Harvest Management of Kangaroos during Drought

A. R. Pople
The Ecology Centre
University of Queensland Q 4072

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Summary

1. Simulation modelling was used to assess the impact of harvesting kangaroos in western NSW during a drought that was extending over the 2002-2003 summer. An unstructured model (i.e. no age, size or spatial components) for red kangaroos was used. The qualitative results should apply to other kangaroo species, which have broadly similar life histories and responses to drought. While an age or spatially structured model would allow more accurate predictions, the qualitative results of comparing management actions are unlikely to differ.
2. If rainfall is 50% below average for the first 6 months of 2003 the model predicts, on average, a 40-50% decline in population size over 12 months to winter 2003 under harvest rates of 0-20%. If rainfall is 20% of the long-term mean, the decline is 60-65%. The structure and parameters of the model are designed to provide conservative estimates of risk. In other words, pessimistic scenarios were modelled because declines are likely to be overestimated.
3. Adjusting the harvest with an aerial survey in February and immediate adjustment in winter with the regular annual aerial survey, results in little change to the projected decline. However, adjusting the harvest in this way to better track density increases the minimum density to which the population is likely to fall over 2002-2012. Thus, increasing survey frequency reduces quasiextinction risk (see glossary). Adjustment of a 15% harvest at two points through a drought year is equivalent to a harvest of 8-10% with no adjustment. The latter offers a cheaper alternative to an additional survey.
4. The appropriate management action depends on the costs of each option. The cost of an additional aerial survey is associated with reduced quasiextinction risk (=social cost) and reduced harvest variability (=industry cost). This must be balanced against a possible reduction in average harvest offtake in the short and possibly longer term (=industry costs), higher kangaroo numbers and lower pasture biomass (=cost to graziers). Lower pasture biomass can also be considered a conservation cost if it is associated with environmental damage.
5. In drought, rainfall is a simple and appropriate predictor of likely population decline. Outside of drought, rainfall is a less reliable predictor, because of variation in pasture response to rainfall and because food may not be the primary limiting factor. At these times, harvest statistics, particularly sex ratio, may indicate population trends or status between aerial survey estimates of population size.
6. An alternative harvesting strategy is to impose a threshold, below which no harvesting occurs and above which the population is harvested at 15%. Quasiextinction risk is reduced, but average kangaroo density and particularly harvest variability increase above a low threshold. It is unlikely that the kangaroo industry could operate at moderate harvest thresholds, but a low threshold is feasible because it presently coincides with a density where the industry is not economically viable. Implementing such a threshold would provide a safeguard against changing economics in harvesting kangaroos.

1. Introduction

This report addresses concerns of overharvesting of kangaroos during a drought in New South Wales that was deepening in late 2002. These concerns were raised by the NSW kangaroo management advisory committee in October 2002.

New South Wales National Parks and Wildlife Service (NSW NPWS) manages the commercial harvest of kangaroos using a proportional harvesting strategy. This strategy has been well studied and is considered relatively safe and efficient for a fluctuating population (Caughley 1987; Engen, Lande *et al.* 1997; McLeod and Pople 1998). However, the strategy requires a regular estimate of abundance on which to set a quota.

Annual quotas are set for a calendar year that represent a percentage (15% for red kangaroos and 13-15% for the two grey kangaroo species) of the population estimated annually (in most areas) by aerial survey in the winter of the previous year. Even if the quotas are taken, the actual rates of harvest will differ from 13-15%, because populations will rarely remain stable. There is therefore some risk of over- or underharvest (see glossary). If the population halves over 12 months, the *actual* harvest rate over the year becomes roughly 21% instead of the *desired* (set by quota) rate of 15%. If the decline is 80% (see below), the annual harvest rate is likely to be around 34%. A doubling of the population will result in a harvest rate of roughly 11%. These actual rates are approximate because they assume constant geometric growth and decline in the population.

Overharvesting may result in reduced long-term yields if harvest rates are much greater than the maximum sustainable yield (MSY). It may also reduce the population to densities that are below some acceptable minimum density. Underharvesting results in higher average population densities that may result in unacceptable grazing impacts. It may also result in reduced long-term yields if harvest rates are well below the MSY.

In most years, this risk of over- or underharvest is likely to be small, because year-to-year fluctuations are relatively small. On a broad scale, *increase* in the population will be constrained physiologically by the reproductive capacity of females, and modified by sex ratio and age structure. The maximum rate of increase, even in a male-biased population with few juveniles, will fall short of doubling. However, the rate of *decline* can be more pronounced as it is unconstrained by an animal's physiology. In the drought of 1982-83, kangaroos declined by approximately 40% over 12 months in the sheep rangelands of eastern Australia (Caughley, Grigg *et al.* 1985). However, most of this decline occurred over a shorter period of perhaps 4 months (Robertson 1986), when possibly the more vulnerable individuals died. Had this period of decline been maintained, the decline over 12 months would have been 80%.

These risks will be exacerbated by uncertainty in population size, which is measured by the standard error or confidence interval of the population estimate. For example, population size may be overestimated through chance (sampling error) alone, resulting in an effective harvest rate higher than 13-15%. This potential overharvest will be compounded if the population then declines.

Changes in population size (i.e. rate of increase) of kangaroos are closely linked to pasture biomass that is driven largely by rainfall in arid areas. Because there is an upper limit to a population's rate of increase, the difference between desired and actual harvest rate is potentially greater during drought than during times of plenty. Moreover, quotas are more likely to be taken during drought because animals are more accessible, graziers are more active in having animals culled and the kangaroo industry will have a relatively greater capacity to take animals as a result of previous higher population densities.

The discussion above has assumed that harvesting affects a population in the same way whether it is increasing or decreasing. Harvest mortality can be *additional* to natural mortality or *compensatory* (Anderson and Burnham 1976). The latter results from some animals being harvested that would have died anyway. For a fluctuating population of herbivores, mortality will tend to be additive during population increases when pasture is abundant, but tend to be compensatory during declines in drought (Pople 1996). Harvesting will therefore have a greater effect on a population's rate of increase when it is increasing than during drought. Harvesting is unlikely to be completely compensatory or completely additive as there will be potential survivors of drought that may be harvested and there is invariably natural mortality even when food is abundant.

There are other harvest strategies that could be adopted during drought. One would be to harvest heavily at the onset of drought in anticipation of mortality and recognizing that much harvest mortality will be compensatory. This could also reduce the decline in pasture biomass and allow greater recovery of the population when the drought breaks. This may not be feasible because of the limited capacity of the kangaroo industry. It may also be unpalatable to a section of the community opposed to kangaroo harvesting.

Given the risk of overharvest, the following questions are addressed:

1. If quotas should be reduced during drought.
2. If so, by how much and when?
3. What can be monitored to indicate the need to reduce quotas?
4. Will quotas adjusted by a population estimate from an aerial survey conducted prior to the annual survey in winter substantially reduce the risk of overharvest?
5. To what extent will risk of overharvest be reduced by imposing a minimum threshold density below there is no harvesting?

The report comprises two parts. The first is an assessment of risk of overharvest during drought using a simulation model. The second component is an assessment of potential indicators of population decline and overharvesting such as harvest statistics that, when some level is reached, could trigger management action such as adjusting the quota.

2. Simulation Modelling

2.1 Methods

During drought, there will be considerable uncertainty in the future dynamics of kangaroo populations. There is uncertainty in the duration and severity of drought (process uncertainty), in the response of kangaroos to drought and harvesting (model uncertainty) and also in the density kangaroos estimated from aerial survey (observation uncertainty). Therefore, simulation modelling was used to assess risk (Burgman, Ferson *et al.* 1993) and included all three forms of uncertainty. The following scenarios were examined:

1. Two alternative population models.
2. Severity of drought being either rainfall 50% of average or 20% of average.
3. Harvesting during drought at rates ranging from 0-20%.
4. During and following the drought, harvesting at a range of harvest rates lower than 15% (including zero), when the population is below some threshold density.
5. Adjusting harvest (offtake not rate) partway through the drought to mimic adjustment triggered by some indicator or a mid-term aerial survey.
6. Precision of population estimates, which determine harvest offtake, varying with coefficients of variation (CV=standard error/mean) of 0-50%.

The additional risk posed to the population through harvesting can be couched in terms of probability of quasiextinction (i.e. population falling below an unacceptably low density), minimum population density, time spent below particular threshold densities, average harvest offtake, and average pasture biomass.

Two models describing the dynamics of kangaroo populations in arid areas were considered: an interactive model described by (Caughley 1987) and a ratio dependent model developed by (McCarthy 1996). In the interactive model, rainfall drives pasture biomass, which in turn determines the rate of increase of the kangaroo population. There are two negative feedback loops. The first is pasture biomass reducing pasture growth. The second is kangaroo density reducing kangaroo rate of increase by reducing the available biomass by eating it. The ratio dependent model is much simpler, with kangaroo rate of increase a function of the ratio of rainfall to population size.

Both models are based on data for red kangaroos, so extrapolation of the results to the two species of grey kangaroos and common wallaroos needs to be made cautiously. In particular, the two grey kangaroo species have lower maximum rates of increase than red kangaroos and perhaps higher rates of decline in drought in arid regions (Bayliss 1987; Robertson 1986). However, the qualitative differences between the species' dynamics are slight, suggesting the qualitative results from the modelling should apply to all four species in an arid environment. New South Wales NPWS accommodates species' differences in lower quotas for grey kangaroos as a percentage of the population.

Contrasting the results of the two models addresses just one form of model uncertainty. A range of parameters for each model can also be considered. This was not done here for two reasons. Firstly, overall model structure was considered a greater influence. Secondly, for the interactive model, the maximum rate of decline was parameterised from a four month period observed in the 1982-3 drought (Caughley 1987). Whether this rate of decline could be maintained over a longer period is presently unknown, but a model allowing this should provide conservative estimates of risk (i.e. tend to overestimate risk).

Both the interactive and ratio dependent models require rainfall as the main input variable, which was introduced into the model seasonally (i.e. three monthly). Rainfall was taken from Menindee Post Office in western NSW (annual mean = 244 mm, s.d. = 106 mm) where Caughley's (1987) interactive model was parameterised. McCarthy's (1996) model was based on the South Australian Pastoral Zone, so Menindee rainfall needed to be rescaled. Risk was considered not just during the drought, but also following drought when the population is expected to recover. Models were therefore run over 20 years. Actual rainfall was used for 1992-2002, while rainfall for 2003-2012 was drawn from a lognormal distribution. Drawing rainfall from a lognormal distribution enabled droughts of different severities to be simulated. A drought where rainfall is 50% below average for 12 months or more would be comparable to the 1982-3 drought. A drought where rainfall is 20% of average rainfall for 12 months would be comparable to the drought of 1967, considered the 'worst drought in living memory' (Robertson 1986). Duration of drought could also be varied, but below average rainfall was only sampled until May 2003 after which average rainfall was sampled. This was for two reasons. Firstly, recent indicators (e.g. SOI) suggest a breaking of El Nino by that time. Secondly, the winter aerial survey in 2003 would enable adjustment of the quota, potentially in late winter 2003.

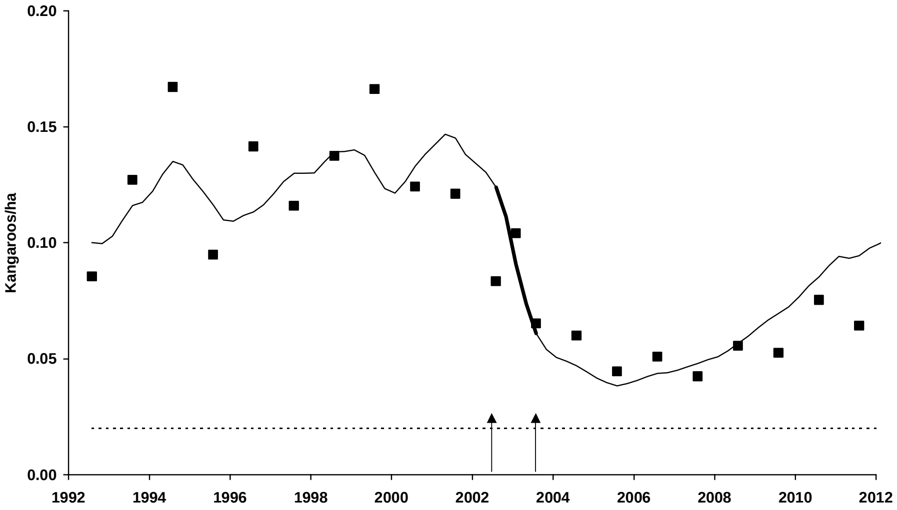
For the interactive model, the kangaroo population was harvested and pasture grew and was grazed down in weekly time steps. Sheep competed with the kangaroo population, consuming 1.5 times the pasture that the kangaroos ate. For the ratio dependent model, the time step was three months. In both models, instantaneous harvest rates were converted to isolated rates of harvesting (Caughley 1977), appropriate to the time step, to simulate harvesting spread evenly throughout each year. Harvest offtake for each three months was determined from a population estimate in the previous year. Harvest offtake was therefore the same for each three months of the year, despite population size changing at each three monthly time step. For 2003-2012, population estimates were drawn from a normal distribution with a mean of the modelled population size and a CV set for that model run. Unless stated, precision was set at CV=20%.

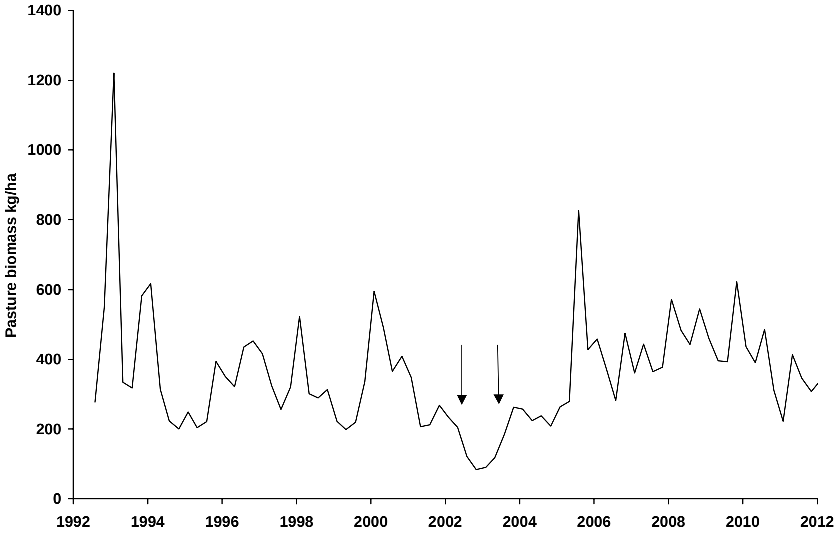
The initial population size (i.e. 1992) was 10 kangaroos km^{-2} (0.1 kangaroos ha^{-1}). For each scenario (i.e. combinations of scenarios 1-6 above), the average of 1,000 simulations is reported. Population models were run in Excel with the add-in POPTOOLS (Greg Hood CSIRO 2002, http://www.dwe.csiro.au/vbc/poptools/index.htm).

2.2 Results

2.2.1 Differences between population models

The two models of population dynamics displayed quite different population behaviour despite fitting data from the South Australian Pastoral Zone reasonably well (McCarthy 1996), Pople *et al*. unpublished). The interactive model generated greater amplitude in population size (e.g. Fig. 1) over time than the ratio dependent model, resulting from weaker density dependence. In the ratio dependent model, the population would recover relatively rapidly from declines in drought and population eruptions were similarly tempered.


Kangaroos/ha
0.00
0.05
0.10
0.15
0.20
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012


Pasture biomass kg/ha
0
200
400
600
800
1000
1200
1400
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012

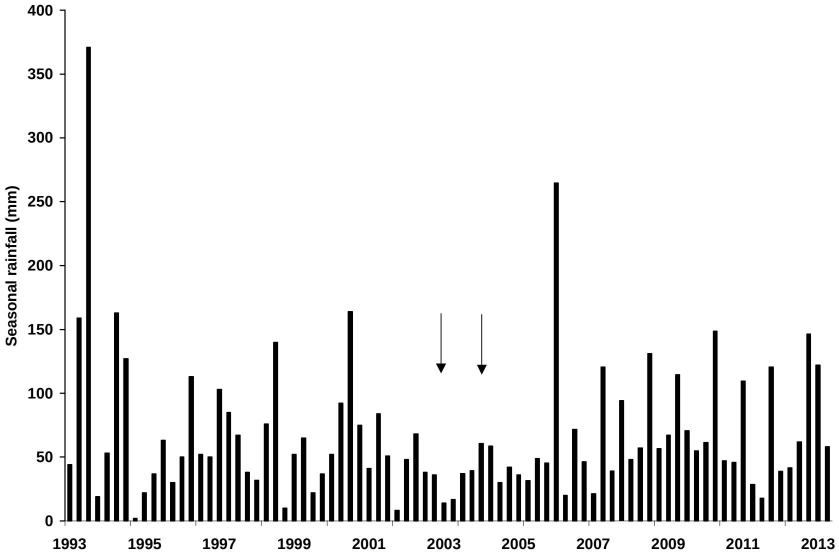

Seasonal rainfall (mm)
0
50
100
150
200
250
300
350
400
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013

Fig. 1. (previous page) Example of a single run using the interactive model. The extension of the drought, in this case rainfall 50% of the long-term mean, occurs between the two arrows in each panel. *Top panel* shows the change in kangaroo density (solid line, thickened for extension of the drought) over time, a quasiextinction density of 0.02 ha^{-1} and density estimated by aerial survey (solid squares) with a precision of 20%. *Centre panel* shows fluctuations in pasture biomass, driven by seasonal rainfall shown in the *bottom panel*.

Furthermore, the ratio dependent model predicted smaller declines for 2002-2004 and particularly 2002-2003 (Figs 2 and 3). This disparity is the result of different rainfall periods ultimately driving population rate of change of kangaroos in the two models. For the interactive model, kangaroos essentially respond to rainfall without any lag. In the ratio dependent model, there is a 12-month lag in the response. A 12-month lag may be appropriate where enhanced juvenile survival is not detected immediately by aerial survey, but it is implausible during drought where there is substantial adult mortality that would be (and has been) detected immediately by aerial survey. A final difference between the two models is that the ratio dependent model generates little effect of harvesting over the range of 0-20% on population decline (Figs 2 and 3), again resulting from its stronger density dependence. Overall these differences result in a lower risk of overharvest in the ratio dependent model, particularly during drought. Therefore a more conservative risk assessment was undertaken solely with the more realistic interactive model.

2.2.2 Severity of drought

Each run of the interactive model had a population of 12 kangaroos km^{-2} in late 2002; the point from which below average (drought) then average rainfall (postdrought) was simulated (Fig. 1). On average, the population declined under a 0-20% harvest regime by roughly 40-50% in the first 12 months with rainfall 50% of long-term mean, and by roughly 60-65% with rainfall 20% of the long-term mean (Fig. 4). While increasing harvest rate exacerbated the decline, the overwhelming influence was the rainfall deficit. Similarly, increasing harvest rate, but particularly increasing severity of drought, reduced the mean minimum density to which simulations dropped over 2002-2012 (Fig. 5).

Adjusting the harvest with an estimate of population size in February (i.e. midway between the annual aerial surveys) *and* immediate adjustment of the harvest in August (i.e. rather than the start of the following year), results in a minor change to the projected decline (Fig. 4), but a more substantial change to the minimum density (Fig. 5). In terms of minimum density, this adjustment of the harvest at two points through the drought when harvesting at 15% was equivalent to harvesting at roughly 8% with no adjustment.

2.2.3 Harvest rate

The probability of the population falling below some low density increased with increasing harvest rate (Fig. 6). Risk does not appear to increase linearly with harvest rate, with risk accelerating from 10-15% and decelerating from 15-20%. This coincides with the maximum sustained yield for this model of 10-15% (Caughley 1987). Not surprisingly, the ratio dependent model described a far lower risk of quasiextinction with no discernible differences between harvest rates of 0-20% (Fig. 7).

An alternative to the probability of quasiextinction shown in Fig. 6 is the time (i.e. number of seasons) spent below particular thresholds (Fig. 8). The pattern is similar, but allows an acceptable threshold to be identified in different terms. For example, it may not be cost-effective for harvesters to operate at densities below ~0.03 ha^{-1}. Figure 8 can then be used to identify the likely period of time when harvesting will not be possible. Alternatively, there may be some socio-political cost of dropping below some density, in which case Fig. 6 is appropriate.

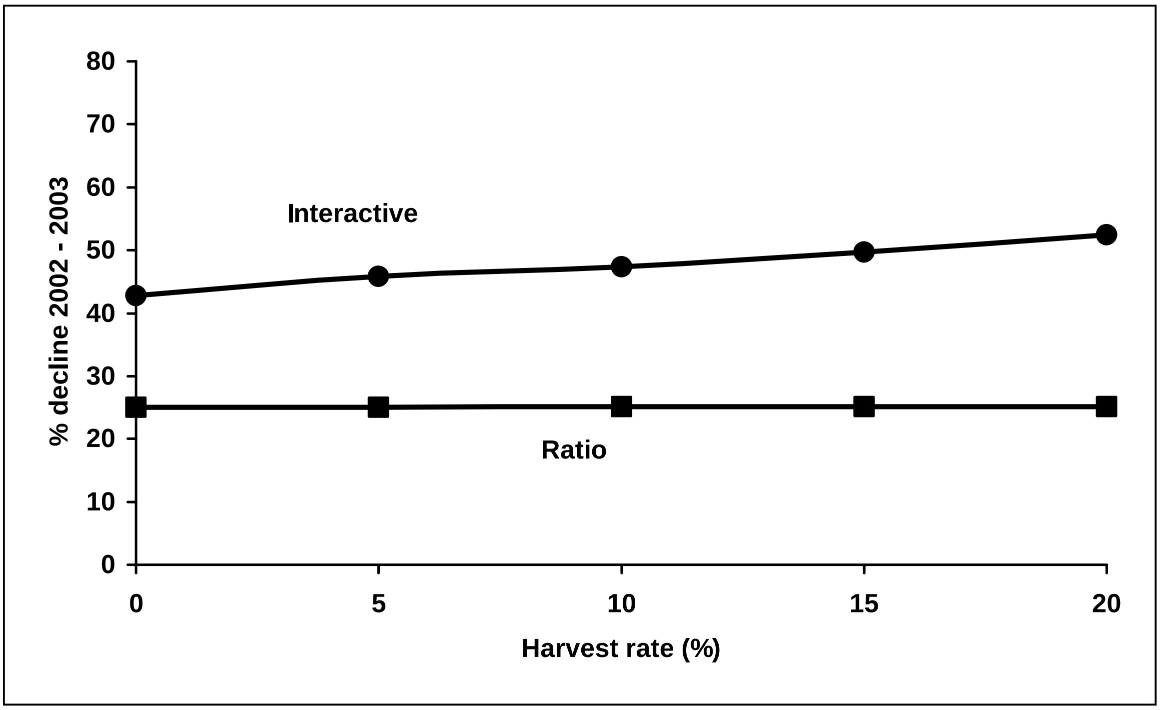


Fig. 2. Mean % decline for two models (interactive and ratio dependent) of a red kangaroo population under harvest regimes of 0-20% over 2002-2003. Points are means of 1,000 simulations.

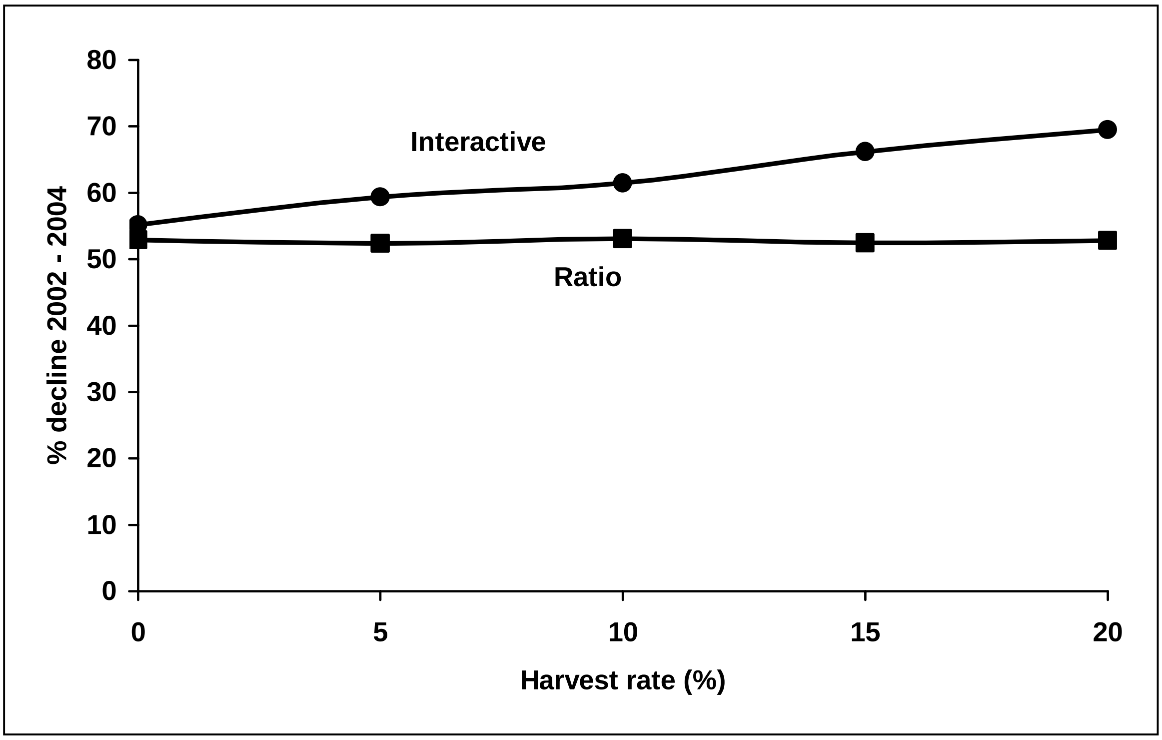


Fig. 3. Mean % decline for two models (interactive and ratio dependent) of a red kangaroo population under harvest regimes of 0-20% over 2002-2004. Points are means of 1,000 simulations.

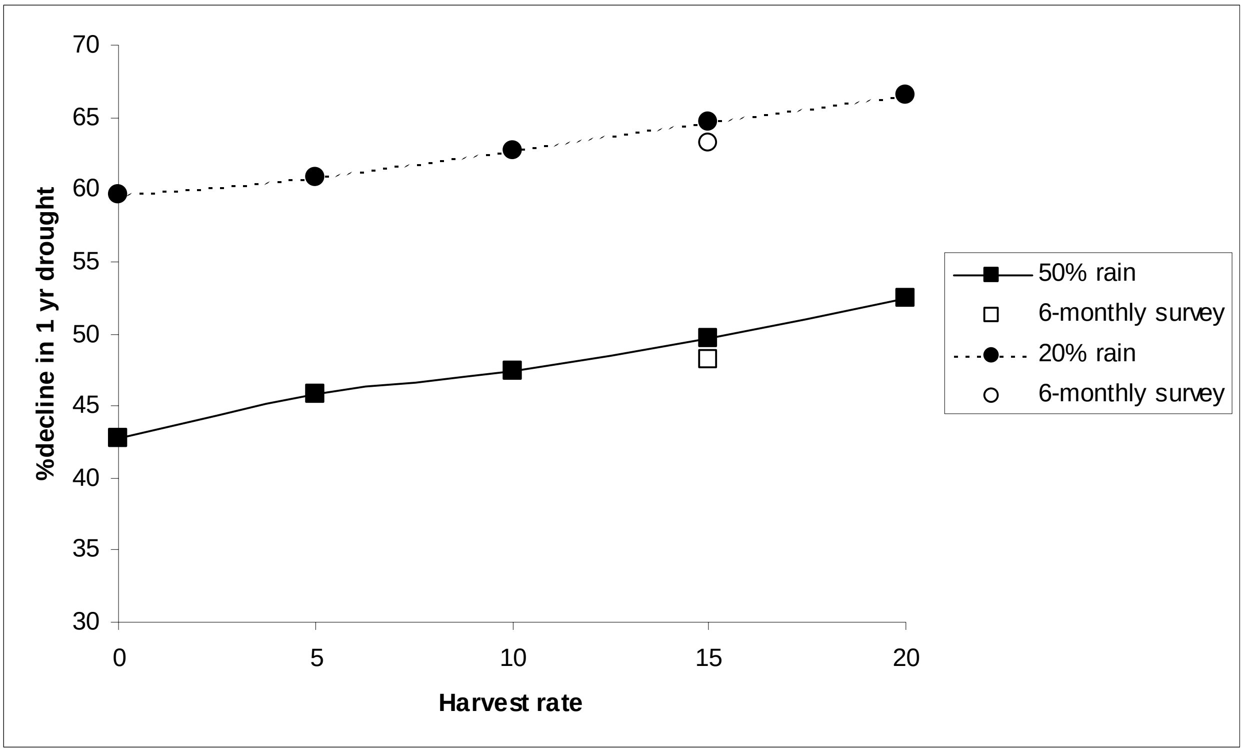


Fig. 4. Percentage decline in size of the kangaroo population over 12 months (2002-2003) when rainfall is 50% (solid line) or 20% (dotted line) of the long-term mean. The decline is shown for a range of harvest rates during the drought. Three monthly harvest offtake was either fixed for the 12-month period (solid symbols) or adjusted at two points during the period (open symbols).

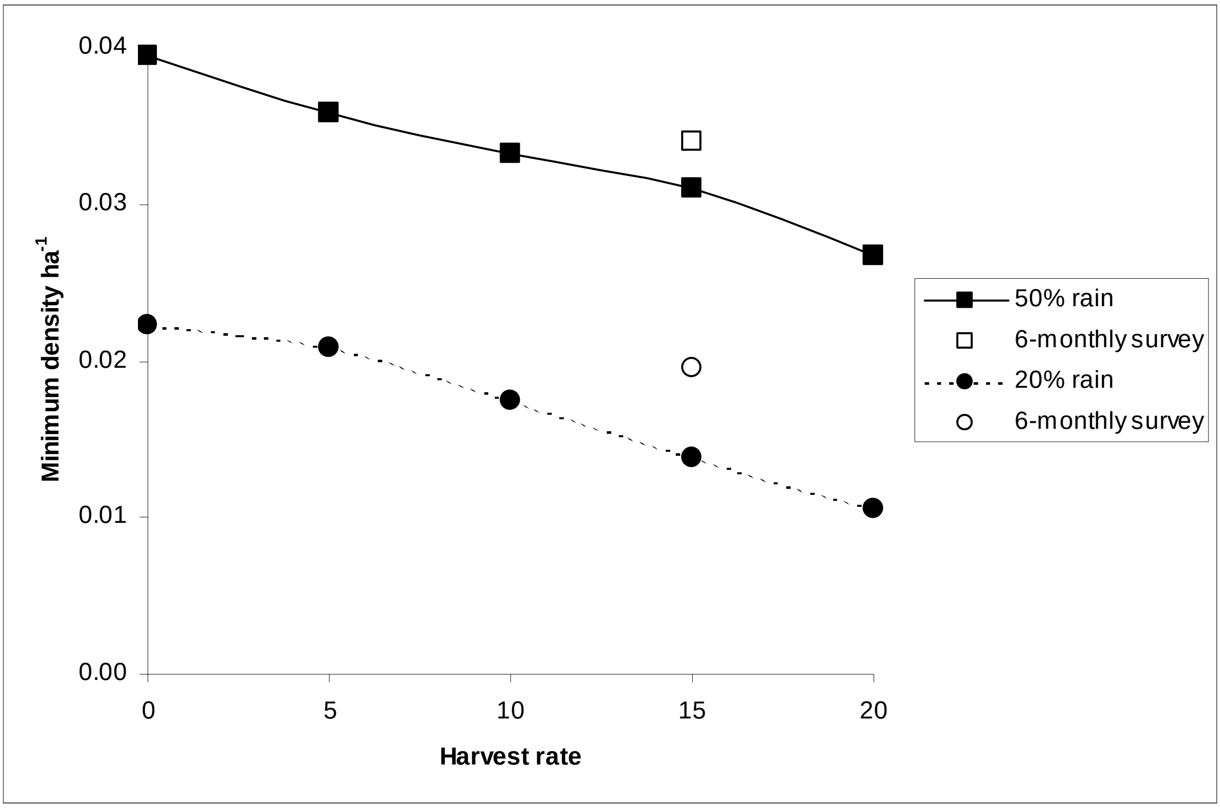


Fig. 5. Mean minimum density for 2002-2012 where the first 12 months experiences rainfall that (on average) is 50% (solid line) or 20% (dotted line) of the long-term mean. The minimum density is shown for a range of harvest rates during the drought. Three monthly harvest offtake was either fixed for the 12-month period (solid symbols) or adjusted at two points during the period (open symbols).

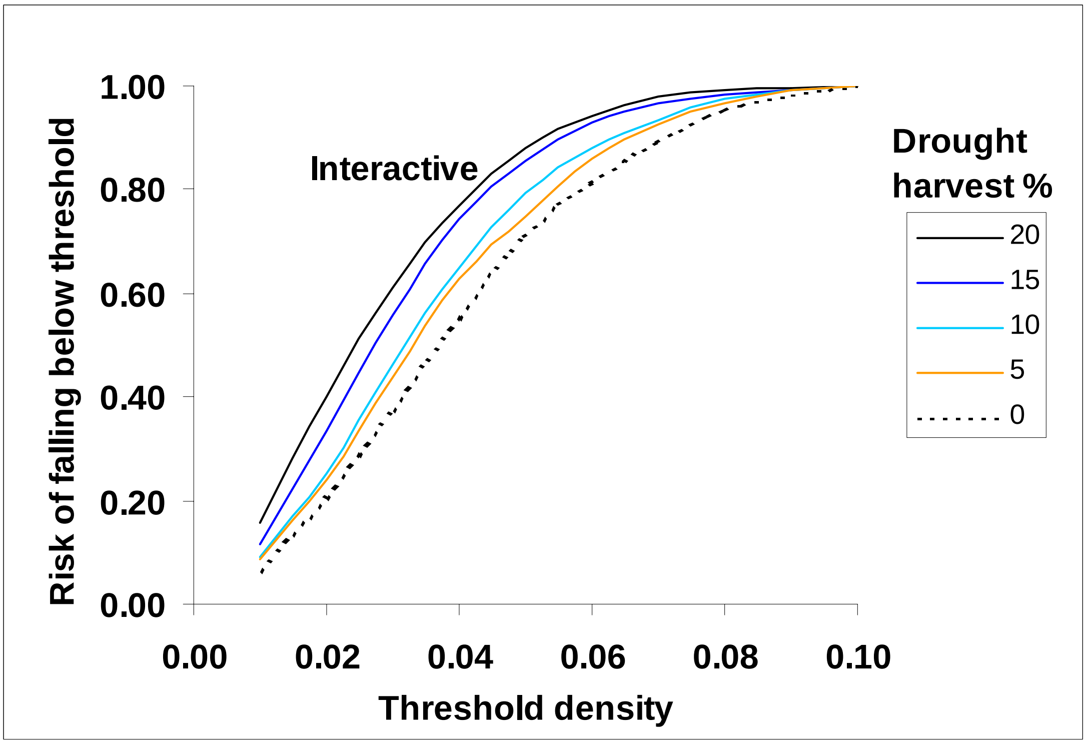


Fig. 6. Probability (i.e. risk) of the population dropping below particular densities over 2002-2012 using the interactive model. Harvest during the 2002-3 drought ranges 0-20%.

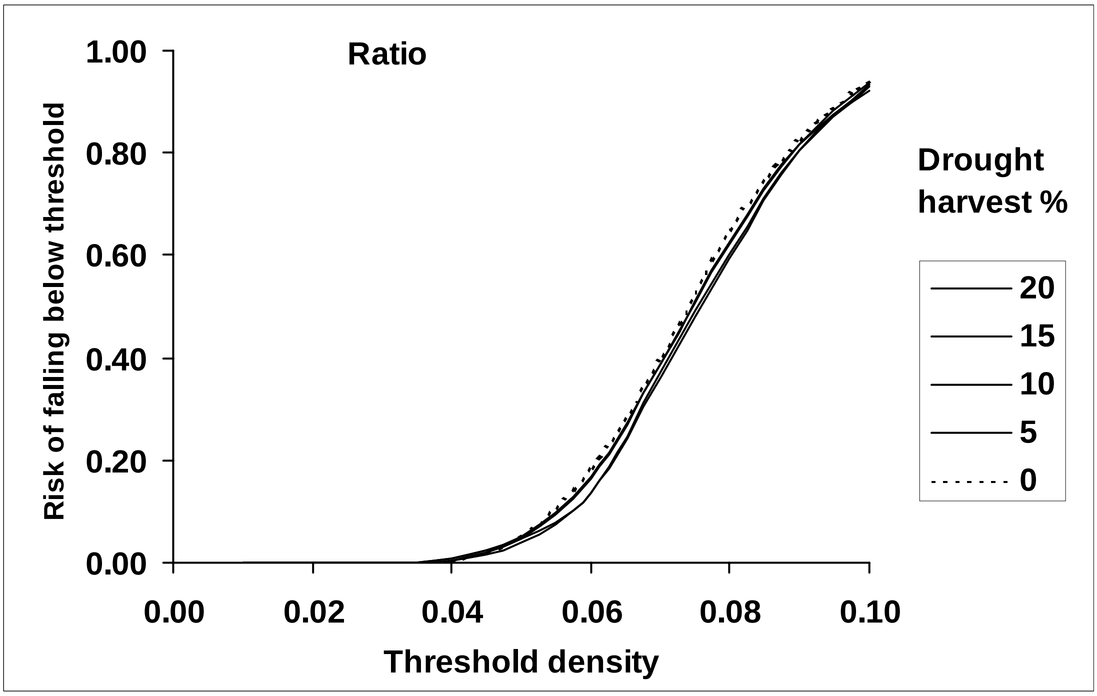


Fig. 7. Probability (i.e. risk) of the population dropping below particular densities over 2002-2012 using the ratio dependent model. Harvest during the 2002-3 drought ranges 0-20%.

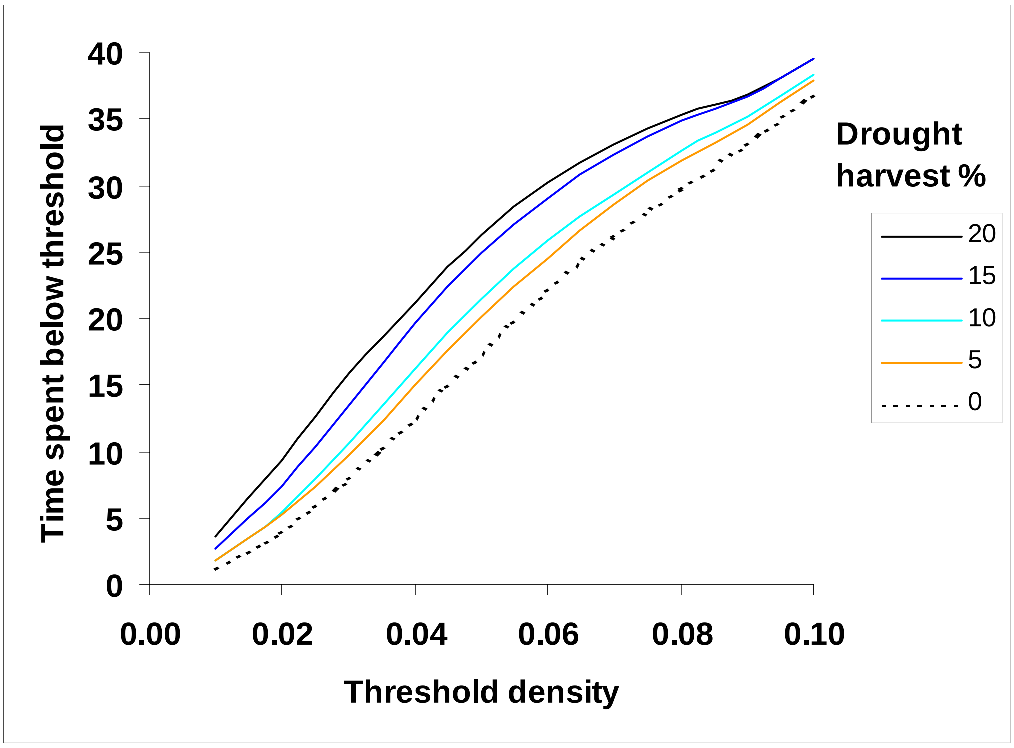


Fig. 8. Mean time (seasons) spent below a range of threshold densities over 2002-2012 for a kangaroo population under various drought harvest regimes.

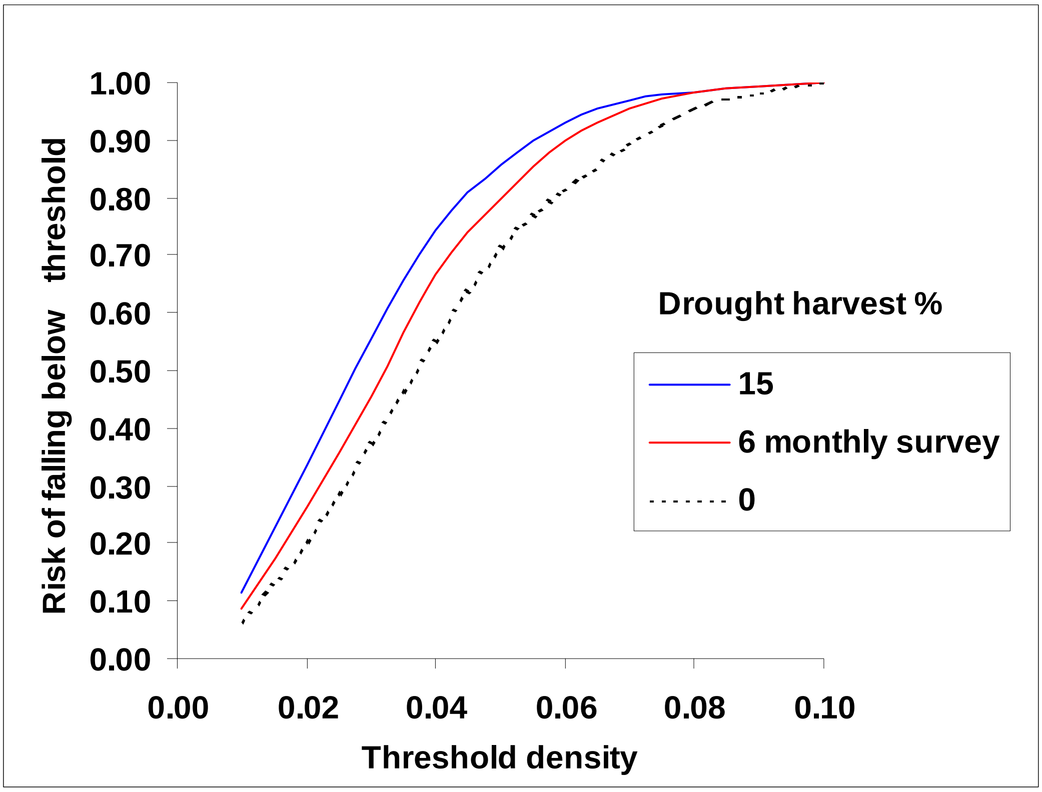


Fig. 9. As for Fig. 6, but showing reduction in risk (6 monthly survey) when a 15% harvest is adjusted at two points during a decline in drought.

If the harvest is adjusted through the drought by a mid-term aerial survey and immediately following the regular winter aerial survey, quasiextinction risk is obviously reduced. Such adjustment is approximately equal to a drought harvest that is ~10% of the 2002 survey estimate, rather than 15% of that estimate (Fig.9).

The average harvest offtake for 2002-2012 appears little affected by the strategy adopted during the drought (Fig. 10). However, the coefficient of variation (CV) of the weekly harvest increases as the drought harvest rate increases over 5-20% (Fig. 10). The average population density over 2002-2012 declines almost linearly with increasing harvest rate during drought, while average pasture biomass increases (Fig. 11).

2.2.4 Threshold harvesting

If there is no harvesting below a threshold density, then the risk of quasiextinction obviously declines as does the time spent quasiextinct (Figs 12 and 13). If a 10% harvest is adopted below a threshold rather than a zero harvest, the reduction in risk is relatively small (Fig. 14). If a drought is not modelled and simulations are run over 20 years (cf. 10 years), then quasiextinction risk is reduced, but the effect of a threshold harvest is similar (Fig. 15)

A threshold harvesting strategy results in increasing average population density (over 2002-2012) as the threshold density, below which there is no harvesting, is increased (Fig. 16). Similarly, average pasture biomass declines with increases in the threshold density (Fig. 16). Mean harvest offtake declines and harvest CV increases with increasing threshold density (Fig. 17). If a drought is not modelled and simulations are run over 20 years, the decline in mean harvest is less steep and the increase in harvest CV is less dramatic (Fig. 18).

2.2.5 Mid-term population estimate

Immediate adjustment of the harvest with estimates of population size in February *and* in August was considered sections 2.2.2 and 2.2.3 and in Figures 4, 5 and 9.

2.2.6 Precision of population estimates

Increasing precision of population estimates from CV=50-0% had little effect on probability of quasiextinction. For example, the probability of falling below 0.02 kangaroos ha^{-1} increased from 0.31 to 0.34, and the probability of falling below 0.01 kangaroos ha^{-1} increased from 0.10 to 0.15. The effect size is small for two reasons. Firstly, probabilities of quasiextinction are calculated as the *mean* of 1,000 simulations and population size has an equal chance of being over or underestimated (i.e. estimates are drawn from a normal distribution that is symmetrical about the mean). Secondly, the impact of drought is large relative to the impact of harvesting over a single year. Notably, the effect size increases (both in relative and absolute terms) with lower threshold densities for quasiextinction. In other words, imprecision becomes more important when considering risk of falling to particularly low population size.

Poorer precision does increase the variability of harvest offtake over 2002-2012, more so than variability in population size (Fig. 19).

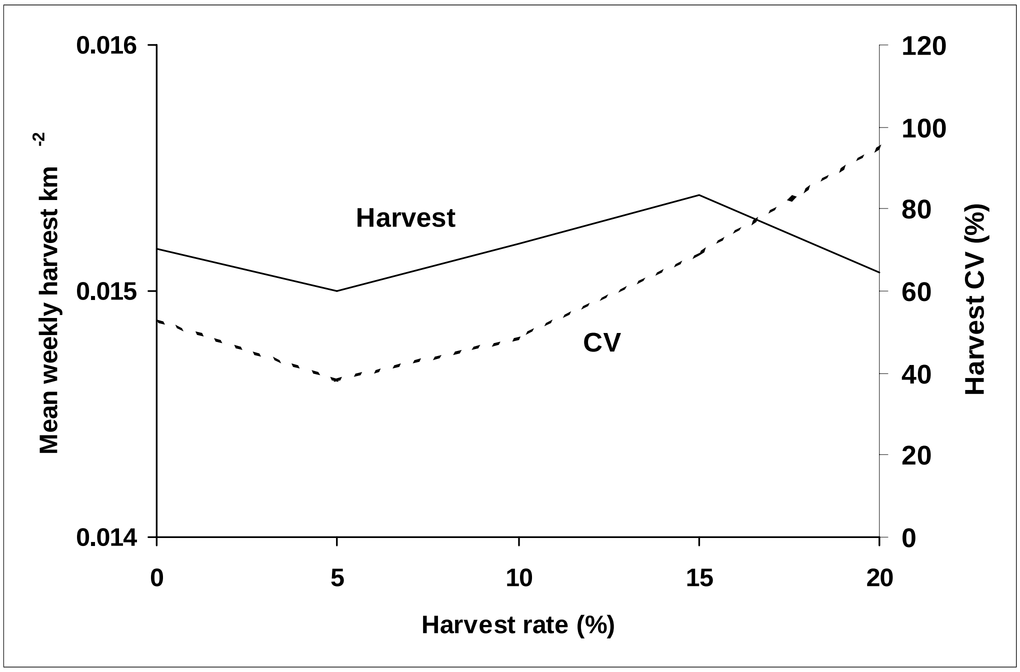


Fig. 10. Average weekly harvest over 2002-2012 and coefficient of variation (CV) of that harvest as a function of harvest rate during drought.

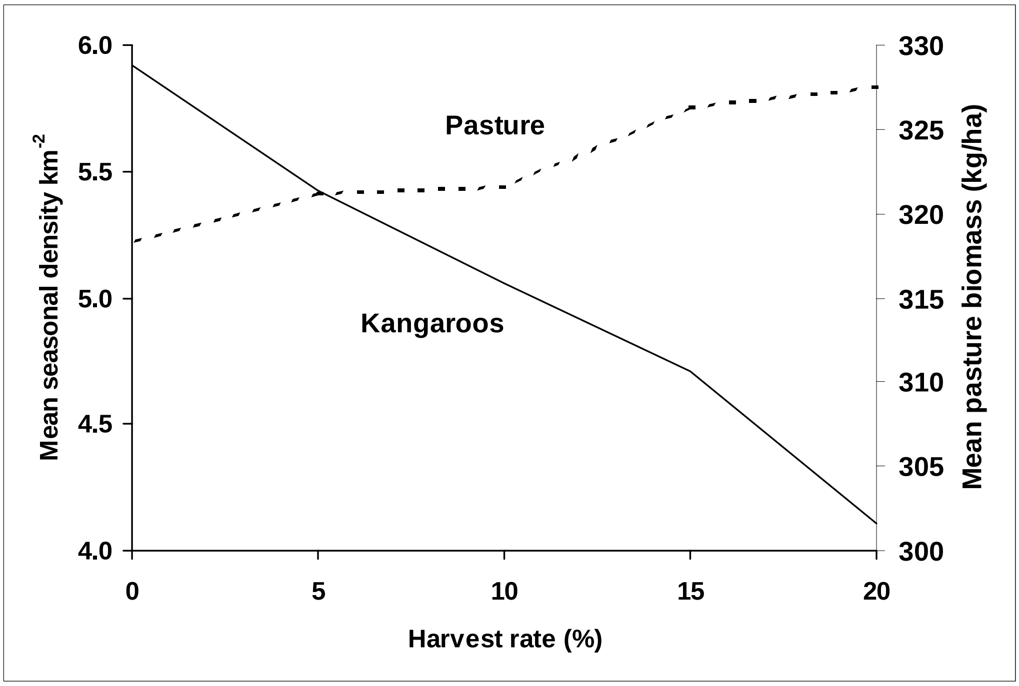


Fig. 11. Average population density and pasture biomass over 2002-2012 as a function of harvest rate during drought.

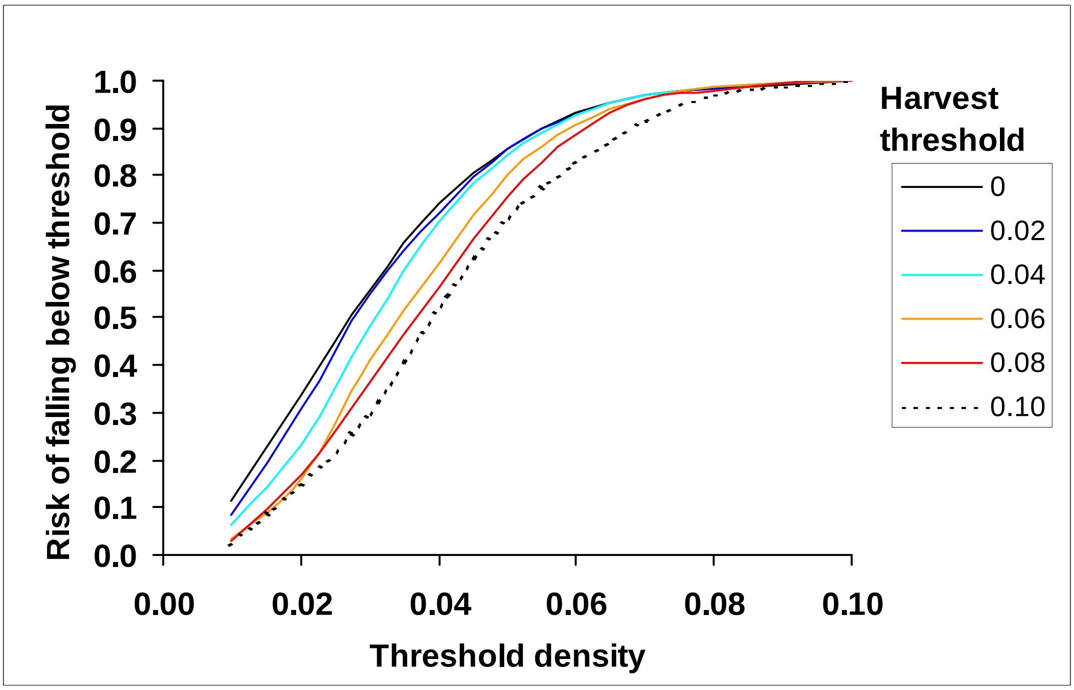


Fig. 12. Probability of quasiextinction over 2002-2012. Each line represents a different threshold density, where harvest rate is 15% above the threshold and zero below it.

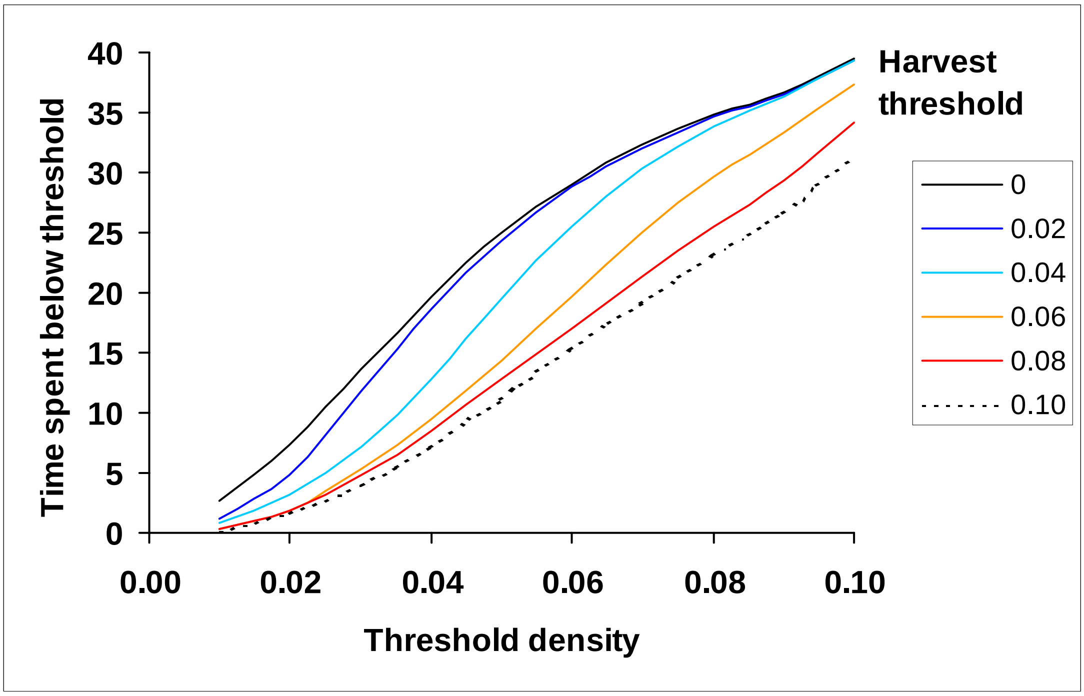


Fig. 13. Mean time (seasons) spent quasiextinct over 2002-2012. Each line represents a different threshold density, where harvest rate is 15% above the threshold and zero below it.

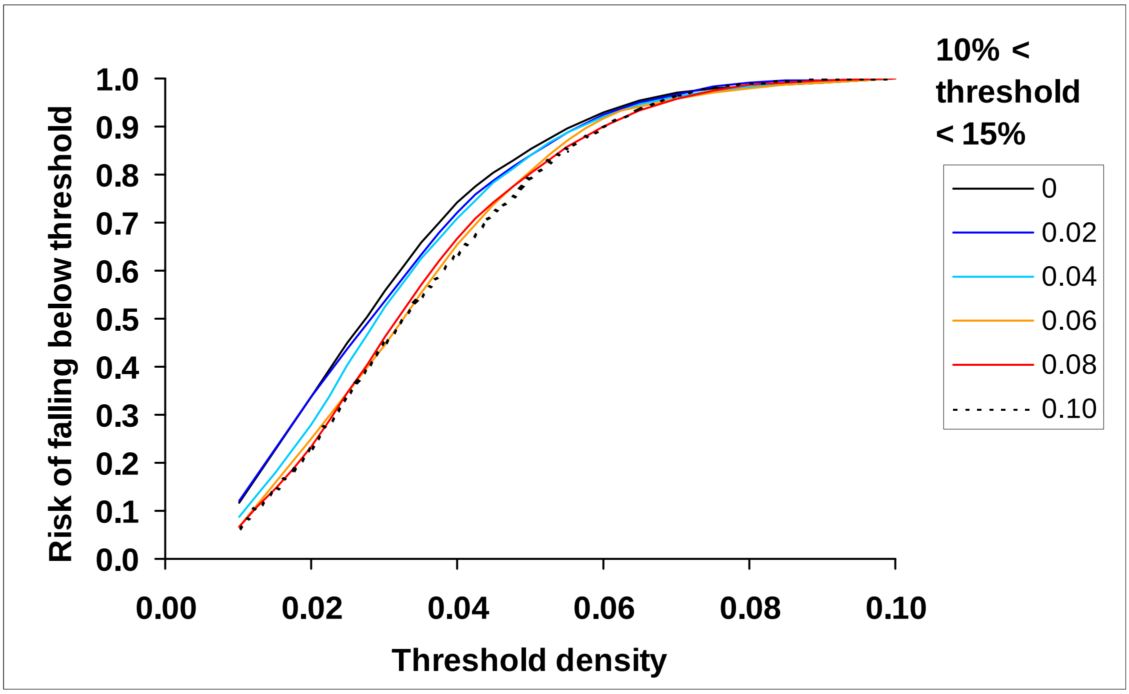


Fig. 14. Probability of quasiextinction over 2002-2012. Each line represents a different threshold density, where harvest rate is 15% above the threshold and 10% (cf. zero in Fig.12) below it.

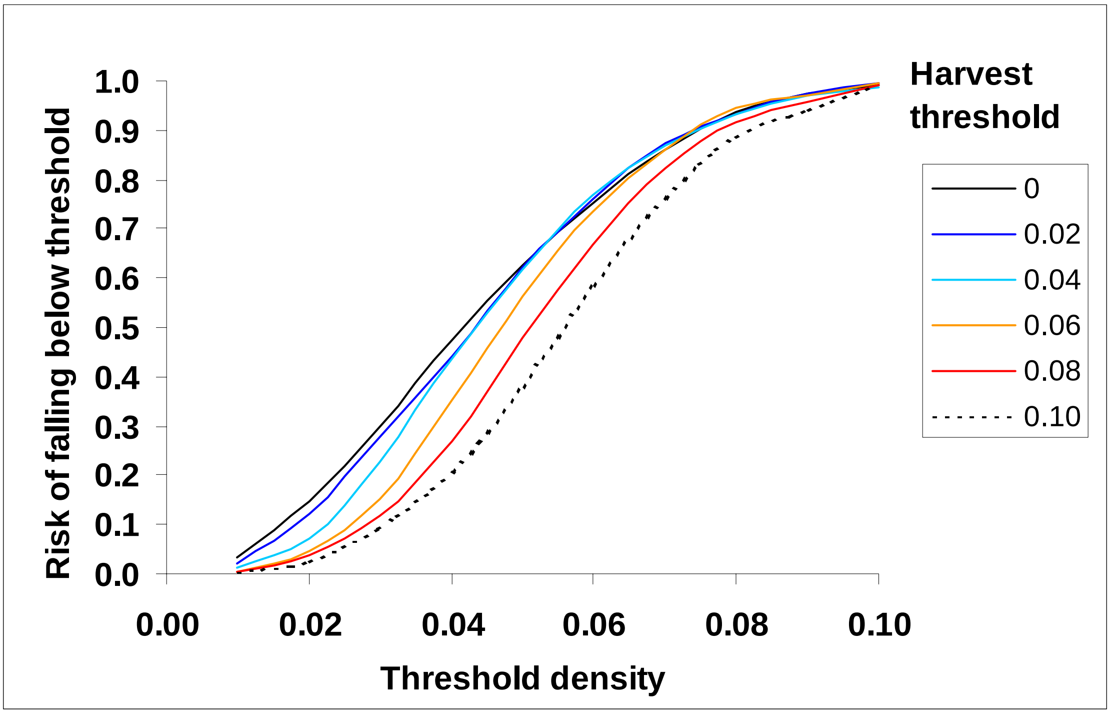


Fig. 15. Probability of quasiextinction over 20 years where a drought is not specifically modelled (cf. Fig. 12). Each line represents a different threshold density, where harvest rate is 15% above the threshold and zero below it.

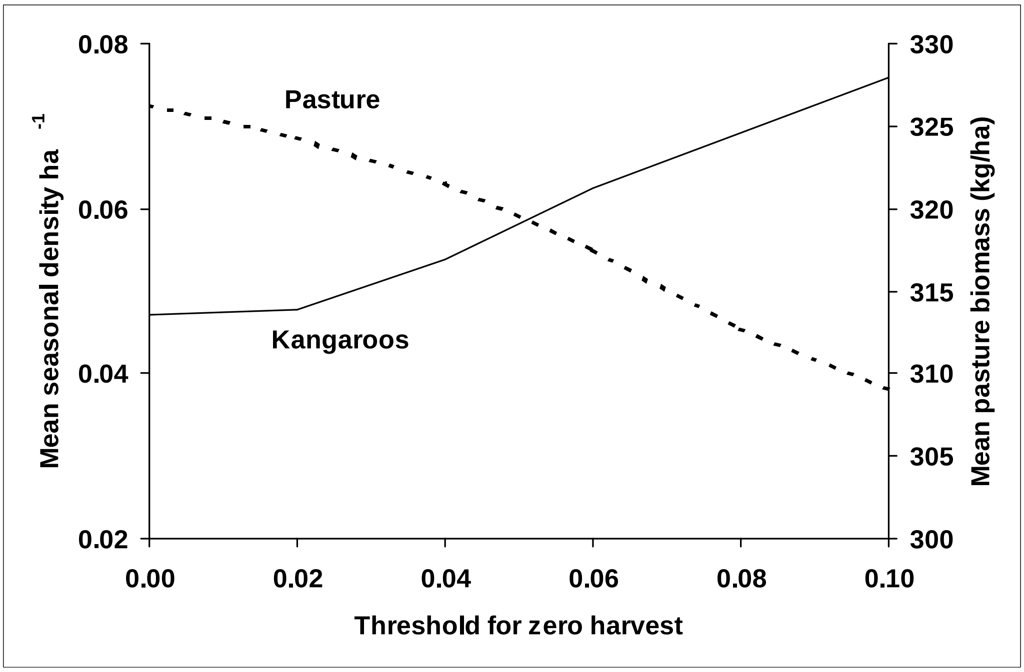


Fig. 16. Average population density and average pasture biomass over 2002-2012 as a function of threshold density, below which there is no harvesting.

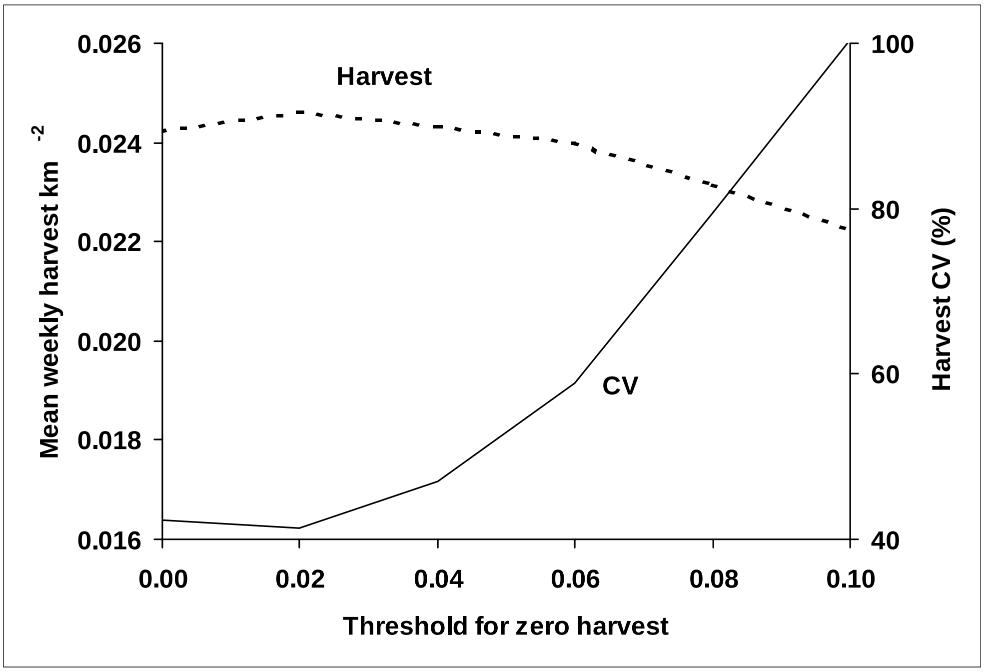


Fig. 17. Average weekly harvest and coefficient of variation (CV) of that harvest over 2002-2012 as a function of threshold density, below which there is no harvesting.

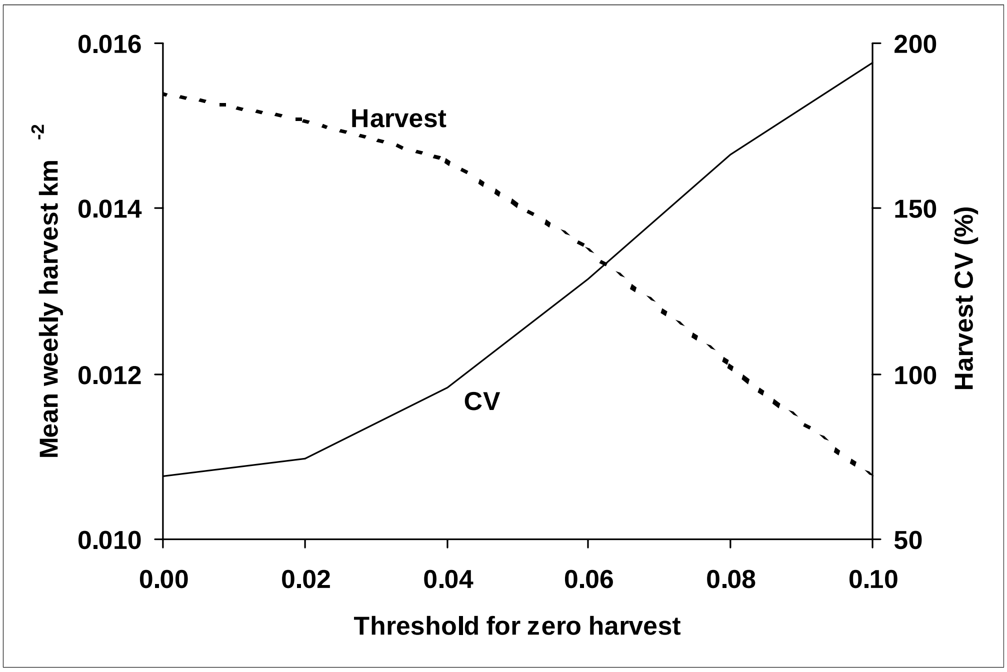


Fig. 18. Average weekly harvest and coefficient of variation (CV) of that harvest over 20 years as a function of threshold density, below which there is no harvesting. Drought is not specifically modelled in these simulations (cf. Fig. 17).

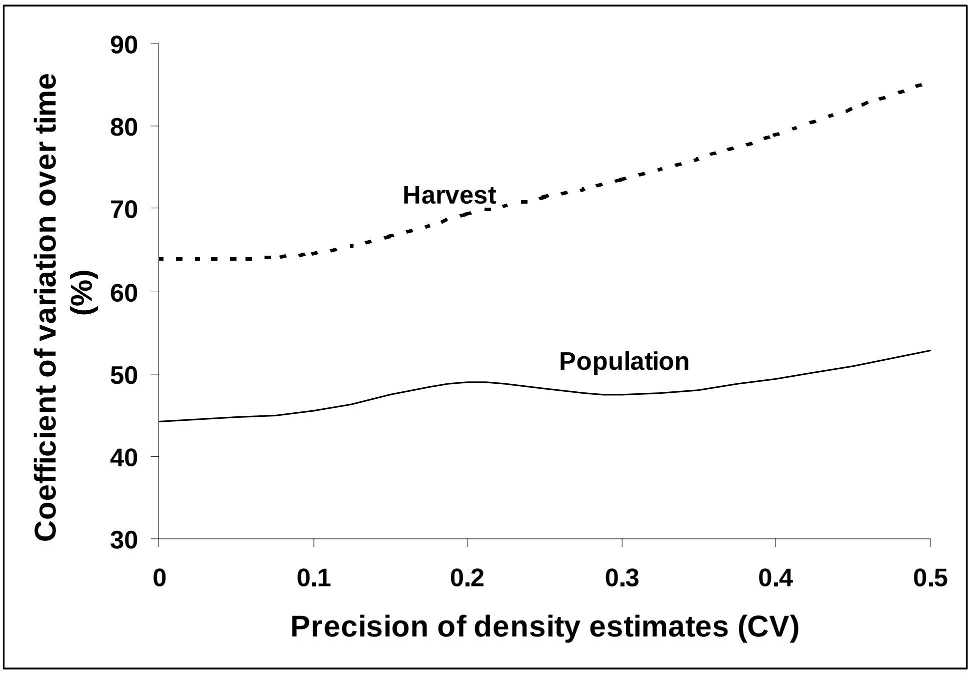


Fig. 19. Variability (CV) in seasonal population size and seasonal harvest offtake over 2002-2012 as a function of imprecision (CV) of annual population estimates.

3. Indicators of population decline and overharvesting

There are several possible indicators of population decline and overharvest, such as rainfall, modelled pasture and harvest statistics (e.g. sex ratio, carcass weight). They are attractive because can be monitored almost continuously and there are historical data with which to compare future data. The ability of some of these statistics to indirectly monitor kangaroo populations is currently being examined as part of a collaborative project between state government conservation agencies (including NSW NPWS) and the Ecology Centre at the University of Queensland and others. While final results are not available, some discussion is possible.

3.1 Rainfall and pasture

Numerical response models, describing the relationship between rate of increase of kangaroo populations and their food supply (either pasture biomass or a surrogate such as rainfall), have been developed in a number of studies including those of (Caughley 1987) and (McCarthy 1996). There is considerable noise in the relationship, resulting in broad confidence intervals in the prediction of future population size. Some of this noise is due to changes in the age structure of kangaroo populations, density dependence, competition from domestic stock, harvesting and variation in pasture response to rainfall. Nevertheless, the overriding influence of rainfall on population growth is clear, particularly during protracted drought. This can be gauged from matching trends in kangaroo numbers over the past 25 years with rainfall over that period (Pople and Grigg 1998). Numerical response models attempt to summarise this relationship.

Food is most obviously limiting during protracted drought and herbivore populations consequently decline. Outside of severe drought, food may not necessarily be limiting and may only be limiting to subsets of the population such as juveniles and groups of individuals in certain habitats. At these times, other limiting factors (e.g. predation, disease) may have a greater effect on rate of increase than food supply. In short, population decline in drought is more readily predictable than population change outside drought. The modelling here provides an estimate of the likely annual decline in kangaroo numbers of ~40-60% given rainfall that is 20-50% of the long-term average (Fig. 5). The model was parameterised on observations in the 1982-83 drought and obviously allows for declines greater than those observed in 1982-83 (see above).

Further problems include identifying the appropriate interval of rainfall to make predictions of population rate of change, discussed above in section 2.2.1, and the size of that increase or decline. Inspection of plots of rate of increase against rainfall for red and grey kangaroos in western New South Wales compiled by (Caughley, Bayliss *et al.* 1984) and (Bayliss 1985; Bayliss 1987) show a range of rates of decline when rainfall has been well below average. This is likely to be the result of both measurement error and regional and temporal differences in the response to drought. The combination of these sources of uncertainty makes accurate prediction of the rate of decline difficult.

3.2 Harvest statistics

3.2.1 Theory

Management authorities throughout Australia have routinely collected a number of harvest statistics. These data may provide information on population abundance (and therefore trend) and status (i.e. under- or overharvest). In New South Wales, carcass sex ratio, carcass weight and animals shot per unit time (i.e. catch per unit effort, CPUE) are presently recorded by NSW NPWS in each kangaroo management zone. In fisheries management, CPUE is a notoriously poor index of population size for a variety of reasons including improved catching efficiency and 'targeting' of fish stock (Hilborn and Walters 1992). Kangaroo harvesting is less prone to some of these problems and so the potential of harvest statistics to indirectly monitor kangaroo populations is worth exploring.

An index I is only useful if the 'proportionality constant' β connecting it to actual population size X (i.e. $I=\beta X$) does indeed remain constant between locations or over time (Lancia, Nichols *et al.* 1996; McCallum 2000). For CPUE to be an effective index of population abundance, a number of assumptions must therefore be satisfied (Caughley 1977). (Southwell 1989) identified several potential violations of these assumptions when monitoring kangaroo populations. These assumptions are discussed in turn below.

1. Harvesting equipment must be standardised.

Unlike fisheries, kangaroo harvesting equipment (i.e. vehicles, rifles, spotlight) has changed little over the past 30 years.

2. Harvesting efficiency must be standardised.

There is variation between shooters (e.g. part-time versus full-time shooters) in the speed in which they can shoot and process animals. As shooters turnover in areas, CPUE will therefore change. This factor will be less pronounced as data are pooled over larger areas.

3. Harvesting conditions (e.g. weather, access to animals and market prices) must be standardised.

As with any index of population size, CPUE is likely to be more useful in comparing estimates of population abundance over time rather than between areas (McCallum 2000). Regional differences in vegetation, road network and distance between towns will invariably lead to regional differences in CPUE. However, shooter success also varies with weather conditions. It is generally accepted that shooting is difficult in wet conditions when the ground is boggy (Prince 1984) or under windy conditions when animals seek cover and are restless, making them difficult targets. Shooting is considered easier during dry times when access is easier, ground cover is low and kangaroos tend to concentrate at watering points and on remaining food patches (Kirkpatrick and Amos 1985).

4. Harvesting of each animal is independent.

The relationship between CPUE and population abundance is unlikely to be linear, because of time saturation (Caughley 1977), whereby CPUE eventually reaches a plateau at some level of population density. Changes in abundance in this zone of saturation will not be reflected in the CPUE. If the density of interest is below this zone of saturation, which may be the case in drought, then the index could obviously still be useful.

5. Kangaroos do not learn to avoid shooters.

This is possible in the longer term of > 10 years, but is unlikely to be a problem for monitoring year-to-year changes in abundance.

These assumptions must also hold if aspects of harvest composition (e.g. sex ratio, carcass weight) are to be useful indices of population size or status. Harvest composition will change in quite different ways to CPUE and so it warrants separate discussion. Changes in the composition of the harvest will reflect one or more of three factors:

1. Changes in shooter selectivity due to the environment, prices or population density
2. Changes in population composition due to harvesting and
3. Changes in population composition due to the environment.

Kangaroos show considerable sexual size dimorphism, with males growing to 2-3 times the maximum size of females (Jarman 1989). Growth, particularly for males, extends well into adulthood and beyond the age at sexual maturity. Shooters are generally paid by carcass weight (although some human consumption shooting will be selective for intermediate sizes) or skin size so, not surprisingly, there is selection for larger, older, predominantly male kangaroos (Pople 1996). As populations decline, the rationale is that shooters will not be able to maintain this selectivity, and will therefore take fewer males, smaller animals and, overall, fewer animals per unit time. Similarly, as harvest rate increases, the age structure and sex ratio of the population will change. The sex ratio of the harvest should therefore shift towards females and average carcass weight should decline.

However, the composition of the population (i.e. size structure and therefore age structure and sex ratio) will also vary in response to the environment regardless of the rate that it is being harvested. In arid areas, it is well documented that kangaroo populations have unstable age distributions, resulting from pulses of recruitment during good seasons and no recruitment during drought (Frith and Sharman 1964; Kirkpatrick and McEvoy 1966; Newsome 1966; Newsome 1977). This is compounded by male-biased mortality during drought (Pople 1996); a mortality that may be further biased towards older animals (Robertson 1986). Assuming shooter selectivity remains constant, a surge in recruitment may lead to an increase in population size, but a decline in the size of harvested animals. Similarly, a shift in the sex ratio towards females during drought would see a decline in the size of harvested animals.

Again, regional environmental differences, affecting shooter access and selectivity, will lead to differences in harvest composition between areas. In addition, there are regional differences in kangaroo morphology, particularly body weight and overall size (Pople 1996), which will be reflected in the composition of the harvest. Harvest statistics will therefore be more useful in monitoring abundance or status over time rather than between areas.

3.2.2 Empirical support

Until recently, there has been limited analysis of harvest data. Pople (1996) examined the relationship between harvest statistics and harvest rate across several regions in Queensland. For red kangaroos, the effect of harvesting appeared to be detected in the size of male skins. However, the effect of drought in on the population sex ratio probably overshadowed any relationship between harvest sex ratio and harvest rate. For eastern grey kangaroos, carcass weight, skin size and harvest sex ratio all appeared to be potential indicators of harvest rate.

As mentioned above, the relationship between harvest statistics and population size is currently under investigation, but preliminary results indicate some potential application in drought.

In the northeast of the South Australian pastoral zone, trends in both the harvest sex ratio and CPUE for red kangaroos show a reasonable correspondence with trends in density over 1980-2001. In particular, the decline in red kangaroo numbers during the 1982-83 drought was accompanied by a sharp decline in the proportion of males in the harvest and CPUE. For western grey kangaroos, the relationships are not as strong.

In Queensland, declines in the densities of red and eastern grey kangaroos during the drought of the early 1990s have been mirrored by declines in the proportion of males in the harvest and in CPUE for each species. The subsequent recovery of the populations has been roughly tracked by the harvest sex ratio, more so than CPUE.

In both Queensland and South Australia, harvest composition and CPUE has varied regionally, but the trends over time have generally been in parallel. Two other factors need to be considered in the interpretation of these data. The trends in harvest statistics have also been matched by trends in harvest rate, which increases during declines and dry conditions. In Queensland, harvest rates dropped sharply in the mid 1990s following a drop in demand and therefore harvest offtake that coincided with population increases on the back of good rainfall.

4. Discussion

It is important to recognise that the results presented in section 2.2 are not predictions; rather, they are comparisons of the risks of various management scenarios. In all cases, it is the contrast between the harvest strategies (e.g. different harvest rates) that is relevant, rather than the actual statistics (e.g. probability of quasiextinction, time spent below a particular density).

More accurate predictions of the likely decline could be achieved with age-structured models. This would allow the impact of a selective harvest to be assessed and could better handle the varying relationships between survival and rainfall among age classes discussed in section 2.2.1. The qualitative results of section 2.2 are unlikely to have been altered by using age-structured model. An age structured model may have produced a *less* conservative assessment of risk, with a smaller decline for a given harvest rate because it is male biased and a more rapid recovery after the drought because of a strongly female-biased population

(Pople 1996). The interactive model uses a numerical response that is a simplification or average of a number of responses to rainfall arising from an unstable age distribution. An important difference between an age structured model and the unstructured model used here, is that the harvest rates modelled here will have a greater impact than the same rate in a harvest selective for males. In other words, the harvest rates examined here are equivalent to somewhat lower rates in practice. A further difference between the model and reality is that harvesting continued at very low densities. In practice, there will be a density below which it is uneconomic to harvest.

Section 2.2 does not identify the most appropriate strategy during drought (i.e. the acceptable level of risk). To do this, the various costs of taking or not taking action need to be traded off. These include the cost to management of increasing the frequency of broad scale survey. The cost to the kangaroo industry will be in reduced mean harvest and increased harvest CV. There are damage costs to the grazing community from increasing kangaroo densities particularly in dry times, perhaps represented as dry sheep equivalents or average or minimum pasture biomass. Lower pasture biomass can also be considered a conservation cost if it is associated with environmental damage. Finally, there are the ‘social’ (cf. economic) costs to the broader community of the population falling below certain densities. Some of these costs are fairly straightforward to estimate, but others are difficult to quantify, particularly in economic terms.

An example of dealing with tradeoffs is when the social cost of a 15% harvest is unacceptable (Fig. 6). The question then is whether to conduct a mid-term aerial survey or reduce the drought harvest rate to 10% (Figs 6 and 9). Adopting the latter incurs a cost to the industry in reduced harvests (Fig. 10) and to the grazing community in lowered pasture biomass and higher kangaroo densities (Fig. 11).

Alternatively, the population could be projected forward using rainfall and annual quotas set on the projections rather than the population estimate from the previous year. Projections would need to include uncertainty in future rainfall and would therefore be bounded by confidence limits. In this study, a continuation of the drought was modelled into 2003, to assess the risk of harvesting under pessimistic scenarios. Had average rainfall been modelled, a smaller decline (32%; 95% CI: 6-59%) resulting from the 2002 drought would obviously have been predicted. Again, an age-structured model would give more accurate predictions. Uncertainty in model parameters has not been included in these projections and would widen the confidence intervals.

A useful prediction from an age-structured model would be the threshold density, below which there is no harvesting, where harvest CV seems to increase steeply and mean harvest declines (Figs 17 and 18). This density is about 2 kangaroos km^{-2} for the interactive model. (Mean population density in the interactive model, when drought is not specifically modelled and there is no harvesting, is about 16 kangaroos km^{-2}) Above this density, costs to the kangaroo industry increase dramatically, mean kangaroo density rises sharply and pasture biomass declines, albeit almost linearly. If the social costs of the risk from this threshold density were acceptable, then it may be worth imposing. Including a low threshold will still reduce quasiextinction risk with little cost to the industry or grazing community. Figure 18 suggests it may even increase harvest offtake. An increased yield from a threshold harvesting strategy has been shown generally for harvesting fluctuating populations under uncertainty (Engen, Lande *et al.* 1997; Milner-Gulland, Shea *et al.* 2001). In practice, under the current economic climate, the industry is not economically viable at a regional density of about 3-5 kangaroos km^{-2} (S. McLeod NSW Department of Agriculture, unpublished data). Imposing a threshold density would effectively be enshrining what currently occurs. This would provide a safeguard in case of increases in the value of harvested kangaroos and increase public confidence that the harvest is sustainable, because they would not be reliant on the industry to stop harvesting because of market forces.

The review of indirect monitoring suggests that different indicators may be appropriate at different times. In drought, rainfall seems a simple and appropriate predictor of likely decline in drought. Outside of drought, rainfall is a less reliable predictor, for the reasons outlined in section 3.1. Obviously, rainfall will be of little help if population density changes in response to factors other than rainfall. Harvest statistics, particularly sex ratio, may indicate population trends or status under these conditions.

Glossary

Quasiextinction risk is the chance of the population falling below some threshold density. This threshold may be unacceptable for conservation, management or aesthetic reasons (Burgman, Ferson *et al*. 1993). For large kangaroos, this density is critical for economic and aesthetic reasons. The density would have to be extremely low to be demographically critical, where demographic accidents, genetic factors and behaviour can influence species' persistence. The sheer size of each kangaroo species' population buffers it against these effects. Problems of small population size are still theoretically possible at a local scale, but the risk will be negated by well-connected local populations (i.e. distribution is not patchy) and only small rates of immigration.

Overharvesting refers to excessively high harvests that are unacceptable on conservation, economic or aesthetic grounds. Overharvesting may result in reduced long-term yields if harvest rates are much greater than the maximum sustainable yield. It may also reduce the population to densities that are below some acceptable minimum density (i.e. quasiextinction). Underharvesting results in higher average population densities that may result in unacceptable grazing impacts. It may also result in reduced long-term yields if harvest rates are well below the MSY.

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