, especially considering the preference for harvesting larger animals. The potential effects of this cannot be determined without detailed analysis of the spatial scale of harvesting across regions. This theme is continued in more detail in section 7.1.

Little is known about the response of individuals and populations to culling at a local scale. The work of Wiggins *et al.* (2010) in Tasmania highlights the capacity of individual animals to change their movement patterns in response to culling-induced reductions in density. Similar investigations in the commercially harvested kangaroo species would reveal the extent to which animal dispersal could counter any localised reductions in density that may result in the event of over-harvesting.

5.5 Genetic Population Structure

At the time of the last review, the genetic structure of wallaroo, eastern grey and red kangaroo populations had been assessed throughout their range. These findings are summarised again here, as they are relevant to a later discussions on potential genetic impacts of harvesting.

Eastern grey kangaroos have extremely high levels of genetic diversity, with strong genetic differentiation between populations in the south (Tasmania, Victoria and NSW) and north (northern Queensland) of their range (Zenger *et al.* 2003). However, there was a paucity of samples from northern NSW and southern Queensland in this study, so the extent of the southern and northern populations remains unknown. There was evidence of significant gene flow between NSW populations, up to distances of 230km, suggesting active dispersal of animals (especially males). For red kangaroos there was only weak population structuring, with no evidence of restricted gene flow throughout their range (Clegg *et al.* 1998). Hale (2004) concluded that the geographic range of genetic populations appeared to encompass the entire red kangaroo species range. However, vast areas of their range were not sampled in these two studies, including all of NSW and the Northern Territory, making it difficult to make finite conclusions. Hale (2004) also reported on the genetic structure of wallaroo populations. In contrast to red kangaroos, he concluded that wallaroo populations were highly structured, with evidence of restricted gene flow between populations. The closest two populations in this study were approximately 670km apart, so the extent to which wallaroo populations are structured over a finer geographic scale remains unknown. Moreover, it is difficult to evaluate the strength of these conclusions for red kangaroos and wallaroos as the raw data are not presented by Hale (2004).

At the time of the last review, comparable data were lacking for the western grey kangaroo. This gap in knowledge has now been addressed. A recent study by Neaves *et al.* (2009) identified five distinct genetic units across the range of the western grey kangaroo and these were associated with landscape discontinuities. The mainland population comprised a single subspecies (*M. f. melanops*) with three genetic units, broadly corresponding to the western, central and eastern sections of their range. The western unit displayed evidence of further structuring, with two subunits (northwestern and southwestern) identified. Kangaroo Island was identified as a separate subspecies (*M. f. fuliginosus*) comprising a single genetic unit. All samples collected within NSW fell within the eastern unit, with no evidence of further genetic structuring. The level of genetic diversity declined from the west to the east of the range. No significant sex-biased dispersal was identified in this species.

Recently hybridisation of eastern and western grey kangaroos has been reported in areas of overlap in their range (Coulson and Coulson 2001; Neaves *et al.* 2010). Such hybridization may be associated with variable conditions and dramatic reductions in densities, but may be useful in allowing populations to incorporate novel diversity while still retaining species integrity (Neaves *et al.* 2010).

Overview

With the recent characterisation of western grey kangaroo genetic population structure by Neaves and co-workers, wildlife managers now have access to data on the genetic population structuring of all four commercially harvested kangaroo species in NSW. However, the intensity of sampling and the types of genetic analyses performed varied between the four species. As such, there is still a need for further detailed investigations of the genetic structure of kangaroo populations, with the notable exception of the western grey kangaroo. Zenger *et al.* (2003) identified two differentiated populations of eastern grey kangaroos (northern and southern), but the borders of these populations were not clearly defined. Hence we do not know whether there is genetic differentiation between populations within northern NSW. Further in depth sampling of red kangaroo and wallaroo populations throughout a greater area of their range would also be useful to confirm the conclusions of Hale (2004).

The identification of a single genetic unit within NSW for western grey kangaroos (Neaves *et al*. 2009) provides support for the current state-based management regime. In the case of eastern grey and red kangaroos, the available data currently supports the same conclusion, but further sampling would be required to confirm that NSW represents a single genetic unit for these species. The wallaroo was the only species for which there was definitive evidence of significant genetic structuring within NSW. Further studies should investigate the extent of fine-scale structuring within individual KMZ for wallaroos. Commercially harvested animals could provide a valuable source of tissue for the genetic analyses discussed here.

6. Population Health (Diseases, Parasites and Pathogens)

In the previous review, Olsen and Low (2006) concluded that disease is unimportant as an agent of mortality in kangaroos as the effects of disease are generally temporally and geographically isolated, with populations recovering rapidly. The health of macropods has been widely discussed within the scientific literature over the past five years. Much of this research has focused on parasitic infections of kangaroos and diseases which also have implications for livestock and human health. There have been a number of novel reports of disease causing agents in kangaroos, but there is no evidence that these agents are likely to influence population viability in response to harvesting.

Cystic hydatid disease, caused by larvae of the tapeworm *Echinococcus granulosus*, has been widely reported in macropodid species. Cysts are most frequently seen in the lungs of affected animals, and may reduce effective lung volume by 55% in males and 70-80% in females (Barnes *et al.* 2007). Severe cases of hydatid disease may cause death in individual animals, or render them more susceptible to predation (Jenkins 2005). Dingoes (*Canis lupus dingo*), foxes (*Vulpes vulpes*) and dogs (*Canis familiaris*) are the definitive hosts of the parasite, and kangaroos are recognised as a significant intermediate host in some areas. For example, Banks *et al.* (2006) demonstrated that macropods and dingos were important reservoirs of disease in northern Queensland, and that the life cycle of the parasite was maintained through the predation of black-striped wallabies (*M. dorsalis*) by dingoes.

Hydatid cysts have been reported in commercially harvested kangaroo carcases. In Queensland, two separate studies reported a low prevalence of infection in eastern grey kangaroos (1.4% and 2.5%) and wallaroos (1.5% and 0.4%) (Banks *et al.* 2006, Barnes *et al.* 2007). Barnes *et al.* (2007) postulated that this low prevalence (which contrasts with earlier studies performed in coastal central Queensland and the tablelands of New South Wales) may be attributed to the higher rainfall and cooler temperatures in the study area. This study also found that female eastern grey kangaroos were twice as likely to be infected than males. The authors suggested that this may be explained by the regular commercial harvesting of kangaroos, where larger males are often harvested in preference to smaller females. This may mean that the males left in the population are on average younger than the females, and as prevalence is known to increase with age, this may result in the observed pattern of higher prevalence in females. Barnes *et al.* (2007) also reported significant clustering of the disease at the property level in southeastern Queensland.

Cystic hydatid disease has clear zoonotic potential; 321 patients were diagnosed with hydatid disease in NSW and the Australian Capital Territory (ACT) from 1987-1992 (Jenkins and Power 1996). The risk of transmission of hydatid disease from kangaroo meat has been identified as a concern to the Australian game meat industry. Preventive measures are therefore in place to minimise the potential for transmission to consumers. Kangaroo carcasses provided for human consumption are required to undergo inspection as outlined in the Australian Standard for the Hygienic Production of Wild Game Meat for Human Consumption (Food Regulation Standing Committee 2007). Any carcass found to contain hydatid cysts must have the lesion and surrounding tissue removed and condemned. Variable prevalence of infection appears to be common at both a local and regional scale. As such, another suitable risk management strategy could be to direct commercial harvesting away from areas of known high prevalence.

The protozoan parasite *Cryptosporidium sp.* is a causative agent of enteric disease in humans and other animals. Power *et al.* (2005) reported the presence of *Cryptosporidium* in a population of wild eastern grey kangaroos in a watershed of the Sydney Hydrological Catchment. They found that the prevalence of *Cryptosporidium* in the population was seasonal and ranged from 0.32% to 28.5%, peaking in the autumn months when higher numbers of more susceptible newly weaned animals were present in the population. Since the last review two new species of *Cryptosporidium* have been identified in marsupials. Marsupial genotype I and marsupial genotype II, which were previously thought to be *Cryptosporidium parvum*, have now been identified as two distinct species; *C. fayeri* (Ryan *et al.* 2008) and *C. macropodium* (Power and Ryan 2008). Furthermore, isolates of *C. fayeri* may be assigned to one of six different subtypes, which are associated with host species and locality (Power *et al.* 2009). The two newly identified species of *Cryptosporidium* seem to be highly host specific, as they have only been identified in marsupial hosts to date. Their zoonotic potential is therefore likely to be minimal, although this needs to be tested experimentally before firm conclusions can be drawn. The ability for *C. fayeri and C. macropodium* to produce debilitating disease in macropods is unknown, however their seasonality and low prevalence suggest it is not a major determinant of mortality in kangaroo populations.

Ovine Johnes Disease (OJD), a disease caused by infection with *Mycobacterium avium* subsp. *paratuberculosis*, causes chronic enteric wasting of sheep. Cleland *et al.* (2010) investigated the presence of this bacterium in macropods grazing with infected sheep on Kangaroo Island. While *M. a. paratuberculosis* was isolated from 1.7% of macropods on this property, it is unlikely that they provided a significant wildlife reservoir of infection, as excretion of large numbers of viable organisms is rare. This hypothesis is supported by a previous study of *M. a. paratuberculosis* in NSW (Abbott 2000), which found that only one of the 206 eastern grey kangaroos sampled was shedding the organism in its faeces. Although macropods may become infected with *M. a. paratuberculosis*, visible signs of disease are often not apparent. The available data therefore suggests that kangaroos are of little significance in the epidemiology of OJD, and that OJD has little impact on free-living kangaroo populations.

In contrast, Banazis *et al.* (2010) reported that kangaroos may play a significant role in the maintenance of the causative agent of Q fever (*Coxiella burnetti*) in the environment. Thirty-four percent of western grey kangaroos from the southwest and central regions of Western Australia tested positive for exposure to *C. burnetti*, but it is not known whether exposure to *C. burnetti* is endemic in other populations. The bacterial load in kangaroo faeces was relatively low, which may indicate that large-scale proliferation of the bacteria does not occur in the gastrointestinal tract. Further research is required to identify the role that kangaroos may play in transmission of this bacterium to domestic animals and humans. Banazis *et al.* (2010) suggested that commercial kangaroo harvesting might pose a risk for direct transmission to humans, particularly those associated with the harvesting and processing of animals. Further studies are required to determine the prevalence of *C. burnetti* in commercially harvested kangaroo species in NSW before the relative risk to humans can be established. The methodology developed by Banazis *et al.* (2010) should prove useful for such investigations.

In South Australia, Waudby *et al.* (2007) identified the hosts of the ornate kangaroo tick (*Amblyomma triguttatum triguttatum)*, in a previously unrecorded population in South Australia. The tick was seen to parasitise black rats *(Rattus rattus*), wild rabbits (*Oryctolagus cuniculus*), western grey kangaroos, tammar wallabies (*M. eugenii eugenii*), domestic cats (*Felis catus*), dogs and humans. The widespread nature of a number of these hosts may have facilitated range expansion in these ticks. Waudby and Petit (2007) described the seasonal fluctuations of tick density, which seem to be associated with climatic conditions such as temperature and humidity. Over the last 5 years a new host parasite relationship has also been discovered between the western grey kangaroo and the tick *Bothriocroton concolor* on Kangaroo Island (Oorebeek and Rismiller 2007). While *B. concolor* is widespread in southeast Australia, it was previously thought to be a host specific parasite found in association with the short-beaked echidna (*Tachyglossus aculeatus*). While ticks themselves may not cause severe illness, they may be involved in the spread of other disease causing organisms. In Queensland, the ornate kangaroo tick has been implicated in the spread of Q fever (Pope *et al.* 1960). As NSW forms a part of the known distribution of the ornate kangaroo tick, it's abundance in the kangaroo population and its affinity with other widespread hosts may be a cause for concern, particularly if kangaroos in NSW are found to be a significant reservoir for *C. burnetti*.

Toxoplasmosis is a disease caused by the protozoan parasite *Toxoplasma gondii*. It is well described within the scientific literature, and is known to cause significant morbidity and mortality in macropods. Recent cases have been reported in captive institutions in the United States and Argentina (More *et al.* 2010; Silvia de Camps *et al.* 2008), and details of the epidemiology, clinical signs, pathology, diagnosis, treatment and prevention of the disease in macropods were recently reviewed by Portas (2010). A recent study of a wild western grey kangaroo population in Western Australia found that 15.5% of kangaroos had been exposed to *T. gondii* and that the prevalence was significantly higher in females (Parameswaran *et al.* 2009). Toxoplasmosis is a disease that has the potential to infect humans through the consumption of contaminated foods. A particular risk is the consumption of undercooked meat, as *T. gondii* cysts (if present) remain infective when meat is not cooked thoroughly (Pereira *et al.* 2010). Although the recent findings of Parameswaran *et al.* (2009) serve as a reminder that kangaroo meat may represent a potential source of infection for humans, the rates of exposure in this study were not significantly different from those reported in previous studies in macropod populations throughout Australia. Although toxoplasmosis can prove fatal in macropods, there was no suggestion that it was a significant cause of mortality in the western grey kangaroo population referred to above.

Oral necrobacillosis (lumpy jaw) is a well recognised disease in captive macropods, but the disease has rarely been documented in wild populations. Borland *et al*. (in press) discovered a high prevalence (54%) of lumpy jaw in a free-living population of eastern grey kangaroos in Victoria. The study was conducted at a time when the population was experiencing the combined stressors of drought, high kangaroo density, limited feed, dry pasture and high faecal contamination, which may have contributed to the high prevalence of lumpy jaw. Harsh feed and faecal contamination are both believed to be predisposing factors for lumpy jaw development in captive macropods (Vogelnest and Portas 2008). The limited reports of this quite obvious disease suggest that the prevalence is probably low in other populations. The population investigated by Borland *et al.* (in press) was a fenced population, and the high population densities and limited opportunities for dispersal may be more akin to those in a captive than free-ranging population with respect to disease transmission. Necrobacillosis is recognised as a potential contaminant of kangaroo meat, and any carcases showing evidence of necrobacillosis abscesses are condemned for human consumption (Food Regulation Standing Committee 2007).

As discussed in the previous literature review (Olsen and Low 2006), Leishmaniasis was previously reported in red kangaroos held in captivity near Darwin in the Northern Territory. A recent report by Dougall *et al.* (2009) at the same facility has identified the same unique species of *Leishmania* in the wallaroo, the black wallaroo (*M. Bernardus*) and the agile wallaby (*M. agilis*). Lesions were observed on the tail, inner forearms, hind legs, ears and cloaca. The life-cycle of *Leishmania* in Australia is still unknown, and nothing is known about the prevalence of the disease in wild populations. This study suggests that one or more native species of macropods may be natural reservoir hosts for Australian *Leishmania*. However, reports of the disease to date are limited to the tropical region of the Northern Territory, and consequently Leishmaniasis is of little concern to the management of harvestable kangaroo populations in NSW.

Little is also known about Ngaingan virus (NGAV), a macropod-associated rhabdovirus which has recently been sequenced (Gubala *et al.* 2010). Opportunistic examination of blood serum samples from wildlife parks and care centres in northern Australia have shown that NGAV is circulating in wallabies, wallaroos and kangaroos in this area. Nothing is known to date about the implications of this virus for the health of macropods, its prevalence or its potential to cause disease in kangaroo populations. As for Leishmaniasis, NGAV has not been reported in NSW, so its relevance to the management of kangaroo populations in this area is questionable.

Since the last review, identification and isolation of a novel herpes virus, Macropodid herpesvirus 3 (MaHV-3), has been described (Smith *et al.* 2008). In 2009, MaHV-3 was detected in an individual from a mob of free-ranging eastern grey kangaroos in Victoria, where severe clinical disease and mortality was observed (Wilcox *et al.* 2011). This was the first case of gammaherpesvirus being reported in a free-ranging Australian macropod, providing evidence that this species may be a natural host of the virus. Herpesviruses are known to establish latent infections, which may become reactivated in times of stress. It may be possible that this reported case was a reoccurrence of the virus as a result of an underling stress or condition. The extent of gammaherpesvirus infection in Australian macropods is currently unknown, as is the ability for infection to cause clinical disease.

Herpes viruses usually show a long-standing co-evolution with their hosts, and as such rarely cross species boundaries (Tischer and Osterrieder 2010).

Novel reports of other pathogens have been also been documented since the last review. *Campylobacter jejuni* was isolated from a red kangaroo in a zoo in Belfast (Stirling *et al.* 2008), and *Blastocystis* was isolated from a western grey kangaroo in a zoo in Western Australia (Parkar *et al.* 2010). While both of these organisms are known to produce disease in humans, they have not been observed in free-ranging populations to date, and while noteworthy are not an immediate concern for the management of kangaroo populations in NSW.

A large portion of kangaroo pathogens and parasites discussed in the scientific literature over the last five years are infective via the faecal-oral route. Garnick *et al.* (2009) discusses faecal aversion in eastern grey kangaroos as a method of reducing parasitic burdens of the gastro-intestinal tract. They found that kangaroos moved though contaminated patches as they were encountered, thereby exhibiting faecal aversion behaviour. Despite preferring taller grass, kangaroos would not accept a higher risk of parasitism over increased nutrient uptake. In contrast Cripps *et al.* (in press) found that reproducing females increased forage intake on faecal- contaminated pasture, increasing the risk of infection by gastrointestinal parasites. While kangaroos generally avoid areas of faecal contamination, the higher nutritional demands of lactation may make them more susceptible to disease.

Overview

While a large number of diseases and their causative agents have been documented within the scientific literature since the last review, there is little evidence that points to disease being a major cause of mortality in the harvestable population of kangaroos in NSW. However, further research is required to determine the prevalence of a number of these parasites and pathogens in the wider kangaroo population of NSW, and the impact that these organisms have on the individuals and populations involved. As discussed in previous reviews by Olsen and Low (2006) and Olsen and Braysher (2000), kangaroos have been documented to recover rapidly after short-term reductions in population numbers resulting from disease epidemics. Recent literature again suggests that the impact of disease on populations is often localised, and may be greater in times of stress (e.g. drought).

Although there is currently no evidence to suggest that disease may affect the long-term viability of kangaroo populations and kangaroo harvesting, the recent example of Tasmanian devil facial tumour disease (DFTD) demonstrates the capacity for emerging infectious diseases to dramatically alter the status of a species. The dramatic spread of DFTD resulted in a global population decline of more than 60% in 10 years, resulting in the Tasmanian devil being “upgraded” from the IUCN category of lower risk/least concern to endangered (IUCN 2011). The dramatic spread of this disease has been linked to very low levels of genetic diversity of devils before the decline (Siddle *et al.* 2007). Given the very high levels of genetic diversity reported in the commercially harvested species (see section 5.5) and their broad range on mainland Australia, it is much less likely that an emerging infectious disease would have the same dramatic effects as those seen in devils. The addendum to the current KMP (Department of Environment and conservation (NSW) 2008), which imposes specific population size trigger points at which commercial harvesting will be suspended, is an important safeguard to protect the viability of kangaroo populations should they significantly decline as a result of varying circumstances such as disease epidemics.

A number of diseases that have been identified in free-living kangaroos also have the potential to cause disease in humans. Identification and mitigation of risks resulting from food borne disease are regularly undertaken by appropriate food authorities, and appropriate practices to minimise the risk of disease transmission to humans are outlined in various documents including the Australian Standard for the Hygienic Production of Wild Game Meat for Human Consumption (Food Regulation Standing Committee 2007).

7. Other threats to population (or harvest) sustainability

7.1 Genetic Impacts

The last two reviews concluded that there was no evidence, or potential, that commercial harvesting could alter the genetic structure of kangaroo populations at current harvesting levels (Olsen and Braysher 2000, Olsen and Low 2006). It was perceived that kangaroo populations would have to be reduced to very low levels for genetic impacts to become significant (Olsen and Braysher 2000). Moreover, at the time of the last review, it was concluded that there was "an absence of theoretical, empirical and modelled evidence of genetic impacts at current levels of harvesting" (Olsen and Low 2006, p50) and there were few, if any, examples of harvest-induced body size selection in terrestrial vertebrates. While there have not been any studies specifically investigating the potential genetic impacts of harvesting kangaroos since the last review, there have been a large number of original research and review papers addressing this question in a range of other vertebrate species, highlighting the perception that the potential genetic consequences of harvesting may be significant.

The human harvest of wild animals is generally not a random process, with harvesters often selecting phenotypically desirable animals, e.g. those with a large body size or elaborate weaponry, such as antlers. This therefore has the potential to impose selective pressure on wild populations, which may result in an alteration to population structure by reducing the frequency of these desirable phenotypes and/or an overall loss of genetic variation (Allendorf *et al.* 2008). Allendorf and Hard (2009) have termed this process "*unnatural selection"*, which is defined as undesirable changes in an exploited population due to selection against desirable phenotypes. Cited examples of the effects of selective harvesting on desirable phenotypes include an increase in the number of tuskless elephants (*Loxodonta africana*) in South Luanga National Park, Zambia, and a decrease in horn size of bighorn sheep (*Ovis canadensis*) because of trophy hunting (reviewed in Allendrof and Hard 2009). In the case of bighorn sheep, the observed genotypic and phenotypic effects resulted from selective harvesting of young males with rapidly growing horns (a trait linked with high reproductive success) before they reached an age where they could achieve high reproductive success (Coltman *et al.* 2003). This study highlights the importance of understanding age-specific trait size, rather than trait size per se.

A recent review by Mysterud (2011) discusses the relative importance of various biotic and abiotic factors that determine the potential for selective pressure from harvesting. In particular, Mysterud highlights the importance of assessing selective harvesting within the context of management regulations, hunting methods, animal trait variance, behaviour and abundance. Mysterud argues that in many cultures large mammal harvesting is not expected to produce strong directional selection in trait size. Although many of the factors discussed are of greater relevance to traditional sport hunting, this review highlights the importance of a number of factors relevant to the commercial harvesting of kangaroos in Australia.

There is certainly evidence for selective harvesting of larger/older animals within kangaroo populations, primarily because the economic performance of kangaroo harvesting enterprises is highly sensitive to variations in average carcase weight (Stayner 2007). Between 1997 and 2009 the total harvest in NSW comprised between 70 and 89% males. In the case of wallaroos, the commercial take is even more strongly biased towards males (almost 90%), because females rarely reach the minimum size dictated by licence and market conditions (Payne 2011). Despite the preference for larger males, it was reported that harvesters target a range of sizes above the minimum, especially when densities are reduced and there are fewer target animals (Payne 2011). There average weight of harvested animals supports this assertion (Table 2).

As reported in the last review (Olsen and Low 2006), studies on the potential effects of size-selective harvesting in kangaroos concluded that although there was potential for genetic consequences of harvesting within a closed population (Tenhumberg *et al.* 2004), the degree of mobility and geographic range of genetic populations of kangaroos would be sufficient to ensure that any localised effects could be countered by immigration (Hale 2004). So, the question remains: does the recent literature on this topic provide any basis for changing the previous conclusions? Probably not. In the big horn sheep example referred to above, the extent of selective harvesting pressure was probably much stronger than occurs in kangaroo populations. In addition, the population was small, isolated and had restricted potential for immigration (Coltman *et al.* 2003), thereby exhibiting characteristics akin to a closed population. As such, this probably represents a more extreme example, where prevailing management and biological factors combined to create strong selective pressure.

Overview

The lack of empirical and modelled evidence of the genetic impacts of current levels of harvesting in kangaroos is still apparent since last review (Olsen and Low 2006). However, there is a plethora of theoretical review papers discussing the potential effects of selective harvesting on desirable phenotypes in particular. Given the attention of this field throughout the last five years, it would be remiss of us to rule out the potential for genetic consequences of harvesting. While all of the available evidence at this point in time suggests that negative genetic effects are unlikely given current population conditions and harvest rates, kangaroo management plans should incorporate an element of genetic and phenotypic monitoring. As discussed in Allendorf *et al.* (2008) genetic monitoring may provide a vast amount of demographic information, warn of any potential losses of genetic variation, and identify responses of key regions of the genome to exploitive selection. Such monitoring will become particularly valuable over extended periods of time or where historical samples are available.

The species that is likely to be most sensitive to size-selective harvesting is the wallaroo. Wallaroos are more patchily distributed throughout their range, which has resulted in greater genetic differentiation between populations than in the other kangaroo species. The selective pressure on the population is also probably higher, as very few females are harvested and the average weight of harvested males is greater than for the other species, despite their lower live weight. As such, wallaroos may represent an ideal model to empirically assess the effects of selective harvesting in macropods. If there is no evidence of genetic effects in wallaroos, then they are also unlikely in the other three species.

Table 2. **Average carcase weight (in Kg) and corrected live weight of the four commercially harvested kangaroo species, compared with average weights (where available) and weight ranges reported for each species.**

Carcase weights represent averages for commercially harvested individuals between 1997 and 2009 (source: Payne 2011). Species weight ranges and means from Van Dyke and Strahan (2008).

	Eastern Grey		Red		Western Grey		Wallaroo	
	Male	Female	Male	Female	Male	Female	Male	Female
Average carcase weight	22.9	16.7	22.6	16.7	24.2	16	21.2	16.3
Corrected live weight*	35.2	25.7	34.8	25.7	32.6	25.1	37.2	24.6
Mean species weights			55	25				
Species weight range	19-85	17-42	22-92	17-39	18-72	17-39	7-60	6-28

* live weights were estimated assuming carcase weight represents 65% of live weight (N. Payne, pers. comm.)

7.2 Climate Change

The effect of climate change on species is a topic that has generated much interest over recent years. Climate change is expected to have substantial impacts on the environment, individual plants and animals and populations of species (Dunlop and Brown 2008). Key environmental effects that have been identified include increases in carbon dioxide, increasing temperatures, changes in rainfall, changes in the frequency, timing and severity of natural phenomena (e.g. floods, storms, heatwaves, fire) and rising sea levels, increasing sea temperatures and acidity (Dunlop and Brown 2008). Climate change may affect individuals by changing forage composition, seasonal events and behaviour (Dunlop and Brown 2008). Lastly impacts on populations of species as a result of climate change may occur by changing species abundance, distribution and genetics (Dunlop and Brown 2008).

Assessing the impact that climate change may have on kangaroo populations is fraught with difficulty as it usually relies on correlative evidence. An assessment of climate change and its likely effects on Australian environments was undertaken by Dunlop and Brown (2008). Overall, Australia is likely to become hotter, particularly during spring and summer and warming will be greater inland than on the coast. Predictions of rainfall are much more difficult, but it is likely that Australia will become drier. Seasonality of rainfall will also change, and rainfall is expected to become more variable and fall in more intensive events, making large storms and cyclones more severe. Changes in humidity, temperature, wind speed and rainfall are likely to cause a significant increase in high fire risk weather under climate change predictions. Expected increases in the number of days greater than 30°C and in storm frequency may also increase the risk of fire. Changes in the frequency, severity and seasonality of fire events are also likely to occur. Land use, water availability, vegetation structure and growing season are also likely to change as a result of changes in climatic conditions.

In order to try and determine the effects of such factors on kangaroo populations, studies modelling kangaroo population dynamics with reference to climatic predictors have been undertaken. Throughout the scientific literature, it is widely accepted that rainfall can be used as a predictor of kangaroo abundance and distribution, due to its expected effects on food availability. However, recent studies attempting to correlate rainfall with kangaroo population dynamics have produced varied results (Jonzen *et al.* 2005; Jonzen *et al.* 2010; Pople 2006; Pople *et al.* 2006; Pople *et al.* 2007; Ritchie *et al.* 2009) (See section 5). Lack of a clear link with environmental factors such as rainfall, make it exceptionally difficult to predict the response of kangaroos to climate change using the available models (Tuljapurkar 2010). Despite these limitations, there is no other way to predict the likely effects of climate change on kangaroo populations.

Ritchie and Bolitho (2008) used BIOCLIM models to determine the effect of predicted changes in temperature and rainfall on large macropods in northern Australia. This study provides evidence that climate change has the capacity to cause large-scale range contractions of kangaroos in northern Australia, and indicates that the distribution of kangaroos in this area is strongly associated with climatic gradients.

As previously discussed in section 5, Jonzen *et al.* (2010) used a stochastic environment model of female red kangaroos to predict the effect of changes in rainfall on survival and fecundity, taking into account current harvesting levels. Their principal finding was that any level of harvesting may be unsustainable if average rainfall drops by more than 10%. Although this study did not attempt to model the predicted effects of climate change per se, the results shed light on one potential outcome if climate change induces a reduction in rainfall throughout the commercial harvest zone.

Overview

Although there have been very few studies on the likely effects of climate change on kangaroo populations, the predicted effects of climate change on kangaroo populations are negative. It is anticipated that species ranges will contract in northern areas of Australia at least. Rainfall reductions in the order of 10% are likely to affect the sustainability of commercial kangaroo harvesting in some areas. More studies along the lines of the Ritchie and Bolitho (2008) study are required for commercially harvested kangaroo species in other areas of their range. Despite the acknowledged limitations of such population modelling, the large volume of work that has described kangaroo population dynamics over the last forty years means that we are in a much better position to predict the responses of kangaroos to climate change than we are for many other species. Although these modelling exercises cannot predict outcomes with certainty, they provide wildlife managers with an indication of the likely direction of population responses, and can therefore play a vital role in developing suitable monitoring regimes. The current annual population surveys and proportional quota system, along with the addendum to the current KMP (which provides provision for a halt to harvesting if populations fall below a critical threshold value), offer considerable protection for kangaroo populations in the event of significant declines in population densities in response to climate change. Indeed, the current kangaroo monitoring program is likely to provide a valuable source of long-term data capable of detecting significant long-term changes in kangaroo species density and range.

7.3 Drought

Droughts are known to have a detrimental effect on kangaroo populations. Olsen and Braysher (2000) concluded that rainfall is the single most important influence on kangaroo populations through its effect on plant productivity. In the most recent review, Olsen and Low (2006) noted that despite the capacity of droughts to substantially reduce kangaroo numbers, populations eventually recover, even with continued harvesting.

Australia experienced a major drought from 2001-2003 resulting in a significant decline in kangaroo numbers at the beginning of this century, reaching a nadir in 2005 (ACRIS Update 2009). Since 2005, kangaroo numbers have either plateaued or gradually increased in NSW. This trend is clearly shown in Figure 1 for each of the four commercially harvested species. But, the data in this figure is not based on a consistent area each year, so year-to-year comparisons cannot be made in most cases (as discussed in detail in section 3.1). To address this issue, we have compiled comparable temporal data for each kangaroo species by taking into account the total area for which population estimates were calculated, therefore giving an estimate of kangaroo abundance expressed as a density (i.e. number/km^2). There is a variable amount of readily available, temporally comparable data for each species, resulting in differing timeframes for each species.

Figure 4 shows the density of red kangaroos within the NSW commercial harvest zone from 1982 - 2010, which incorporates the droughts of 1981-83, 1991-93 and 2001-03. The 1981-83 drought resulted in a significant decline in red kangaroo numbers, to the lowest recorded population size for this area in 1984 (approximately 1.6 million animals or 3.2/km^2). Thereafter, the population steadily increased, peaking seven years later (approximately 4.4 million or 9.1/km^2). The 1991-93 drought caused a slight decline or stabilisation of population size, before significant declines were observed in response to the 2001-03 drought (minimum approximately 2.2 million animals or 4.3/km^2). Comparable data for eastern grey kangaroos is readily available from 1989 (Figure 5). Peak population densities for this species were observed in 1993 and 2003 (13.5 and 14.4/km^2 respectively), before significant declines were observed, presumably in response to the long drought periods. The lowest density was reported in 2005, with an estimate of 4.4/km^2. According to Figure 5, the eastern grey kangaroo population seems to have undergone a dramatic increase in size between 1992 and 1993 (from 5.8 to 13.5/km^2 within one year). However, there was a change in survey methodology at this point in time (Payne 2010) making direct comparisons of absolute numbers between those years invalid. The trend for western grey kangaroo populations is similar to that observed for eastern grey kangaroos. Population densities were relatively high leading into the 2001-2003 drought, peaking at 5.0/km^2 in 2002, before declining to a minimum of 1.3/km^2 in 2005 (Figure 6). Comparable data for wallaroos are not readily available, given the changes to the commercial harvest zone for wallaroos (Figure 2) and changes to survey methodology outlined in section 5.2.1.

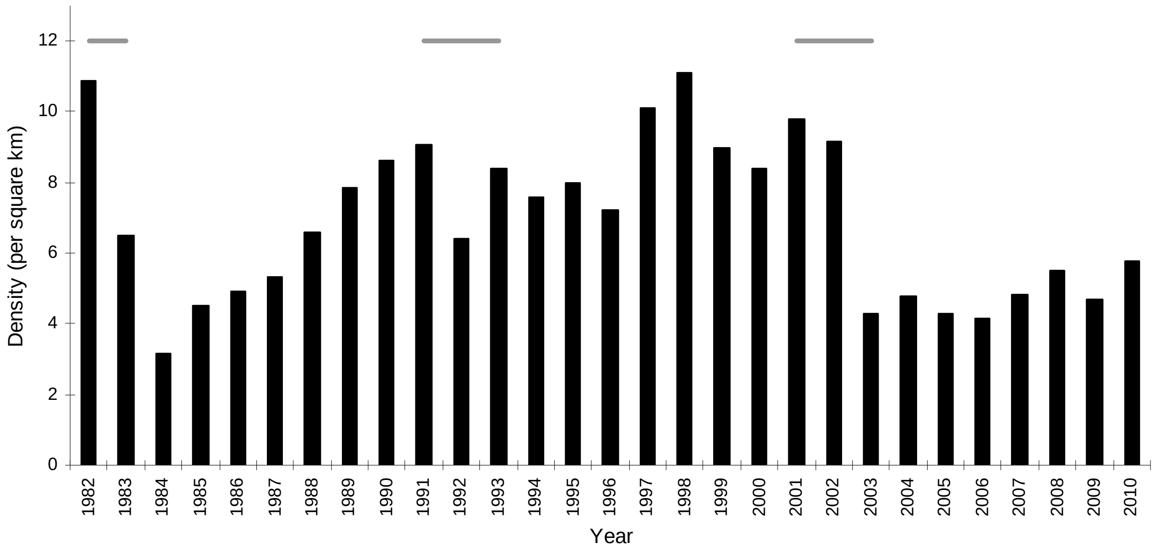

Figure 4. Red kangaroo population densities (kangaroos per km^2) in the commercial harvest zone of NSW in relation to the occurrence of major droughts (horizontal grey lines) in 1981-83, 1991-93 and 2001-2003.

Fixed wing survey methodology changed in 1993 and 2001, making direct comparisons between 1992 – 1993 and 2000 – 2001 invalid. For further details see: http://www.environment.nsw.gov.au/resources/nature/kmp/KMP2011QuotaReport.pdf

[Data supplied by the Kangaroo Management Program, Office of Environment and Heritage, Department of Premier and Cabinet (NSW), with densities calculated based on the size of the commercial harvest zone in each year]

All three kangaroo species seem to have taken longer to recover from this most recent drought. There have not been any published accounts of the long-term response of kangaroo populations to the 2001-03 drought in NSW, so the reasons for this prolonged recovery are unclear. As commercial harvesting quotas have not changed over this period of time, and there has generally been a decline in the percentage of the quota filled (Table 1), the delayed recovery from the most recent drought is unlikely to be related to harvesting practices. A cursory look at recent climatic data provides one possible explanation. The first decade of this century was the warmest on record. Many areas of southeastern Australia (including NSW) experienced a record sequence of below-average rainfall years (termed the “long dry”), for example, 2010 was the first year of above average rainfall in the Murray-Darling basin since 2001 (Bureau of Meteorology 2010, 2011). This multi-year meteorological drought may have retarded the capacity of kangaroo populations to recover. In 2010 the majority of NSW experienced “very much above average rainfall” and this was the third wettest year on record (Bureau of Meteorology 2011). If our hypothesis is correct, we would expect kangaroo population densities to increase over the coming years in response to the end of the “long-dry”.

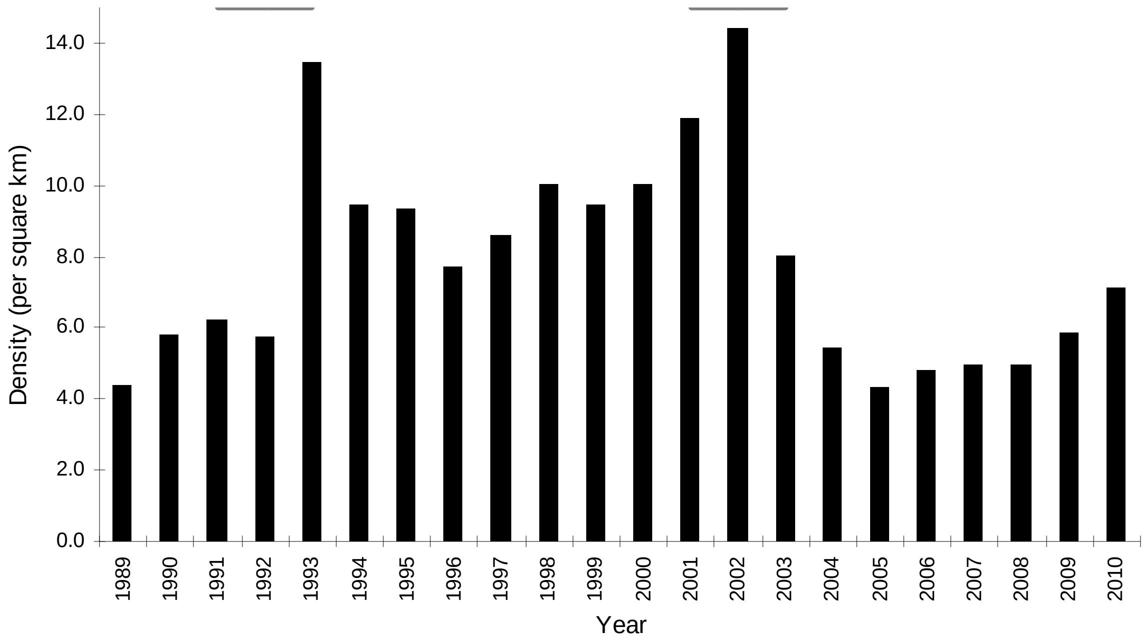

Figure 5. Eastern grey kangaroo population densities (kangaroos per km^2) in the commercial harvest zone of NSW in relation to the occurrence of major droughts (horizontal grey lines) in 1991-93 and 2001-2003.

Fixed wing survey methodology changed in 1993 and 2001, making direct comparisons between 1992 – 1993 and 2000 – 2001 invalid. For further details see: http://www.environment.nsw.gov.au/resources/nature/kmp/KMP2011QuotaReport.pdf

[Data supplied by the Kangaroo Management Program, Office of Environment and Heritage, Department of Premier and Cabinet (NSW), with densities calculated based on the size of the commercial harvest zone in each year, including the addition of new KMZ 16, 48 and 49 in 2004 and 2009]

Since the last review by Olsen and Low (2006), the majority of studies investigating population-level responses to drought have involved the development of complex predictive models (already discussed in section 5), with the exception of Coulson (2006).

Coulson (2006) reported on the demographic responses of western grey kangaroos to severe drought in the Victorian Mallee. Before the drought, which occurred from late 2001-mid 2003, there was a high density of kangaroos in the study area. In mid 2002, approximately six months into the drought, a non-selective cull sample was heavily female biased (79%). Only 26% of females had young and these young were female biased. In 2003, only two young-at-foot were observed in the study area. Contrary to previous studies, animals that died during the drought were predominantly middle aged. However, the age structure before the drought was unknown, so it was not possible to identify age classes that were most susceptible to drought (Coulson 2006).

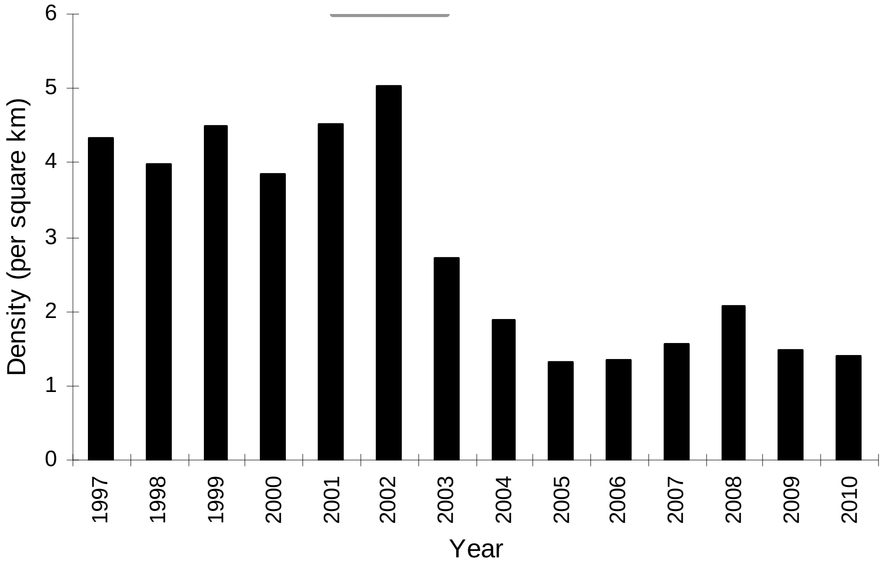

Figure 6. Western grey kangaroo population densities (kangaroos per km^2) in the commercial harvest zone of NSW in relation to the occurrence of major drought (horizontal grey line) in 2001-2003.

Fixed wing survey methodology changed in 1993 and 2001, making direct comparisons between 1992 – 1993 and 2000 – 2001 invalid. For further details see: http://www.environment.nsw.gov.au/resources/nature/kmp/KMP2011QuotaReport.pdf [Data from Payne 2010].

A number of other studies have discussed the physiological responses of individuals to drought.

Munn and Dawson (2008) investigated the physiological mechanisms that drive high mortality rates in juvenile red kangaroos during drought. They found that juvenile animals had higher energy and water requirements for growth and thermoregulation than adult animals, and that these requirements could not be met on poorer quality (high fibre) forage during drought.

Dawson *et al.* (2007) discussed the mechanisms by which red and eastern grey kangaroos are able to tolerate hot arid conditions. Both species were seen to exhibit adaptive heterothermy, a variable body temperature, which is believed to be an adaptive response to living in hot conditions. Red kangaroos were less affected than eastern grey kangaroos, as evidenced by their smaller change in body temperature and evaporation levels.

Underhill *et al.* (2007) determined the need for red kangaroos to supplement dietary water intake during a period of drought from February to July 2002. They found that larger animals needed to drink throughout the whole period, while smaller animals did not need to supplement their dietary intake until conditions became very dry. This is due to the fact that water requirements increase with body mass, while energy requirements scale at a lower rate. As female red kangaroos are smaller than adult males, it can be assumed that female red kangaroos are able to survive periods of water shortage better than their male counterparts, which may explain previous observations of male biased mortality during extended dry periods. There were some limitations to this study, related to limited numbers of observations and the use of extrapolated values from previous studies for some variables. Nonetheless, the trends observed in this paper warrant further investigation.

Fensham and Fairfax (2008) identified that the density of red kangaroos may be limited at a distance of greater than 7km from a water point, which was much greater than that identified for cattle or sheep. Overall, red kangaroos are not known to exhibit strong water-focused grazing behaviour except in hot and dry conditions.

Overview

Since the last review (Olsen and Low 2006) we have again observed the response of kangaroos to drought. Kangaroo populations in NSW have experienced significant declines throughout the last decade and they have been slow to recover to pre-drought levels. While it is anticipated that kangaroo populations will increase in response to the heavy rains that were experienced in 2010, further research should investigate the factor(s) that limited population recovery over the last decade. The modelling work described in section 5 highlights that there is still much that we don't understand about the relationship between kangaroo densities and rainfall. The research reported in this section helps to shed light on the physiological processes that drive demographic shifts in response to drought. Research on the physiological tolerance to drought will become even more valuable as we attempt to predict the effects of climate change on species distributions.

7.4 Interactions between Kangaroos and Other Species

Interactions between species may pose a threat to populations by mechanisms such as predation and competition. In the previous review, Olsen and Low (2006) concluded that dingoes can limit kangaroo populations. The relationship between dingoes and kangaroos has received more attention over the last five years.

Letnic and Koch (2010) investigated the effect of dingo exclusion on mammal communities by comparing mammal assemblages on either side of the dingo fence. Mammal assemblages differed markedly on either side of the dingo fence, and the effect of dingoes on the abundance of mammal species was seen to scale with body size. This indicates that dingoes have a role in regulating mammal populations in arid Australia. Red kangaroos and grey kangaroos were more abundant in the absence of dingoes. However, other land use factors such as sheep grazing, kangaroo harvest and a greater density of artificial watering points were also associated with the absence of dingos and may explain some of this result. Fillios *et al.* (2010) also discussed kangaroo abundance on either side of the dingo fence and found similar results to Letnic and Koch (2010) in terms of kangaroo abundance. They also observed a dramatic increase in animal remains in the absence of dingoes. Purcell (2010) reported a novel observation of dingoes attacking a swimming eastern grey kangaroo, while Allen (2010) reported incidental observations of dingoes scavenging cattle, red kangaroo, wedge tailed eagle (*Aquila audax*) and other dingo carcasses during a chronic food shortage.

Interactions with other animal species may also come in the form of competition. Kangaroos may compete with a range of native and introduced herbivores. Davis *et al.* (2008) examined the diets of introduced hog deer (*Axis porcinus*), native swamp wallabies (*Wallabia bicolor*), European rabbits, eastern grey kangaroos and native common wombats (*Vombatus ursinus*). Overlap in food use by the five herbivores was high, and in the case of kangaroos, particularly high with rabbits and wombats. This high level of overlap suggests that there is a high potential for competition for food resources between these species particularly if resources are limiting (for example in times of drought).

The interactions of kangaroos with domestic livestock (in particular sheep), is an area which has caused considerable debate over the years, with many pastoralists assuming that competition with kangaroos is causing reduced stock production and carrying capacity. Munn *et al.* (2010) compared the feeding biology of the red kangaroo with sheep. They found that while both species spent approximately the same amount of time grazing each day, kangaroos ingested less food than sheep. Kangaroos also tended to forage in the morning and the evening and rest during the middle of the day, while sheep fed in short bursts, and spent additional time ruminating. Water use by kangaroos was 13% of that of sheep, and in addition kangaroos were able to concentrate their urine more effectively. The larger energy requirements for rumination in sheep may contribute to their higher water requirements. When taking into account these differences in physiological ecology it can be assumed that kangaroos are likely to have less grazing impacts than sheep.

The level of impact that kangaroos have on the arid rangelands is summarised in a review by Dawson and Munn (2007). It is currently widely accepted that a kangaroo has a competitive impact equivalent to 0.7 sheep (in dry sheep equivalents DSE), but recent data suggests that the actual value is approximately 0.4 DSE when taking body size into consideration. They concluded that the competitive impacts of kangaroos on stock were normally not an issue in the arid rangelands when vegetation conditions are good, a conclusion also drawn by last review (Olsen and Low 2006). However, complex situations occurring during times when pasture conditions are poor may complicate things, for example degradation of vegetation may increase dietary overlap and hence increase competition between the species. Since the publication of Dawson and Munn's review (2007), Munn *et al.* (2009) have calculated an updated DSE of 0.35, by comparing the field metabolic rate of the red kangaroo with the domestic sheep. Such results do not alter previous conclusions that kangaroos and sheep generally do not compete to a significant degree.

Overview

As reported in the last review, dingo predation may limit kangaroo populations, but the correlative nature of many studies make it difficult to determine the relative effect of dingoes and other land-use variables on kangaroo populations. There is still no conclusive proof of a regulatory effect. Kangaroos may compete with wombats and rabbits, especially if resources are limiting, but there is little evidence of competition between kangaroos and sheep. These conclusions support shifts in management from culling kangaroos for reasons of damage mitigation (i.e. competition with sheep), to the idea that kangaroos can be a sustainable resource that may be exploited.

7.5 Habitat Loss and Modification

Olsen and Low (2006) noted that range expansions have been observed for three of the commercially harvested kangaroo species. Eastern grey kangaroos have expanded westward and western grey kangaroos have shifted northwards into more arid areas, presumably in response to an increase in artificial watering points, while red kangaroos have expanded eastwards into more mesic areas, possibly in response to land clearing (Pople 2006).

Woinarski *et al.* (2006) reported on the change in vertebrate fauna in central Queensland over a 30 year period which coincided with broad scale vegetation clearance. They detected a significant decline in the numbers of eastern grey kangaroos and euros (a sub species of the common wallaroo), quantified using spotlight surveys. These declines were probably not related to vegetation clearance, as significant declines were also observed in uncleared sites. It is possible that these declines may be more related to sampling artefacts (e.g. insufficient precision, changes in climatic conditions at the time of the surveys), rather than regional declines in abundance. This study highlights the need for rigorous survey design when conducting long-term monitoring of wildlife populations.

Increased urbanisation and the building of roads may cause the death of individual kangaroos in road incidents and impact upon local populations. Ramp and Rodger (2008) identified kangaroos and wallabies as the animals most commonly involved in collisions in NSW, accounting for 47% of collisions. While these crashes occurred across the state, a number of clustered hotspots were identified along the eastern coast. In a study along the Silver City Highway in Fowlers Gap, NSW, the road was seen to influence the spatial distribution of kangaroos and was associated with increased kangaroo mortality. Road kill of kangaroos, however was not seen to affect population demographics or community composition (Lee and Croft 2008). A study conducted by Kloecker *et al.* (2006) on a section of outback highway in far western NSW, similarly showed that there was no effect on population demographics with the age structure of road killed kangaroos being similar to age structures of source populations, with no sex bias.

Overview

The general consensus seems to be that habitat modification and clearance has generally been beneficial for kangaroos, facilitating range expansions in three of the commercially harvested species. The increase in the number of roads and road usage may result in more individual animals being killed from collisions, but there is no evidence to suggest that roads affect population demographics or sustainability.

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