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Kangaroo management options IN THE MURRAY-DARLING BASIN

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MURRAY-DARLING BASIN COMMISSION

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MURRAY-DARLING BASIN COMMISSION

NSW Agriculture

Foreword

Consistent with the Murray-Darling Basin Commission's vision of integrated catchment management, the Commission initiated research in the mid 1990s to look at ways of reducing total grazing pressure in the rangelands. Managing the impacts of grazing by kangaroos on pastoral land was one of the key challenges identified. However, balancing the differing objectives for kangaroo management of the four major interest groups – pastoralists, kangaroo harvesters and processors, non-government conservationists and wildlife management agencies – has presented a challenge to effective policy and implementation. The Commission identified that investment in new science-based kangaroo management strategies that satisfied these multiple objectives was needed.

The project *Evaluating alternative management strategies for kangaroos in the Murray-Darling Basin* was undertaken by NSW Agriculture in partnership with the Murray-Darling Basin Commission from 1998 to 2003. The research looked at the effect of harvesting on the biology of kangaroo populations, the response of the resources they consume, and the potential effect that alternative harvesting strategies may have on the commercial industry. This work complements the earlier Commission project *Total grazing pressure in the mulgalands* led by Queensland Department of Primary Industries in partnership with NSW Agriculture from 1997 to 1999.

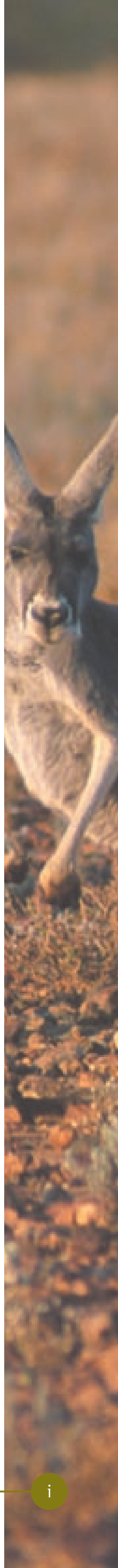
The project developed three models – a 'temporal' model to predict the trajectory of kangaroo populations over time, a 'spatial' model to estimate the distribution of harvest over the landscape in response to economic factors and kangaroo density, and a 'genetic' model to explore the potential effects of size-selective harvesting on the gene frequency of kangaroo populations and the capacity of unharvested refuges to counteract these effects.

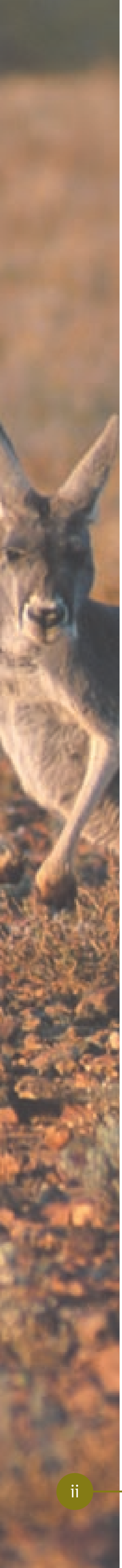
This work has shown that there are options for managing kangaroo populations in the rangelands that will broadly meet the objectives of all the major stakeholder groups. The need for refuges to protect kangaroo populations from the effects of size selective harvesting was found to be questionable, with migration (and therefore gene flow) between harvested and non-harvested areas and the extensive 'economic refuges' created as a consequence of normal commercial operations.

The project steering committee comprising all four major interest groups has ensured that the results delivered by the research are well grounded. Findings have been considered in the recent reviews of kangaroo management programs both at the Commonwealth and State levels. The recommendations, including overcoming impediments to implementation, developed in consultation with the stakeholder form a valuable basis for future policy discussions on the future of kangaroo management as part of the total grazing pressure in the rangelands of the Murray-Darling Basin.

Warwick McDonald

Director, Integrated Catchment Management Business





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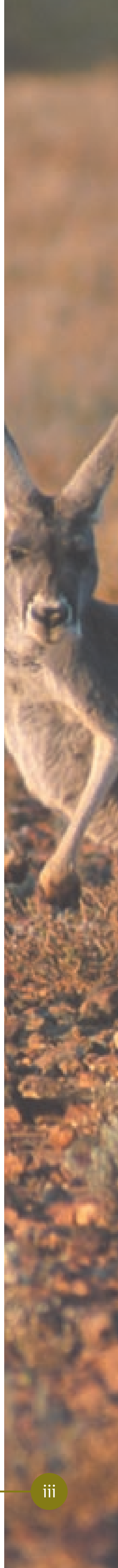
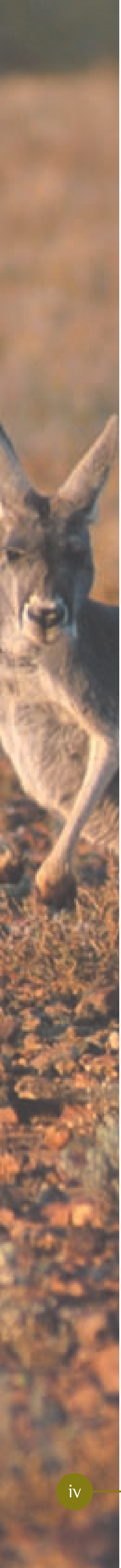




Acknowledgments

This work was undertaken by New South Wales Agriculture with funding from the Murray-Darling Basin Commission's Strategic Investigations and Education Program through project D8003 (Evaluation of alternative management strategies for kangaroos in the Murray-Darling Basin). Some 60 pastoralists, conservationists, scientists and administrators contributed to the workshop discussions that shaped the development of the project, and considered its results. Foremost, however, were the members of the project steering committee who met on 8 occasions over 3 and a half years. These included Mr Peter Alexander, Mr Ross Blick, Dr David Butcher, Mr Wayne Cornish, Dr David Freudenberger, Mr Joshua Gilroy, Mr John Kelly, Dr Geoff Lundie-Jenkins, Dr Judy Messer, Mr Jeff Newton and Dr Bob Crouch. Ms Lisa Robins, Dryland Coordinator for the Murray-Darling Basin Commission provided constructive advice and sensible oversight throughout the project.

Particular thanks are due to the property owners and kangaroo harvesters who provided access to their properties, extended hospitality during field work and allowed team members to observe their operations in fine detail: Ken and Viv Turner, John and Janet Houghton, John Edmondston, Bob and Diana Browne, Bernard O'Shannessey, Robert Kemp, Chris Paull and Barry Brown. Matt Gentle and Greg Jones provided competent assistance with field work. Toni George's assistance with arrangements for meetings and workshops was much appreciated.

Executive Summary

Background

High total grazing pressure in the rangelands of the Murray-Darling Basin, including from domestic livestock, kangaroos and feral goats, has been a chronic problem for many decades. Repeated calls from pastoralists for increased kangaroo harvesting to ease total grazing pressure have been opposed by those concerned about the possible effects on kangaroo populations. The main focus of this project was therefore to evaluate how well particular kangaroo management options might satisfy a range of interests.

The project has produced both basic and applied results from which stakeholders have formulated recommendations for future kangaroo management programs, and related R&D. These are thus put forward with confidence that their adoption can produce benefits both for species conservation, and for the industries that depend on, or co-exist with, kangaroos in the Murray-Darling Basin.

Taking a participatory approach

A participatory approach was taken throughout the project, with representatives from key stakeholder groups, including pastoralists, non-government conservationists, kangaroo harvesters and processors, and wildlife management agencies, closely involved in shaping its development. Ongoing dialogue with these groups allowed stakeholder objectives to be defined, management options to be evaluated from multiple perspectives, and specific issues of concern to be investigated.

Workshops were a key feature of stakeholder involvement. At the first workshop, held in February 1999, stakeholder representatives defined their aspirations for kangaroo management and identified strategies that should be evaluated in the course of the project. At the second, held in July 2002, substantially the same group reconvened to consider the results. In the interim, stakeholder representatives on the Project Steering Committee provided overall direction and advice for the research team, and evaluated interim findings.

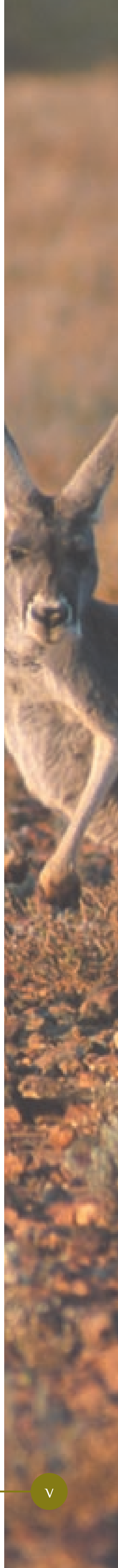
Defining and evaluating management strategies

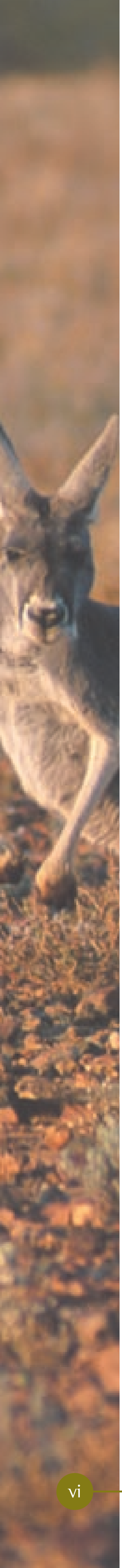
Attention focussed on management strategies identified by stakeholder representatives that could be addressed within the constraints of the project. These mostly involved various harvest constraints (e.g. commodity value, kangaroo age or kangaroo density) combined with varying harvest rates (or quotas) and harvest sex ratios (or male bias). These combinations resulted in 891 alternatives that required, for evaluation, a capacity to predict the temporal trajectory of kangaroo populations – a 'temporal' model. A few strategies related to spatial rather than temporal aspects of the harvest; their evaluation required a 'spatial' model that estimated the distribution of harvesting over the landscape in response to economic factors and kangaroo density. Finally, a 'genetic' model was developed to explore the potential effects of size-selective harvesting on the gene frequency of kangaroo populations, and the capacity of unharvested refuges to counteract these effects.

Key findings

The results of modelling undertaken during this project indicate that ways do exist to manage kangaroo populations to the satisfaction of all stakeholders. These management strategies will require the joint manipulation of harvest rate and harvest sex ratio. Under current economic conditions in the kangaroo industry, the best compromise between stakeholder interests would be achieved by a harvest rate of 20 per cent with males comprising 70 per cent of the harvest. However, a range of management objectives, or kangaroo densities, may be achieved by jointly varying these parameters. The rule of thumb is that density will decrease with increasing harvest rate and decreasing male bias. Tactical application of this rule of thumb would allow a range of management objectives to be achieved as required either through time or across the landscape.

Implementation of such a program, however, would require some attitudinal change on the part of all stakeholders. Pastoralists, for example, would need to accept that the reduction of kangaroos to very low densities (<5 per km2) over large areas is neither commercially feasible, ecologically defensible, nor economically justified. The kangaroo industry would need to accept





that harvest practices could be modified to produce a kangaroo population more acceptable to pastoralists without economic damage to the industry. Conservationists would need to accept that current harvest practices present no threat to species conservation and that the establishment of 'economic refugia' substantially reduces concerns about any imminent threat to the genetic composition of the population. Finally, wildlife management agencies would need to be prepared to establish and administer programs that are more prescriptive than at present.

Although the models developed in this project allow specific predictions to be made, the actual response of kangaroo populations to any change in management strategy should be tested using robust experimental methods. Combining an active adaptive management procedure with the hypotheses derived from the temporal model (in particular) should promote rapid improvement in the management of harvested kangaroos to the satisfaction of all stakeholders.

Recommendations

The key findings of this project were discussed by stakeholders at the second workshop in July 2002. Consideration of these findings led to a number of recommendations directed to government agencies, kangaroo and pastoral industry organisations, non-government organisations and research funders and providers. These recommendations, summarised below, represent the distillation of the project:

1. Evaluate the practicality of managing both the harvest rate (quota) and the sex ratio in the harvest for individual species.
2. Develop collaborative programs to better inform relevant stakeholders and the wider community of the scientific evidence supporting the sustainability and benefits of the kangaroo industry, and its management of animal welfare.
3. Establish 'non-selective shooting' or 'no-shooting' areas through incentive schemes and other innovative strategies.
4. Identify opportunities to reduce the complexity and cost of current kangaroo management programs in the light of findings that the commercial industry is not viable at kangaroo densities that might threaten the conservation of the species.
5. Evaluate and promote options for the incorporation of kangaroos into viable rangeland businesses.
6. Develop a generic framework under ISO 14001 for development of Environmental Management Systems within the kangaroo industry that address environmental and animal welfare issues.
7. Establish the capacity within both Commonwealth and State agencies to effectively and independently manage the commercial and regulatory aspects of kangaroo management programs.
8. Develop a program of funded R&D to address the new knowledge requirements identified by the project.

Background

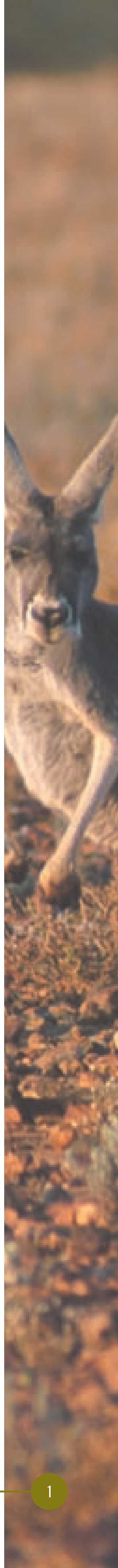
Despite decades of biological and historical research, population monitoring and official enquiries the management of kangaroos remains one of the most controversial issues in wildlife management both in Australia and abroad. For those whose inclinations or lifestyle promote more than a passing interest, kangaroos are often a cause of frustration, conflict or concern. Pastoralists in the sheep rangelands often see kangaroos as competitors with livestock for forage, as an uncontrolled herbivore restricting their capacity to manage land in a sustainable way, or as a cause of physical damage to property infrastructure. For kangaroo harvesters and processors they are the basis of a viable industry with potential for growth and the natural clean-and-green advantage of products harvested from the wild. Tourist operators may also view them as a resource but one whose value lies in non-consumptive uses. For some conservationists their management represents a challenge to apply the principles of ecologically sustainable development. For others, their status as wildlife and protected fauna renders any form of consumptive utilisation entirely unacceptable.

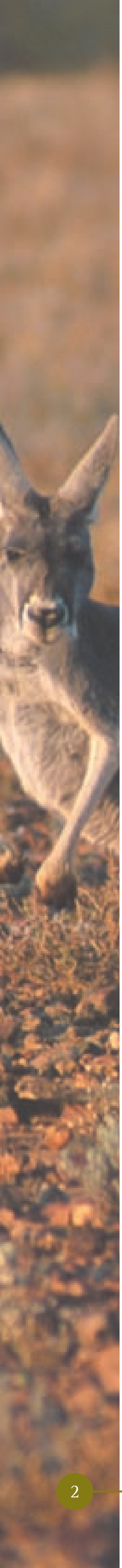
All of these interests cannot be completely reconciled. However, research summarised in this report has identified options for future management that have potential to reduce current conflicts.

The studies described here had their origins in concerns of pastoralists, scientists and administrators for the management of total grazing pressure in the rangelands of the Murray-Darling Basin. Subsequently, in the course of discussions with stakeholder representatives and within the research team, the focus shifted towards an examination of the extent to which particular management options might satisfy a range of interests. The result has been a participative R&D process in which stakeholders, particularly through the project steering committee, have been closely involved with the work in progress and have helped shape its development. This ongoing dialogue has allowed stakeholder objectives to be defined, management options appropriately evaluated, specific issues of concern investigated and outputs considered from multiple perspectives.

The findings are therefore put forward with confidence that their incorporation into future kangaroo management programs can produce benefits both for species conservation and for the industries that depend on, or co-exist with, the kangaroos of the Murray-Darling Basin.

Map showing locations of four field sites within the Murray-Darling Basin





Defining stakeholder aspirations

Major stakeholders in the kangaroo debate are represented by four broad groups – pastoralists, non-government conservationists, kangaroo harvesters and processors, and wildlife management agencies. Differences may be readily recognised within these groups. The views of non-government conservationists, for example, range from tolerance of commercial harvest under strict regulation to rejection of commercial utilisation under any circumstances, and from a primary focus on habitat protection to concern principally for individual species. Views that reflect the ideals of animal liberation may also be included in this broad group. However, as supporters of this philosophy oppose any manipulation of the population they will not be considered further. Similar divergence of opinion may be found among the other broad groups. Kangaroo harvesters, for example, may not always consider their interests to be coincident with those of processors, despite some obvious commonality. Pastoralists differ in their opinions about the magnitude of the kangaroo 'problem' although few would be entirely unconcerned.

Given this diversity of opinion it is difficult to capture succinctly the aspirations of stakeholders, even in qualitative terms. Nevertheless, it became apparent early in the project that any attempt to evaluate alternative management strategies required some understanding of what these various groups wished to achieve by kangaroo management. Furthermore, it was necessary to express these aspirations in biological or ecological terms, and if possible quantitatively.

The first major activity of the project was therefore a workshop that sought to identify these aspirations and to propose strategies that might achieve them (Hacker and McLeod 1999, Hacker *et al.* 1999). Participants included several representatives of each of the four major stakeholder groups, together with wildlife biologists who provided technical input to the discussions. At the workshop, stakeholders initially worked in separate groups to formulate and present their aspirations. A second round of discussions followed in which each group considered its position in the light of aspirations proposed by other stakeholders. During this round, groups were asked to look for common ground and opportunities for compromise, although consensus was not expected. This process proved to be effective and the clear recognition of stakeholder aspirations led to constructive dialogue rather than confrontation.

Each group identified numerous aspirations. Some of these were ecological – related to aspects of the biophysical system – and others were non-ecological – related more to matters of economics, policy or administration. Some, particularly in the non-ecological category, were beyond the scope of the project but were flagged for future reference. These are listed in Appendix 1. Others were essentially management strategies and were considered as such. Those aspirations that could be stated as objectives[1], and addressed to some degree by the project, are summarised below.

Pastoralists

1. Kangaroo density maintained at 3–5 kangaroos/sq km, depending on land capability.
2. Kangaroo density (expressed as dry sheep equivalents, DSE) maintained at 5–30% of the estimated safe livestock carrying capacity, depending on land capability. (Note: this is an alternative to objective 1 above and is intended to indicate the density of kangaroos that can be carried in addition to the estimated safe carrying capacity for livestock.)
3. 'Improvement' in range condition through reduced kangaroo density (while maintaining the option to increase kangaroo density if required, and without impact on the genetic diversity of the kangaroo population).

Non-government conservationists

Kangaroo management must be consistent with the principles of ecologically sustainable development and should include:

- an adaptive management approach
- creation of refugia
- creation of baseline and non-harvest areas (for future population comparisons)
- maintenance of adaptive genotypes
- understanding of the potential effects of climate changes (for example, temperature and rainfall) on kangaroo population dynamics.

1 While workshop participants stated these objectives they do not necessarily represent the official position of any stakeholder organisation.

Kangaroo industry

1. Full-time professional harvesters are able to harvest 5000 kangaroos of greater than 20 kg carcase weight/annum.

2. Large, medium and small kangaroos can be harvested in roughly equal numbers from a population of moderate density (Note: a population of moderate density is one from which 50 animals can be harvested in 7 hours of actual shooting, including field processing.)

3. A harvester can harvest, in an ecologically sustainable manner, 50 kangaroos of greater than 20 kg body weight in 7 hours of actual shooting (including field processing). (Note: This objective is an alternative to 2 above rather than a third objective.)

Government wildlife management agencies

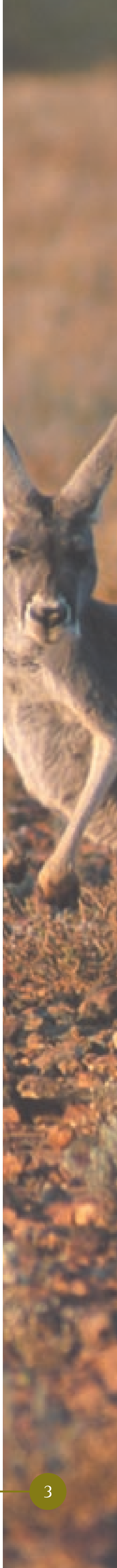
1. Kangaroo populations are maintained at levels that do not threaten remnant vegetation. (Note: this objective requires the simultaneous establishment of vegetation conservation targets.)

2. Kangaroo grazing pressure is reduced to low levels (say less than 5/sq km) for 10–30 years. (Note: this objective is related to 1 above and requires the simultaneous establishment of soil and vegetation recovery criteria.)

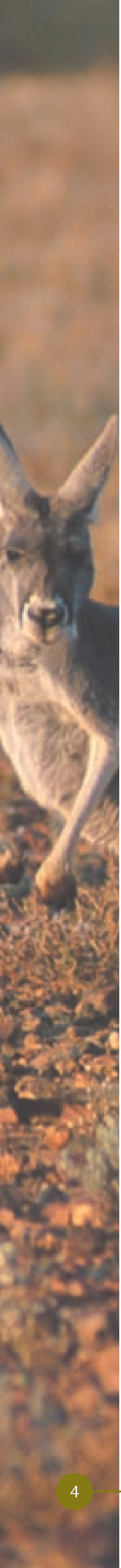
3. Kangaroos are conserved across Australia, requiring as a minimum that:

- kangaroo populations are conserved in every region
- viable populations[2] are distributed across each region.

4. Landholders receive economic benefit from kangaroos on their properties equal to the dry sheep equivalence of the population.



2 'Viable populations' are taken to mean populations that would not qualify for the International Union for the Conservation of Nature (IUCN) Red List categories of 'Vulnerable' or 'Near Threatened' according to the criteria approved by the 40th meeting of the IUCN Council, 30 November 1994.



Defining and evaluating management strategies

Following the establishment of stakeholder objectives, workshop participants discussed the management strategies that the project might evaluate. Suggested strategies fell broadly within the areas of:

- harvest administration – how licences and quotas are allocated
- harvest methods – intensity of harvesting, presence or absence of restrictions
- harvest economics – the relative prices of various kangaroo products
- other – a variable group that included alternative methods of managing kangaroo density (for example, use of fences or the role of dingoes).

From these suggestions, and subsequent discussions with stakeholder representatives within the project steering committee, a range of management strategies amenable to detailed study was defined. Not all strategies suggested by workshop participants could be evaluated. Those that were beyond the scope of the project are listed in Appendix 1.

Evaluation of most strategies required a capacity to predict change in kangaroo abundance and population structure over time – a temporal model – and to express the results in terms of performance indicators that reflected stakeholder objectives. Strategies requiring this approach are listed in Table 1(a). Performance indicators, derived from model outputs, are listed in Table 1(b).

Evaluation of the remaining strategies required a capacity to examine the likely distribution of harvest effort over the landscape – a spatial model. Strategies requiring this approach are listed in Table 2.

Finally, evaluation of the likely impact of harvesting on the genotypic composition of kangaroo populations, a concern expressed by non-government conservationists in particular, required development of a genetic model. This model was used to examine the potential effects of both size-selective harvesting and the establishment of refugia (see Table 2).

Table 1. Management strategies and performance indicators.
(a) Management strategies evaluated by assessing population changes over time using the temporal model.

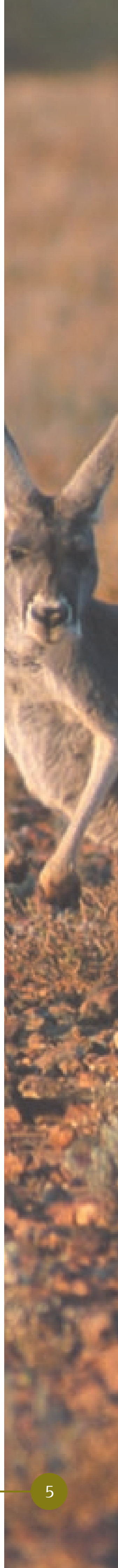
Group	Strategy*	Comment
Current commercial harvest	Low value products	These strategies evaluate the implications of current practices under a range of economic conditions. Value of kangaroo products is reflected in the rate at which the allocated quota (or harvest rate) is taken over the year. For low value products the quota is distributed evenly over the year but harvest offtake is only three-quarters of the available quota. For current value products the quota is distributed evenly over the year and fully taken. For high value products the quota is distributed over the first two seasons of the year (summer and autumn) and fully taken.
	Current value products	
	High value products	
Age-based harvest	No harvest of animals ≥10 yrs	Regulations are imposed to protect either the old (large) or young (small) animals in the population.
	No harvest of animals ≤1.5 yrs	
	No age restriction	
Density-based harvest	Above 0/sq km	Regulations are imposed to prevent harvest below specified target densities. Above the target density, harvest is regulated in a similar manner to the current value products strategy above.
	Above 5/sq km	
	Above 15/sq km	

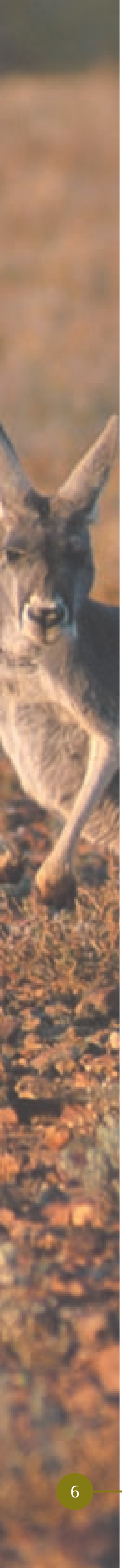
* Strategies were evaluated for all combinations of annual harvest rate (varying from 0–90%, in 10% increments) and male bias (varying from 0–100% of males in the harvest, in 10% increments)

(b) Performance indicators for evaluation of model output against stakeholder objectives.		
Number	**Indicator**	**Comment**
1	P(TSDM) $\geq$ 300kg/ha	Probability that total standing dry matter will be $\geq$300kg/ha, the threshold for competition between kangaroos and sheep (Short 1987).
2–4	P(male kangaroo density) $\leq$5/sq km P(female kangaroo density) $\leq$5/sq km P(total kangaroo density) $\leq$5/sq km	Probability that kangaroo density will be $\leq$5/sq km. A measure of the success of the strategy in reducing the kangaroo population to levels desired by pastoralists.
5	P(quasi-extinction)	The probability that the density of a harvested population would be less than the minimum density predicted for an unharvested population subject to identical climatic (rainfall) variation (see Ginzburg *et al.* 1982).
6	Similarity index	An index of the similarity, in terms of structure and density, of the harvested population to an unharvested population. The index is the Bray-Curtis measure described in Krebs (1989).
7–9	Mean male kangaroo density Mean female kangaroo density Mean total kangaroo density	A measure of the overall population level (animals/ha).
10–12	Mean standard deviation of male density Mean standard deviation of female density Mean standard deviation of total density	A measure of the variability of the kangaroo population over time, calculated as the mean standard deviation over 100 individual runs of each management option.
13	Mean total standing dry matter (TSDM)	A measure of pasture biomass available for other herbivores, calculated as the mean level of TSDM (kg/ha) over 100 individual runs of each management option.
14	Mean standard deviation of TSDM	A measure of the variability of pasture biomass available for other herbivores over time, calculated as the mean standard deviation over 100 individual runs of each management option.
15–17	Mean male yield Mean female yield Mean total yield	The average yield of kangaroos (kg/ha/quarter).
18–20	Mean standard deviation of male yield Mean standard deviation of female yield Mean standard deviation of total yield	A measure of the variability of yield over time, calculated as the mean standard deviation over 100 individual runs of each management option.
21	Mean area (sq km) required to harvest 25,000kg dressed weight per quarter	A measure of the profitability of the population for harvesters. Assumes a harvester requires 5000 animals of 20kg average carcase weight per annum.
22	Mean consumption of safe (livestock) grazing capacity (SGC)	Average annual forage demand (kg/ha) of the kangaroo population expressed as a percentage of the safe livestock carrying capacity. Safe livestock carrying capacity is calculated as 17% of the average annual biomass production per ha (Johnston *et al.* 1996).
23	Mean standard deviation of SGC	A measure of the variability of SGC, calculated as the average standard deviation over 100 individual runs (each of 100 years) of each management option.
24	Mean recovery time index	An index of the time required, after harvesting ceases, for the structure and density of a harvested population to equal that of an unharvested population (years; populations that failed to recover within 50 years were assigned an arbitrary value of 401).
25	Mean minimum density (animals/ha)	A measure of the combined effects of harvesting and drought.
26	Mean maximum density (animals/ha)	A measure of the combined effects of harvesting and good seasons.
27	Mean age of unharvested males (yrs)	—
28	Mean age of unharvested females (yrs)	—
29	Mean age of unharvested population (yrs)	—
30	Mean age of harvested males (yrs)	—
31	Mean age of harvested females (yrs)	—

Table 2. Management strategies evaluated by analysis of the distribution of harvesting over the landscape using the spatial model.

Strategy	Comment
Use of individual transferable quotas	Quotas are allocated to landholders and are transferable. Similar to the current South Australian situation.
Use of individual, non-transferable quotas	Quotas are allocated to landholders and are non-transferable. Similar to the current New South Wales situation.
Use of a non-allocated, total allowable harvest quota	Quota is allocated competitively among harvesters, with no allocation to individual landholders. Similar to the current Queensland situation.
Creation of refugia or non-harvest areas	This is an objective for non-government conservationists, but can also be considered a strategy.
Maintain kangaroo density at 3–5/sq km	To be evaluated in terms of impact on the kangaroo industry.





Data collection

Development of both the temporal and spatial models was based on data collected from field sites in western New South Wales and south-west Queensland. Available models of kangaroo population dynamics were considered incapable of providing the explicit treatment of population age or sex structure, and harvest composition, required for the evaluation of the management strategies outlined above. No model was available describing the spatial distribution of harvest effort.

Data collection thus aimed to estimate parameters, or establish relationships, required for development of the physiologically structured temporal model, and the spatial model, where these could not be sourced from the literature. Estimates were required of age- and sex-specific survivorship of kangaroos, reproductive output (females only) and kangaroo density (over properties and in specific habitats). In addition, the operation of harvesters was quantified, including harvest bias as a function of kangaroo weight and sex, harvester functional response (offtake as a function of kangaroo density) and constraints on time and movement.

The animals

Three of the commercially harvested kangaroo species were studied in this project – the red kangaroo (*Macropus rufus*), the western grey kangaroo (*Macropus fuliginosus*) and the eastern grey kangaroo (*Macropus giganteus*).

Red kangaroos are widely distributed across the arid and semi-arid interior of Australia. Their preferred habitats are open shrublands and grassy plains. Eastern grey kangaroos occur over most of eastern Australia but extend no further west than the New South Wales-South Australia border. Their preferred habitat is open woodland and forest. Western grey kangaroos also prefer open woodland and forest, but tolerate open areas to a greater extent than eastern greys. They are distributed throughout the winter rainfall zone of southern Australia. The biology and ecology of the species have been described by Frith and Calaby (1969), Caughley *et al.* (1987) and Dawson (1995).

Field sites

Data to support model development were collected from four sites, chosen for the dominant species of macropod they contained.

Red kangaroos were sampled at Boorungie Station (58,853 ha) in far western New South Wales (31°28'S, 142°26'E). Western grey kangaroos were sampled at Coombie Station (62,667 ha) in central western New South Wales (32°50'S, 145°21'E). Eastern grey kangaroos were sampled at two sites – Blackbank Station (15,356 ha, 28°47'S, 146°48'E) and Weelamurra Station (23,508 ha, 28°13'S, 146°12'E) – both located in south-west Queensland.

The broad vegetation types and landforms of each property, together with tracks and major drainage features, are shown in Figure 1(a–d).

Field data collection procedures

Weather permitting, data were collected from field sites every 3 months. At Coombie, Blackbank and Weelamurra sampling commenced in winter 1999 and finished in autumn 2001. Sampling at Boorungie commenced in autumn 2000 and finished in winter 2001.

Harvested kangaroo samples and sampling periods

Both biased and unbiased samples of kangaroos were shot[3] at the field sites on the dates given in Table 3. Biased samples were the result of normal commercial harvesting. Unbiased samples – for determining shooter bias, survival rates and fecundity – were taken at night by the project team and were essentially random. Particular effort was made to minimise age or size-selective bias in these samples (for example, by always shooting the right-most individual in a group). However, bias arising from any age-, size- or sex-specific preference for habitats that could not be sampled (for example, closed woodland), or from differential vulnerability of specific age classes to shooting, could not be controlled.

Other field data were collected at approximately the same times.

Kangaroo density

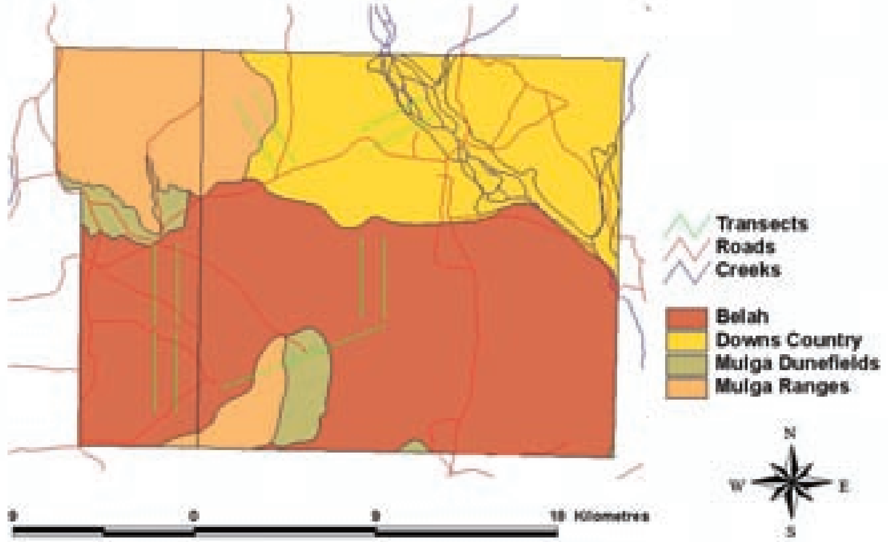
We used walked line transects (Southwell 1994) to provide an unbiased estimate of kangaroo density on all field sites, and driven line transects to provide a biased estimate of the density encountered by commercial harvesters during a foray.

3 Samples were shot either by a licensed kangaroo harvester (biased samples) or under scientific licences granted by the New South Wales National Parks and Wildlife Service and the Queensland Department of Environment and Heritage (random samples). All kangaroos were taken in accordance with the Code of Practice for the Humane Shooting of Kangaroos (CONCOM 1990). Those shot by the project team were taken under authority issued by the Animal Ethics Committee, Orange Agricultural Institute, New South Wales Agriculture.

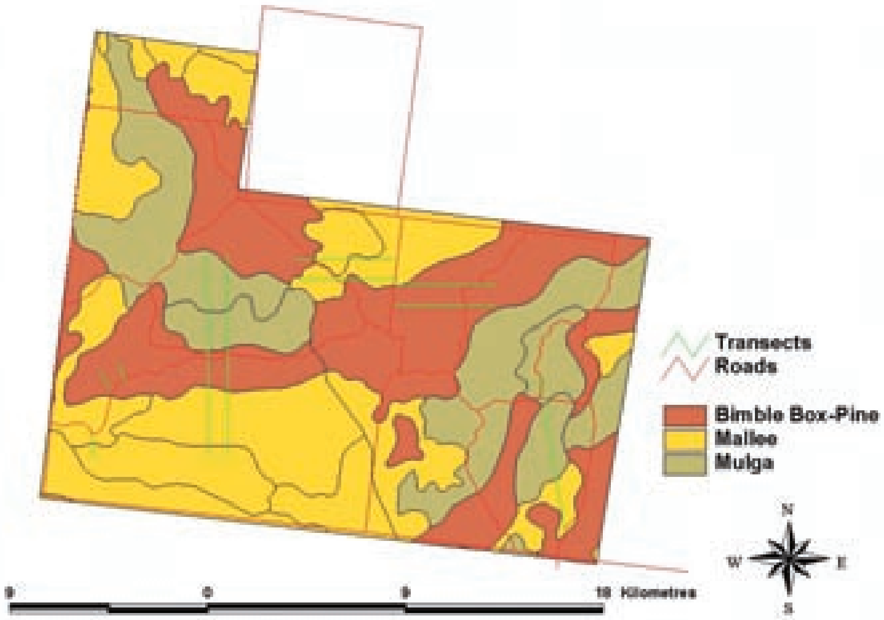
Figure 1 (a–d). Physical characteristics of the study sites.

The location of transects used for kangaroo surveys is also shown.

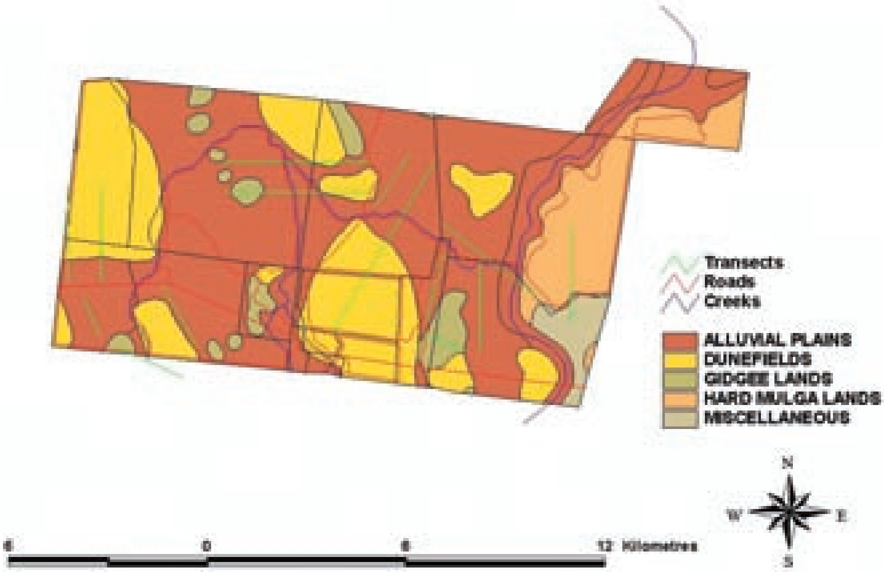
(a) Boorungie



b) Coombie



(c) Blackbank



(d) Weelamurra

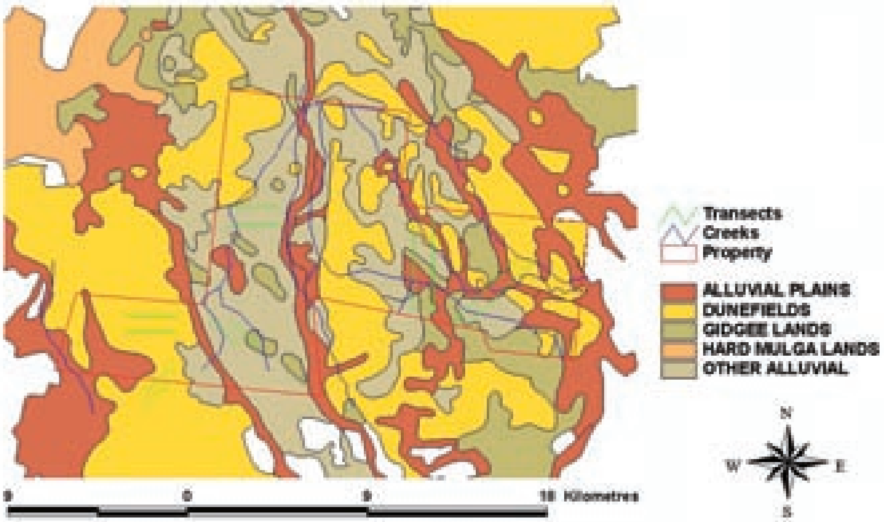
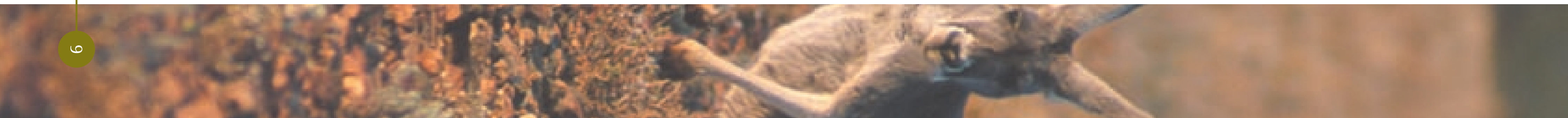
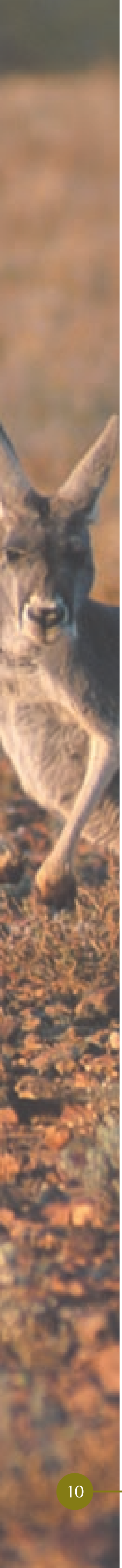


Table 3. Sampling dates for shot samples.
(Other field data were collected at approximately the same times; NS = not sampled)

Site	Sample	Winter '99	Spring '99	Summer '00	Autumn '00	Winter '00	Spring '00	Summer '01	Autumn '01	Winter '01
Boorungie	Biased	NS	NS	NS	26/4/2000	31/7/2000	3/11/2000	22/1/2001	1/5/2001	27/7/2001
	Random	NS	NS	NS	27/4/2000 - 28/4/2000	30/7/2000 - 1/8/2000	31/10/2000 - 1/11/2000	21/1/2001 - 23/1/2001	28/4/2001 - 29/4/2001	28/7/2001 - 1/8/2001
Coombie	Biased	22/6/1999	3/11/1999	7/2/2000	20/4/2000	13/9/2000 - 14/9/2000	26/10/2000	17/1/2001	26/4/2001	NS
	Random	23/6/1999 - 24/6/1999	2/11/1999 - 5/11/1999	6/2/2000 - 8/2/2000	21/4/2000 - 22/4/2000	24/7/2000 - 25/7/2000	27/10/2000 - 28/10/2000	16/1/2001 - 19/1/2001	24/4/2001 - 25/4/2001	NS
Blackbank	Biased	11/5/1999	NS	24/1/2000, 10/2/2000	22/5/2000 - 23/5/2000	19/8/2000 - 20/8/2000	NS	14/3/2001	NS	NS
	Random	12/5/1999 - 13/5/1999	27/9/1999 - 29/9/1999	25/1/2000, 11/2/2000	21/5/2000 - 25/5/2000	17/8/2000 - 18/8/2000	NS	10/3/2001 - 12/3/2001	NS	NS
Weelamurra	Biased	2/7/1999, 17/7/1999	24/9/1999	21/1/2000	NS	15/8/2000	NS	9/2/2001	31/5/2001	NS
	Random	29/6/1999 - 2/7/1999	23/9/1999	19/1/2000 - 20/1/2000	18/5/2000 - 19/5/2000	13/8/2000 - 14/8/2000	NS	10/2/2001 - 11/2/2001	1/6/2001 - 2/6/2001	NS





Walked line transects were permanently established and allocated proportionally to habitats within each study site (Figure 1a–d). Total length varied from 40–50km per site, and transects were usually paired for practical convenience. Transects were usually walked by a single observer. When two people conducted the surveys, only one made observations while the other recorded. In either case, observations were recorded using a micro-cassette. At each sighting of a group of kangaroos[4], the radial distance, the sighting angle to the centre of the group and the number of kangaroos in the group were recorded. Radial distances and sighting angles were measured with a Bushnell laser rangefinder and a Suunto prismatic compass, respectively.

Transect walking began after kangaroos had stopped feeding in the morning. Our intention was to minimise reactive movement of animals by walking during the inactive, resting period. Each transect pair typically took 4–5 hours to complete.

Driven transects were carried out at night. Observations were made by a single individual from the tray of a 4WD utility, with the aid of a 100W spotlight. Animals on either side of the vehicle were observed, using the same procedures described for the walked transects. Data were recorded by the driver directly into a laptop computer. Driven transects were located in the more open habitats that kangaroo harvesters would typically use. The estimates of kangaroo density they provided were therefore more representative of the populations encountered by the harvesters.

Density estimates from both walked and driven transects were derived using the DISTANCE computer program (Thomas *et al.* 1998).

Age and size

Routine use of the molar progression technique (Kirkpatrick 1964, 1965, 1970) to determine the age of shot kangaroos was not feasible. This method requires the molar row of the maxilla to be exposed and measured. It is thus impractical if the maxilla is damaged by a shot to the head (required by both the code of practice and the animal ethics approval granted for the project), or if the head must be retained on the carcase (a requirement for all animals harvested for human consumption). For many vertebrates, however, the weight of the eye lens increases with age. We therefore developed an alternative approach based on the relationship between molar index and eye lens weight (see below).

An eyeball was removed from all shot animals and stored in formaldehyde. Later, the eye lens was removed and dried at 70°C for two weeks until weight had stabilised. The heads of some animals were removed to allow calculation of the molar progression index – the number of molars (to the nearest 0.1) that had progressed past a reference line running across the anterior rim of the eye orbits.

Shot animals were weighed to the nearest half kilogram and their pes length (heel to base of nail) was recorded. For mature females, the sex and tail length of any pouch young present were also recorded. Age of pouch young was subsequently determined from tail length (Russell 1982). Immature females were identified by the presence of capped teats and a tight pouch (Frith and Sharman 1964).

Reproductive status

Reproductive status (immature or mature with young of specified age and sex) was determined for all females taken during field studies, whether by random sampling or by kangaroo harvesters. Immature females were identified by the presence of four small teats capped with dark pigmentation, and a tight pouch (Frith and Sharman 1964).

Harvesting

Location of harvested animals

The location of all animals shot, either by a commercial harvester (biased sample) or the project team (random sample), was recorded with a global positioning system (GPS) (Figure 2 a–d). Most animals, in either sample, were taken close to roads or in open, easily accessible areas.

Operational parameters

Harvesting of kangaroos was carried out by commercial harvesters who cooperated with the project team. The course of their nightly forays was logged by a GPS located in the vehicle. Members of the project team accompanying the harvesters also recorded the time required to acquire and process each animal. 'Acquisition time' commenced when a kangaroo was first sighted and ceased when the search for the next animal began. It included the time taken to dispatch the kangaroo and to find and load the carcase. 'Processing time' was the time required to dress the carcase in the field (if shot for human consumption) or to remove the skin (if shot for the fur/leather trade). Observations were also made of the total time available for harvesting on the property, and of the maximum range over which harvesters shot animals in particular vegetation types. Only one harvester operated on each field site.

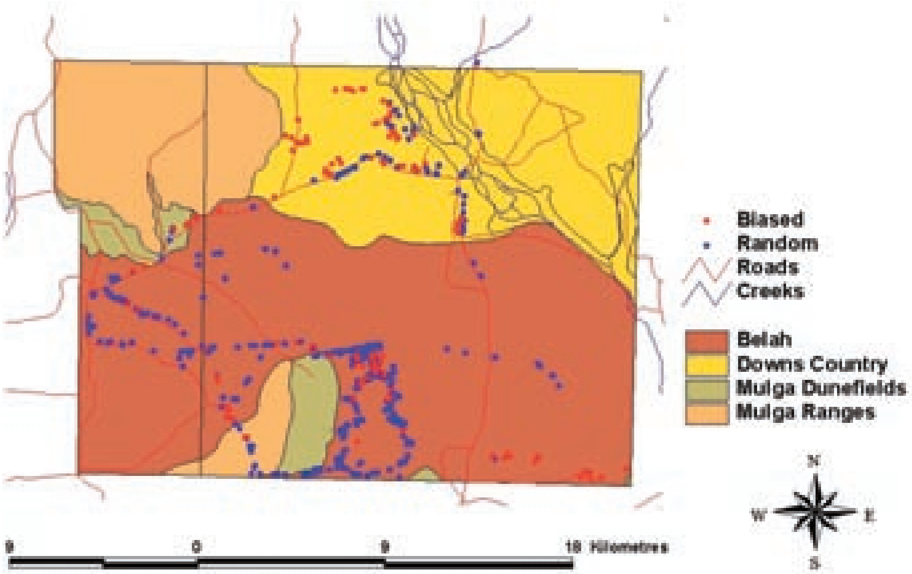
Costs

Economic data were collected from cooperating harvesters, including the costs of vehicle operation, maintenance of equipment, ammunition and royalty tags.

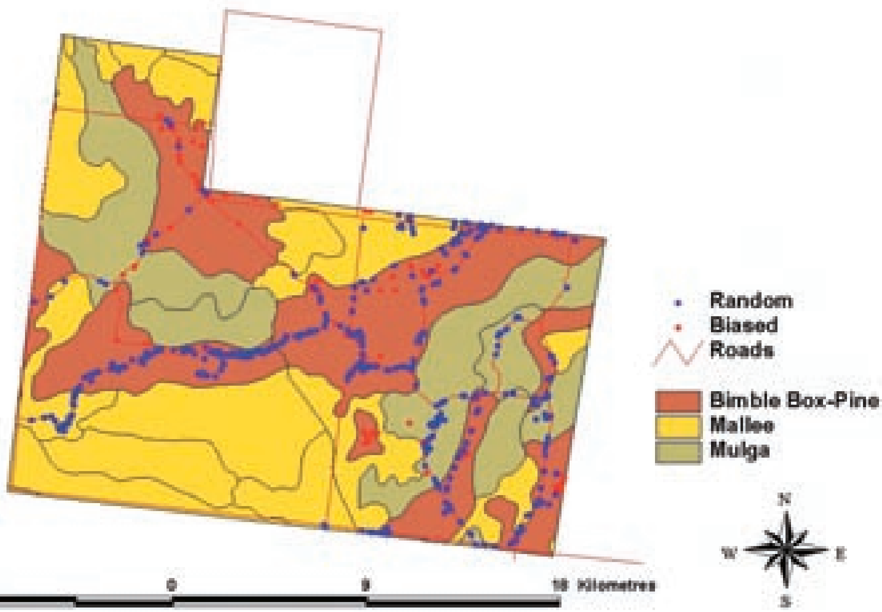
4 A group of kangaroos was defined as one or more kangaroos, where the members of the group were less than or equal to 10 metres from their nearest neighbour.

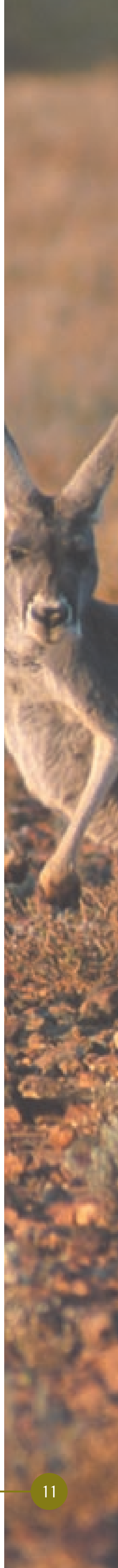
Figure 2 (a–d). Location of kangaroos shot during population sampling (random sample) and by a commercial kangaroo harvester (biased sample).

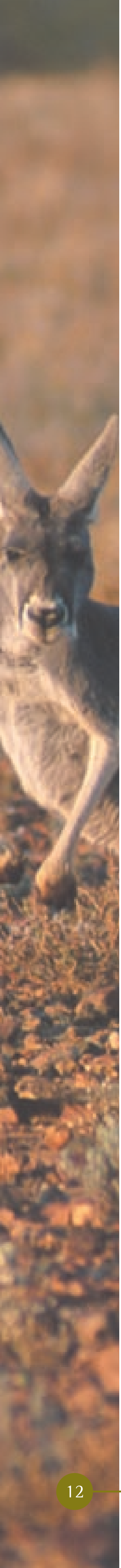
(a) Boorungie



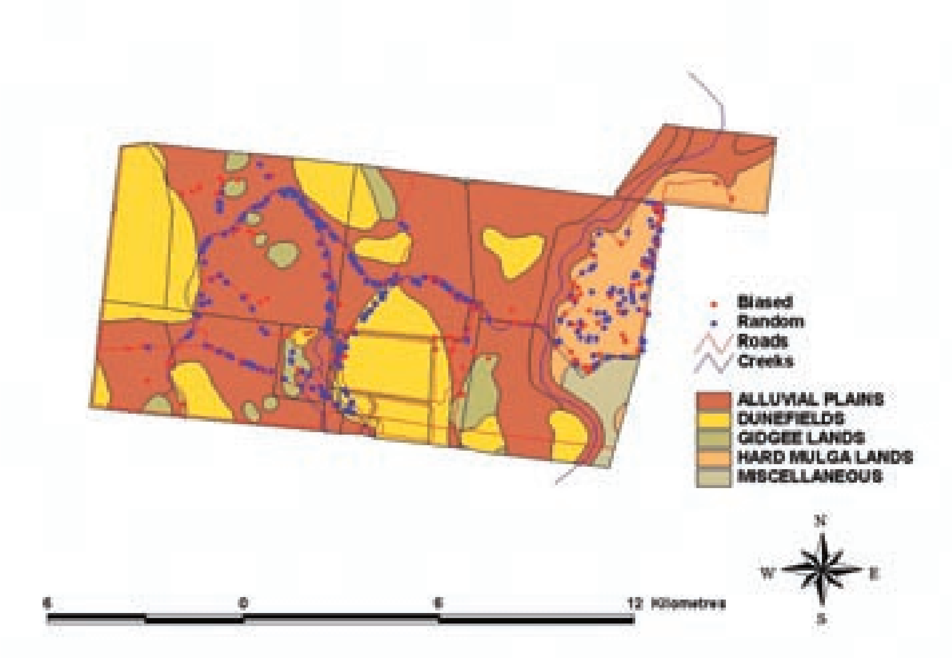
(b) Coombie



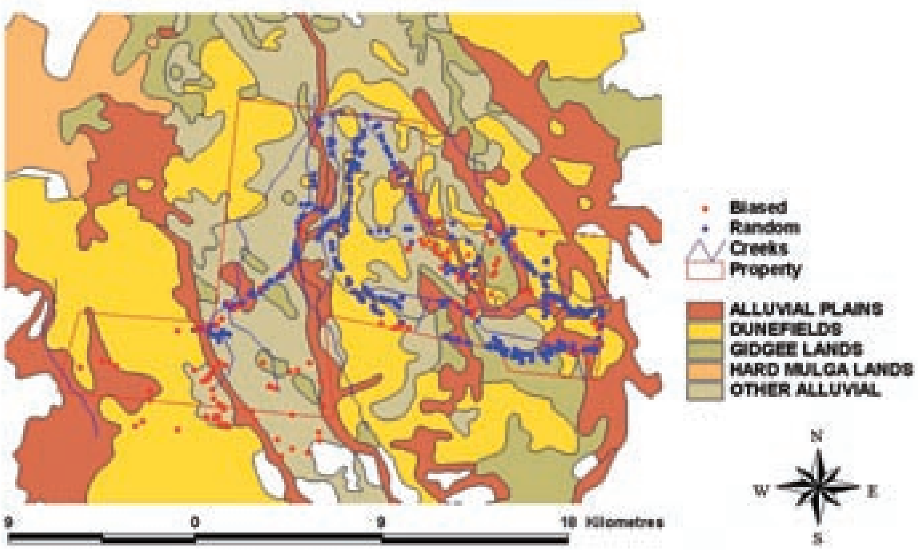




(c) Blackbank



(d) Weelamurra



Summary of field data

Key biological relationships

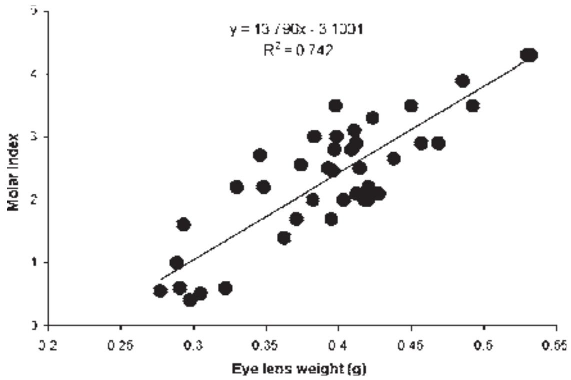
Age-eye lens weight

The relationships between age, expressed as molar index, and eye lens weight for the three kangaroo species are shown in Figure 3. We used these relationships, and published relationships between molar index and age (Kirkpatrick 1964, 1965, 1970), to determine the age of shot kangaroos.

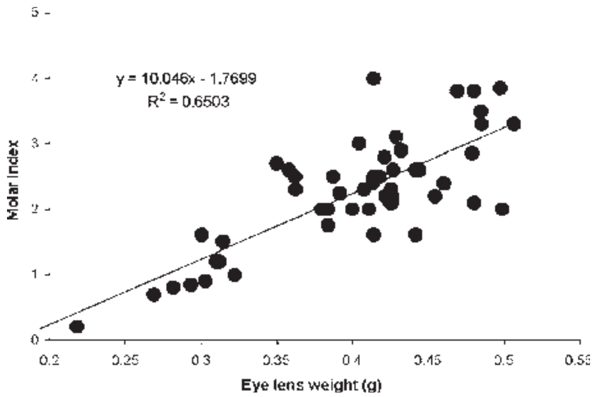
Apart from pouch young which were aged separately, kangaroo age derived in this way was used to determine the frequency of (yearly) age classes in the populations, from which age-specific survivorship was calculated (see below).

Figure 3 (a–c). Regression of molar index and eye lens weight.

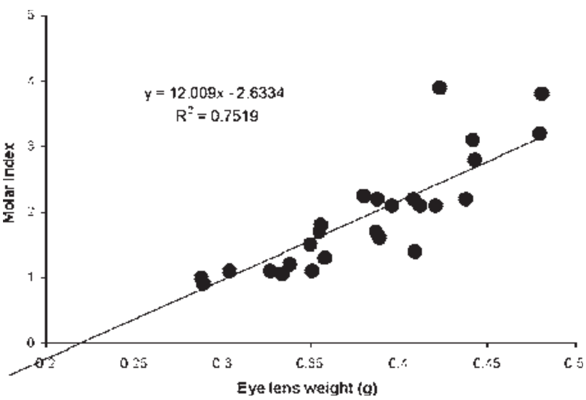
(a) red kangaroos

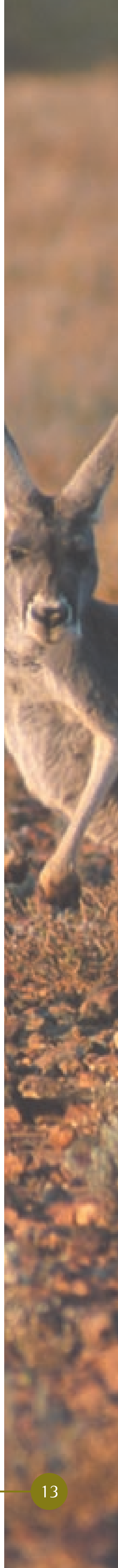


(b) western grey kangaroos



(c) eastern grey kangaroos





Harvester functional response

The functional response curve (Murdoch 1973) describes the relationship between kangaroo density and the number of kangaroos taken per harvester per unit of time (that is, harvest rate). Mathematically this relationship can be described as

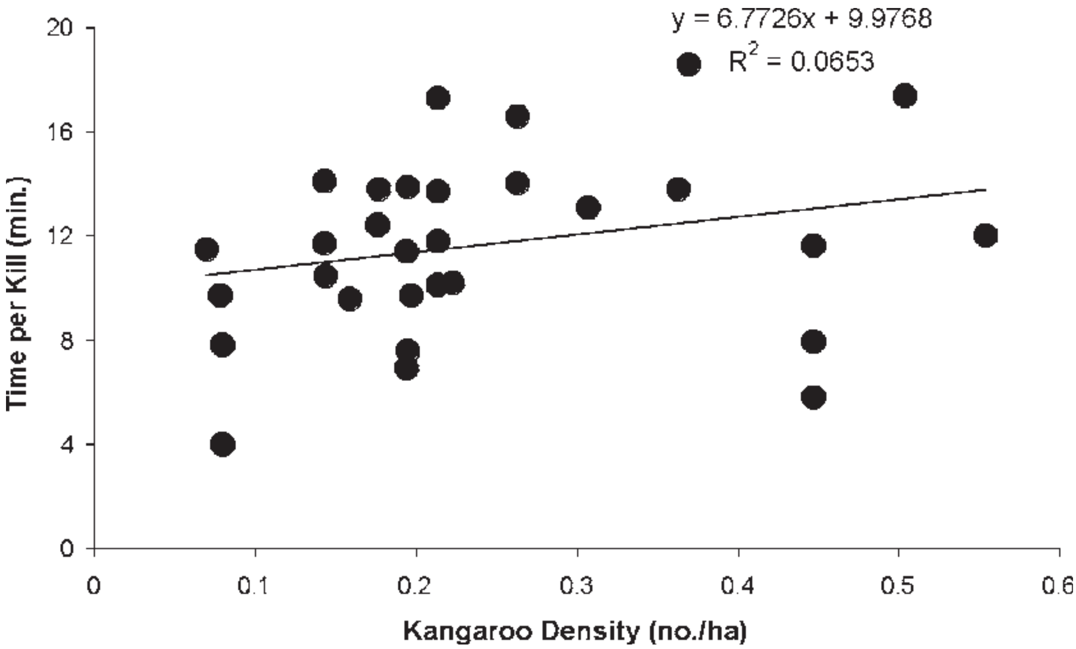
$$n_a = \left[\frac{an}{(1+abn)}\right]T$$

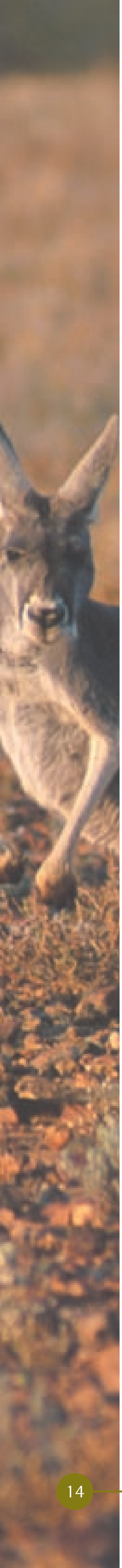
where n_a is the number of kangaroos taken per foray, n is kangaroo density, a is the rate of capture (kangaroos per unit time), b is the handling time (time taken to pick up and dress a carcase, time per kangaroo), and T is the total time available for harvesting (time per foray).

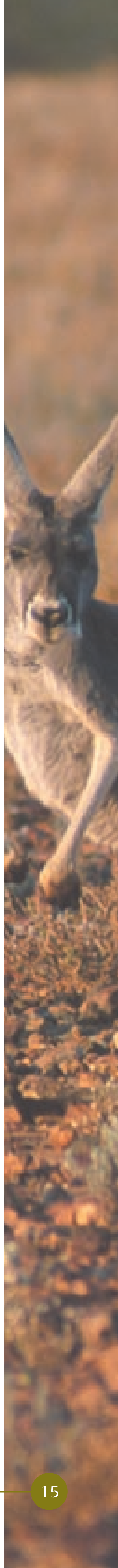
Given that for any one night's shooting the handling time (b), the total time available to harvest kangaroos (T) and kangaroo density (n) are constants, harvest rate will be directly proportional to the rate of capture (a). Thus, the relationship between density and the rate of capture (a) or its inverse (time per kill) can be used as a proxy for the functional response.

Over a wide range of densities (0.07–0.57 kangaroos/ha) there was no relationship between density and time per kill (Figure 4). Failure to detect the expected relationship suggests that all observations were above the threshold density below which search time limits harvest rate and/or that search time is highly variable among harvesters or locations. Further studies are required to establish the functional response of harvesters to kangaroo density.

Figure 4. Relationship between time per kill (the inverse of harvest rate) and kangaroo density – the harvester functional response. (No significant relationship was found. Each data point was derived by calculating the time per kill [foray time/number of kills] for an individual foray. Data for all sites and sampling periods combined).







Population and harvest data

Density

Variations in kangaroo density are shown in Figure 5 (a–d). Over the course of the study, the density of red kangaroos at Boorungie declined while eastern grey kangaroos increased slightly at both Blackbank and Weelamurra. At Coombie there was no clear trend in the density of western grey kangaroos.

Harvester bias and selectivity

Bias. Most of the harvesters observed during the study showed a bias in favour of males (Table 4). The exception was Boorungie where females dominated the harvest. This site also had the highest ratio of female to male kangaroos, which might partially explain the slight dominance of females in the harvested (biased) sample.

Selectivity. A simple measure of selectivity, Manly's α (Manly *et al.* 1972), is based on a comparison of the probability that an individual (harvester) will encounter a resource (kangaroo) of a certain type (sex and size cohort) and the probability that once encountered that resource will be taken. When the number of prey is small relative to the number available, α can be estimated as

$$\alpha_i = \frac{r_i}{n_i} \times \frac{1}{\sum_{j=1}^{m} \left(\frac{r_j}{n_j} \right)}$$

where α_i = Manly's alpha index for cohort i,
r_i and r_j = proportion of cohort types i and j in the harvested sample,
n_i and n_j = proportion of cohort types i and j in the environment,
m = number of cohorts available.

Manly's α is a normalised index so

$$\sum_{i=1}^{m} \alpha_i = 1.0$$

When harvesting is unselective, $\alpha_i = 1/m$. If α_i is greater than $1/m$ then the harvested cohort is preferred. Conversely, if α_i is less than $1/m$ the cohort is avoided.

The extent to which harvesters preferred a specific cohort, as determined by Manly's α, is shown in Figure 6 (a–h). Generally preference increased with body size. The apparent tendency to avoid large males at both Boorungie and Weelamurra is probably an artefact due to the low frequency of these size classes, a few of which were taken in the random sample.

Survival

We used consecutive age structure samples of the kangaroo populations to determine age-specific survival (Caughley 1977, McCallum 2000). This method makes no assumptions about the rate of increase of the population, or the stability of the age structure, and is thus appropriate for kangaroo populations in which both size and age structure vary widely. If the size of the population is known, survival rates can be calculated from the relative abundance of age classes after correcting for differences in the effort expended (that is, the proportion of the population sampled).

Estimated survival rates for each field site are shown in Figure 7. These rates were derived from data pooled over sexes and sampling periods for which the age structure was not significantly different, and smoothed by means of a non-linear regression. Survival probability of each age cohort was derived from the regression function. At Boorungie, age structures demonstrated a significant sex x sampling period interaction and survival probabilities were thus determined separately for males and females.

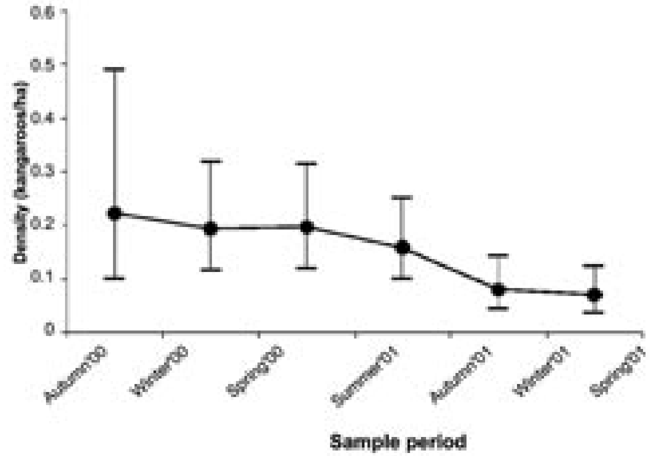
Given the favourable seasonal conditions under which data were collected (some field trips were cancelled due to rain) the survival rates of Figure 7 are considered to estimate the background mortality under non-limiting forage conditions.

Table 4. The sex ratio of commercially harvested (biased) and randomly shot kangaroos for each study site.

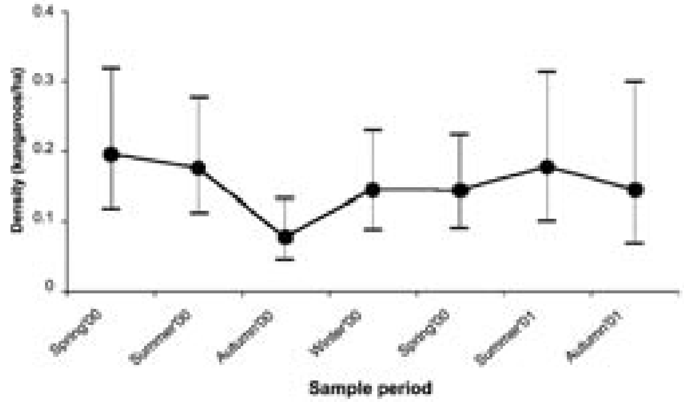
Site	Sample	Male	Female	Sex ratio (M : F)	Chi-square	P
Boorungie	Biased	107	140	1 : 1.31	2.22	0.14
	Random	269	418	1 : 1.55	16.4	0.0001
Coombie	Biased	122	61	1 : 0.5	10.5	0.0012
	Random	402	362	1 : 0.9	1.05	0.31
Blackbank	Biased	117	16	1 : 0.14	44.9	<0.0001
	Random	310	318	1 : 1.03	0.05	0.82
Weelamurra	Biased	131	24	1 : 0.18	42.0	<0.0001
	Random	298	378	1 : 1.27	4.75	0.029

Figure 5. Density of kangaroos on the study sites estimated by line transect methods. Bars represent 95% confidence limits.

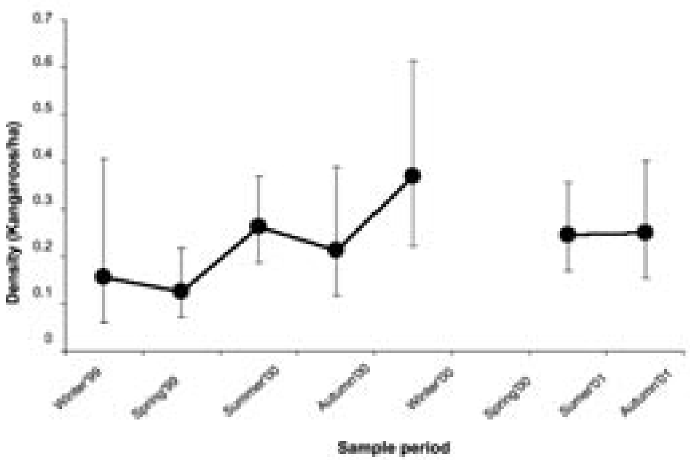
(a) red kangaroos at Boorungie



(b) western grey kangaroos at Coombie



(c) eastern grey kangaroos at Blackbank



(d) eastern grey kangaroos at Weelamurra

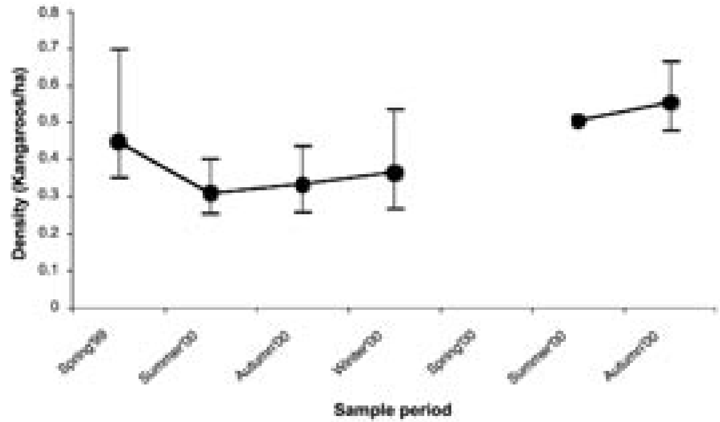
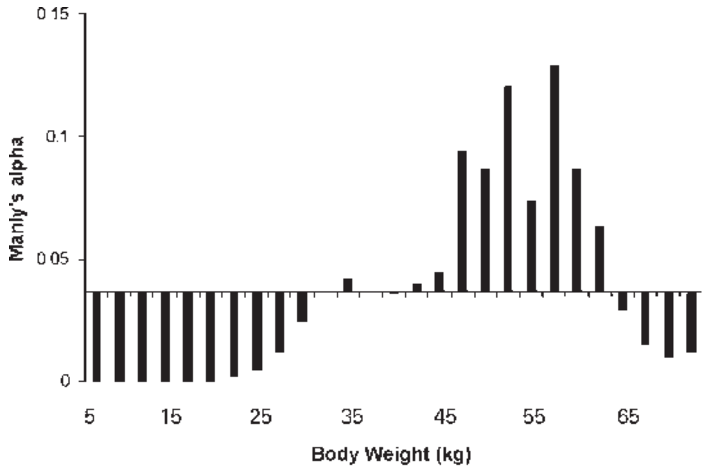
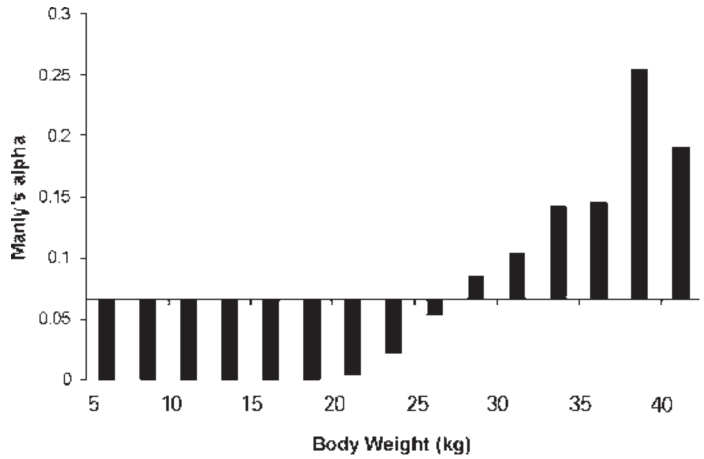


Figure 6 (a-d). Commercial harvester selectivity for kangaroos of particular body size. Columns above the x-axis indicate preference, while those below indicate avoidance.

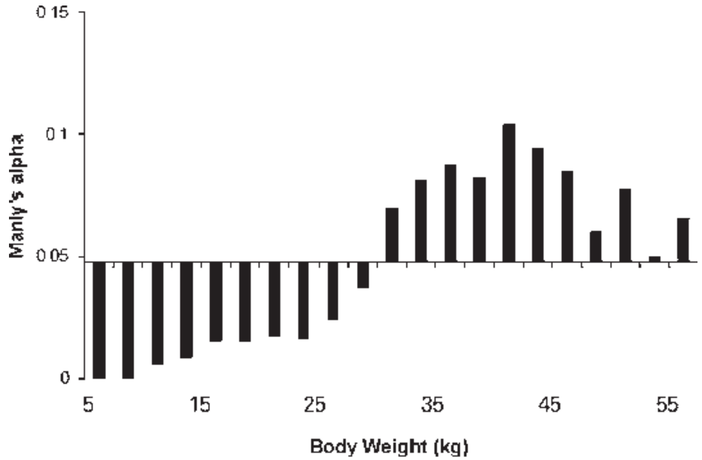
(a) male red kangaroos at Boorungie Station.



(b) female red kangaroos at Boorungie Station.



(c) male western grey kangaroos at Coombie Station.



(d) female western grey kangaroos at Coombie Station.

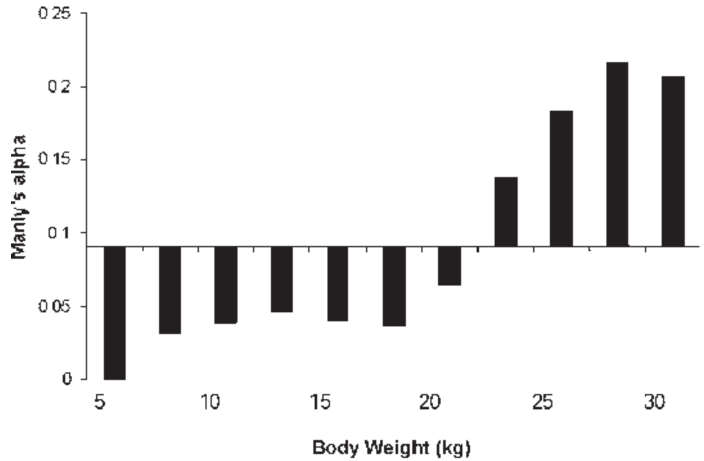
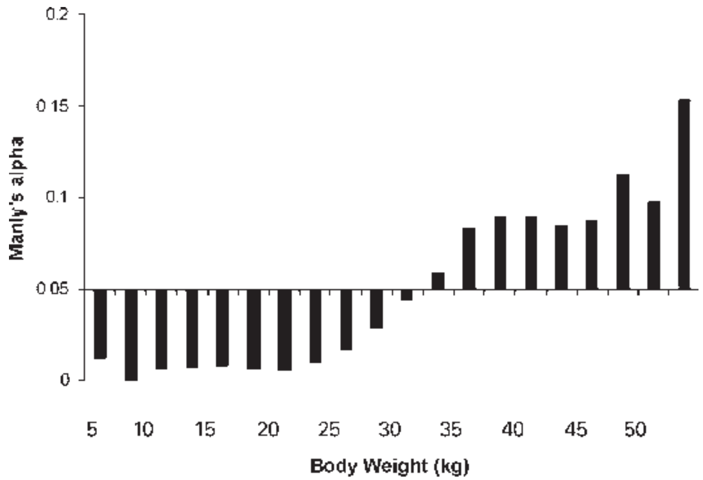
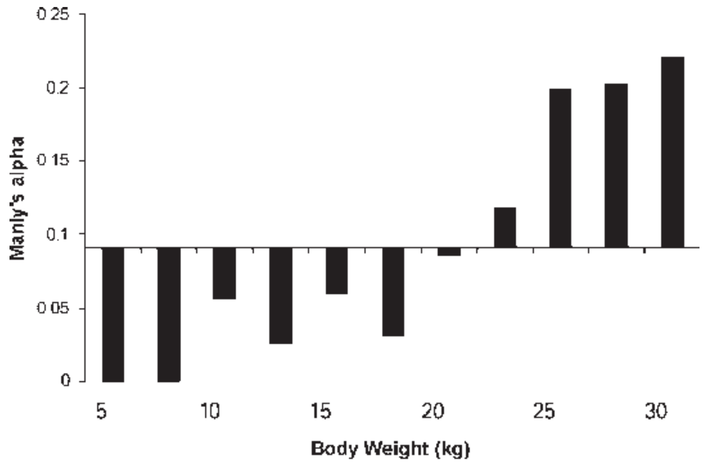


Figure 6 (e-h). Commercial harvester selectivity for kangaroos of particular body size. Columns above the x-axis indicate preference, while those below indicate avoidance.

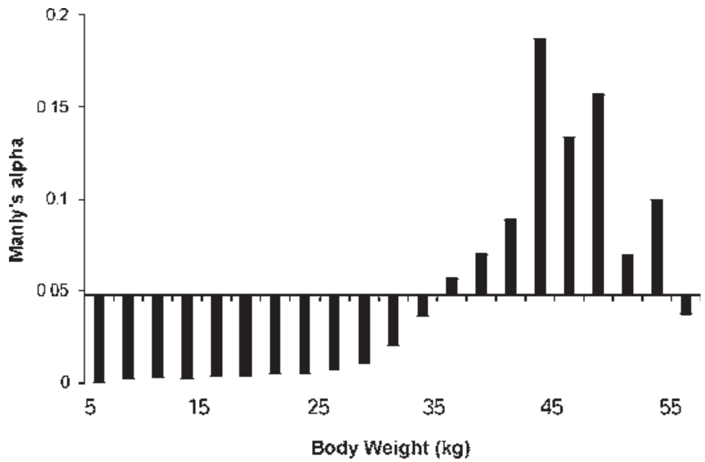
(e) male eastern grey kangaroos at Blackbank Station.



(f) female eastern grey kangaroos at Blackbank Station.



(g) male eastern grey kangaroos at Weelamurra Station.



(h) female eastern grey kangaroos at Weelamurra Station.

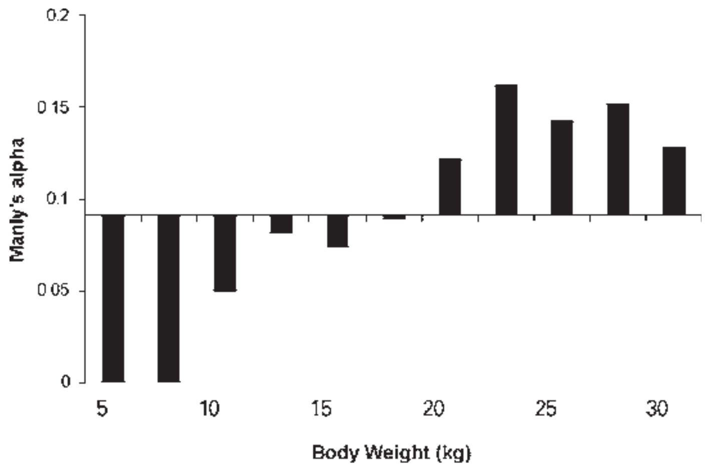
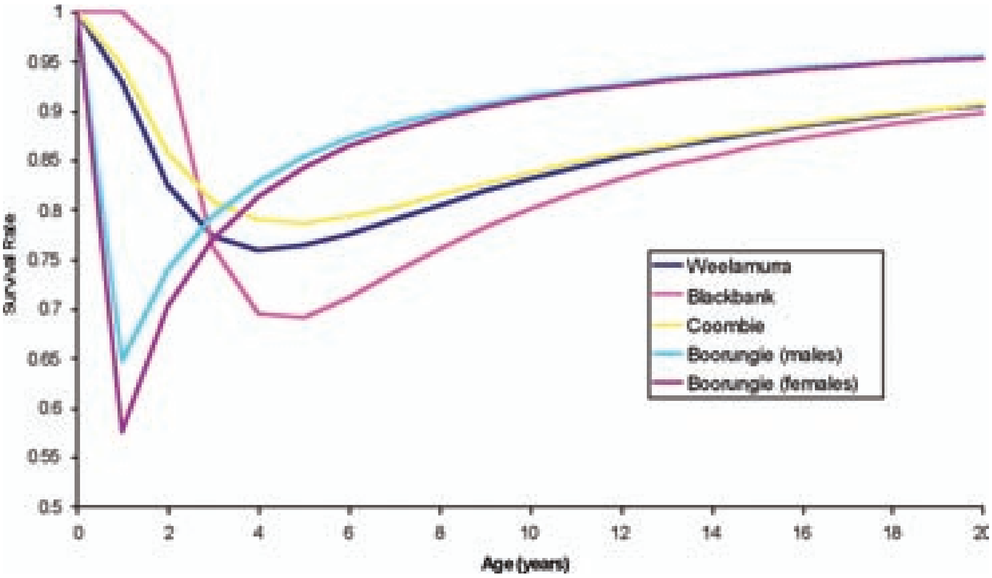


Figure 7. Survival probabilities for the field sites (Boorungie – red kangaroos; Coombie – western grey kangaroos; Blackbank and Weelamurra – eastern grey kangaroos)



Sex ratio and fecundity

Sex ratio of pouch young did not differ significantly from parity at any of the study sites (Table 5).

Fecundity of the three species over the four seasons is shown in Figures 8, 9 and 10. In all species most females were reproductive at any time of observation. Although red kangaroos are capable of continuous breeding under suitable seasonal conditions, a few females were anoestrous in each season (Figure 8 a–d). For western greys the peak of breeding activity was in spring and summer (Figure 9 a–d) although most females were reproductive at other seasons.

The peak of breeding activity in eastern greys occurred in spring (Figure 10 a–d) although again most females were reproductive in other seasons. For both eastern and western greys the pattern is consistent with the more seasonal nature of reproduction in these species. As with survival, fecundity measured at the field sites is considered to be unlimited by forage availability, given the seasonal conditions that prevailed during field work.

Table 5. The frequency of male and female pouch young recorded at Boorungie station (red kangaroo), Coombie station (western grey kangaroo) and Blackbank and Weelamurra stations (eastern grey kangaroo).

Site	Male	Female	Chi-square	P, df = 1
Boorungie	167	182	0.32	0.57
Coombie	157	139	0.55	0.46
Blackbank	119	89	2.17	0.14
Weelamurra	134	139	0.05	0.83

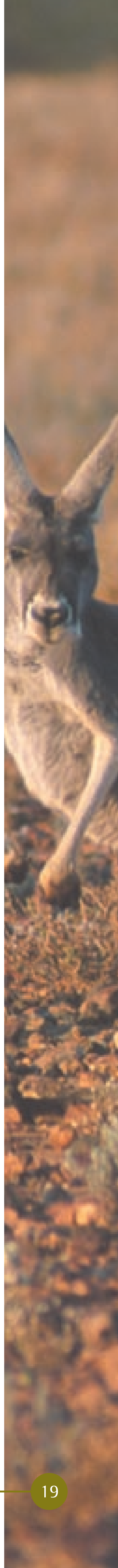
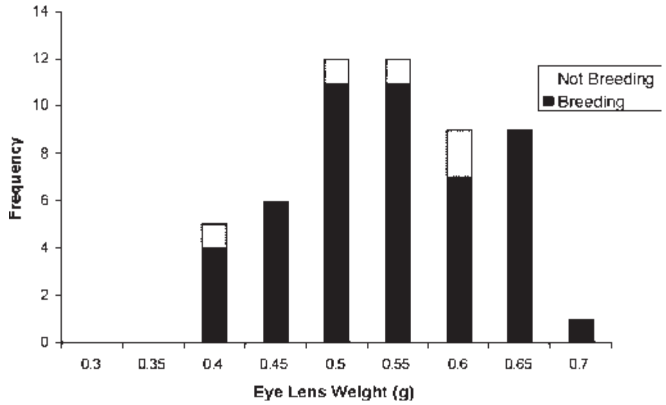
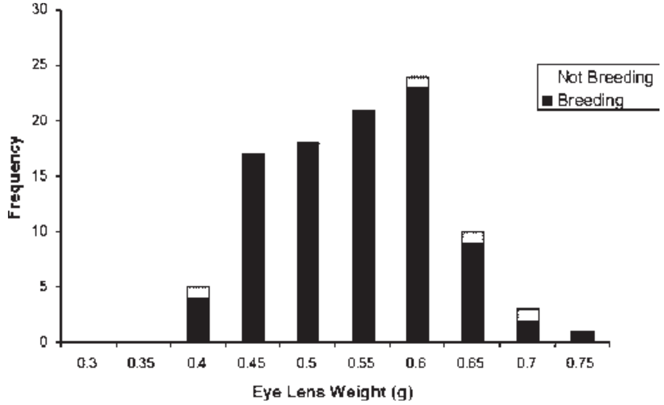


Figure 8 (a–d). Number of breeding female red kangaroos sampled at Boorungie Station.

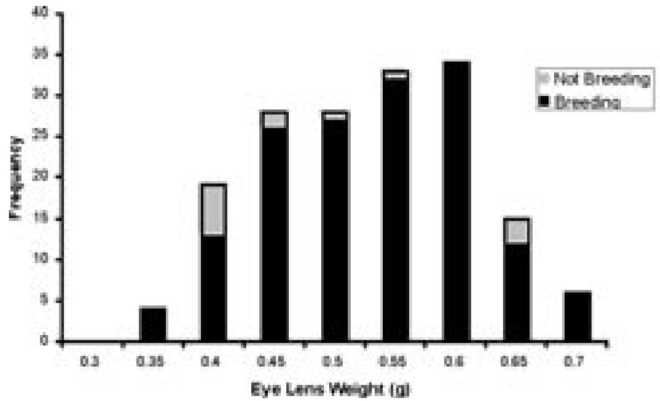
(a) summer



(b) autumn



(c) winter



(d) spring

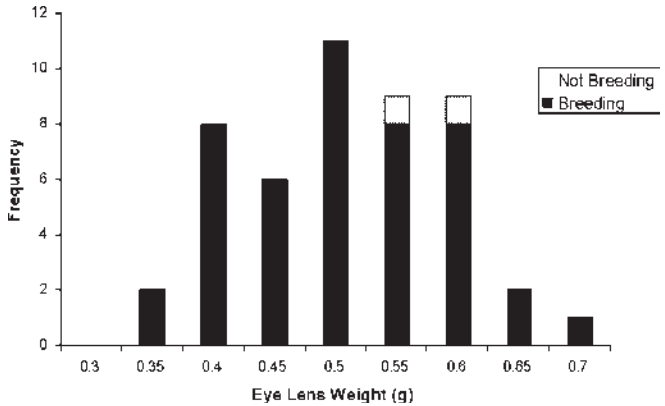


Figure 9 (a–d). Number of breeding female western grey kangaroos sampled at Coombie Station.

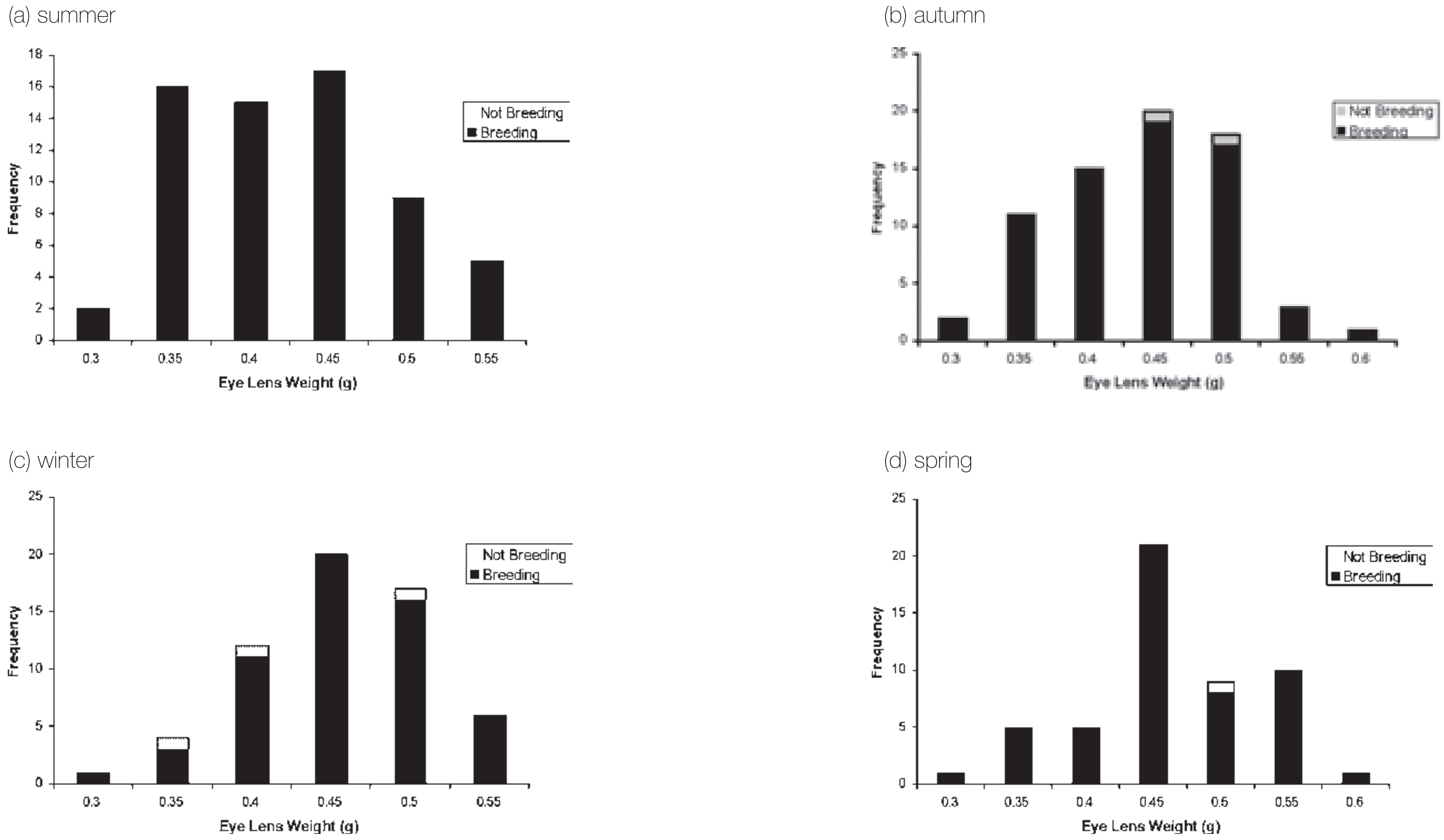
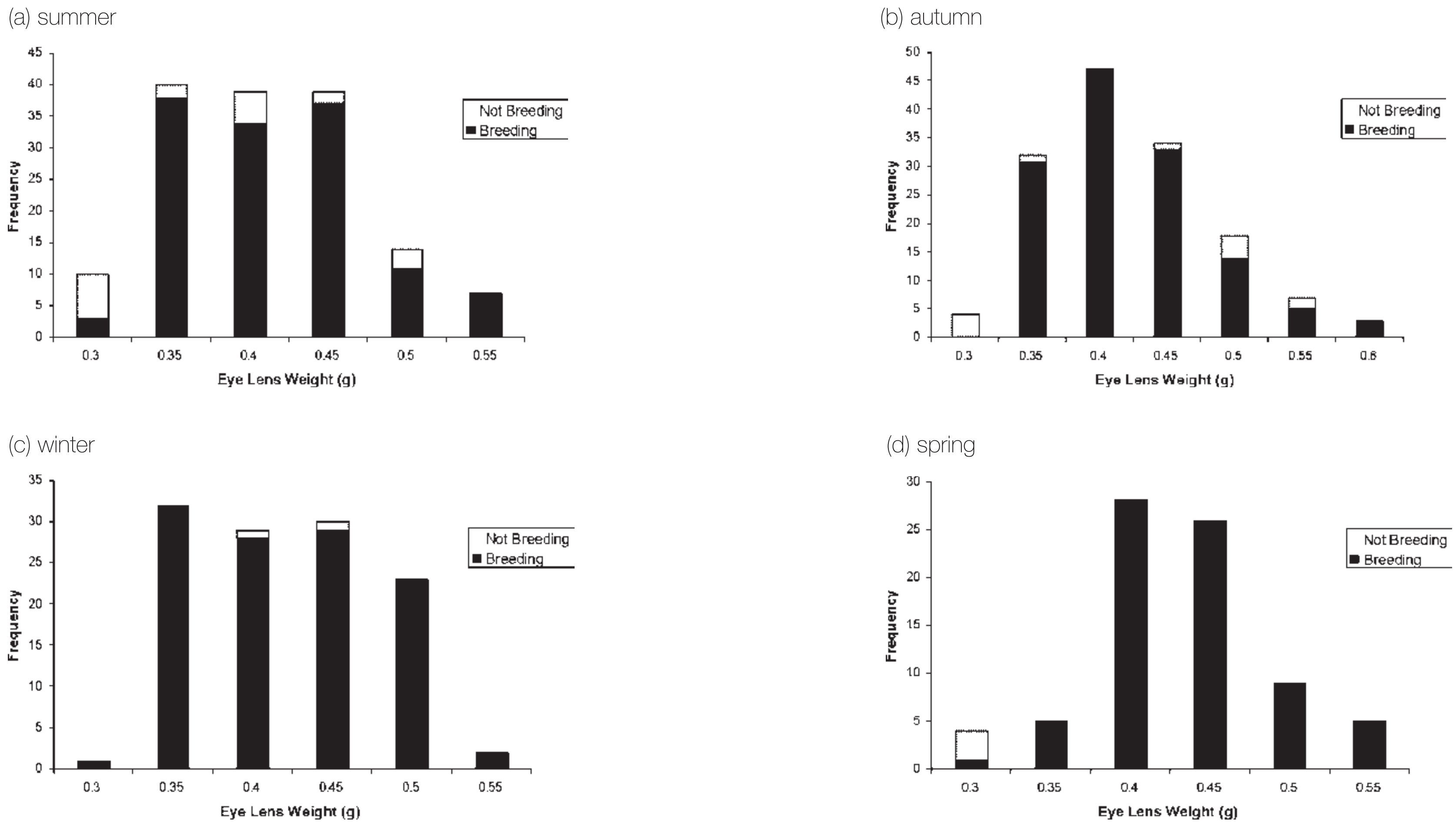


Figure 10 (a–d). Number of breeding female eastern grey kangaroos sampled at Blackbank and Weelamurra stations (combined data).



Model development

The temporal model

To simulate changes in kangaroo populations over time in response to imposed management strategies we developed a physiologically structured population model based on the escalator boxcar train concept (De Roos *et al.* 1992). Models of this type are more appropriate for continuously changing and highly unpredictable environments, such as the Australian rangelands, than matrix models based on discrete transitions from one life stage or season to another. They are also computationally more tractable than alternative formulations based on partial differential equations, can incorporate feedback between populations and their environment, and can readily accommodate continuous reproduction.

The model was derived with the specific intention of allowing population structure, and sex and body size bias in the harvest, to explicitly influence population dynamics. Previous models have either treated kangaroo populations as homogenous groups without sex or age structure (Caughley 1987a) or have incorporated unreasonable assumptions regarding vital rates or population dynamics (for example, Kirkpatrick and Nance 1985, Nance 1985). The importance of population structure for the dynamics of harvested kangaroo populations has recently been emphasised (Pople 1996). We therefore modified Caughley's (1987a) interactive red kangaroo model, which incorporates feedback between kangaroo populations and their environment, to include cohorts of age and sex.

A flowchart of the basic structure is given in Figure11. The model simulates the dynamics of a kangaroo population that feeds on a growing pasture. The vital rates of the population – fecundity and survival – depend on pasture biomass which, when low, reduces the rates below the upper limits determined from the field data. Pasture growth depends primarily on rainfall, but also on kangaroo density since kangaroos consume forage according to a relationship – the functional response – between pasture consumption and pasture biomass (Short 1985, 1987). Kangaroo populations thus cannot grow indefinitely since the negative feedback loop that connects pasture biomass and kangaroo density limits their rate of increase.

The model operates on a 3-month time step, corresponding to the seasons of the year. While the quota is calculated only once a year, in winter, under most harvesting strategies it is then allocated equally between the seasons in the following year. The only exception to this pattern of allocation occurs under the 'high value products' strategy, where the quota is evenly allocated to summer and autumn of the following year.

Each of the strategies listed in Table 1 was evaluated for various combinations of annual harvest rate and male bias. Harvest rates were incrementally increased from 0% (that is, no harvest) to 90%, in 10% increments. Male bias was increased incrementally from 0% (female only harvest) to 100% (male only harvest) in 10% increments. Each strategy was thus evaluated for 99 different combinations of (non-zero) harvest rate and male bias, a total of 891 combinations. In addition, nine combinations representing unharvested populations were also simulated. Each combination was simulated 100 times, with each simulation comprising a run of 100 years (400 quarters). The average of each performance indicator (that is, the global average over the 100 repeated simulations) was saved for later use in multi-criteria decision analysis (see page 24).

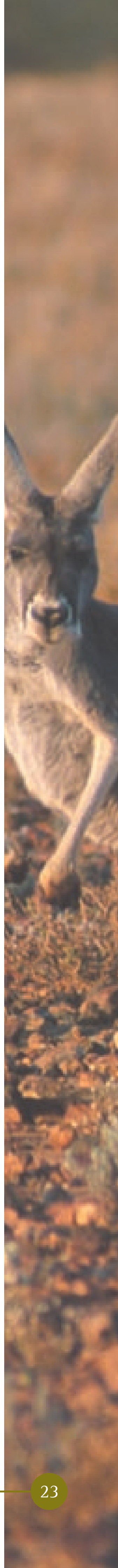
The spatial model

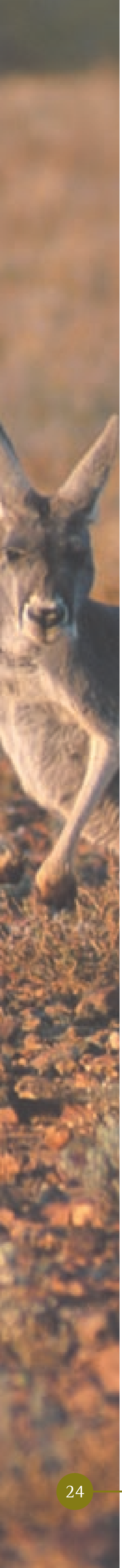
We developed a model within the ArcView geographic information system framework to examine the likely distribution of commercial kangaroo harvesting over the landscape. Reasons for this development included concerns of non-government conservationists for the establishment of harvest refugia, objectives of both wildlife management agencies and pastoralists that required either a temporary or permanent reduction in kangaroo density, and the specific management strategies detailed in Table 2.

Property level model

The spatial model was developed initially at the property level (Druhan and Pradhan 2001). The basic assumptions are that for a given commodity price, profitability of harvesting is determined by:

- the time taken to get to the harvest location
- the efficiency with which the harvester can search the area
- the cost of processing the carcases in the field; and
- the density and size of kangaroos available for harvest.





Put another way, the profit required by a harvester determines the kangaroo density at which harvesting will cease in a given area. Properties are divided into grid cells and the model is used to calculate the minimum density required within each cell to achieve a specified level of profitability. A separate model was developed for each field site, with grid cells of either 100 x 100m or 50 x 50m.

For each cell, the model is of the form

$$(MAP + TC) / (ST - TT) = Y - SC - CC \qquad (1)$$

where

MAP	= minimum acceptable profit ($/foray)
TC	= travel cost ($/foray)
ST	= shooting time on the property (minutes)
TT	= time of the return journey from the property entry point to the cell (minutes)
Y	= yield from harvesting within the cell ($/minute)
SC	= search cost within the cell ($/minute)
CC	= carcase cost per minute of harvest time within the cell ($/minute).

The variables on the left hand side of equation (1) define the rate, in $/minute of actual harvesting time, at which kangaroos must be acquired to satisfy the profit expectations of the harvester. Calculation of the variables on the right hand side is outlined in Figure 12. Kangaroo density is the only unknown in these relationships and equation (1) can thus be reformulated to provide, for each cell, the minimum density of kangaroos required to satisfy the harvester's profit expectation. In practice cells are not harvested independently. However, since interest resides only in the density below which harvesting is unprofitable, and not in the path taken to reach that density, an independent treatment of cells is the appropriate limit case.

Both non-spatial and spatial variables (input grids) contribute to the calculations outlined in Figure 12.

Non-spatial variables

Variables that have no spatial dimension and were therefore constant for all cells within any given simulation, included:

- Processing time (minutes/kangaroo) – times recorded from forays were averaged for each harvester, and for each commodity type (carcase or skins).
- Acquisition time (minutes/kangaroo) – calculated as above.
- Fixed carcase costs ($/kangaroo)- the average cost per head of rifle, ammunition, royalty tags, knives and sundries.

Figure 11. Flowchart of the temporal model.

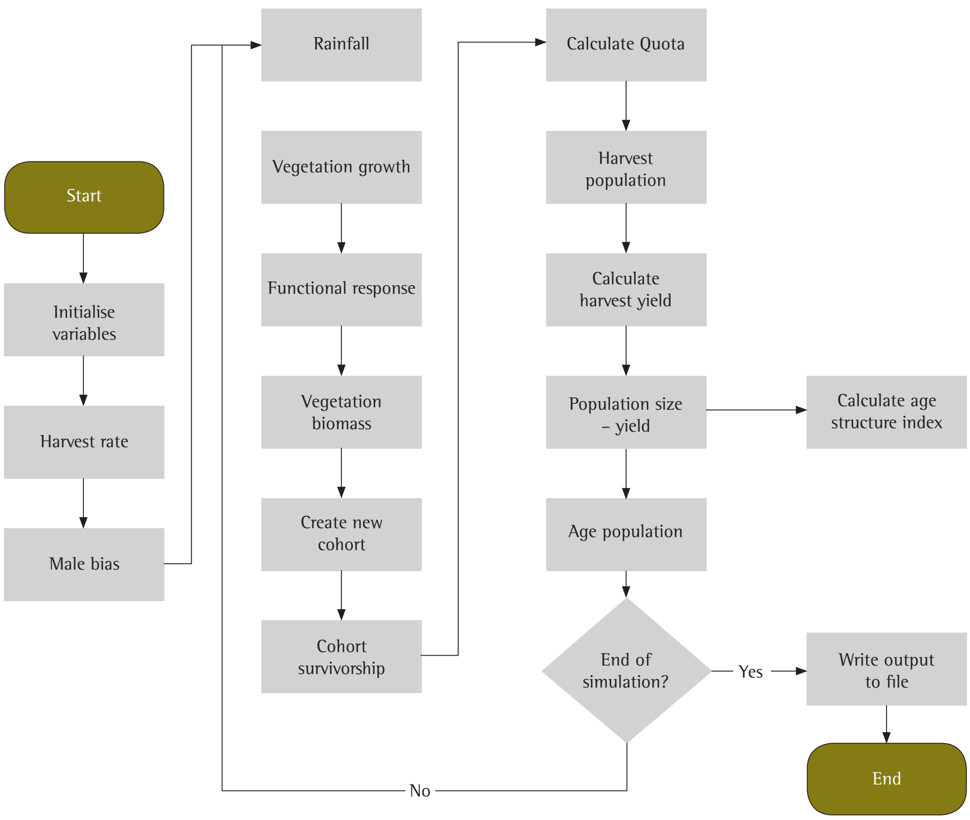
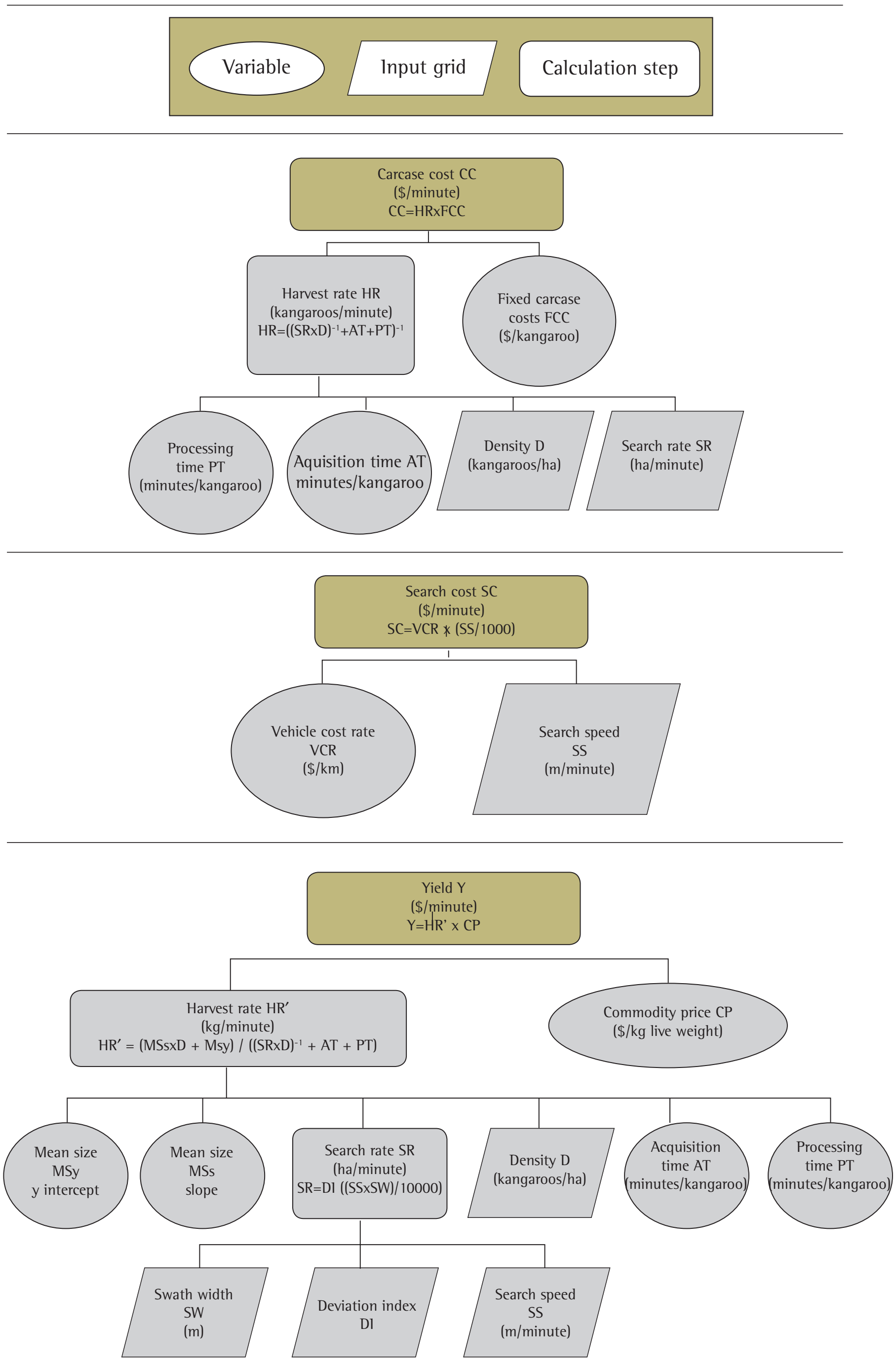
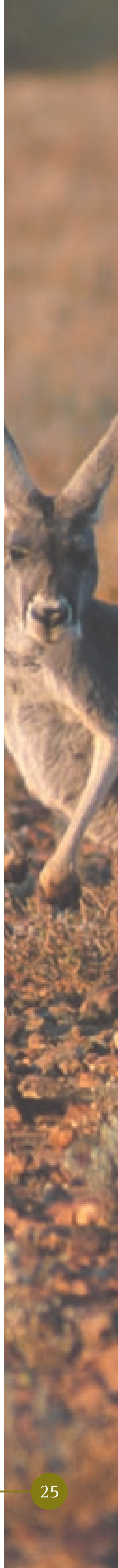
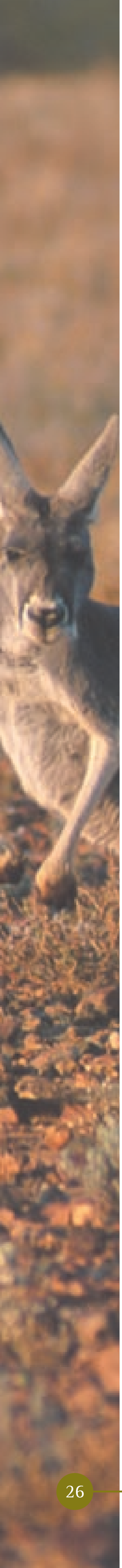


Figure 12. Calculation of terms in the spatial model. Rearrangement of equation (1) allows calculation of the (minimum) density grid, D.



- Vehicle cost rate ($/km) – costs taken from Switala (1997) were expressed on a per km basis. This value was adjusted for the Boorungie model to account for the exceptional mileage that the harvester was able to obtain from his vehicle.
- Shooting time on the property (minutes) – the total time available per night minus travel time to and from the property entry point.
- Commodity price ($/kg live weight) – prices quoted for large, medium or small skins, or per kilogram of carcase weight, were converted to a common live weight basis for use in the model.
- Mean size function: y-intercept and slope – the parameters of the linear regression relating mean kangaroo weight to kangaroo density. This relationship summarises the effect of size-selective harvesting on the average size of the remaining animals. The relationship was determined empirically for each property. An optimisation model, initialised with the density and size distribution of the observed population, was used to calculate the average weight and density of the remaining population as kangaroos were selectively harvested. The relationship between these variables was then summarised by a linear regression.





Spatial variables

Spatial variables were represented in the model as input grids and were related primarily to variation in vegetation and topography across the property. Available land form/vegetation or land system maps were taken as the basis for landscape stratification and cells were allocated to the dominant landscape unit within them. Spatial variables derived from data for landscape units included:

- Search speed (metres/minute) – average speed of travel.
- Swath width (metres) – maximum range over which harvesters shot animals.
- Deviation index – a unitless parameter, derived from analysis of harvesters' tracks, reflecting the reduction in search rate caused by the negotiation of obstacles.
- Accumulated cost (minutes) – the minimum travel time to any cell from a single point of entry to the property. Accumulated cost was calculated using the CostDistance function in ArcView–Spatial Analyst. The calculation requires the construction of an impedance grid, specifying the time required to traverse each cell. A primary impedance grid was first constructed using data for the average speed of off-track travel within each landscape unit, and maps indicating the location of fences and other barriers to movement. Tracks and their associated impedance values, derived from the average speed of along-track movement, were then overlaid to produce the final impedance grid. The accumulated cost grid produced by the CostDistance function was converted to integer values by multiplying by 1000. The travel time (TT) term in equation (1), being for the return journey, was calculated as twice the accumulated cost.

No further input grids are required to compute the minimum kangaroo density required to satisfy harvester profit expectations. However, one further grid was required for interpretation of model output:

- Kangaroo density – the actual density of kangaroos in each grid cell. Density estimates derived from line transect surveys were calculated for open and non-open areas, averaged over the number of surveys available, and assigned to landscape units categorised on the same basis.

Model results

The calculated density grid represents the minimum density of kangaroos required to meet specified harvester profit expectations. Harvesting would only be expected to occur in areas where the actual density exceeds the minimum. Comparison of the minimum and actual density grids thus allowed areas of restricted, breakeven and unrestricted harvest to be identified. These were defined as areas in which actual kangaroo density was, respectively, more than 10% below, within plus or minus 10% , or more than 10% above the calculated minimum density.

Regional level model

The region selected for study was the Western Division of New South Wales. Since skin shooting does not occur in this region the model assumes carcase harvest only. Development of the model to the regional scale required only an enlargement of the grid cell size (to 1x1km) and explicit treatment of the travel cost (TC) term in equation (1). In the property model, travel cost to the point of entry was fixed for each property studied, and the model defined harvest economics only within the property boundary. In the regional model, property boundaries were ignored and travel cost for the journey to and from the nearest chiller (an approximation for the round trip from base) was calculated explicitly for each cell.

The regional model was thus of the form:

$$(MAP + TC) / (FT - TT) = Y - SC - CC \quad (2)$$

where MAP, Y, SC and CC are identical with equation (1) and

TC = travel cost of the return journey to a chiller by the fastest route ($)
FT = foray time (minutes – set to 600 minutes)
TT = minimum travel time from the cell to a chiller (minutes)

The foray time (FT) represents the total time available for harvesting and transport of the night's harvest to the chiller. It does not include travel from home to the field since harvesters are able to vary their time of departure to keep the foray time more or less constant. Travel time (TT) is thus for only a one-way journey from cell to chiller. As with the property model (Fig. 12), kangaroo density contributes to the calculation of both yield and carcase cost and is the only unknown in the equation.

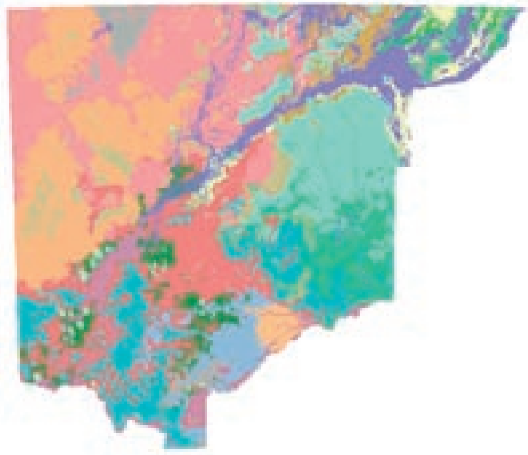
Solution of the regional model required development of a generalised form of the average weight-density relationship, together with regional analogues of the geographic information system layers that were derived from empirical data for the four field sites. Extrapolation from these sites was based on the land systems and land surface types described by Walker (1991). A total of 252 land systems has been mapped in the Western Division, aggregated into 19 land surface types (Figure 13a). Each 1x1km grid cell was allocated to the dominant land surface type within it.

Search speed, search width and deviation. Grid cell values for these variables were extrapolated from field site data on the basis of similarity of landform and vegetation.

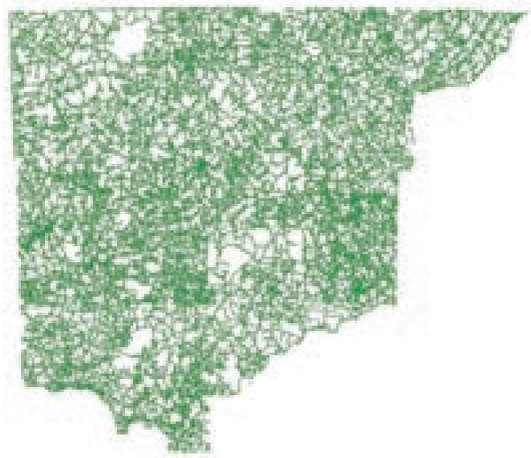
Impedance. The regional impedance grid was developed by a process that modified preliminary values for 100x100m cells, extrapolated from the

Figure 13. Spatial data sets used to derive data layers required for the regional model.

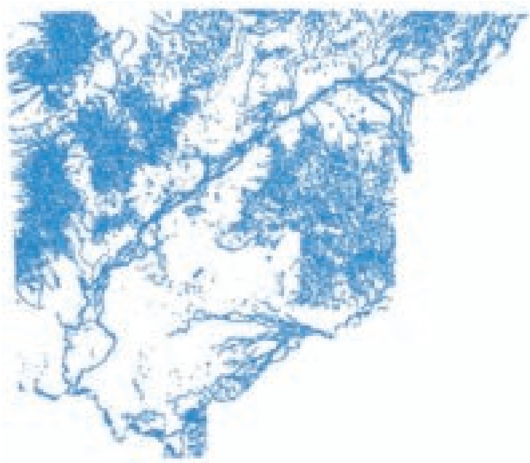
(a) land forms, after Walker 1991



(b) roads and tracks



(c) drainage



(d) chillers and processing plants

property models, for the presence of tracks/roads and drainage features defined by the New South Wales spatial data set (Figure 13 b and c). Assumed speeds of travel on roads and tracks ranged from 100 km/h on major roads to 40 km/h on minor tracks.

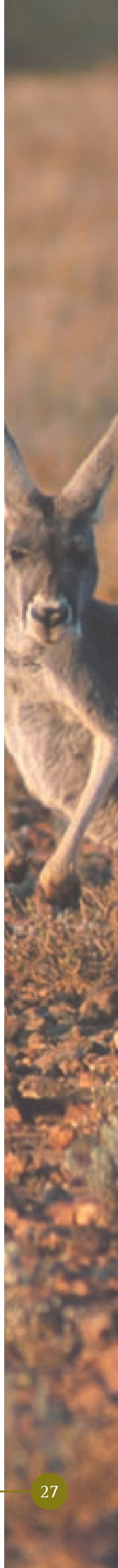
Travel time. The CostDistance function in ArcView – Spatial Analyst was used to calculate the minimum travel time (minutes) from each cell to a chiller or processing plant based on locations provided by the New South Wales National Parks and Wildlife Service (Figure 13d). This function selected the fastest, but not necessarily shortest, route from a cell to any of the available receiving points. For modelling purposes, several chillers located outside the region, but known to receive kangaroos from within it, were located in the closest boundary cell with road access. The impedance value of this cell was increased by the estimated travel time to the actual location.

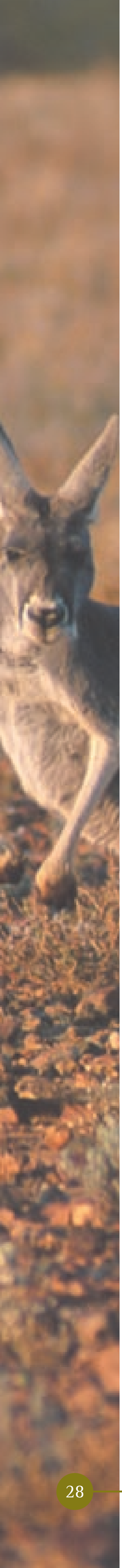
Travel cost. The cost of the return journey from cell to chiller was determined by assuming an average speed of 80 km/h (1.33 km/minute) for travel along the minimum time path. This speed was assumed since the minimum time path will make the greatest possible use of tracks and roads. Travel cost was thus calculated as

$$TC = 2(TT \times AS \times VCR)$$

where

TC	= travel cost ($/foray)
TT	= travel time (minutes)
AS	= average speed (km/minute)
VCR	= vehicle cost rate ($/km).





For the analyses reported here the vehicle cost rate ($0.52/km) was derived as an average of $0.598/km (Switala 1997) and the equivalent cost determined for one of the cooperating shooters ($0.443/km).

Kangaroo density. Grid values for the actual density (animals/sq km) of red and grey kangaroos were derived from 2001 survey data provided by the National Parks and Wildlife Service. Raw data comprised average density estimates for one-degree aerial survey blocks. The final estimates for 1x1km grid cells were derived by first iteratively smoothing the original density values, applied to 0.1 degree – 10x10km – sub-blocks. The resulting population within each sub-block was then distributed among land surface types based on their area (the number of 1x1km cells allocated to the surface type) and a subjectively assigned habitat preference rating (0–5) for the species. The final calculated density was truncated at 100/sq km for both reds and greys independently, as well as for the combined density grid made by summing the two truncated species grids. The final density distributions (Figure 14 a and b) were visually similar to those of Caughley (1987b).

Sensitivity testing

Table 6 indicates the % change in net yield for the property-level model (essentially the right hand side of equation 1) resulting from a 50% reduction in each of the input variables. Commodity price is by far the most influential and its effects were examined in detail for all sites. Although results are sensitive to acquisition time, this variable was not altered in the simulations as it was measured in the field and not estimated.

Table 6. Sensitivity of net yield to variation (50% reduction) in parameter values. (Only absolute values are shown. Response to individual variables could be either positive or negative.)

Parameter	% deviation
Commodity price	64
Acquisition time	44
Density	37
Mean size function (slope)	34
Mean size function (y int.)	31
Processing time	27
Carcase cost	9
Vehicle operating cost	5
Search rate	5
Total time	4
Travel time	2

Sensitivity testing of the regional model (in terms of the effect of changes in input variables on the area over which the calculated minimum density exceeded the actual density) confirmed the importance of commodity price and also indicated greater sensitivity to vehicle operating costs than shown in Table 6. Changes in vehicle cost rate produced a roughly proportional response in the output variable. However, since the rate used is conservative, the model will tend to overestimate rather than underestimate the impact and distribution of harvesting and will thus support precautionary conclusions in terms of implications for kangaroo conservation.

The genetic model

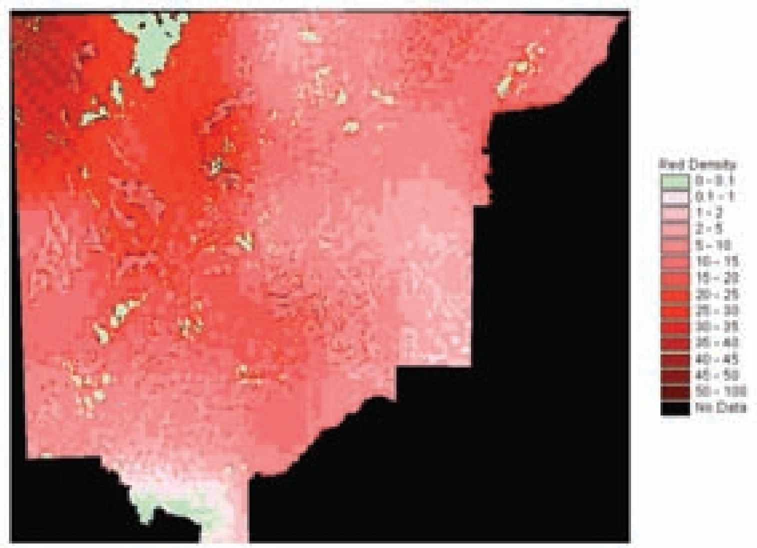
This model explored the potential effects of size-selective harvesting on the gene frequency of kangaroo populations, and the capacity of unharvested refuges to counteract these effects. It was constructed as a stochastic individual-based model parameterised with data for red kangaroos. The underlying genetic architecture assumed that kangaroo growth is determined by balancing selection. In contrast to directional selection, which results in fixation of the trait value that is associated with the highest fitness, balancing selection maintains genetic variation by trading-off different traits. In life history theory it is usually assumed that growth is traded off with survival, so that the cost of being large is a decreased survival probability. The genetics model assumed a trade-off between growth and survival probability under drought conditions. Genes for size and drought resistance could replace each other in the genome of individual animals. This drought resistance is analogous to tolerance of stress caused by poor nutrition and dehydration during periods of low rainfall.

The model assumed there are two benefits of increased growth rate. First, male size is correlated with mating success. Larger individuals usually win in the competition for access to a female. This does not mean that small individuals are excluded from mating, but their mating success is reduced compared to larger counterparts. Second, since age at maturity depends on size, larger females tend to reach maturity earlier than smaller individuals. As the response of individual growth components to natural selection is unknown, two alternative models were explored in which size genes affected either the growth rate or the asymptotic (final) size.

The model includes both demographic and environmental stochasticity. Demographic stochasticity means that at any point in time there is a probability that an individual dies or reproduces. There is thus the possibility, for example, that by chance an individual with a low survival probability may reach old age. Environmental stochasticity enters the model through rainfall which influences population dynamics through its effect on food availability and hence reproduction, growth and survival. Inclusion of environmental stochasticity results in large fluctuations in the population size.

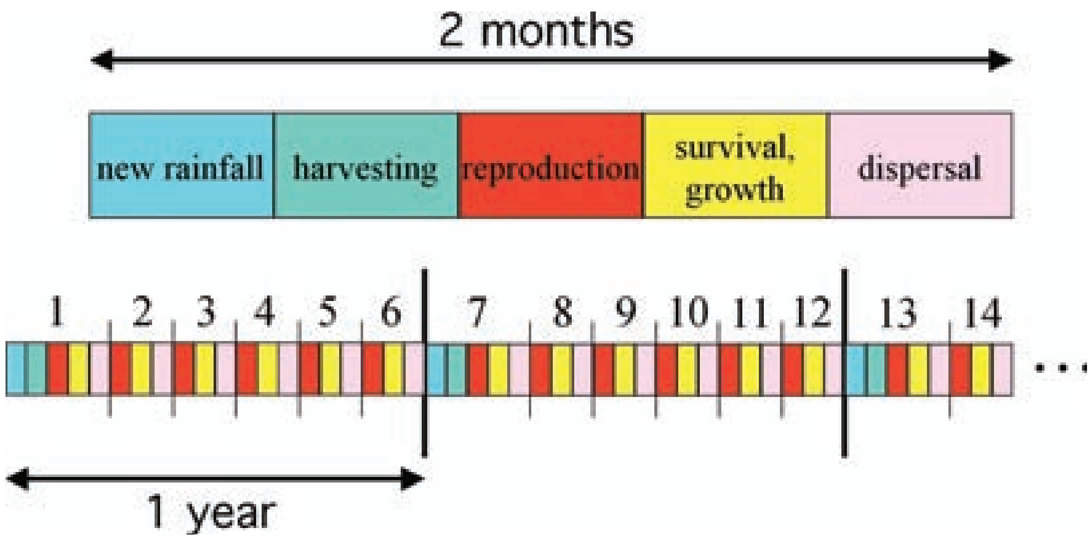
Figure 14. Calculated distribution of red and grey kangaroos (eastern and western combined) in the Western Division of New South Wales

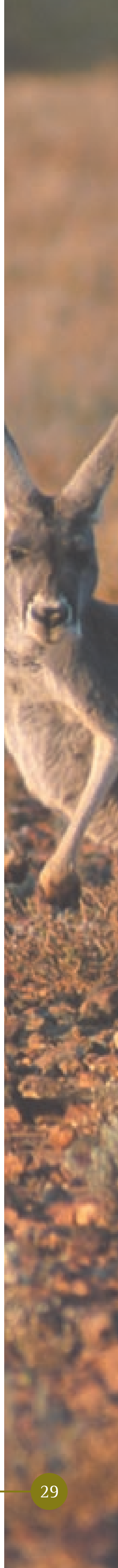
(a) red kangaroos

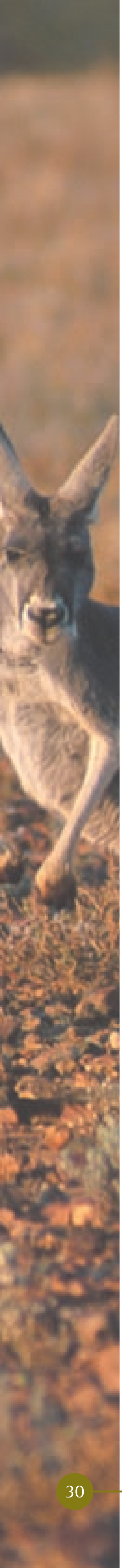


(b) grey kangaroos

Figure 15. Overview of sequentially modelled population processes in the genetics model. Note that determination of annual rainfall and harvesting occur only every 6th time step.







The model operates in time steps of 2 months. As it is individual-based, each individual in the population is tracked. Individuals are assigned an age that is the midpoint of its age class – 1 month, 3 months 5 months and so on. Every time step the model cycles over lists of males and females, and determines the fate of each individual. The different population processes occur sequentially as illustrated in Figure 15.

(1) Rainfall: At the beginning of each year the annual rainfall is determined by randomly drawing a number from the historical rainfall record (123 years) for Menindee in western New South Wales. This parameter is treated as an indicator for the availability of resources, such as food and water, for the whole year.

(2) Harvesting: Harvesting starts 100 years after the beginning of a model run, to allow the gene frequencies and age distributions to reach equilibrium. At the beginning of each following year the number of kangaroos to be harvested is calculated from the kangaroo density and the harvesting quota. Individuals are picked randomly from male and female lists and exposed to harvesting. The probability of being shot depends on both the size of the selected individual and kangaroo abundance.

(3) Mating and reproduction: Each female without a pouch young mates and gives birth to a pouch young with probability f; the sex is assigned randomly with sex ratio 1:1. The father of the offspring is determined in two steps: first, the female encounters a male picked randomly from the list of mature males; second, the probability of a successful mating depends on the size of the selected individual relative to all other males. Both successful and unsuccessful males go back to the list and are eligible to be selected again. This process is repeated until the female is successfully mated. It is possible that a male can have more than one opportunity to mate with a particular female and sometimes even very small males can mate successfully. Newborn kangaroos can die at birth, the probability of death increasing with increasing kangaroo abundance.

(4) Natural mortality, ageing and growing: Each time step there is a chance that an individual will die. If a female dies, her offspring die with her. Dead individuals are removed from the lists. Surviving individuals age by one time step and increase in size. Based on the new age an individual may move up one stage class. For example, at the age of 8 months pouch young turn into young-at-foot, and at the age of 12 months young-at-foot turn into sub-adults. New sub-adults are now independent from their mother's fate and, depending on their sex, they are added to female or male lists. Whether female sub-adults reach maturity depends not only on age but also on their size and rainfall.

(5) Dispersal: Every time step some individuals move between harvested and un-harvested (refuge) populations. Movement occurs in both directions but the net movement is from refuge to harvested population. Dispersing individuals from the refuge replace harvested individuals to some extent and increase the genetic variability of the harvested population. Movement can be halted to represent the situation in which no refuge is available.

Multi-criteria decision analysis

We used a form of decision analysis to compare outputs of the temporal model, in particular, with stakeholder objectives. Decision analysis provides a formal mechanism for integrating the outcomes of alternative options, so that a course of action can be provisionally selected (Clemen 1996). Multiple criteria decision analysis (MCDA) establishes preferences among management alternatives by reference to explicit objectives, for which measurable performance indicators have been established.

We used the SMARTER form of decision analysis (Simple Multiple Attribute Rating Technique Extended to Ranks; Barron and Barrett 1996) to analyse the outputs of the temporal model with respect to the objectives of non-government conservationists, wildlife management agencies, pastoralists and the kangaroo industry.

The analysis involves:

- Calculating the performance indicators that measure the outcome of each management option against the stakeholders' objectives. The complete list of performance indicators is given in Table 1(b). Only eight of these that were considered independent (Table 7) were used in the MCDA.
- Ranking each performance indicator to reflect its relative importance. Table 7 lists the ranks, and their corresponding weights, used to perform the analyses. Stakeholders' rankings reflect their objectives and were assigned after workshop discussion and feedback on preliminary analyses. A neutral group, which weights all performance indicators equally, was also included.
- Summing, for each management option, the cross-products of performance indicator values and their respective weightings. The option with the highest value gives the best overall fit to an individual stakeholder's objectives.
- Testing the sensitivity of the results to changes in scores or weights.

Performance indicators that were used in the MCDA are defined further below and in Table 1b.

Area – the area (sq km) that a harvester would need to cover to harvest 25,000kg of dressed kangaroo meat per quarter.

CV yield - the coefficient of variation of the total yield (derived from mean yield and mean SD as defined in Table 1b).

P(quasi-extinction) – the probability that the density of a harvested population would be less than the minimum density predicted for an unharvested population subject to identical climatic (rainfall) variation.

Similarity – an index of similarity, in terms of structure and density, of the harvested population to an unharvested population.

Mean recovery time index – an index of the time required, after harvesting ceases, for the structure and density of a harvested population to equal that of an unharvested population.

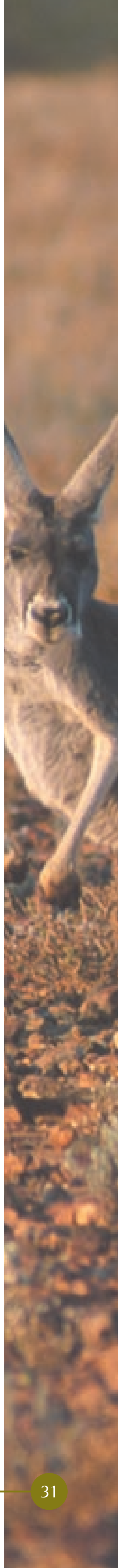
P(TSDM) ≥300 kg/ha – the probability that total standing dry matter is greater than or equal to 300 kg/ha/quarter.

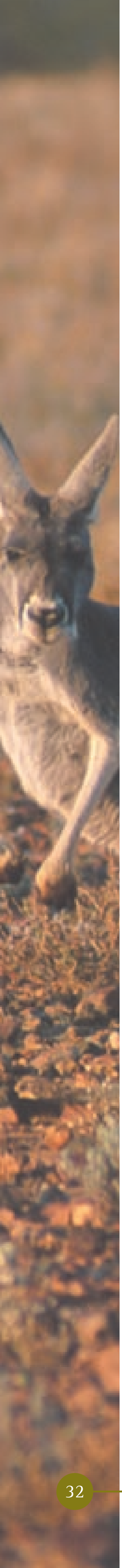
Mean consumption of SGC – mean consumption by kangaroos of safe grazing capacity.

P(total density) ≤0.05 ind./ha – the probability that total kangaroo density is less than or equal to 0.05 kangaroos/ha.

Table 7. Performance indicators and their rankings and respective weights (in brackets) used in the multi-criteria decision analysis. (Weights reflect the importance of the performance indicators for achieving the objectives of the stakeholder groups. Note that the weights add to 1.)

Performance indicators	Non-government conservationist	Wildlife management agency	Kangaroo industry	Pastoral industry	Neutral
Area			1 (0.75)		(0.125)
CV yield			2 (0.25)		(0.125)
P(quasi-extinction)	1 (0.61)	2 (0.27)			(0.125)
Similarity	2 (0.28)	1 (0.52)			(0.125)
Mean recovery time index	3 (0.11)	3 (0.15)			(0.125)
P(TSDM) ≥300 kg/ha				1 (0.75)	(0.125)
Mean consumption of SGC				2 (0.25)	(0.125)
P(total density) ≤0.05 ind./ha		4 (0.06)			(0.125)





Results and discussion

Most output from the temporal model was based on parameters for a red kangaroo population, with climatic data drawn from the historical record for Broken Hill. These conditions are assumed in the results that follow, unless otherwise stated.

Comparing management options with stakeholder objectives

Results of multi-criteria decision analyses

Although the temporal model was run in total for 891 combinations of strategy (from Table 1a), harvest rate and male bias, only the results of the 'current value products' strategy are discussed in detail here. These represent the options that are most likely to be achievable within the constraints of the current kangaroo industry.

Inspection of MCDA scores for the harvest rate/male bias combinations within this strategy indicates that the combinations best able to satisfy stakeholders' objectives distinguished between three groups: non-government conservationists and wildlife management agencies (Figure 16a–b); the kangaroo industry (Figure 16c); and pastoralists (Figure 16d).

The best solutions for non-government conservationists and wildlife management agencies were very similar, reflecting the similarity in performance indicator weightings used in the analysis (Table 7). These solutions included a high proportion of males (0.9–1) for all harvest rates (Figure 16 a–b). The lowest harvest rate (10%) also produced high MCDA scores that declined as more females were included in the harvest. Combinations of annual harvest rate in the range 40%–90% with less than 70% males in the harvest performed poorly. The best overall combination was an annual harvest rate of 10% with male-only harvesting. The performance indicators and weightings chosen by these groups emphasised options that resulted in a low probability of quasi-extinction and maintained high densities of kangaroos (Figure 17 a–b).

The indicators and weightings chosen by the kangaroo industry reflected an interest in minimising the cost of harvesting while obtaining an economically desirable yield (minimising the area to harvest 25,000 kg per quarter) and minimising the variability of yield (Table 7). The best solutions were strongly male biased, and although other harvest rate/male bias combinations appeared to provide comparable solutions, they achieved much lower yields (Figure 17c). The best overall combination was male-only harvesting at an annual rate of 40% (Figure 16c).

The best solutions for pastoralists were characterised by harvest rates greater than 30% per annum made up of at least 30% females (Figure 16d). The best overall combination was an annual harvest rate of 90% with 70% females. The attributes chosen by pastoralists reflected a desire to minimise the effect of kangaroos on available pasture biomass (Table 7 and Figure 17d). In contrast to the best overall solutions for the other stakeholders, scores for harvest rate/male bias combinations that involved male-only harvesting were universally poor.

For the neutral MCDA (Figure 18), two groups of harvest rate/male bias combinations produced the best solutions. One was a strong male bias (70%–100%) across all harvest rates and the other, low annual harvest rates (10%–20%) across all combinations of sex ratio. The best overall combination was an annual harvest rate of 20% with 70% males – not greatly different to the harvest achieved under the present management program in each state. Combinations including high annual harvest rate and strong female bias performed poorly.

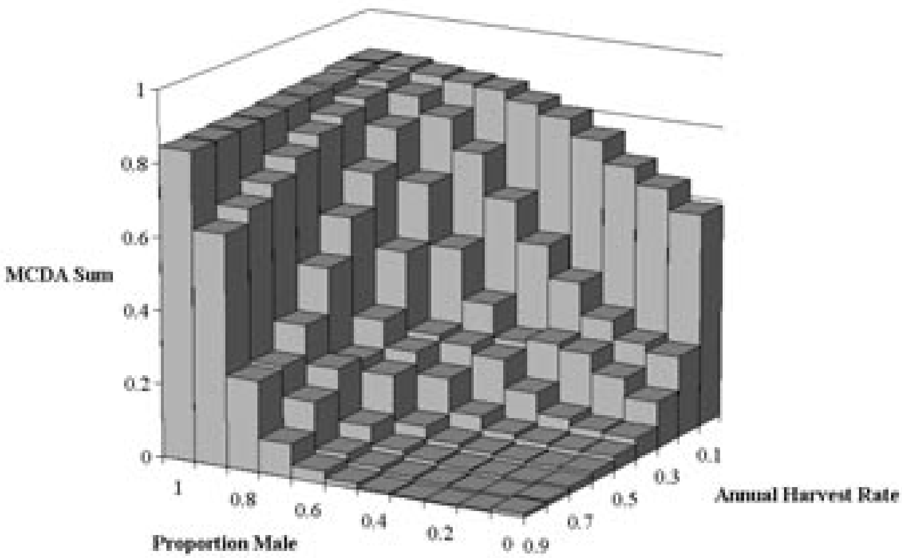
The major differences between stakeholders' preferred solutions lie in the sex ratio of the harvest. Non-government conservationists, wildlife management agencies and the kangaroo industry favour a harvest with strong male bias (90–100%) while pastoralists favour a strong female bias. The former will maintain higher kangaroo densities than regimes that harvest a greater proportion of females, simultaneously allowing the kangaroo industry to achieve high yields with a low risk of quasi-extinction. The latter will lead to low densities, relative to an unharvested population, with subsequent small increases in average forage biomass.

Unfortunately, no harvest rate/male bias combination represents the best solution for all stakeholders, given their current performance indicator weightings. In this situation, the neutral analysis may provide the best approach to balancing competing objectives. It is perhaps serendipitous that the best solution identified by this analysis is not greatly different from the regime achieved by the current industry.

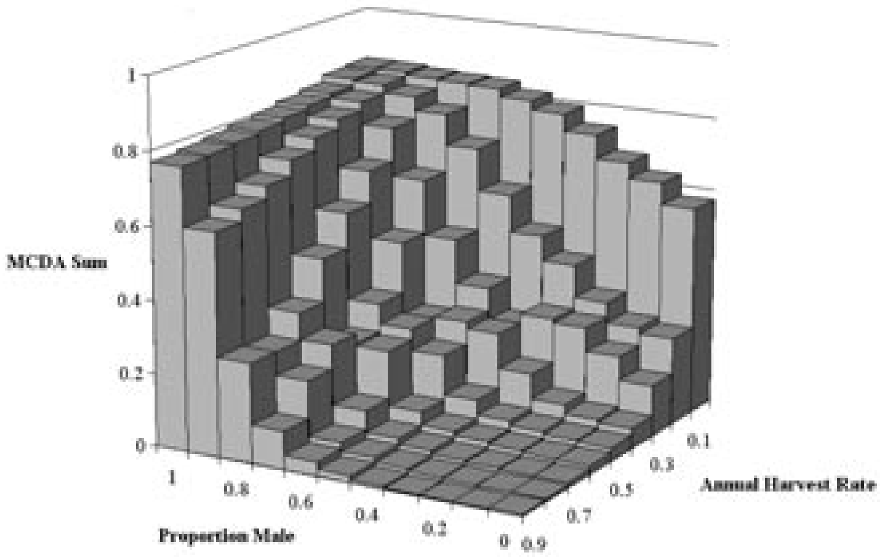
The greatest scope for reconciling the goals of the stakeholder groups, or for achieving specific management objectives, lies with adjustments to the sex ratio of the harvest. These adjustments could be applied tactically (for example, in response to seasonal conditions) or locally (for example, in response to individual landholder aspirations). If the goal of management is to minimise the effect of harvesting on kangaroo populations, then a harvest strategy that includes

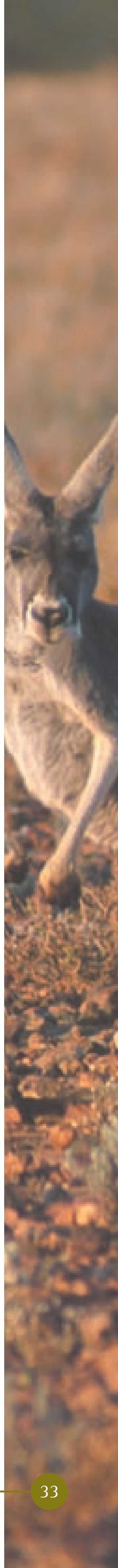
Figure 16. Scores from multi-criteria decision analysis for the current value products strategy.

(a) non-government conservationists

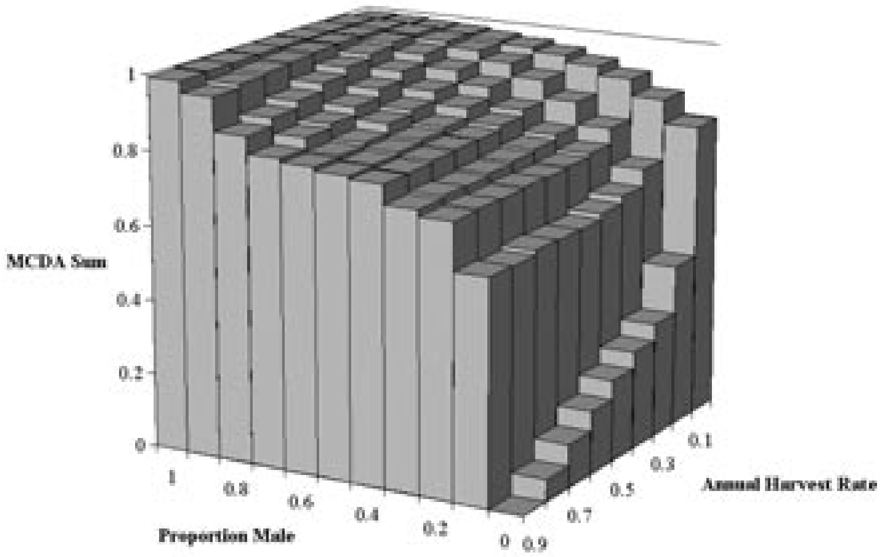


(b) wildlife management agencies





(c) kangaroo industry



(d) pastoral industry

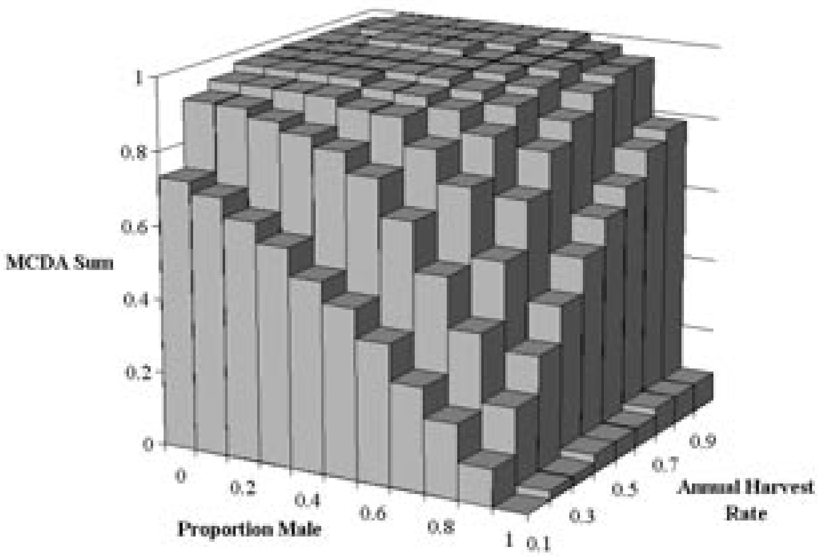
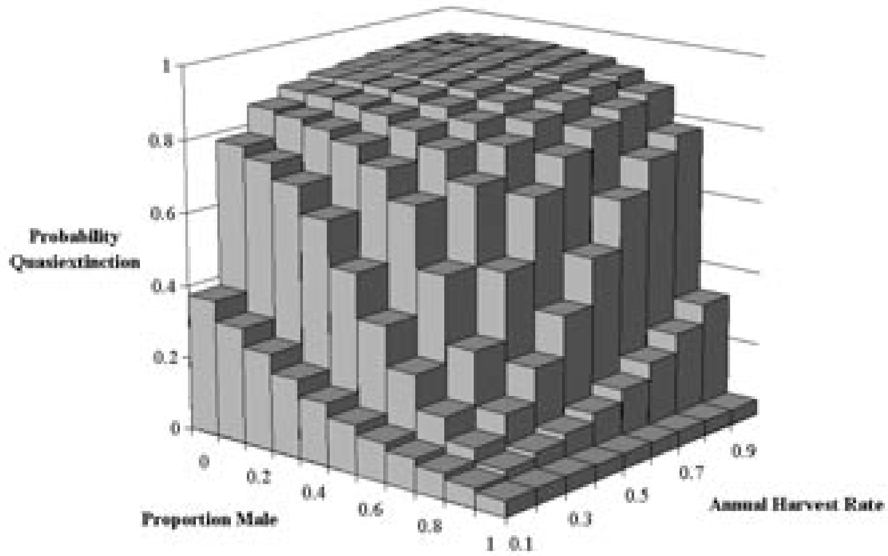
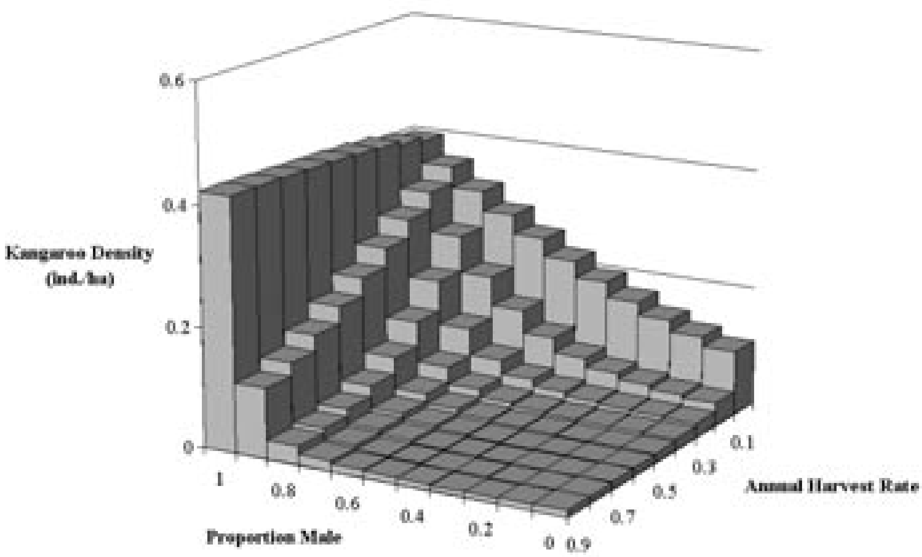


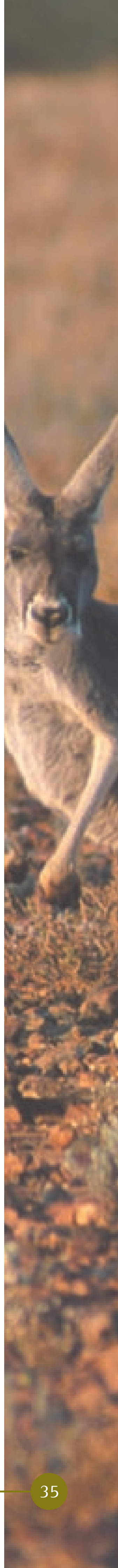
Figure 17. Quasi-extinction probabilities, average kangaroo densities, average yields, and average pasture biomass resulting from harvest rate/male bias combinations within the current value products strategy.

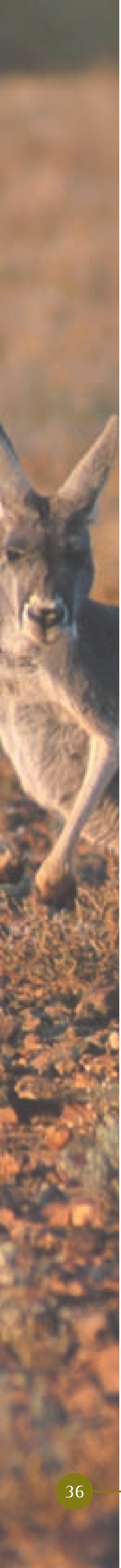
(a) probability of quasi-extinction



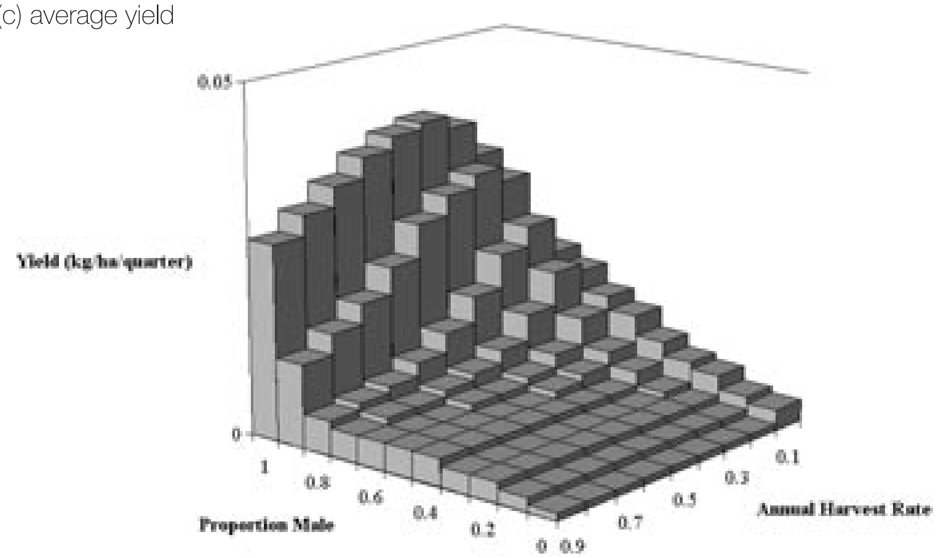
(b) average kangaroo density







(c) average yield



(d) pasture biomass

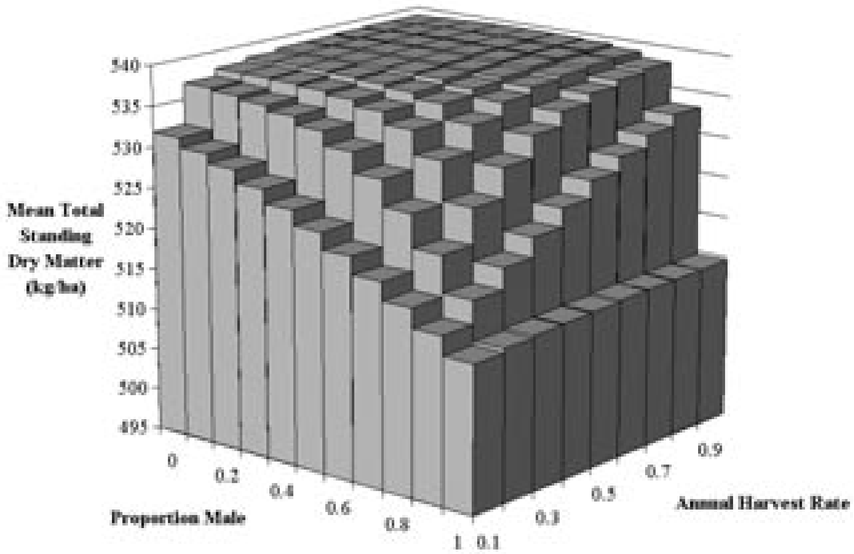
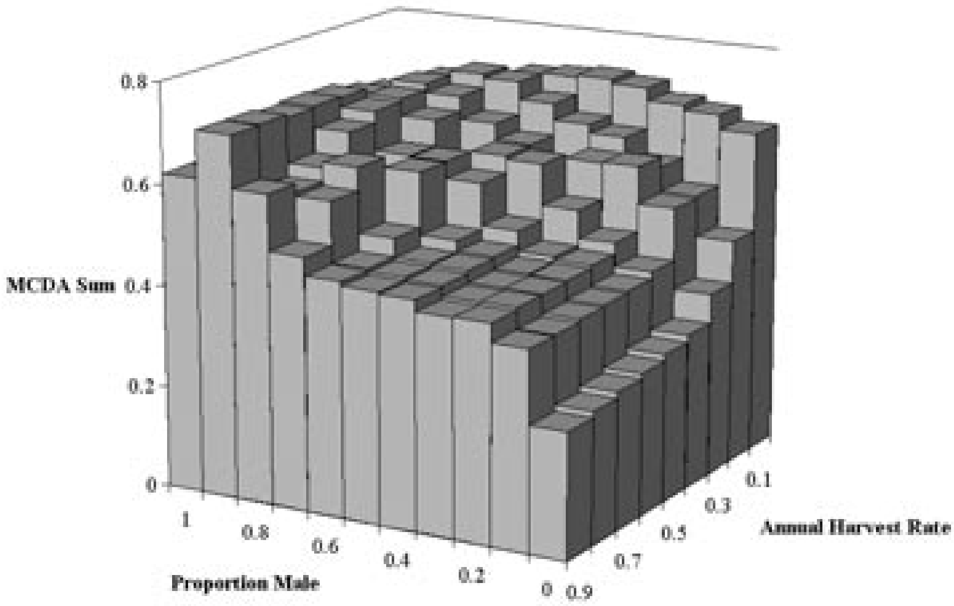


Figure 18. Scores from the multi-criteria decision analysis for neutrally weighted attributes (current value products strategy)



a high proportion of males in the harvest at a low annual rate will be favoured. A similar male-biased strategy, but with a slightly higher annual harvest rate, would be used if the goal of management is to achieve a high yield. But if the goal of management is to minimise the impact of kangaroos on forage availability, a high annual harvest rate and a female bias will be favoured.

Sensitivity analysis

Sensitivity analyses indicated that the multi-criteria decision analysis results were robust to changes in the relative weightings of selected performance indicators for all stakeholder groups.

Strategies for long-term average population densities

Management of kangaroo populations to achieve desired long-term average population densities, rather than sustainable yield, is sometimes advocated as a means of reducing impact on the pastoral industry. Results for the 900 management alternatives simulated using the temporal model (strategies x harvest rate x male bias, including unharvested combinations), allow an evaluation of the options available, and their implications for the kangaroo industry.

The relationship between (long-term) mean kangaroo density and minimum kangaroo density for these options is shown in Figure 19. Density of unharvested populations in these simulations rarely fell below a minimum of 5 individuals/sq km. Although the critical minimum density is not clearly defined, populations below 2/sq km would generally be considered at risk of extinction. On this basis, Figure 19 suggests that any option resulting in an average long-term density of less than 10/sq km should be rejected since in all such cases the minimum density is likely to fall below the critical level. Some options producing long-term average densities in the range 10–15/sq km also produced minimum densities below the critical level although most were above this threshold.

The management options available to produce a range of long-term average densities are summarised in Table 8. A large number of options are available for all density classes. However, as the desired density range increases, the number of options decreases, maximum harvest rate decreases and minimum male bias increases. As a rule of thumb, long-term average population density will decrease with decreasing male bias and with increasing harvest rate.

Figure 19. Relationship between mean (long term) kangaroo density and minimum density for all combinations of strategy, harvest rate and male bias. Values for unharvested populations are included. (All values are the mean of 100 simulations)

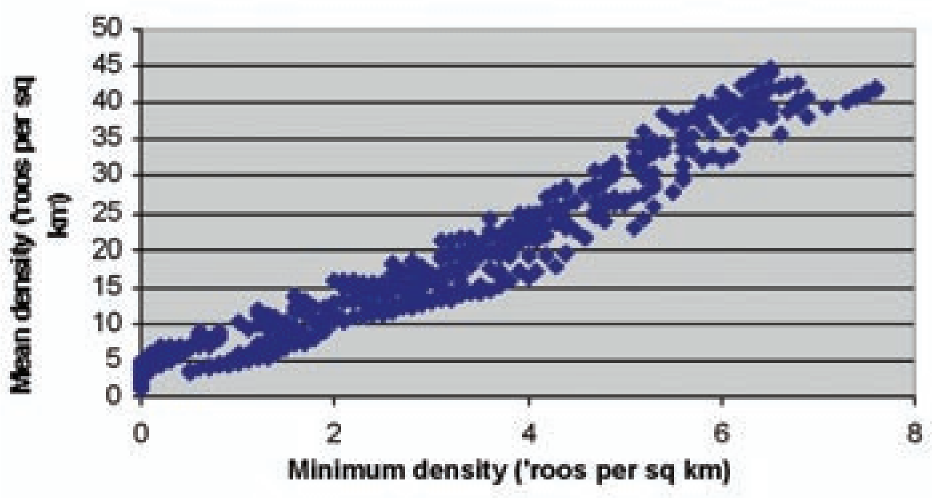
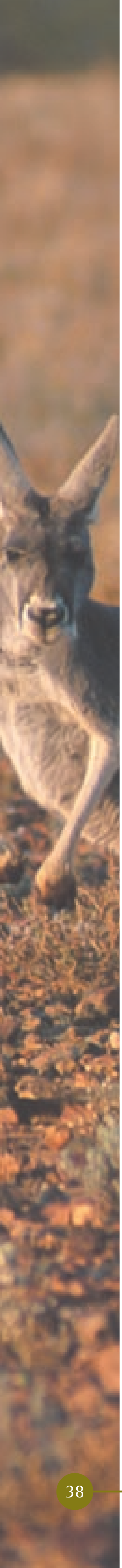


Table 8. Summary of the management options available to produce a range of long-term average kangaroo densities.

Density range (kangaroos/sq km)	No. of options	Harvest rate	Male bias	Mean yield (kg/ha)	Relative mean yield*
10–15	72	0.1–0.9	0–0.9	0.006–0.142	0.46–10.9
15–20	69	0.1–0.9	0–0.9	0.005–0.103	0.39–7.9
20–25	50	0.1–0.9	0–0.9	0.006–0.092	0.46–7.08
25–30	38	0.1–0.7	0.4–0.9	0.007–0.099	0.54–7.62
30–35	29	0.1–0.4	0.6–0.9	0.008–0.098	0.62–7.54

* Relative to average yeild produced by current industry practice, taken as the mean of the long term average yields produced by harvest rate/male bias combinations of 0.1/0.6 and 0.2/0.6, for the 'current value products' strategy (0.013 kg/ha)



Density range (kangaroos/sq km)	No. of options ¶	Harvest rate	Male bias	SD of yield*
10–15	10 (3)	0.1–0.8	0–0.9	0.006–0.022
15–20	15 (3)	0.1–0.7	0.2–0.9	0.010–0.031
20–25	14 (8)	0.1–0.6	0–0.9	0.009–0.033
25–30	12 (8)	0.1–0.4	0.5–0.9	0.008–0.034
30–35	9 (1)	0.1–0.3	0.7–0.9	0.011–0.034

Table 9. Summary of management options that would result in yields relative to the current industry in the range 1.0–2.0.

¶ Figure in brackets is the number of options that fall within current industry practice, defined as harvest rate of 0.1–0.2 and male bias of 0.5–0.7.

* Standard deviation of yield. The standard deviation produced by current industry practice (harvest rate/male bias combinations of 0.1/0.6 and 0.2/0.6) is 0.008.

Not all of the options summarised in Table 8 could be implemented by a commercial industry. The data for relative mean yield indicate that some options would be expected to yield less than the current management regime, necessitating a contraction in the industry. Others would yield much more than the current markets could be expected to absorb in the short to medium-term. Options that lead to either result are impractical and may be dismissed from further consideration.

Table 9 summarises the options that would lead to relative yields in the range 1.0–2.0, that is, equivalent to, or up to twice, the yield from current industry practice. These options imply either no contraction in the industry or opportunities for substantial but probably not unrealistic expansion. While these options appear reasonable in terms of

Table 10. Management options for a range of long-term average densities that are consistent with current industry practice.

Density range (kangaroos/sq km)	Strategy	Harvest rate	Male bias
10–15	No harvest of animals ≥10 yrs	0.2	0.6
	No age restriction	0.2	0.6
	No harvest restriction above 0/sq km	0.2	0.6
15–20	Low value products	0.2 0.2	0.5 0.6
	Current value products	0.2	0.7
20–25	No harvest of animals ≥10 yrs	0.1 0.1	0.5 0.6
	No age restriction	0.1 0.1	0.5 0.6
	No harvest restriction above 0/sq km	0.1 0.1	0.5 0.6
	No harvest restriction above 5/sq km	0.1 0.1	0.5 0.6
25–30	Current value products	0.1 0.1	0.6 0.7
	Low value products	0.1 0.1	0.5 0.6
	No harvest restriction above 5/sq km	0.1	0.7
	No harvest restriction above 0/sq km	0.1	0.7
	No harvest of animals ≥10 yrs	0.1	0.7
	No age restriction	0.1	0.7
30–35	Low value products	0.1	0.7

actual or potential demand for kangaroo products, the data for standard deviation of yield indicate that many would result in more variable offtake than the industry currently experiences. Further, most would require considerable change in industry practice. Only relatively few fall within the range of current practice, assumed to be represented by harvest rates of 0.1–0.2 and male bias of 0.5–0.7, except within the density range of 20–30/sq km. Much of the current industry operates within this density range. Those options that fall within the range of current industry practice are detailed in Table 10. All of these would lead to higher yield variation than experienced by the current industry. Those that do not fall within current harvest parameters are given in Appendix 2; application of these options would require a capacity to strictly regulate the harvest, particularly the male bias, in order to achieve the desired outcome.

Table 10 indicates that the combination of 20% harvest rate and 70% male bias, for the current value products strategy, produces a relatively low average kangaroo density. This is also the combination identified in the MCDA (above) as the best solution for the neutral indicator weightings. This option should thus be seriously considered as a means of achieving a reasonable compromise between stakeholder groups. Figure 14 (a and b) indicates that a long-term average density of 19.5/sq km (the modelled value for this combination) would be less than the 2001 combined density of reds and greys over much of western New South Wales. However, while this and other low-density combinations described in Table 10 are within the range of industry practice, a consistent harvest rate of 20% is probably beyond the current state of industry development. Harvest rates lower than this have not been consistently achieved in Queensland, New South Wales or South Australia. Market development would therefore be essential if management were to aim successfully for lower average long-term densities.

Results for eastern and western grey kangaroos

The multi-criteria decision analyses for red kangaroos, discussed above, were repeated for eastern and western grey kangaroos. These analyses used versions of the temporal model parameterised with species-specific data derived from the field sites (for example, survival probabilities – Figure 7). Pasture growth estimates for the 3-monthly model time step were derived from daily growth predictions of the GRASP model (Littleboy and McKeon 1997) based on climatic data for either Charleville (eastern greys) or Cobar (western greys).

Results for both species were similar to those for red kangaroos. Neutrally weighted MCDA scores indicated that conservative harvest rates (10–20%) and male biases in the range 60–90% produced the best compromise between stakeholders' objectives. Corresponding figures for red kangaroos were 10–20% and 70–100 %. For all three species, combinations of high annual harvest rate and strong female bias produced low scores.

The results indicate that the combination of 20 % harvest rate and 70% male bias identified for red kangaroos could be applied also to eastern and western greys. The three species could thus be subject to a single management program, in the expectation that their response to harvesting would be similar.

Implications of long-term average population densities for resource sustainability and pastoral production

A number of performance indicators for the 'practical' options identified in Table 10 are listed in Table 11, together with comparable values, where applicable, for an unharvested population. These indicators are intended to provide a more explicit assessment of both sustainability and the potential benefits to pastoralists.

Mean and minimum kangaroo densities under these options conform to the selection criteria discussed above. Generally, the minimum density is comparable to the unharvested population except in a few instances where it only slightly exceeds the critical threshold. Variability in density, however, is always less than the unharvested population suggesting that harvesting may limit the extent of population booms and busts. The probability of quasi-extinction is inevitably larger than for the unharvested population. While this probability is generally less than 0.1, it is sufficiently high in some instances, including the 'current value products, harvest rate 0.2, male bias 0.7' option discussed above, to require that the implementation of any such changes to kangaroo management should proceed with caution, within an adaptive management framework.

Table 11 indicates that only small increases in mean total standing dry matter, and the proportion of time with biomass above 300 kg/ha, will result from any of the management regimes, although a substantial reduction in the consumption of safe grazing capacity will be achieved. These effects reflect the overriding influence of seasonal variation, rather than kangaroo density, on biomass production and total standing dry matter.

Detailed evaluation of the effect of kangaroo harvesting on pastoral production was beyond the scope of the project. However, a preliminary evaluation (Hacker *et al.* 2000) indicated that even relatively small changes in the temporal profile of forage availability, due to harvesting for maximum sustained yield, could result in substantial

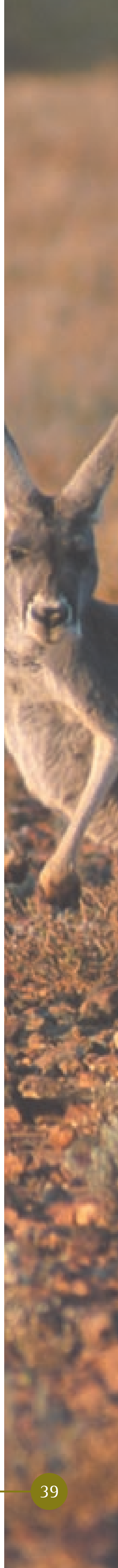


Table 11. Summary of sustainability indicators for practical strategies aimed at achieving a range of average long-term population densities.

Strategy	Harvest rate	Male bias	P(TSDM) ≥300kg/ha	P(total density) ≤0.05ind./ha	P(quasi-extinction)	Mean total* density (ind./ha)	SD total density	Mean TSDM (kg/ha)	Mean consumption of safe grazing capacity	Mean minimum total* density (ind./ha)
Low value	0.1	0.5	0.90	0.18	0.01	0.26	0.21	522	55.12	0.04
Low value	0.1	0.6	0.89	0.16	0.01	0.28	0.23	520	60.25	0.05
Low value	0.1	0.7	0.89	0.14	0.01	0.30	0.24	518	65.63	0.05
Low value	0.2	0.5	0.91	0.34	0.04	0.15	0.15	529	32.18	0.02
Low value	0.2	0.6	0.90	0.27	0.02	0.19	0.17	526	39.71	0.03
Current value	0.1	0.6	0.90	0.15	0.11	0.25	0.19	522	51.30	0.05
Current value	0.1	0.7	0.89	0.12	0.09	0.29	0.21	520	57.61	0.05
Current value	0.2	0.7	0.90	0.23	0.17	0.20	0.15	527	37.97	0.04
No harvest ≥10 yrs	0.1	0.5	0.90	0.22	0.13	0.22	0.18	525	45.43	0.04
No harvest ≥10 yrs	0.1	0.6	0.89	0.18	0.11	0.25	0.20	523	51.19	0.04
No harvest ≥10 yrs	0.1	0.7	0.89	0.15	0.08	0.28	0.22	521	57.37	0.05
No harvest ≥10 yrs	0.2	0.6	0.91	0.36	0.24	0.15	0.13	531	29.24	0.02
No age restriction	0.1	0.5	0.90	0.24	0.12	0.20	0.17	525	40.03	0.04
No age restriction	0.1	0.6	0.90	0.19	0.09	0.23	0.19	523	45.42	0.04
No age restriction	0.1	0.7	0.89	0.16	0.07	0.26	0.21	521	51.23	0.05
No age restriction	0.2	0.6	0.91	0.40	0.25	0.13	0.13	530	25.09	0.02
Above 0/sq km	0.1	0.5	0.90	0.24	0.12	0.20	0.17	525	40.03	0.04
Above 0/sq km	0.1	0.6	0.90	0.19	0.09	0.23	0.19	523	45.42	0.04
Above 0/sq km	0.1	0.7	0.89	0.16	0.07	0.26	0.21	521	51.23	0.05
Above 0/sq km	0.2	0.6	0.91	0.40	0.25	0.13	0.13	530	25.09	0.02
Above 5/sq km	0.1	0.5	0.90	0.14	0.04	0.22	0.17	524	46.19	0.04
Above 5/sq km	0.1	0.6	0.89	0.12	0.04	0.25	0.19	522	51.07	0.04
Above 5/sq km	0.1	0.7	0.89	0.10	0.03	0.28	0.21	520	56.43	0.04
Unharvested	0	0	0.88	0.09	0.00	0.37	0.28	513	82.56	0.06

* Total = males + females

improvements in wool production per head. It was thought unlikely that such improvements would be realised universally. Indeed, verification with a more sophisticated modelling approach would be desirable even for the mulga woodland community on which the analysis was based. It is notable that the average kangaroo density produced by harvesting in this analysis was 0.2 kangaroos/ha (20/sq km), essentially identical to that resulting from the best option identified by the neutral MCDA discussed above.

Effects of climate change

Non-government conservationists at the first workshop expressed an interest in the potential effects of climate change on kangaroo population dynamics. Although no detailed analysis of this topic was possible in the time frame of the project, a broad assessment may be based on climate change scenarios suggested by CSIRO's Climate Impact Group (CSIRO 2001).

The most important effects of climate change on the dynamics of kangaroo populations will be related to changes that influence the frequency and intensity of drought. Predictions of various climate models do not provide consistent indications of the likely change. However, some predictions regarding changes to average climate can be made. Within the next 70 years, average annual temperature in the Murray-Darling Basin is predicted to increase by 1– 6°C. Evaporation will increase commensurately. Rainfall is predicted to increase slightly in summer and autumn, with smaller increases in winter and spring. The net effect of these changes on soil moisture available for pasture growth is highly uncertain. However, areas dominated by summer growing perennial grasses in the northern regions of the Basin may be most affected. In any event, possible changes in the seasonal distribution of forage, and in the frequency and intensity of drought, reinforce the requirement for an adaptive approach to the implementation of the management options discussed above.

Outcomes of the spatial analysis – property and regional scales

Property model

An example of the results obtained by application of the spatial model to one of the field sites is shown in Figure 20 (a–f). Even with a commodity price of $0.60/kg live weight, considerably above the current level for human consumption, substantial areas of the property would be only a breakeven proposition for harvesting. At lower prices these areas, and others, could not satisfy reasonable profit expectations and would probably remain unharvested. The highly localised nature of the actual harvest is confirmed by the locations of the animals taken (Figure 2 a–d).

Figure 21 indicates the proportion of each of the four properties studied that would be subject to restricted harvesting at a range of commodity prices. Given current prices about 20–40 % of these properties could not be economically harvested. The sensitivity to an increase in commodity price varies between properties depending on the mix of land types.

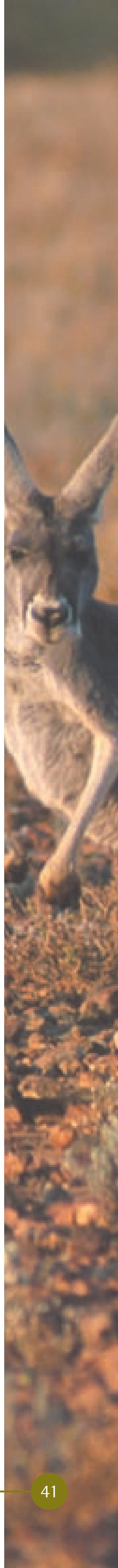
Regional model

Figure 22 presents a commodity price sequence for the Western Division of New South Wales equivalent to that presented above for an individual property. The area of the Western Division that would be subject to restricted harvest at a range of commodity prices and harvester profit expectations is shown in Figure 23. The proportion of the kangaroo population occurring within these restricted harvest areas is shown in Figure 24.

These data indicate that even with commodity prices considerably in excess of current levels an area of about 30,000 sq km, containing about 5% of the kangaroo population, would remain uneconomic and subject to restricted harvesting in the Western Division. This area would be complemented by the area of national parks and other reserves, estimated to contain about 3% of the kangaroo population, and areas that will remain unharvested on individual properties but are not reflected at the grid size of the regional model. Collectively, these areas may act as refugia with potential to offset the effects of size-selective harvesting on population genetics. This potential will be discussed further below.

Figure 25 plots cumulative area in relation to minimum economic density. Figures on the y-axis in this graph represent the area for which the minimum economic density is equal to or less than the corresponding figure on the x-axis. Only very small areas are economically harvestable at kangaroo densities less than or equal to 5/sq km, the density originally considered desirable by pastoralists, even with substantially increased prices. Commercial harvesting could neither reduce kangaroo density to this level nor be sustained if the density were reduced by other means. Furthermore, as discussed above, strategies that produce average densities of less than 5/sq km would result in minimum densities less than 2/sq km and could be considered a threat to species conservation. The strategy identified in Table 2 (maintain kangaroo density at 3–5/sq km) may thus be dismissed from further consideration.

However, as minimum economic density increases above 5/sq km the area that is economically harvestable increases rapidly and the response is highly sensitive to commodity price. Attempts to increase the price of kangaroo products should



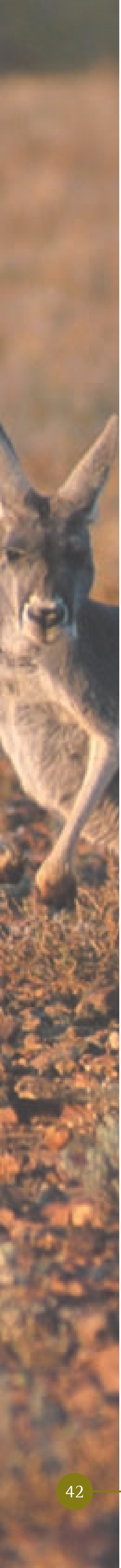


Figure 20 (a–f). Results of application of the spatial model field sites to the Weelamurra.

Minimum kangaroo density (kangaroos/sq km) required to satisfy a minimum profit expectation of $160/night at commodity prices of $0.40, $0.50 and $0.60/kg live weight is shown in (a), (b) and (c) respectively. Corresponding areas of the property in which actual kangaroo density will result in restricted harvest, breakeven or unrestricted harvest are shown in (d), (e) and (f) respectively. (Note: Division by 0.71 will convert commodity prices to an approximate carcase weight value.)

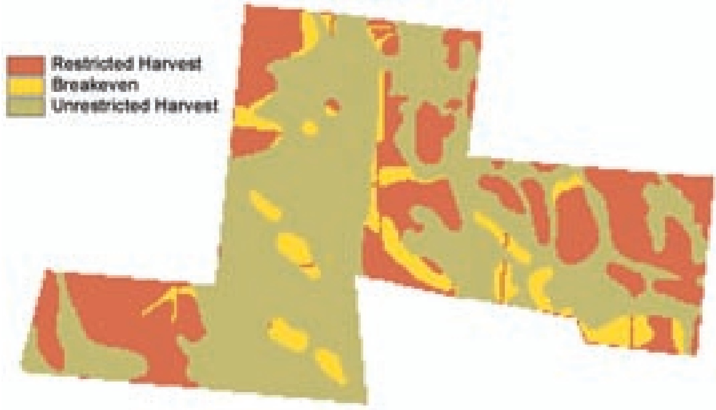
(a) Minimum density – $0.40/kg live weight

(b) Minimum density – $0.50/kg live weight

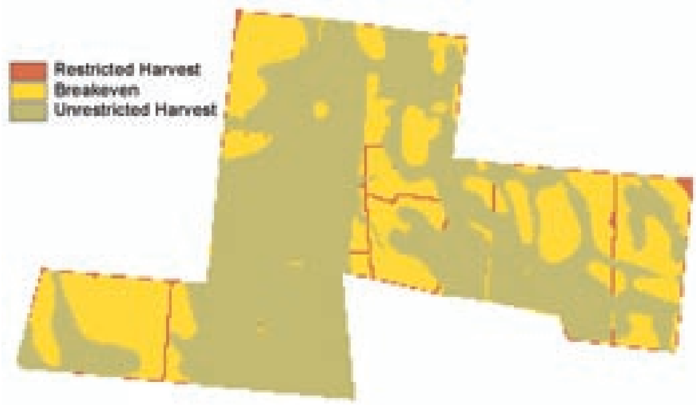
(c) Minimum density – $0.60/kg live weight

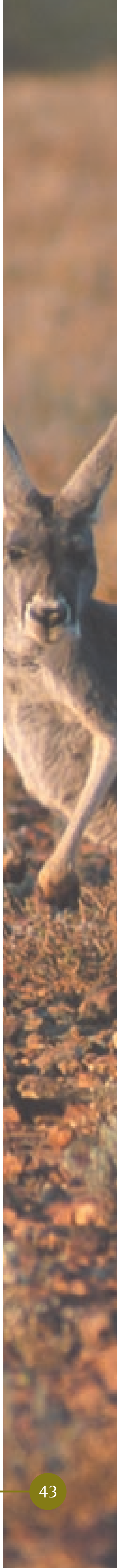
(d) Harvest areas – $0.40/kg live weight

(e) Harvest areas – $0.50/kg live weight



(f) Harvest areas – $0.60/kg live weight





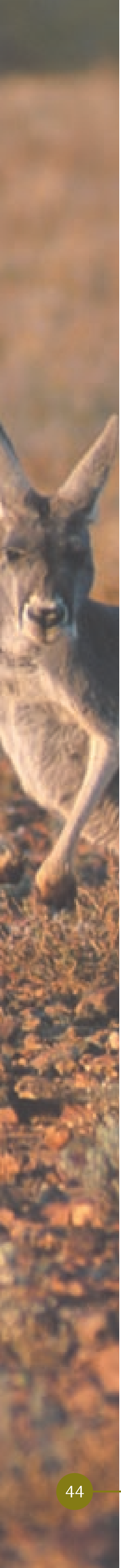


Figure 21. Proportion of properties with restricted harvest at a range of commodity prices.

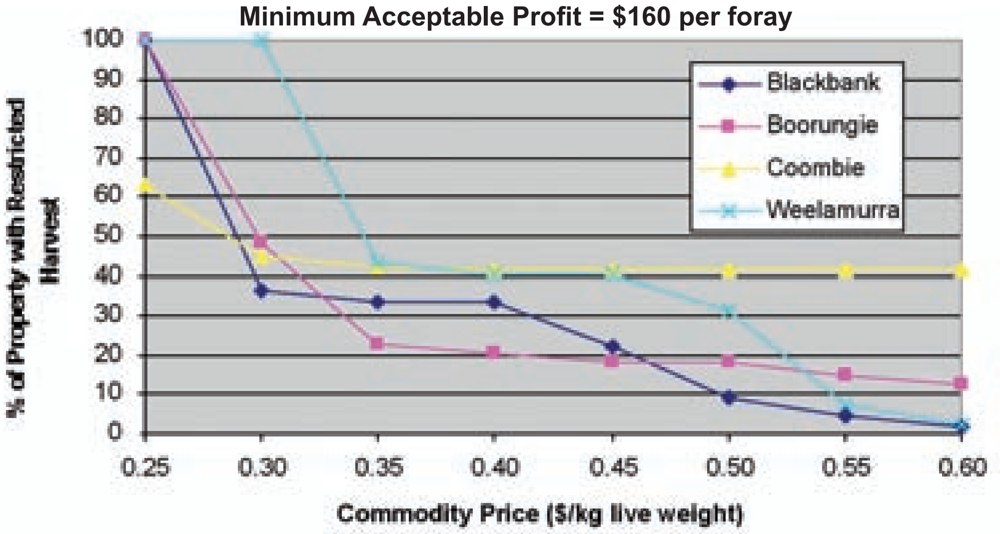
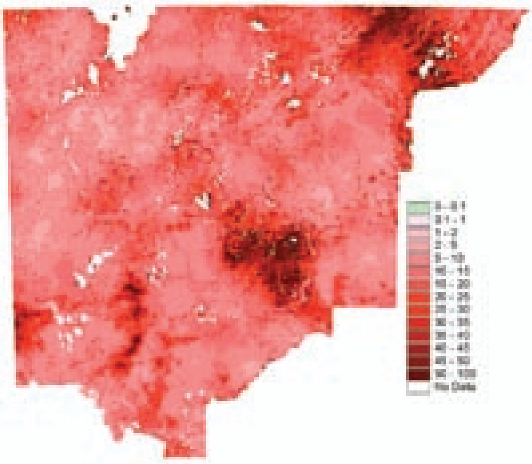


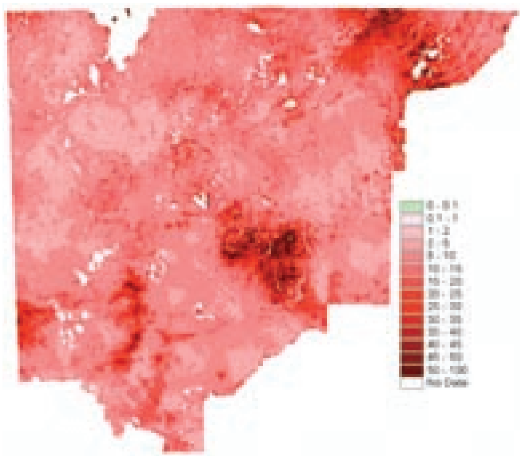
Figure 22 (a–f). Results of application of the spatial model to the Western Division of New South Wales.

Minimum kangaroo density (kangaroos/sq km) required to satisfy a minimum profit expectation of $160/night at commodity prices of $0.40, $0.50 and $0.60/kg live weight is shown in (a), (b) and (c) respectively. Corresponding areas in which actual kangaroo density will result in restricted, breakeven or unrestricted harvest are shown in (d), (e) and (f) respectively. (Note: Division by 0.71 will convert commodity prices to an approximate carcase weight value.)

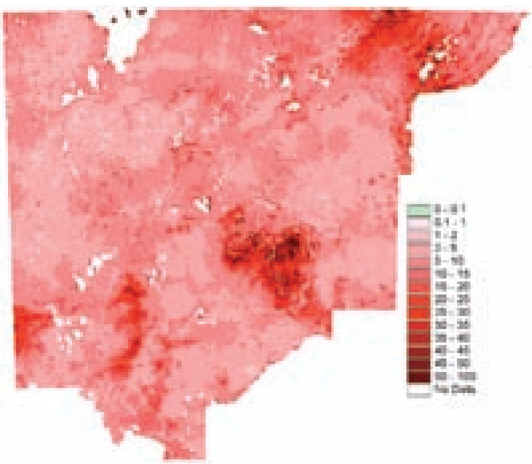
(a) Minimum density – $0.40/kg live weight



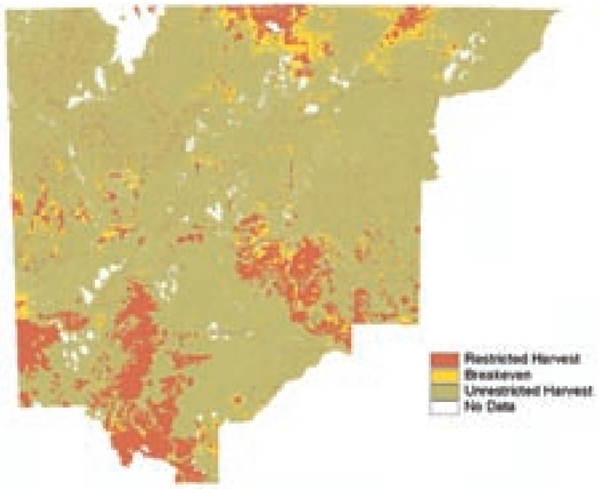
(b) Minimum density – $0.50/kg live weight



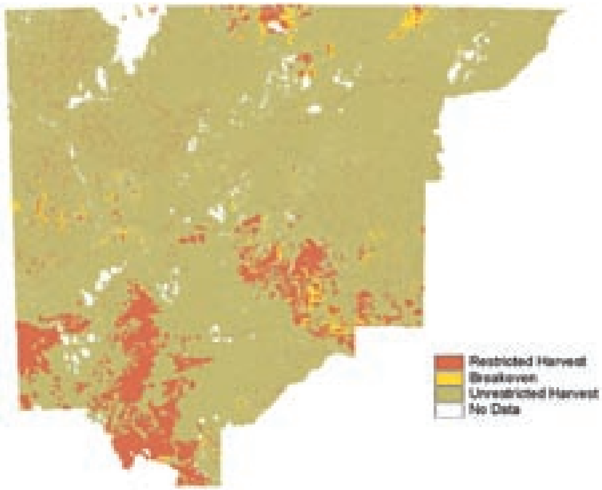
(c) Minimum density – $0.60/kg live weight



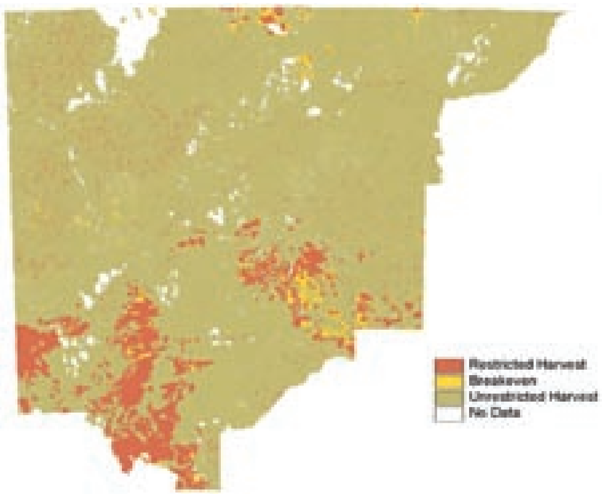
(d) Harvest areas – $0.40/kg live weight

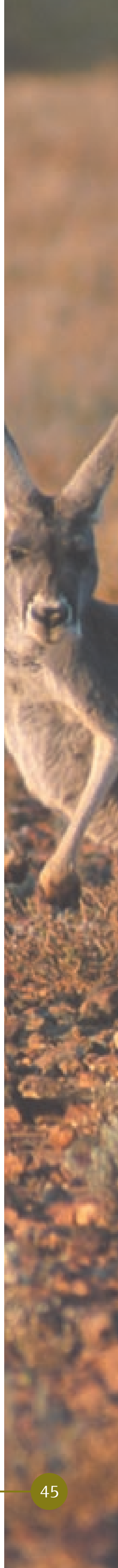


(e) Harvest areas – $0.50/kg live weight



(f) Harvest areas – $0.60/kg live weight





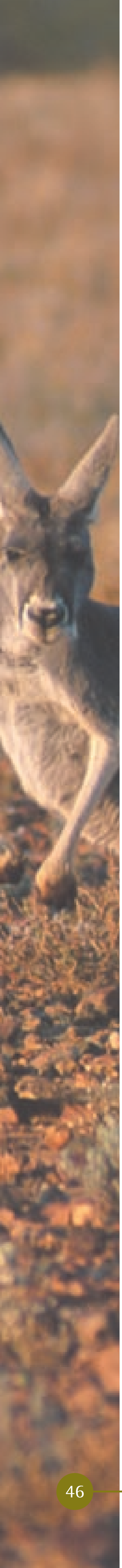


Figure 23. Area of the Western Division of New South Wales that would be subject to restricted harvest in relation to commodity prices and harvester profit expectations.

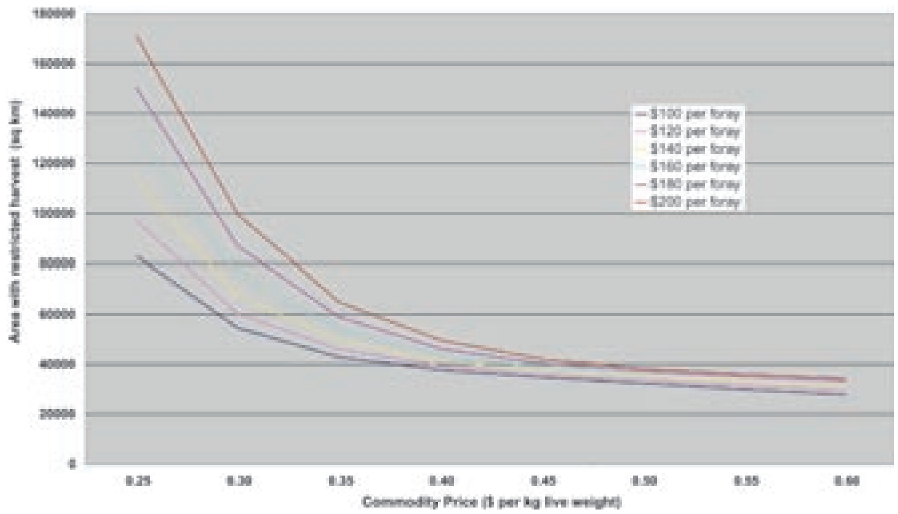


Figure 24. Proportion of the kangaroo population within restricted harvest areas in relation to commodity prices and harvester profit expectations.

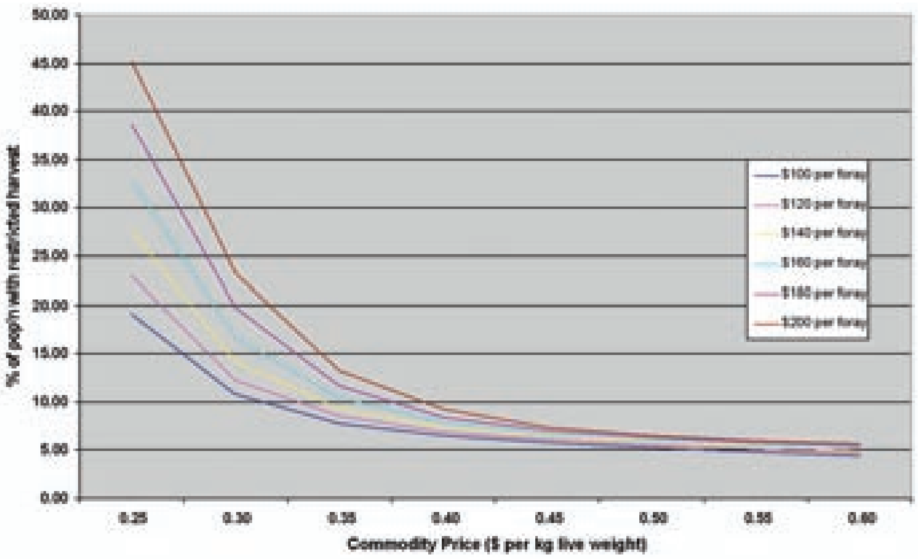
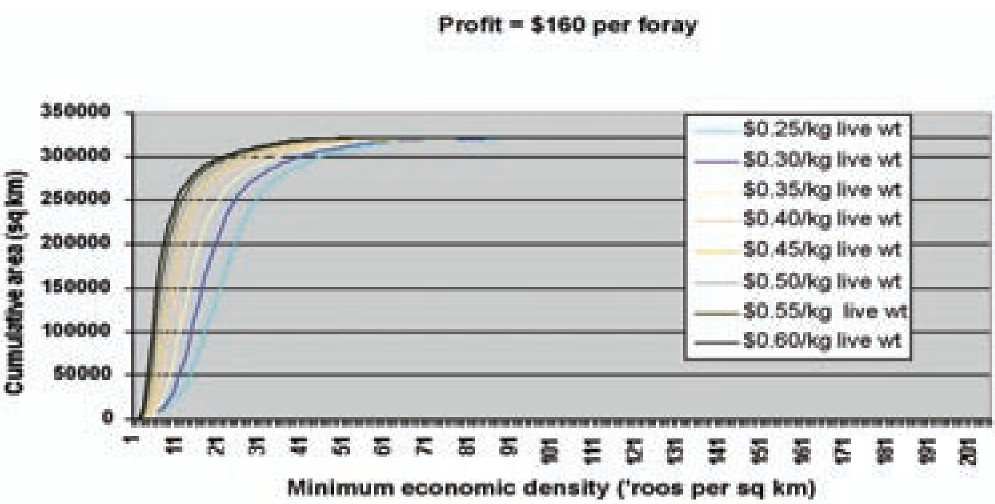


Figure 25. Cumulative area in relation to minimum economic density at a range of commodity prices for the Western Division of New South Wales.



thus potentially have benefits for both pastoralists and kangaroo harvesters.

Although commercial harvesting cannot reduce kangaroos to very low densities, some increase in forage availability compared to a no-harvest situation could still be expected (Table 11). The preliminary evaluation (Hacker *et al.* 2000) discussed above indicated that in mulga woodlands relatively small shifts in the temporal pattern of forage availability could generate economically worthwhile gains in wool production at an average kangaroo density of 20/sq km. Reduction of kangaroos to less than 5/sq km is not only unachievable by a commercial industry, and undesirable from a conservation perspective, but is unwarranted. Any benefits of harvesting to pastoralists are likely to be achieved at considerably higher densities.

Figure 26 shows the difference between actual kangaroo density and minimum economic density across the Western Division of New South Wales. Areas in which this difference is higher will be more attractive for harvesting due either to reduced cost (for example, proximity to chillers, quality of road access or country type) and/or the current density of kangaroos. Harvesters would be expected to preferentially exploit these areas if tags were transferable between landholders or not allocated to landholders. The expected result would be a concentration of harvest. This concentration would not threaten species survival as harvesting over most of the region ceases to be economically viable at densities considerably higher than those commonly regarded as minimum levels for conservation. Concentration of harvest could only be avoided by the allocation of regional quotas and restrictions on transferability of quotas. The importance of achieving a more uniform harvest distribution (for example, to ensure that perceived benefits to pastoralists are distributed more equitably) will thus determine which of the various strategies listed in Table 2, or other variants, might be adopted by management agencies.

Outcomes of the genetic analysis

Because of the trade-off incorporated in the genetic model, drought resistance and size genes can replace each other in the genome of the individual and in the population as a whole. The genetic composition of the population may thus be expressed as the number of size genes relative to the maximum possible number (S). For example, S = 0.6 means kangaroos have on average 60% size genes and 40 % drought resistance genes. An indicator of the magnitude of genetic change may be calculated as the difference between the value of S in the year before harvesting commences, S_1, and the value after 100 years of harvesting, S_2, that is, $\Delta S = S_2 - S_1$. A negative value of ΔS indicates that kangaroos get smaller on average and vice versa.

Trends in gene frequency for baseline cases of harvested and unharvested populations are shown in Figure 27. With no dispersal from a refuge population, and a high minimum harvesting size (s_{min} = 35 kg), the proportion of size genes, S, in the harvested population decreases after harvesting commences while the proportion in the refuge population remains stable at about 0.5. Size-selective harvesting thus has potential to reduce the average size-at-age of kangaroos. This result is consistent with data from heavily harvested populations of several aquatic species. As a result of the particular trade-off chosen in our model, size-selective harvesting will correspondingly increase the degree of drought resistance (or stress tolerance).

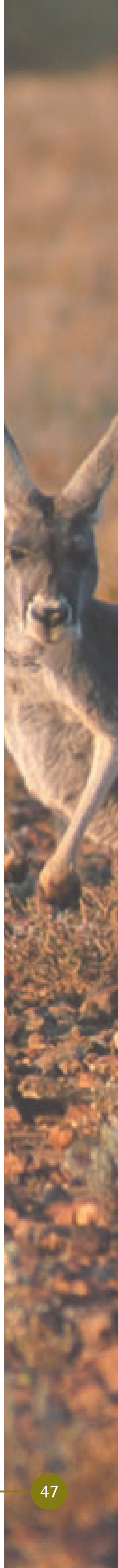
In the majority of runs the effect of size-selective harvesting was not reversible so it is possible that the proportion of size genes will not return to its pre-harvest level after harvesting ceases. However, in scenarios with dispersal between refuge and harvested populations, the proportion of size genes remains at about the pre-harvesting level in both ($\Delta S \approx 0$).

Extensive testing of the model was conducted to determine the sensitivity of model predictions to uncertainty in the parameter estimations and the potential of different management strategies to counteract the effect of size-selective harvesting. The partial rank correlation coefficient (PRCC) was used to express the statistical relationship between each input parameter and ΔS while keeping all other input parameters constant at their expected value.

Sensitivity testing indicated that the results are robust to uncertainty in the parameter estimates and to assumptions about how genes influence growth.

To counter the effects of size-selective harvesting, kangaroo mangers could manipulate the harvest rate, q, the size distribution of the harvested animals (that is, s_{min}) and they could set aside harvest refuges. Without dispersal from harvest refuges, 100 years of size-selective harvesting resulted in a reduced proportion of size genes (ΔS less than 0) in most of the runs (Figure 28 A and B). Regardless of the mode of action of the size genes, their proportion decreases with increasing harvest rate (PRCC [genes affect growth rate] = –0.58; PRCC [genes affect asymptotic size] = –0.49) and with increasing minimum size (PRCC [genes affect growth rate] = –0.32; PRCC [genes affect asymptotic size] = –0.32). The effect of harvest rate is relatively larger than the effect of minimum harvest size.

In contrast, in the scenarios with dispersal from harvest refuges the effect of size-selective harvesting disappears completely if size genes affect the growth rate (all PRCCs not significant) or is very small if size genes affect the asymptotic size. This small effect is influenced by the minimum



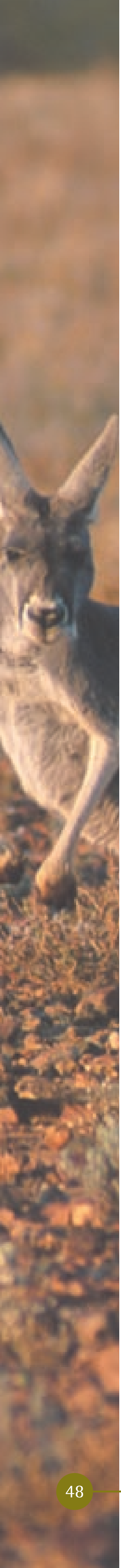


Figure 26. Difference between actual density and minimum economic density. Minimum acceptable profit $160/foray, commodity price $0.40/kg live weight.

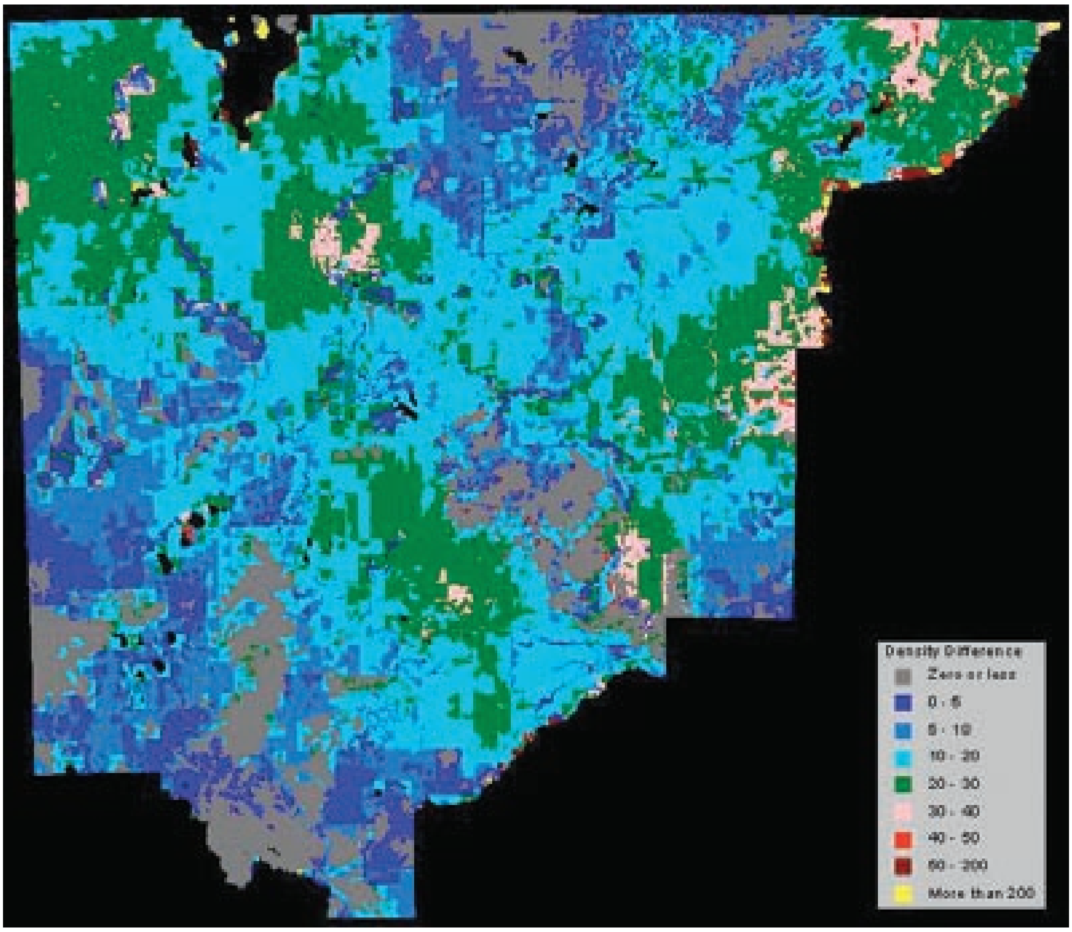


Figure 27. Average number of size genes as a proportion of its maximum in the harvested population (solid line) and the unharvested population (dotted line). Harvesting commences after 100 simulated years; the minimum size of harvested animals, s_{min} = 35kg; size genes determine asymptotic growth; baseline case with no dispersal between harvested and refuge populations.

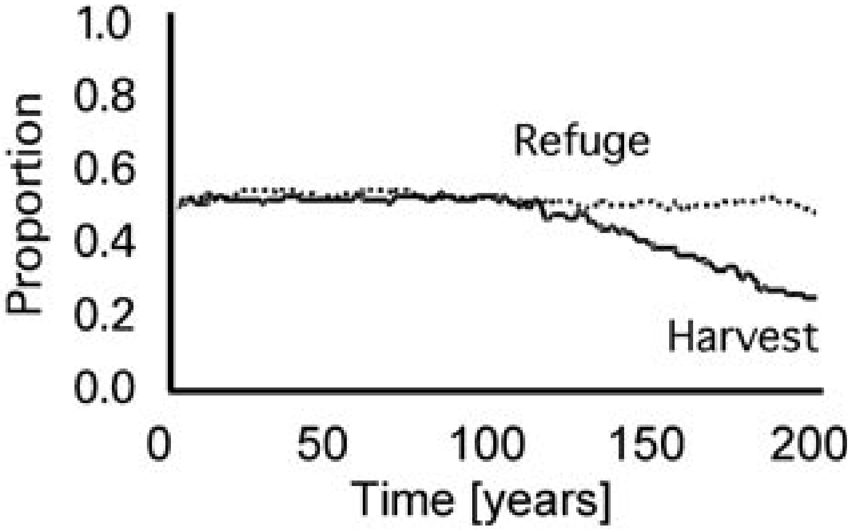
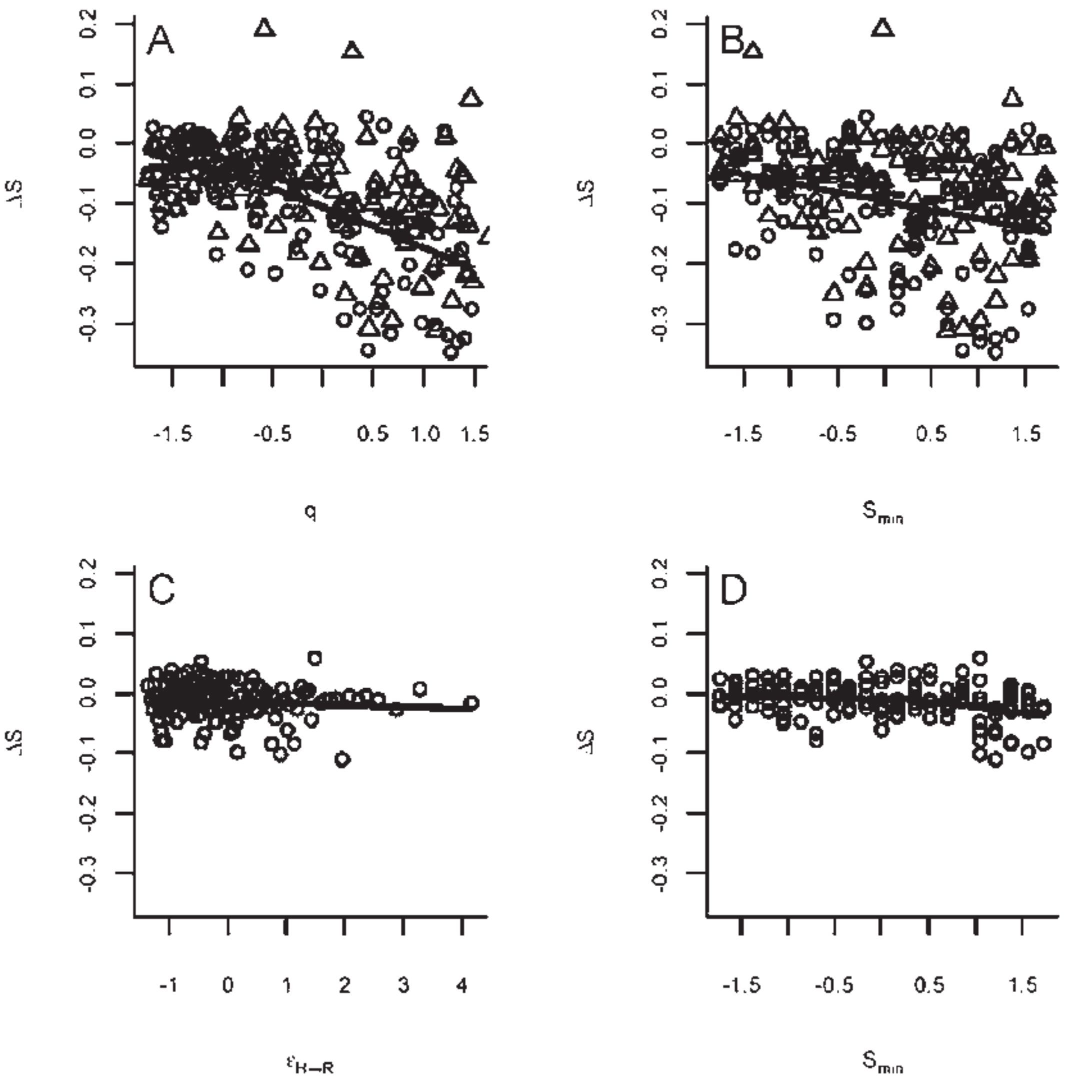


Figure 28. Influence of size selective harvesting on the frequency distribution of size genes for the scenarios with no dispersal (A, B), and with dispersal from harvest refuges (C, D). The circles (solid line) indicate the runs where the size genes determine the asymptotic (final) size of individuals, l_{∞}, and the triangles (dashed line) where the size genes determine the growth rate, *r*. The lines were created using a smooth spline function. ΔS specifies the change in the proportion of size genes after 100 years of harvesting; there is no change if $\Delta S = 0$. Parameter values for harvesting rate, *q*, the minimum size of harvested animals, s_{min}, and the dispersal rate from the harvested population into the un-harvested (refuge) population, $\varepsilon_{H \to R}$ are expressed as standard deviations above or below the mean (0 indicates mean parameter value).

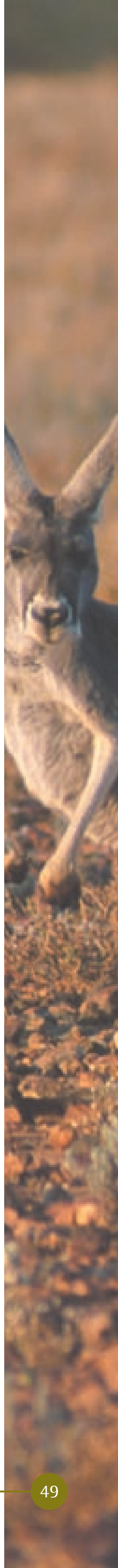


harvest size, s_{min} (PRCC = –0.29) and the dispersal rate from the harvested population into the refuge population, $\varepsilon_{H \to R}$ (PRCC = – 0.33) (Figure 28 C, D).

Are harvest refuges required?

Conservationists have stressed the need for establishment of harvest refuges to ensure that sections of the population are protected from the effects of size-selective harvesting (Table 2). The genetic analyses described above indicate that size-selective harvesting can indeed result in long-term changes in gene frequencies, the magnitude of the effect increasing with increasing harvest rate and with the minimum size of the harvested animals. Under the assumptions of the genetic model, these changes result in smaller kangaroos at any given age, with higher probability of survival under drought conditions. However, with moderate dispersal from an unharvested population virtually all effects of harvesting on genetic structure disappear.

Analyses based on the spatial model indicate that under current price conditions extensive areas of individual properties, and of regions such as the Western Division of New South Wales, will be subject to only limited, if any, harvest. Increases in price will produce varying responses on individual properties but across the Western Division some 30,000 sq km (9% of the region) containing an estimated 5% of the kangaroo population would remain essentially unharvestable despite price increases of at least 50%. A further 3% of the

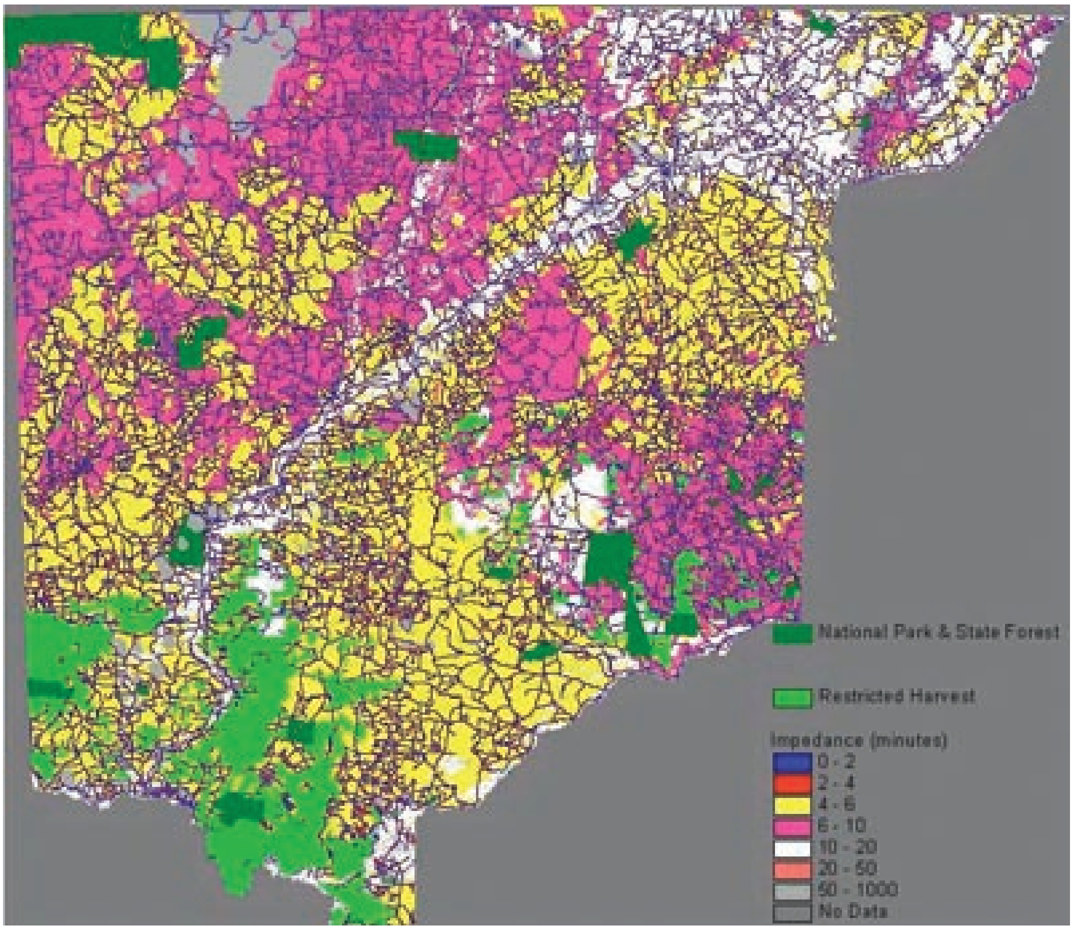


kangaroo population would be protected in national parks, state forests and other reserves within the region.

The effectiveness of these unharvested areas in terms of maintenance of gene frequencies cannot be established by the present study. However, Hale (unpublished report, NSW NPWS, 2001) found no significant differences in levels of gene diversity in red kangaroos and wallaroos between unharvested and harvested areas based on an examination of allozymes and microsatellite loci. These findings are consistent with the predictions of the genetic model and suggest that in at least some places the size of the non-harvested area, and the dispersal rate between harvested and non-harvested populations, are sufficient to counteract the effect of size-selective harvesting.

Given likely short to medium-term prices for kangaroo products there seems little need to establish additional refuges by administrative intervention. Nevertheless the potential should not be ignored for areas managed for conservation under other trade-off or incentive programs to serve also as harvest refuges. Figure 29 provides guidelines for assessing this potential. In this figure the impedance grid of the Western Division has been overlaid with national parks and state forests, and areas of restricted harvest, under current economic conditions, assuming that distance to chillers does not constrain harvesting (that is, travel time and travel cost in equation 2 are set to 0). Areas of restricted harvest under this scenario should be unaffected by any relocation of chillers and could be considered core areas. Apart from the road network that is reflected in this figure, areas of low impedance that are remote from either reserves or these core areas should be the best sites for establishment of refuges. These areas are the most accessible to harvesters and are thus least likely to incorporate areas of restricted harvest as a normal consequence of commercial operations. Assessment of site location, based on these considerations, could contribute to the development of incentive payments, evaluation of the conservation benefits of individual land parcels, or the administrative establishment of refugia should this been deemed necessary under future economic conditions.

Figure 29. Impedance grid of the Western Division of New South Wales. The grid is overlayed with national parks and state forests, and areas of restricted harvest (assuming current economic conditions and that chiller location does not constrain harvester access).



Conclusions

Our results indicate that options do exist to manage kangaroo populations to the satisfaction of all stakeholders. These management strategies will require the joint manipulation of harvest rate and sex ratio. Given current economic conditions in the kangaroo industry the best compromise (for both red and grey kangaroos) would be achieved by a harvest rate of 20% with males comprising 70% of the harvest. However, a range of management objectives or kangaroo densities may be achieved by jointly varying these parameters. The rule of thumb is that density will decrease with increasing harvest rate and decreasing male bias. Tactical application of this principle would allow a range of management objectives to be achieved as required, either over time or across the landscape.

Caution should be exercised when the outcome of a change in management strategy is uncertain, and subject to the vagaries of future climate change. Although the analyses presented here justify specific predictions, that are supported by some observations (for example, Pople 1996), the predicted responses of kangaroo populations should be carefully tested using robust experimental methods. Combining an active adaptive management procedure with the hypotheses derived from the temporal model (in particular) should promote rapid improvements in stakeholder satisfaction with the management of harvested kangaroos.

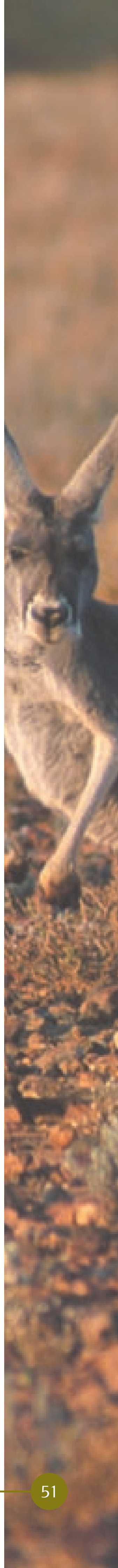
Implementation of such a program, however, would require some attitudinal change. Pastoralists, for example, would need to accept that reduction of kangaroos to very low densities (less than 5/sq km) over large areas is neither commercially feasible, ecologically defensible nor economically justified. The kangaroo industry would need to accept that harvest practices could be modified to produce a kangaroo population more acceptable to pastoralists without economic damage to the industry. Conservationists would need to accept that current harvest practices represent no threat to species conservation and that the establishment of economic refugia as an inevitable consequence of commercial harvesting substantially reduces concerns for the genetic integrity of kangaroo populations. Finally, wildlife management agencies would need to be prepared to establish and administer programs that are more prescriptive than at present.

The key findings of this project were discussed by stakeholders at a workshop in July 2002. Participants included as many as possible of those who had contributed to the initial workshop in which stakeholder objectives and strategies were defined. Discussion focussed on the major findings of the project, and their implications for kangaroo management, summarised in Table 12.

Consideration of these findings led to the recommendations summarised in the next section, for both policy and R&D, and directed to government agencies, kangaroo and pastoral industry organisations, non-government organisations and research funders and providers.

Table 12. Key findings and implications of the project.

Key finding	Implications
1. Effect of harvesting on kangaroo populations is strongly influenced by both harvest rate and sex ratio in the harvest. Sex ratio varies among harvesters. • At constant harvest rate, population declines with increasing female harvest. • Male-only harvesting can result in slightly higher long-term density than no harvest. • Male-only harvesting has negligible effect on pasture biomass regardless of harvest rate. • Manipulation of both harvest rate and sex ratio, in particular, could be used to produce desired long-term average population densities.	• Effect of harvesting on kangaroo populations may vary locally depending on harvest rate and sex ratio. • Markets or policies that favour a higher proportion of females will result in a greater reduction in the population, and higher pasture biomass. • Markets or policies that favour a higher proportion of males will result in a smaller reduction in the population (possibly no reduction) and lower pasture biomass. • Use of the commercial industry to reduce the long-term average kangaroo density would require market development to allow increased quotas to be taken consistently.



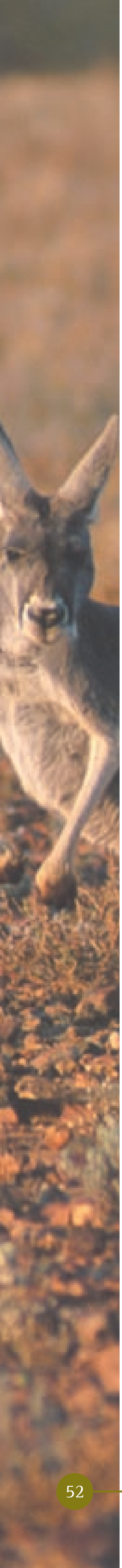
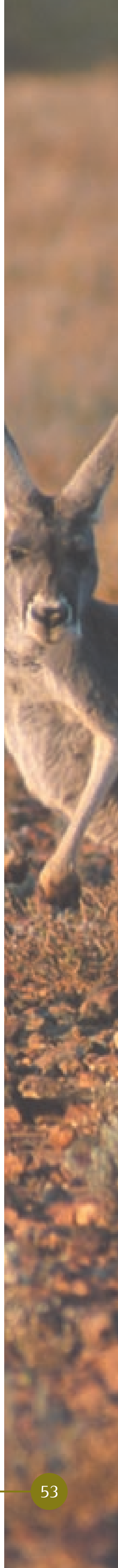
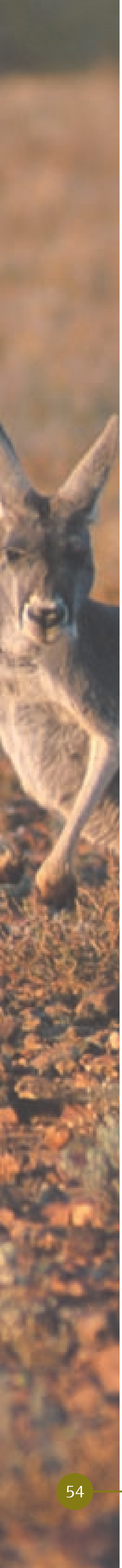


Table 12. (cont) Key findings and implications of the project. cont.	
Key finding	**Implications**
2. Forage availability for livestock does not vary greatly among harvest strategies or harvest rate/male bias combinations. • Changes in the temporal distribution of forage may be significant for pastoral production but the magnitude of the effect has not been precisely quantified. • Optimal harvest rate/male bias combinations for pastoralists (identified by multi-criteria decision analysis) generally result in long-term average kangaroo densities greater than 5/sq km.	• Seasonal conditions are the major determinant of forage availability for livestock. • Significance of altered forage profiles requires experimental verification. • Any pastoral production benefits resulting from kangaroo harvesting could be expected at kangaroo densities greater than 5/sq km.
3. Harvest rates (greater than 30%) and male bias (less than 50%) required to reduce kangaroo forage consumption to less than 20% of the safe livestock grazing capacity will have a large effect on kangaroo density and yield. • An unharvested population will consume about 80% of safe grazing capacity.	• Management that reduces pasture consumption by kangaroos to levels desired by pastoralists at the first workshop is unlikely to be consistent with the objectives of conservationists and the kangaroo industry.
4. At any harvest rate, total yield falls exponentially as female bias increases. • Male-only harvesting minimises the area required to harvest 25,000kg of kangaroo carcase per quarter (the target established by kangaroo harvesters).	• Increasing the female harvest may benefit pastoralists but may require an increase in the value of kangaroo products to compensate for reduced yield and greater cost of harvesting.
5. Probability that kangaroo density will be less than 5 /sq km increases rapidly with harvest rate to 40–50% per annum, with little change thereafter.	• Increasing harvest rate leads to diminishing returns in terms of impact on the kangaroo population. • As a precautionary measure, harvest rate should initially be conservative and increased in small steps.
6. Probability of quasi-extinction (the nominal value of kangaroo density taken to indicate the effective loss of the species) depends on sex ratio in the harvest. • Probability of quasi-extinction increases with the proportion of females in the harvest.	• A high female harvest will favour population suppression but increases vulnerability to stochastic events (events occurring randomly but with a known probability, for example, drought). These may lead to extinction in extreme cases.
7. Age structure of the population is influenced by harvest rate/bias, with differential effects on males and females. • Harvesting causes only minor changes in mean age at rates less than 20% per annum. • Harvest rate has little effect on mean female age (2.5–3.75 yrs). • Harvest rate has a large effect on mean male age (1.6–16.1 yrs), depending on the level of male bias. • High harvest rates and strong female bias lead to a low Similarity Index (an index measuring the similarity between the harvested population and an unharvested population. Lower values indicate less similarity).	• Present harvest rates are unlikely to be having much effect on kangaroo age structure. • Higher harvest rates can result in large changes in age structure, especially for males; populations with a dominance of young animals may be unattractive for harvesters. • Populations with male age structure strongly skewed toward older individuals are unnatural. • Lower annual harvest rates (10%) and high male bias will maintain a population age structure similar to an unharvested population.

Table 12. (cont) Key findings and implications of the project. cont.	
Key finding	**Implications**
8. Kangaroo density and product price greatly influence the area available for commercial harvesting. The area available at densities: • less than 5/sq km is small and not sensitive to product price • 5–20/sq km is relatively large and very sensitive to product price.	• Kangaroo density can only be reduced to less than 5/sq km over large areas by non-commercial means. • Reduction of kangaroo density to less than 5/sq km over large areas would result in the demise of the kangaroo industry. • Increasing the price of kangaroo products could greatly increase the area over which commercial harvesters could reduce kangaroo populations. • Over most of the landscape commercial harvesting will cease to be economically viable at densities well above those that represent a threat to species conservation.
9. Size-selective harvesting has potential to alter gene frequencies but the effect can be modified by migration from unharvested populations. • Without migration, size-selective harvesting results in smaller kangaroos with higher drought resistance. The effect increases with increasing minimum size of harvested individuals and increasing harvest rate. • With migration, and with all parameters in the model set to mean values, harvesting has no effect (if size genes influence growth rate) or a very small effect (if size genes influence the maximum size of individuals).	• Areas of restricted harvest have potential to offset any genetic effect of selective harvesting.
10. Harvest economics result in areas of restricted harvest. • About 20–40% of the area of the individual properties studied could not be economically harvested at current prices; price sensitivity varies between properties. • Harvesting will remain uneconomic over about 30,000 sq km of the Western Division of New South Wales, containing about 5% of the kangaroo population, even with substantially increased product prices. • A further 3% of the kangaroo population occurs in national parks and other reserves. • Areas of restricted harvest remain even when the limitation due to chiller location is removed.	• Migration from reserves or areas of restricted harvest may offset effects of selective harvesting on population genetics (at local or regional scales) but the magnitude of any effect has not been quantified. • Areas with high accessibility that are remote from reserves or permanently restricted areas (harvest is uneconomic in these areas even when the restriction due to chiller location is removed) would be priority locations for refuges if these were to be established.





Recommendations

Recommendation 1:

Evaluate the practicality of managing both the harvest rate (quota) and the sex ratio in the harvest for individual species.

New knowledge requirements

- Effect of current variations in harvest sex ratio on kangaroo populations.
  Anecdotal evidence suggests that harvest sex ratio may vary in time and space in relation to kangaroo abundance and the selectivity available to harvesters. Implications of this variation for stakeholder interests need further definition.
- Minimum densities consistent with species survival. Management regimes intended to suppress populations for specific purposes will require information concerning threshold densities below which species conservation is compromised. These densities can be predicted from project results but require field verification.

Recommendation 2

Develop collaborative programs to better inform relevant stakeholders and the wider community of the scientific evidence supporting the sustainability and benefits of the kangaroo industry, and its management of animal welfare.

New knowledge requirement

- Effect of kangaroo density on land condition, biodiversity and wool production.
  The effect on wool production of altered temporal forage profiles resulting from kangaroo harvesting requires further quantification. Effects of kangaroo reduction on land condition and biodiversity also require investigation.

Recommendation 3

Establish non-selective shooting or no-shooting areas through incentive schemes and other innovative strategies.

New knowledge requirements

- Migration rates and distances for all species from unharvested areas.
  Quantification of the size and location of refuges necessary to eliminate effects of size-selective harvesting requires definition of the effects of species, sex/age class, habitat, seasonal conditions and density on migration rates and distances. Effectiveness of migrating animals in transferring their genes to the harvested populations could be studied with molecular techniques.
- Validation of predicted refugia at property and regional scales.
- Validation of the relationship between harvest rate and kangaroo density.
- Development of a spatio-temporal model of kangaroo dynamics incorporating migration.

Recommendation 4

Identify opportunities to reduce the complexity and cost of current kangaroo management programs in the light of findings that the commercial industry is not viable at kangaroo densities that might threaten the conservation of the species.

Recommendation 5

Evaluate and promote options for the incorporation of kangaroos into viable rangeland businesses.

New knowledge requirement

- Economic conditions required to induce pastoralists to incorporate kangaroos in their enterprise mix.

Recommendation 6

Develop a generic framework under ISO 14001 for development of environmental management systems within the kangaroo industry that address environmental and animal welfare issues.

Recommendation 7

Establish the capacity within both Commonwealth and State agencies to effectively and independently manage the commercial and regulatory aspects of kangaroo management programs.

Recommendation 8

Develop a program of funded R&D to address the new knowledge requirements identified by the project.

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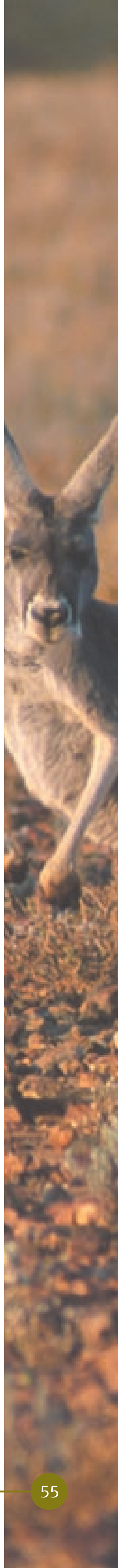

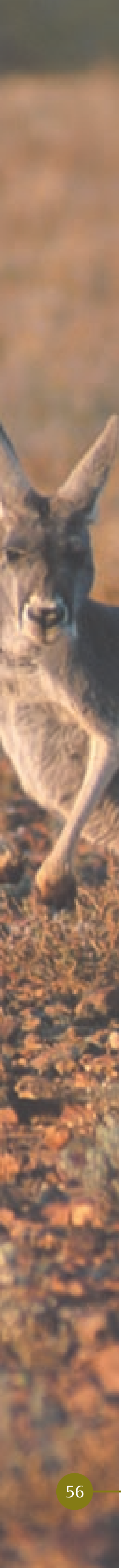

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Appendix 1.

Aspirations, issues and strategies identified by workshop participants that were beyond the scope of the project

(a) Aspirations and issues

Pastoralists

Ecological

- Limit or reduce the range expansion of eastern and western grey kangaroos. (This objective has a lower priority than the others given in the main text.)

Non-ecological

- Examine methods of reducing kangaroo numbers, comparable to existing capability for rabbits, goats and livestock.

Non-government conservationists

Ecological

- Examine effects of climate change, including the potential effects of:
  - changes to grasslands and other vegetation types
  - elevated carbon dioxide levels.

Non-ecological

- Kangaroo management strategies should be based on adaptive management. Management units should include:
  - monitoring/review/refinement of data collected from harvest management programs
  - publicly accountable process (access to data records)
  - modelling of the economic outcomes for, or impacts on:
    - kangaroo industry
    - tourism
    - pastoralism
    - conservation (including conservation on private land).

Kangaroo industry

Non-ecological

- Sufficient flexibility in the management program to allow individuals to develop innovative enterprises (for example, vertical integration).
- A community that is well informed about the scientific basis and environmental wisdom of the harvest.
- The development of a kangaroo harvesting business with recognised markets.
- A set number of tradeable licences, with a minimum number of kangaroos to be taken.

Government wildlife management agencies

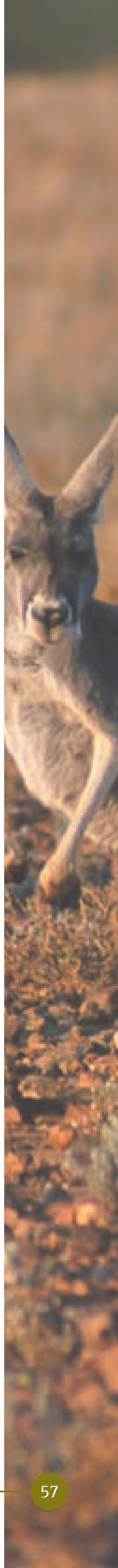
Non-ecological

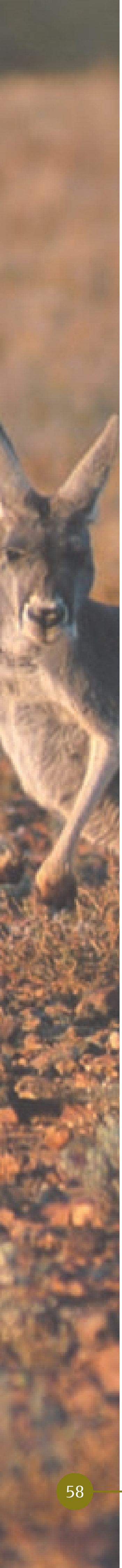
- Harvesting is conducted humanely.
- Kangaroo management is integrated with regional development strategies, including ecological and economic priorities (for example, fragmented natural areas in agricultural landscapes, wildlife corridors).
- Diversification of economic opportunities by developing sustainable kangaroo harvesting strategies.
- Kangaroos are promoted as a legitimate economic resource by providing clear statements of kangaroo management strategies for national and international audiences. (These kangaroo management strategies may not be consistent across governments.)

(b) Management strategies

- A deregulated harvest industry that works within the code of practice.
- Reduction in sheep numbers (evaluated in terms of the effect on kangaroo numbers).
- Various harvest rates, with different mixes of domestic stock and kangaroos – evaluated in terms of economic returns at the harvester level and ecological consequences.
- Alternative methods of reducing kangaroo density including:

- reduced access of kangaroos to water
- use of fences to minimise damage
- effects of predation by dingoes or indigenous people (hunter-gatherers).





Appendix 2

Management options resulting in acceptable average yields (1–2 times current industry level) but requiring harvest characteristics outside current industry parameters

Density range (kangaroos/sq km)	Strategy	Harvest rate	Male bias
10–15	Current value products	0.8 0.4	0.9 0.8
	Harvest only above 15 kangaroos/sq km	0.2	0
	Harvest only above 5 kangaroos/sq km	0.1	0.1
	Harvest above 0 kangaroos/sq km	0.8	0.9
	No harvest of animals ≤1.5 yrs	0.1	0.1
	No age restriction	0.8	0.9
15–20	Current value products	0.3 0.6 0.7	0.8 0.9 0.9
	High value products	0.4	0.8
	No harvest of animals ≥10 yrs	0.1	0.4
	No harvest of animals ≤1.5 yrs	0.1 0.1	0.2 0.3
	No age restriction	0.1	0.4
	Harvest above 0 kangaroos/sq km	0.1	0.4
	Harvest only above 5 kangaroos/sq km	0.1 0.1 0.1	0.2 0.3 0.4
20–25	High value products	0.6 0.5 0.3	0.9 0.9 0.8
	Low value products	0.1	0.4
	Harvest only above 15 kangaroos/sq km	0.1 0.1	0 0.1
25–30	High value products	0.4	0.9
	Current value products	0.2	0.8
	No age restriction	0.1	0.8
	Harvest above 0 kangaroos/sq km	0.1	0.8
30–35	High value products	0.2 0.3	0.9 0.9
	Current value products	0.1	0.8
	Low value products	0.1	0.8
	Harvest only above 5 kangaroos/sq km	0.1 0.1	0.8 0.9
	No harvest of animals ≥10 yrs	0.1 0.1	0.8 0.9

Integrated catchment management in the Murray-Darling Basin

A process through which people can develop a vision, agree on shared values and behaviours, make informed decisions and act together to manage the natural resources of their catchment: their decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

Our values

We agree to work together, and ensure that our behaviour reflects that following values.

Courage

- We will take a visionary approach, provide leadership and be prepared to make difficult decisions.

Inclusiveness

- We will build relationships based on trust and sharing, considering the needs of future generations, and working together in a true partnership.
- We will engage all partners, including Indigenous communities, and ensure that partners have the capacity to be fully engaged.

Commitment

- We will act with passion and decisiveness, taking the long-term view and aiming for stability in decision-making.
- We will take a Basin perspective and a non-partisan approach to Basin management.

Respect and honesty

- We will respect different views, respect each other and acknowledge the reality of each other's situation.
- We will act with integrity, openness and honesty, be fair and credible and share knowledge and information.
- We will use resources equitably and respect the environment.

Flexibility

- We will accept reform where it is needed, be willing to change, and continuously improve our actions through a learning approach.

Practicability

- We will choose practicable, long-term outcomes and select viable solutions to achieve these outcomes.

Mutual obligation

- We will share responsibility and accountability, and act responsibly, with fairness and justice.
- We will support each other through the necessary change.

Our principles

We agree, in a spirit of partnership, to use the following principles to guide our actions.

Integration

- We will manage catchments holistically; that is, decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

Accountability

- We will assign responsibilities and accountabilities.
- We will manage resources wisely, being accountable and reporting to our partners.

Transparency

- We will clarify the outcomes sought.
- We will be open about how to achieve outcomes and what is expected from each partner.

Effectiveness

- We will act to achieve agreed outcomes.
- We will learn from our successes and failures and continuously improve our actions.

Efficiency

- We will maximise the benefits and minimise the cost of actions.

Full accounting

- We will take account of the full range of costs and benefits, including economic, environmental, social and off-site costs and benefits.

Informed decision-making

- We will make decisions at the most appropriate scale.
- We will make decisions on the best available information, and continuously improve knowledge.
- We will support the involvement of Indigenous people in decision-making, understanding the value of this involvement and respecting the living knowledge of Indigenous people.

Learning approach

- We will learn from our failures and successes.
- We will learn from each other.